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THEORETICAL ANALYSIS OF WIND TURBINE USED TO POWER A STAND-ALONE SOLAR DESALINATION UNIT IN SELECTED COASTAL AREAS OF EGYPT

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ABSTRACT

Theoretical analysis of wind turbine used to power a stand-alone solar desalination unit in selected coastal areas of Egypt is presented in this work. The selected coastal areas are; Mersa-Matruh and Sidi-Barrani on the Mediterranean Sea coast and Hurghada on the Red Sea coast. In these areas, the fresh water shortage is significant problem and the wind energy is usually high that used in renewable energy applications. The available wind data of the selected areas are collected from meteorological station along these coastal areas of Egypt. The wind data are analyzed in a form useful for wind turbine characteristics and wind energy computation. The annual mean wind speeds are 5.3, 5.0, and 6.3 m/s for Mersa-Matruh, Sidi-Barrani, Hurghada, respectively. The acoustic noise analysis and calculation from the proposed wind turbine are presented. The proposed solar desalination system is considered as conventional solar still and simple system of breaking the boundary layer of the basin water surface to enhance the performance of the solar desalination system. This simple system is helical shaft that installed near to the basin water surface. The helical shaft is running with slow speed by using small motor. This motor powered by the considered wind energy. This study aimed at evaluating of the mean wind speed for the selected areas to determine the

characteristics of the suitable wind turbine and compute the amount of captured wind energy to power the proposed solar desalination system. Analytical assessment is presented to determine the power available from the wind stream. The analytical assessment reveals that the coastal areas of Egypt offer sufficient wind energy for economic utilization of requirement of energy in these communities. The results show that Hurghada and Mersa-Matruh have the highest amount of wind energy, power and distillate water productivity due to the climatic district.
KEYWORDS: desalination, renewable energy, wind energy, wind power and wind turbine characteristics.

1- INTRODUCTION

Energy conservation, pollution prevention, resources efficiency and the importance of clean energy sources are vital terms for suitable investigation of the alternative energies. Wind energy seems to be a promising alternative and renewable energy. Egypt has two coastal zones that show significant promise for wind energy exploitation, the north coast on the Mediterranean Sea and east coast on the Red sea. Mediterranean coasts are strong wind and are characterized by a wide flat coastal area along the sea. Wind energy applications in Egypt are still limited despite the fact that there are coast and some of remote desert areas enjoying a sufficiently high wind potential and at the same time most of them being with or without expensive access to fuel supply and electricity. Also, these areas are suffering from the shortage of the fresh water. This study aimed to desalinate the sea water in the selected areas by the proposed solar desalination system depends on the generated wind energy. There are many researches on wind energy applications, wind turbine systems and its performance analysis (Ozgener (2006), Fuglasng & Madsen (1999), Robinson (1996), and Sadhy (1995)). Wind average speed depends on many parameters and can vary a lot in the same area. The wind laminar flow over the surface is distributed by many obstacles and topographic variations. This has two consequences: wind speed decreasing near the earth and turbulences. Both of them diminish as the height increases. A reasonable security margin is 10m above any obstacle within 100m. Even in smooth areas, 10m is advisable, (Spera (1994) and Sahin et al. (2006)). Renewable energy is abundant and its technologies are well established to provide complete security of energy supply. Among renewable energy sources, wind energy plays an important role, (Wrixon et al. (2000)). Ideally, applied research activities should conducted by several technical disciplines, such as; aerodynamic, materials, structures, fatigue, meteorology, aero acoustics, control and power systems and manufacturing, (Snel (2003), Muljadi & Mckenna (2001), Van Dam et al. (2002), Rasmussen et al. (2003) and Mallick (1997)). Before the installation of any wind turbine, it is necessary to estimate the expected power output in order to assess the economic viability of the investigation, usually based on wind data measured over a period of at least one year, (Barthelmie & Palutikof (1996)). Provisional estimation of the energy output of wind generators is presented (Pallabazzer (2004)).

This work presents theoretical analysis of wind turbine used to power a stand-alone solar desalination system in some of coastal areas of Egypt. The proposed solar desalination unit consists of conventional solar still and simple system which it is used to break the boundary layer of the basin water surface. This simple system is a helical shaft that installed near to the basin water surface. The helical shaft is running with slow speed by using small motor. This motor powered by the considered wind energy. Average wind energy and power densities of the chosen wind turbine are presented. Data analysis for resource characterization and wind energy generation are presented.

2- THEORETICAL ANALYSIS OF THE PRESENT SYSTEM

The system analysis includes wind characteristics, wind turbine, acoustic noise and solar desalination unit.

2-1 Wind Turbine

The present wind turbine is characterized as the following

1- Horizontal axis.

2-Upwind type

3-Three blades which fixed blade pitch with stall control and composite-fiber glass reinforced plastic.

4- Orientation: self aligning (Free Yaw).

2-1-1 Available wind power

The specific power available from the wind stream in a cross area (A, m^2) perpendicular to the wind stream moving at speed (V_W, m/s) is equal to the rate of the incoming kinetic energy (E_K) as the following:

$$P_W = \dot{m} \times E_K = \frac{1}{2} \dot{m} \times V_W^2 \quad \text{, Watt} \tag{1}$$

Where $\dot{m}$ is the air (wind) mass-flow rate, kg/s and equals as follows:

$$\dot{m} = \rho \; A \; V_W \quad \text{, kg/s} \tag{2}$$

Where □ is incoming wind density, and at normal temperature and pressure, equals (1.225kg/m^3) and A is the rotor disk area.

From equations (1) and (2), the theoretical wind power (P_W) can be expressed as:

$$P_W = \frac{1}{2} \rho \; A \; V_W^3 = 0.635 \quad A \; V_W^3 \quad \text{, Watt} \tag{3}$$

The wind power density (power per unit area) is written as follows:

$$\frac{P}{A} = \frac{1}{2} \rho \quad V_W^3 \text{, W/m}^2 \tag{4}$$

The average wind power density based on hourly average is written as:

$$\frac{\bar{P}}{A} = \frac{1}{2} \rho \quad \bar{V}_W^3 \quad k_e \quad \text{, W/m}^2 \tag{5}$$

It is noted that: [$100 W/.m^2 \; (poor) \geq \frac{\bar{P}}{A} \geq 700 \; W/m^2 (great)$] (6)

Where k_e is energy pattern factor and $\bar{V}_W$ is average annual wind speed.

$$k_e = \frac{1}{N \quad \bar{V}_W^3} \sum_{i=1}^{N} v_{W,i}^3 \tag{7}$$

Combining Equations (5) and (7), the average wind power density becomes as:

$$\frac{\bar{P}}{A} = \frac{\rho}{2 \quad N} \sum^{N} v_{W,i_i}^3 \tag{8}$$

Wind energy generated by the present wind turbine E_g, kWh, by the wind turbine is $\left(\frac{\bar{P}}{A}\right)(N \times \Delta t)$ where N is number of hours in a year and equals 8760. Thus, the total power of the wind stream is directly proportional to its cross area (A) and cubic of its velocity. The maximum theoretical power that may be converted into mechanical energy by impeller is 59.3 % of the kinetic energy in the wind, (Marks Handbook).

The sources of the physical and climatologically data employed in this work are provided by Egyptian Meteorological Authority (EMA data (1995)). These data are provided for a period of more than 10 years, Table 1. These data are mean annual values. It is clear from the Table 1 that the wind speed has a maximum value of 6.3 m/s at Hurghada.

Table 1 Physical features and climatologically data of the selected coastal areas

Selected Coastal areas	Coordinate		Elevation, m	Ws, m/s	I, kWh/m^2d	S, hours	T_o, ^oC
	Lat, deg.	Long., deg.					
-Mersa-Matruh	31°2\`	27.13	28.3	5.3	5.62	9.3	19.35
-Sidi-Barrani	31° 38\`	25.28	21.0	5.0	5.3	9.38	19.35
- Hurghada	27°17\`	33°46\`	1.0	6.3	7.8	10.66	22.65

2-1-2- Acoustic noise of the present wind turbine

Wind turbine generated sound that is perceived at any given location and is a function of wind speed as well as turbine design, distance, ambient sound levels and others. A three-bladed horizontal axis wind turbine with a radius assumed 5.0m downwind model is presented. A computational methodology for the noise prediction of a horizontal axis wind turbine (HAWT) rotor in time domain is demonstrated in this section. The noise source mechanisms considered are the unsteady thickness and loading components of the overall sound propagation. The overall noise magnitudes obtained by integrating contributions of all acoustic sources over the actual rotor's geometry for any observer position. The value of equivalent A-weighting sound pressure level, SPL_{eq}, of a continuous steady sound within a specified time interval starting at t_1 and ending t_2 that has the same mean square sound pressure as a sound under consideration, whose level values with time is given as the following formula:

$$SPL_{eq} = 10 \log \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \left(\frac{p_A(t)}{p_o} \right)^2 dt \right], \text{ dB} \qquad (9)$$

Where $P_A(t)$ is the aero-acoustic pressure of noise in Pascal (Pa).

The value of sound pressure level, SPL (f), in decibels, is determined using the frequency weighting network, and the reference sound pressure, P_o is 20□Pa (2x10^{-5} N/m^2). On the basis of the source strength level, $L_{s,\,ref}$ of the sound power of the wind turbine at the reference wind speed that is radiated in the downwind direction and therefore relevant for the sound pressure levels in the environment of the wind turbine, the sound pressure level, SPL_s, in the downwind direction at the distance, L, from the base of the tower to the point of prediction, which describes hemispherical propagation over reflecting ground, is predicted as the following formula:

$$SPL_s = L_{s,\,ref} - 10 \log (2\pi (L^2 + H^2)) - \alpha_a \sqrt{L^2 + H^2}, \text{ dB} \qquad (10)$$

Where α_a is the frequency-dependent sound pressure air absorption coefficient, and estimate here 0.005dB/m, H is the hub height, m and $L_{s,\,ref}$ was recorded according to IEA International Energy Agency procedures. Upwind of wind turbine there may be locations where no sound is heard. On the other hand, sound may be propagated more easily downwind.

The time domain numerical results from the above analyzed predication method, are Fourier analyzed and converted to frequency domain, [17]. The resulting solution P_A (f) is used for the computation of the sound pressure level spectrum of the noise radiation. This SPL is determined by:

$$SPL\ (f) = 10 \log \left(\frac{P_A\ (f)}{P_o} \right) \qquad (11)$$

The directivity of a single source for equally spaced circular observer positions at standard frequency is also, presented.

2-2- Present solar desalination system

The fresh water shortage is a significant problem in many areas of the world such as remote areas, deserts and coastal zones. However, renewable energy potential in these areas is usually high using solar and wind energy. A solar desalination unit is modified by using a rotating shaft that installed near to the basin water surface. The rotating shaft is running used special motor which powered by the considered wind energy. The target of using the rotating shaft is breaking the boundary layer of the basin water surface, thus increasing the water vaporization and condensation. The performance of the present solar desalination system will also be increased. To calculate the power needs of the rotating shaft, some analysis are drawn.

The rotating shaft motion during breaking the boundary layer of the basin water is considered as a forced convection and can be described as the following equation:

$$q_m = h_{Cm}\ (T - T_\infty)\ \text{W/m}^2 \qquad (12)$$

Where h_{Cm} is the convective heat transfer coefficient and can be calculated as:

$$h_{Cm} = Nu\,\frac{K_s}{D}\quad \text{W/m}^2\ {}^{o}\text{C} \qquad (13)$$

Where D (m) is the shaft diameter, K_s (W/m ^{o}C) is thermal conductivity of the rotating shaft, Nu (dimensionless) is Nusselt-number and can be calculated from:

$$Nu = C \times \mathrm{Re}^m \times \mathrm{Pr}^{\frac{1}{3}} \qquad (14)$$

Where C is constant, $0.4 \le \mathrm{Re} \le 4 \times 10^5$ *and* $\mathrm{Pr} \ge 0.7$ (15)

The power transmitted by the motor is determined as the following equation:

$$P_m = V_m\ I_m \cos\phi\ \text{W} \qquad (16)$$

Where V_m is the voltage, volts, I_m is current, amperes, and ϕ is the phase angle in range of 0.75 to 0.9^o. Here, motor current flow, I_m = 10 amps, motor voltage, V_m = 38 volts, output power, P_m = 0.5 hP $\approx$ 0.37 kW, armature resistance, R_a = 0.1 Ω and motor angular speed, ω_m = 100 rad./s = 958 r.p.m.

The efficiency, η of the modified solar desalination system using the rotating shaft is expressed by the ratio of daily distillate water productivity (W_d in liter/m^2 day) to the net input energy (q_{net} in W/m^2) that utilized in water vaporization and rotating shaft as:

$$q_{net} = q_{ew} - q_m \text{ , W/m}^2 \tag{17}$$

Where $$q_{eW} = \frac{W_d \times 10^{-6} \times \rho_W \times L_W}{3600} \tag{18}$$

Then the efficiency of the proposed desalination system is:

$$\eta = \frac{q_{outputt}}{q_{net}} = \frac{W_d \times \rho_W \times L_W}{(I_S - P_m)} \ \% \tag{19}$$

Where, W_d is distillate water productivity from this modified desalination unit.

3- RESULTS AND DISCUSSIONS

From the current study, the theoretical results and discussions are presented. Figure (1) shows the effect of common heights (10, 30 and 50m) of wind turbine above the ground level on the annual average specific wind power. It is found that Hurghada has the highest average wind power due to its highest wind speed, (Red Sea) at all common heights of the wind turbine, while Mersa-Matruh and Sidi-Barrani has average wind power in amount of 65 and 85W/m^2 at a height 10m, 170 and 205W/m^2 at a height 30m, however, 260 and 305 W/m^2 at 50m, respectively according to its wind speed where the wind power is directly proportional of cubic wind speed.

To fully evaluate the potential wind power density, it is desirable to develop refined data (recorded wind speed). To choose the appropriate wind turbine size for fulfilling the requirements of a desired application, Figs. (2) is plotted. This Figure indicates the wind power density that may be expected using assumptions in relation to various wind speeds and rotor diameters. If a well-designed rotor with an efficiency of 75% of the theoretical value and a generator with an efficiency of 90% are assumed. It is an important indicator of wind characteristics at selected sites. The wind power-speed curves for the selected sites are estimated and illustrated in Fig. (3). Using Equation (3), Table (1) and above assumptions, the wind power captured per unit swept area, (A_S), is: $\frac{P_W}{A_S} = 0.254\ V_W^3,\quad W/m^2$. It is found that Hurghada site has the highest captured wind power as the results of the highest recorded wind speed. Figure (4) shows the daily wind energy generated by several wind turbines due to wind speed, E_g, kWh. From this Figure, the order to obtain reasonable and required wind energy of the case study can be chosen. It is found that Hurghada site has wind energy of 0.61, 1.4, and 3.9 kWh by the selected wind turbines (1, 2, and 4kW), respectively which its average wind speed was 6.3 m/s. Sidi-Barrani site has 0.25, 0.51, and 2.2 kWh by the same selected wind turbines while; Mersa-Matruh has 0.4, 0.58, and 2.25 kWh by the same wind turbine. From these results analysis, medium size wind turbine is suitable and may be used for the mentioned desalination unit. Figure (5) shows the view of observer reference frame (ORF). The zero azimuthally angle starts at y-axis (ψ = 0) and the rotation is clockwise. The polar form of noise radiation for a single frequency source of 400 Hz is shown in Fig. (6). Figures (7-9) present the overall broadband spectra for near and far field observer positions. It is clearly stated that far-field radiation is significant increasing the community annoyance. Therefore, the difference between near and far field is almost 15 dB for the regarded blade passage frequency as shown in the figures. The predicted far-field sound spectra produce significant peaks in low and mid-range frequencies. The desalination system efficiency for the selected sites is presented in Fig. (10). It is found that the efficiency of the proposed desalination system in Hurghada site > Mersa-Matruh.> Sidi-Barrani. These results due to the climatic conditions of the sites (wind speed and solar radiation).

4- CONCLUSIONS

This work presented theoretical analysis of wind turbine used to power a stand-alone solar desalination unit in selected coastal areas of Egypt. From the theoretical results, the following conclusions are drawn:

1- The wind energy potential along the coast of the selected areas is quite promising, because the chances of having wind speeds are 5.3, 5.0, and 6.3m/s for Mersa-Matruh, Sidi-Barrani, and Hurghada, respectively, Table 1.

2- The selected sites are very suitable for electric wind applications, because the wind speed range for electricity generation is 5-6 mls, [18].

3- The study of the available average wind power at the common heights of wind turbine (10, 30 and 50m) for the selected sites indicates that, these selected sites have good wind power.

4- Hurghada has the highest average wind power, (Red Sea) at all common heights of the wind turbine, while Mersa-Matruh and Sidi-Barrani has average wind power in amount of 65 and 85W/m^2 at a height 10m, 170 & 205W/m^2 at a height 30m, and 260 and 305 W/m^2 at 50m, respectively according to its wind speed where the wind power is directly proportional of cubic wind speed.

5- Hurghada site has wind energy of 0.61, 1.4, and 3.9 kWh by the selected wind turbines (1, 2, and 4kW), respectively.

6- Sidi-Barrani site has 0.25, 0.51, and 2.2 kWh by the same selected wind turbines.

7- Mersa-Matruh has 0.4, 0.58, and 2.25 kWh by the same wind turbine.

8- The medium size wind turbine is suitable and may be used for the mentioned desalination unit.

9- The difference between near and far field is almost 15 dB for the regarded blade passage frequency

10-The predicted far-field sound spectra produce significant peaks in low and mid-range frequencies.

11-The efficiency of the proposed desalination system in Hurghada site > Mersa-Matruh.> Sidi-Barrani.

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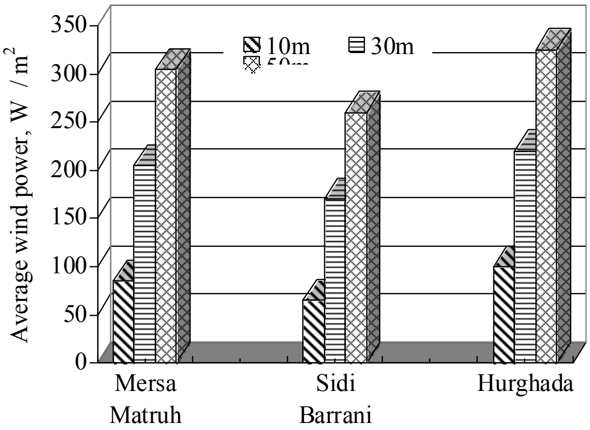

Fig. (1): Averge wind power at the common heights of wind turbine for the selected sites

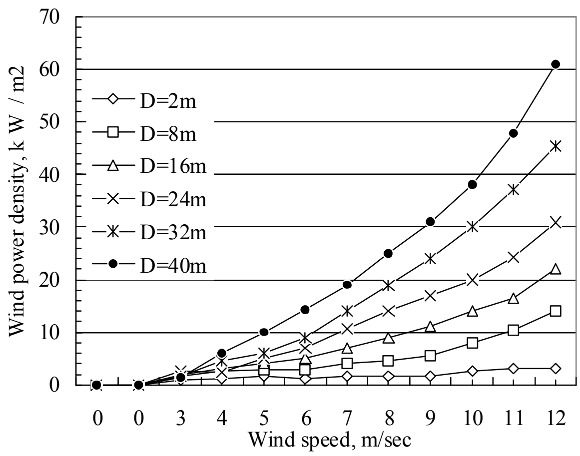

Fig. (2): Wind power density for small size wind turbines

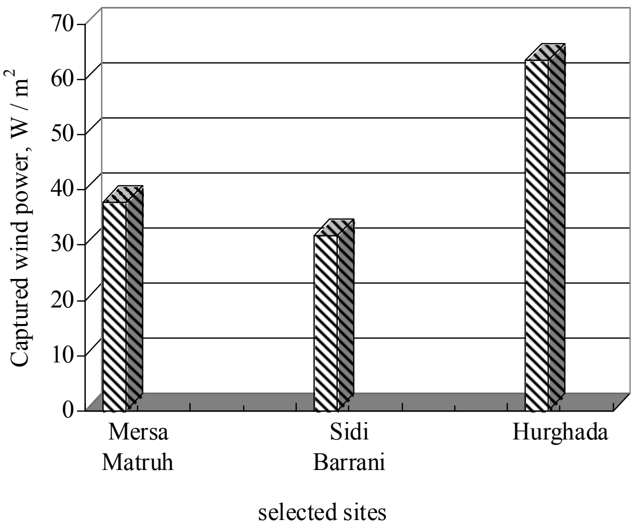

Fig. (3): Wind power-speed chart for the selected sites

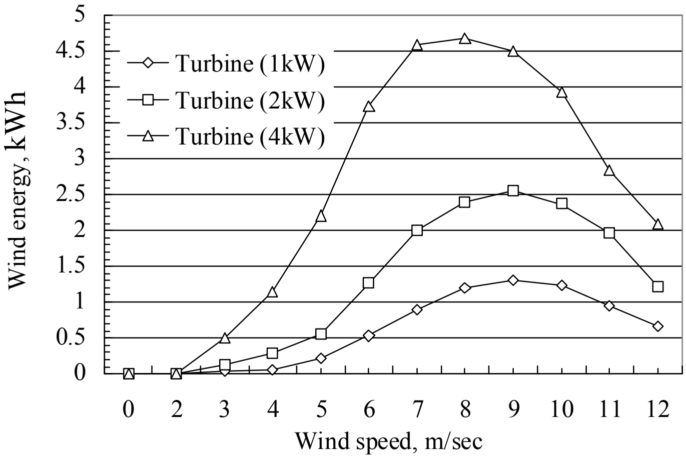

Fig. (4): Wind energy generated by several wind turbines at height 10m

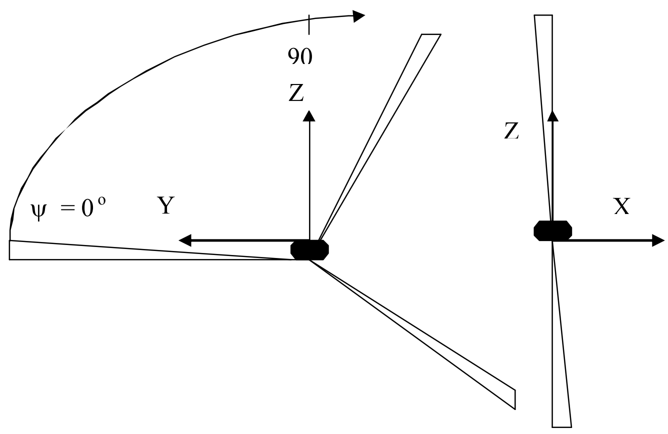

Fig. (5). View of observer reference frame (ORF).

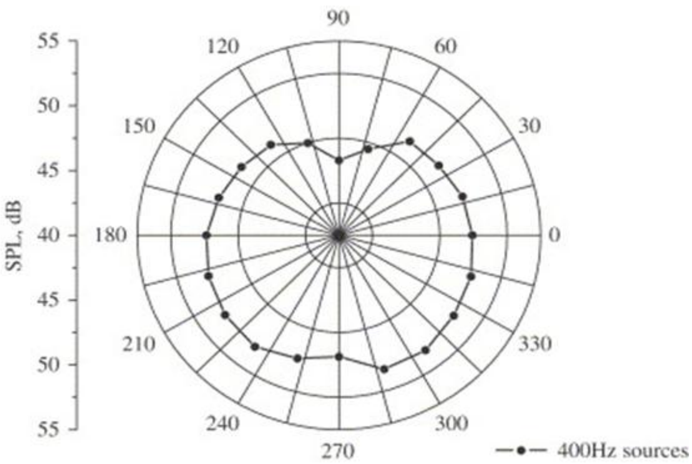

Fig. (6): Polar form of noise radiation for a single frequency source of 400 Hz

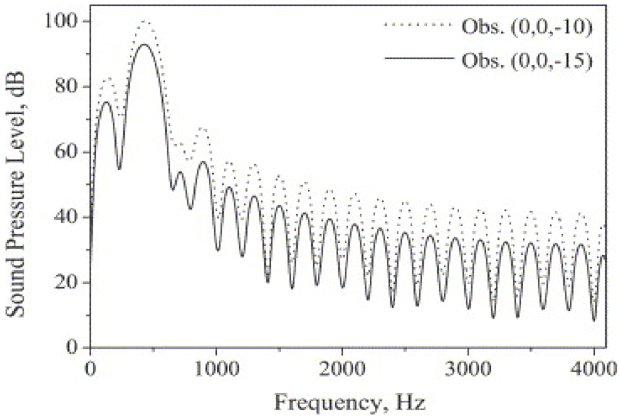

Fig. (7): Noise spectra for different observer positions

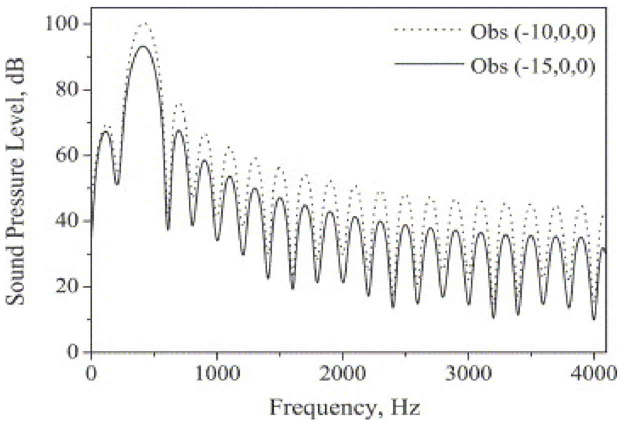

Fig..(8): Noise spectra for different observer positions

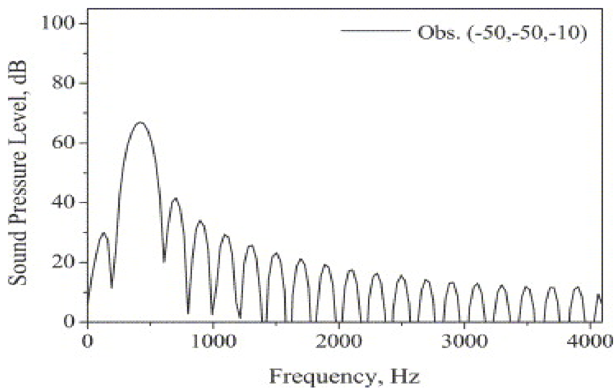

Fig. (9): Predicted far field noise spectra.

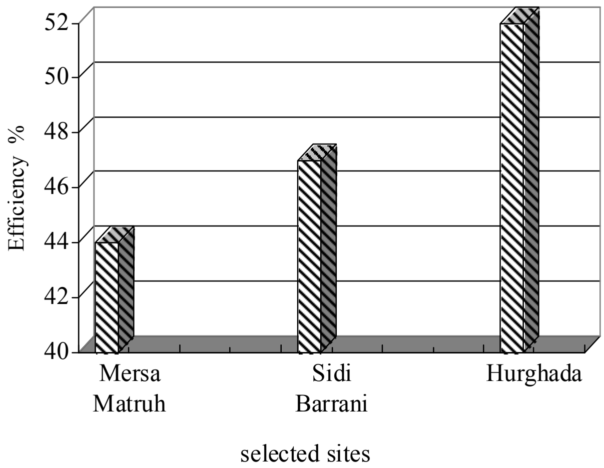

Fig. (10): Desalination system efficiency for the selected sites.

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Long-range sound propagation over the sea with application to wind turbine noise

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Abstract

Spherical wave propagation is not valid at large distances from a sound source in the atmosphere due to the influence of wind and temperature gradients that refract, i.e., bend the sound waves. This will in the downwind direction lead to a cylindrical type of wave spreading for large distances (>1 km). Cylindrical spreading will give a smaller damping with distance as compared to spherical spreading (3 dB/distance doubling instead of 6 dB). But over areas with soft ground, i.e., grass land, the effect of ground reflections will increase the damping so that, if the effect of atmospheric damping is removed, behaviour close to a free field spherical spreading often is observed. This is the standard assumption used in most national recommendations for predicting outdoor sound propagation, e.g., noise from wind turbines. Over areas with hard surfaces, e.g., desserts or the sea, the effect of ground damping is small and therefore cylindrical propagation could be expected in the downwind direction. This observation backed by a limited number of measurements is the background for the Swedish recommendation (Swedish Environmental Protection Agency report no. 6241), which suggests that cylindrical wave spreading should be assumed for distances larger than 200 m for sea based wind turbines. The purpose of this work was to develop measurement procedures for long range sound transmission and to apply this to investigate the occurrence of cylindrical wave spreading in the Baltic Sea.

Introduction

In the light of the Kyoto protocol development of large off shore wind turbine farms are currently planned or under construction in large parts of Europe[1]. However, to be accepted by the population this development should not add new noise disturbances. Therefore the need to establish correct and accurate models for long distance sound propagation over see is considered urgent.

When a source is placed at a sufficient height above the ground, in a stable atmosphere, the sound waves propagates spherically. However, at long range, the spherical sound wave propagation model cannot be applied anymore. The wave refraction effects due to wind and temperature gradients during downwind conditions tend to produce a more cylindrical wave spreading. The sound waves are curved downward towards the ground due to the gradients, then reflected up and the process is repeated leading to a trapped sound wave and a cylindrical type of wave spreading. In certain cases, the sound attenuation from the ground can nullify this effect and the propagation become close to a free field transmission. However, when the ground damping is weak, over areas with high impedance like rocky terrain, desserts and seas, cylindrical spreading could be expected[2,3,4,5]. Present knowledge[2] shows that there exists a risk for low frequency noise disturbances from sea based wind turbines. This risk is attributed to a cylindrical sound propagation under downwind conditions and that this can be especially pronounced under certain atmospheric conditions, e.g. “low level jets” and to the fact that the sound attenuation is weak over the sea.

A simple model[6] to calculate noise from wind turbines has been suggested by the Swedish Environmental Protection Agency. Based on a small number of old observations, e.g., Ref. 3, the procedure[6] recommends that for sea based wind turbines cylindrical wave spreading should be assumed for distances larger than 200 m. The 200 m choice for the breaking point is motivated in Ref. 2.

Concerning more recent investigations of sound transmission over the sea the work Konishi et al.[7] and Konishi and Maekawa[8] should be mentioned. They investigated long range and long term sound transmission for frequencies between 250 and 1000 Hz for receivers placed between 5 and 6 km from the source. A maximum length sequence signal (MLS) correlation method was used in order to perform measurements with a low signal-to-noise ratio. But in the analysis the acoustic data was not linked to the atmospheric conditions, e.g., humidity and temperature. It is therefore difficult to use their results for the total acoustic damping, to obtain the damping due to geometrical wave spreading, which is the quantity of main interest here.

The purpose of this work is to investigate the relative occurrence of cylindrical wave spreading over the sea and to judge its importance for noise imission from sea based wind turbines. The paper will first describe the measurement procedure developed for long range measurements of sound and then the measurements performed in the Baltic region during June 2005 and 2006.

Sound propagation over the sea at large distances

In order to obtain a simple model that describes the effect of downwind refractive effects and a resulting cylindrical wave spreading we now introduce a reflecting layer in the atmosphere at height H. In the case of strong reflecting phenomena such as so called “low level jets”, H can be interpreted as the average height of the jet. Low Level Jets (LLJ)[9] are phenomena that can occur during certain periods of the year over the Baltic and give rise to rapid changes (gradients) in the wind speed at relative low heights (a few hundred meters). Due to the reflecting layer sound from a source will be enclosed and spherical waves will at distances $r > H$ appear (on the average) as a cylindrical wave, see Figure 1. For distance $r > H$ the sound power W from the source is propagating along a cylindrical surface. This gives:

$$W = \frac{\tilde{p}_r^2}{\rho c} \cdot 2\pi r H, \tag{1}$$

the power can also expressed assuming a free field reference position at r_0:

$$W = \frac{\tilde{p}_{r0}^2}{\rho c} 4\pi \cdot r_0^2, \tag{2}$$

where $\tilde{p}_r^2$ is the sound pressure at the receiver point, r is the distance of the propagation, H the (average) height of the reflecting atmospheric layer (e.g. a LLJ), W the sound power of the source, $\tilde{p}_{r0}^2$ is the sound pressure measured at the reference distance $r_0 = 1\text{m}$ (in our case), ρ the air density and c the sound speed. It can be noted that equation 2 is the standard formula used for wind turbine power determination, i.e., to pick a reference position, measure the sound pressure, compensate to obtain a free field value and then by assuming an omni-directional source obtain the sound power (IEC 61400-11). Equation 1 is equivalent with the formula suggested by Ljunggren[6] with H=200m. However, *here* this arbitrarily introduced[6] breaking point has been related to the height of an atmospheric inversion layer trapping the sound waves.

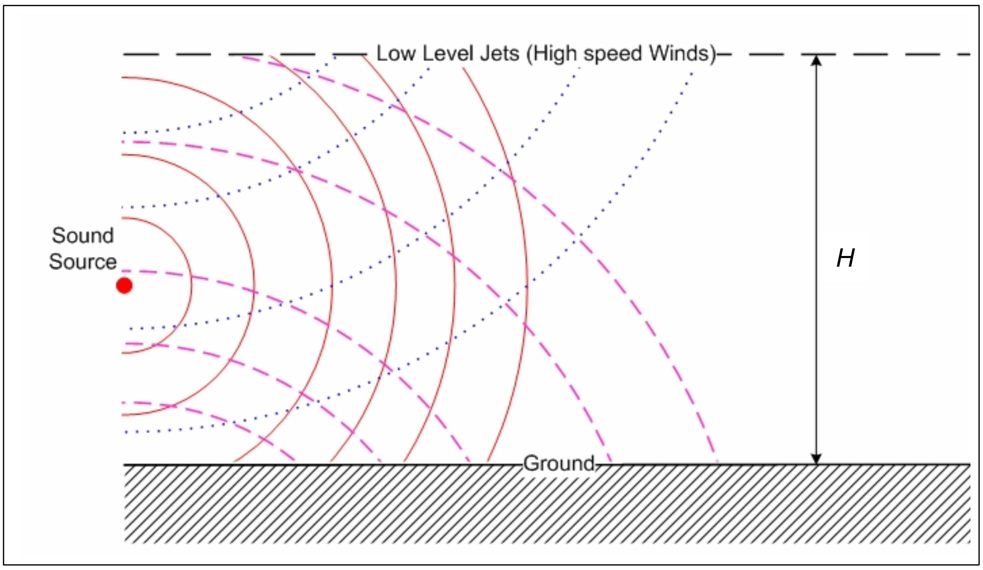

Figure 1: Effect of the LLJ over sea on the sound waves.

From equations 1 and 2, a model for sound propagation over the sea including the effect of atmospheric gradients trapping the sound below a layer at height H, can be written as:

$$\tilde{p}_r^2 = \frac{2\tilde{p}_{r0}^2 r_0^2}{r^2} \cdot \frac{r}{H} \cdot e^{-\alpha r} \cdot \tau_{shore} \cdot \tau_{ground} \cdot \tag{3}$$

where α is the atmospheric absorption coefficient, τ_{shore} represents the attenuation due scattering at a sea-shore line interface effect and τ_{ground} is the attenuation due to propagation over ground over a certain distance (<< r). From equation 3 the attenuation of sound or the transmission loss between the source reference position and the receiver point can be calculated:

$$TL_{tot} = 10 \cdot \log_{10} \frac{\tilde{p}_{r0}^2}{\tilde{p}_r^2} = 10 \cdot \log_{10} \frac{r_0^2}{rH} - 3 + \alpha \cdot \log_{10} r + D_{shore} + D_{ground} \text{ , [dB]} \qquad (4)$$

where $D = 10 \cdot \log_{10} 1/\tau$. Few studies have been made of the shoreline scattering effect. But Johansson[5] made simulations using the parabolic equation for different cases by changing both the ground impedance and the wind profiles at a certain distance from the source to represent the shoreline. The comparison with constant sound profile and ground boundary conditions shows a typical attenuation for low frequencies (< 100 Hz) of 3 dB.

Measurement methods

Measurement site The measurements were performed in the Kalmar strait towards the island Öland in the Baltic Sea (see Figures 2 and 3). This location has been chosen, firstly; because the facilities available on the lighthouse at Utgrunden permitted strong acoustic sources to be mounted and, secondly; because a wind farm is planned at this location (www.eon.se).

The emission point was situated 9 km from the shore on a lighthouse ("Utgrundens fyr"), presently used as a scientific test station. The receivers were located on Öland at 750 m from the shore and 7 m above sea level.

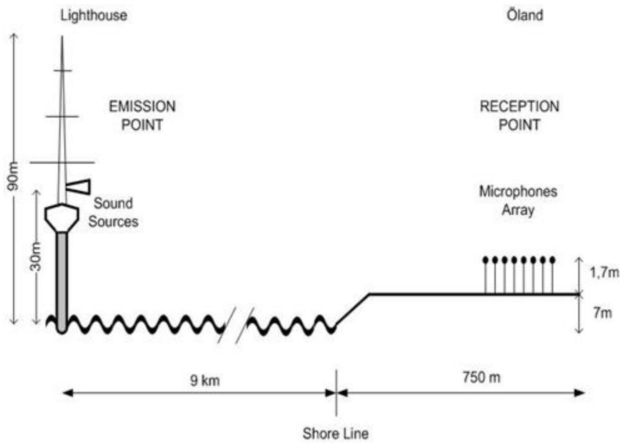

Figure 2: In situ Setup.

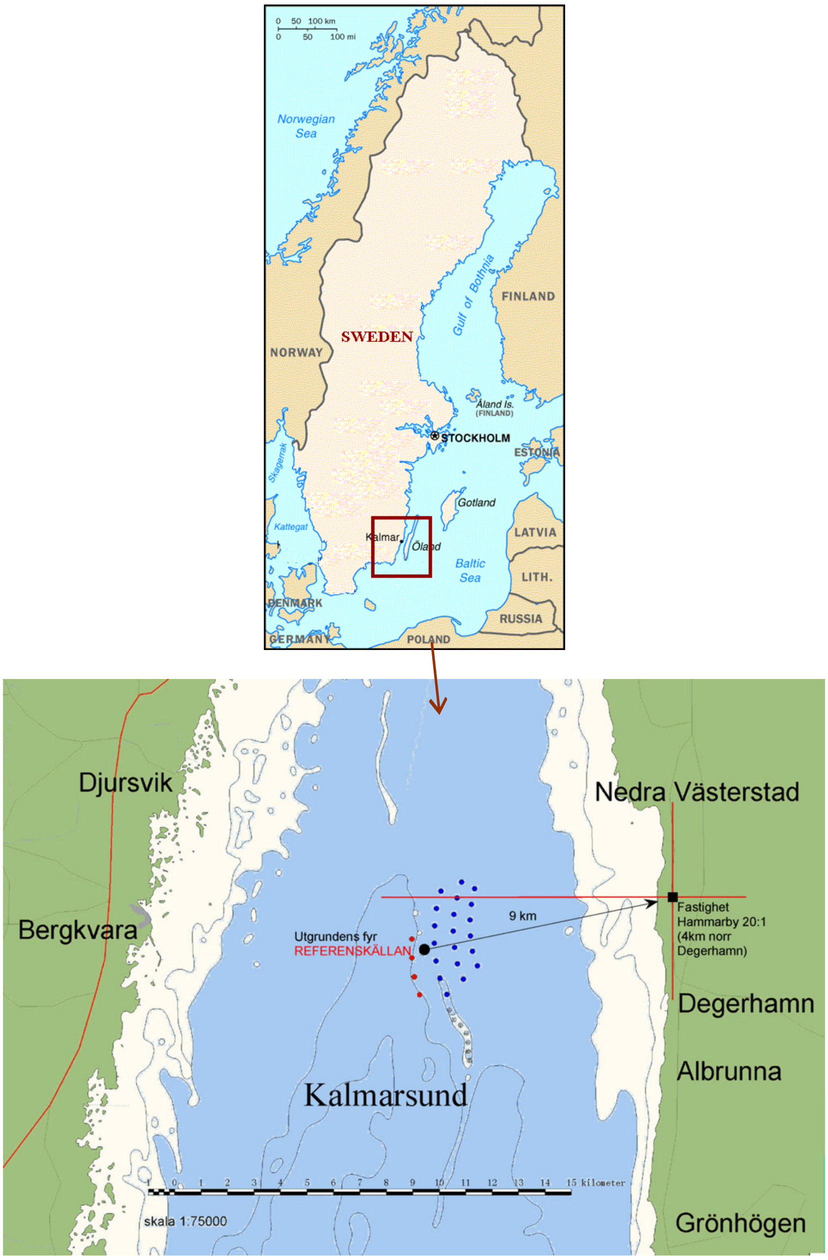

Figure 3: Site for the measurements was the old lighthouse at Utgrunden now converted to a measurement station operated by E.ON.

Sound sources As depicted in Figure 4, two sound sources were employed simultaneously. The first one was a compressed-air-driven sound source (Kockum Sonics Supertyfon AT150/200 with Valve Unit TV 784) placed at a height of 30 m. A microphone positioned at 1m in front of the siren was used to measure a 10-second source signal on each occasion. The signal from the source had an average sound pressure level of 130 dB at the fundamental frequency of 200 Hz. Moreover, the first harmonic, at 400 Hz, could also be used. The siren gave variations of the order of 1% in frequency and about 20 dB in level depending on the meteorological conditions. Also the level was not constant during operation possibly due to standing wave effects in the connecting pipes carrying the compressed air. In order to have a constant and more stable sound source and to investigate the sound propagation at other frequencies, a second source, consisting of a frequency generator + amplifier coupled to a loudspeaker and a quarter-wave resonator (1.2 m-long) was used. Also in this case a microphone was recording the signal at 1m from the source. The loudspeaker produced a 1 minute long signal at 80 Hz giving a constant sound pressure level of 113 dB at 1 m distance.

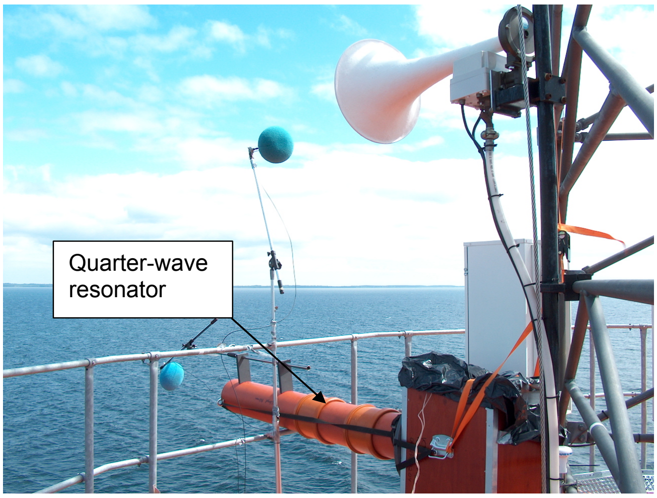

Figure 4: Sound Sources at the Utgrunden Lighthouse. The siren was driven by compressed air and produced a fundamental tone at 200 Hz (130 dB rel. 20 μPa at 1 m). The quarter-wave resonator produced a tone at 80 Hz (113 dB rel. 20 μPa at 1 m).

Receivers As the expected transmitted sound level will be very low; a microphone antenna was designed to increase the signal-to-noise ratio. The receiver point was situated at a house closest to the shoreline in a very quiet residential area. Eight ½-inch microphones were placed on a line parallel to the direction of the emission point to create an end-fire microphone array (See Figure 5).

Figure 5: Microphone array at the receiver point. Note, along the main direction of the array there was a clear path towards the sea.

The microphones were placed at 1.7 m height accordingly to ISO 1996. The distance between the microphones was set to 40 cm to optimize the directivity pattern pointing towards the sound source at 200 Hz. The advantage of using a microphone array compared to a single microphone is that the directivity pattern of the array allows cancelling of the disturbances due to background noise coming from other directions. For instance, influence of the noise coming from a small road situated 100 m inland from the measurement position could be minimized.

Moreover, to prevent the effect of the pseudo noise from wind blowing into the microphones a special elliptical shaped wind shield was used. This wind shield was tested in the wind tunnel at the Marcus Wallenberg Laboratory before the field measurements. See Figure 6 for the test setup.

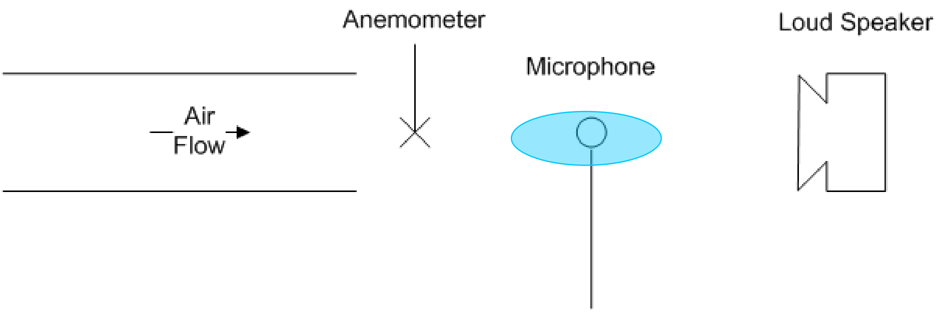

Figure 6: Setup for the measurement of the wind shield performance. The modified wind shield was made of foam plastic similar as the one used in the standard B&K shield. The shape was elliptical with a diameter of 200 mm in the horizontal plane and a vertical thickness of 100 mm (see also Figure 5).

The measurement showed that this wind shield was up to 5dB more efficient at 200 Hz than the standard B&K wind shield at a wind speed of 10m/s.

Meteorological measurements The wind speed was measured at 38, 50, 65, 80 and 90 m above sea level on a meteorological mast at Utgrunden. We used 10 min average automatically recorded at 38 m height for all our calculations. The wind direction was determined with wind vanes at 38 m and 80 m heights. The temperature and humidity were measured at five heights: 6, 38, 50, 65 and 80 m. The values closest to the sound sources were used for all the calculations (38 m). During the measurements performed in June 2005, wind profiles around the receiver location were measured during the day using single theodolite tracking of free flying balloons[9]. Detailed results from these measurements are presented in Refs. 9 and 13.

Post-processing techniques

The expected propagation time between the source and the receiver can be calculated from:

$$\frac{\text{distance (m)}}{\text{sound speed (m/s)}} = \frac{9750}{343} \approx 28{,}4s$$

However, due to the large distance and the unpredictable wind effects, it was not possible to predict exactly when the sound would reach the microphones. Thus, the noise was recorded during 2 min which also provided a good knowledge of the background noise. The first aim of the post processing was then to isolate the sound source signal (10s for 200 and 400 Hz, 1 min for 80 Hz).

Time domain averaging The first method developed to extract the signal is based on a synchronized time domain averaging (TA). The time signal recorded is divided in different segments $1/f_1$ in size, where, f_1 is the frequency of the sound source, e.g., 200 Hz. Then all the segments contained in a $\Delta T=0.5$ second long record are added together. The components of the signal at the studied frequency and its harmonics will always add in phase to each other, whereas components at other frequencies will be reduced. The method is simple and fast, giving valuable information about the sound pressure level of the source signal and its position in the recorded track. This method was very useful to reduce the calculation time of the FFT and the Kalman analysis method.

Kalman filtering Another method to extract the signal is to use a Kalman filter[10]. In 1960, R.E. Kalman[11] presented a new approach to linear filtering and provided a new way of solving the problem of separation of random signals from random noise introduced by Wiener. A Kalman filter combines all available information about the measurement in order to find an estimate of the desired variable with a minimal error. In our case as the frequencies of the sound source signals are known they can be implemented in the filter.

The Kalman filter method is more accurate than the time averaging technique. Since no averaging is computed over a time sequence in the Kalman filtering, the result is more precise in time. Another advantage is that no contributions from higher harmonics are introduced. The beginning and end of the source signal can be more accurately determined. The signal to noise ratio is also higher than with the time averaging method but the Kalman method is slower. For a 30 s signal the analysis by Kalman filtering required approximately 100-120 s to converge on a standard PC, whereas only a few seconds were needed for the time averaging method.

Fast Fourier Transform The last method used is a classic Fast Fourier Transform (FFT) over the part of the measurement containing the signal from the source. As it was not possible to distinguish the sound source signal in the 2 min measurement period, a first analysis through the Kalman filter and the Time Averaging method had to be performed. This allows us to know exactly the start and stop of the studied signal. Then by computing an FFT we could know the exact frequency of the signal. Moreover, by computing a FFT a few seconds before or after the signal, the level of the background noise could be determined and compared with the level of the sound source. When the two levels presented a difference of less than 10 dB, the measurement was dismissed.

Furthermore, two FFT´s have been calculated: the first was performed over the time signal directly from the array, the second over the time signal after the Kalman filter. Both gave essentially the same result, which proved that the Kalman Filtering did not add any gain to the signal.

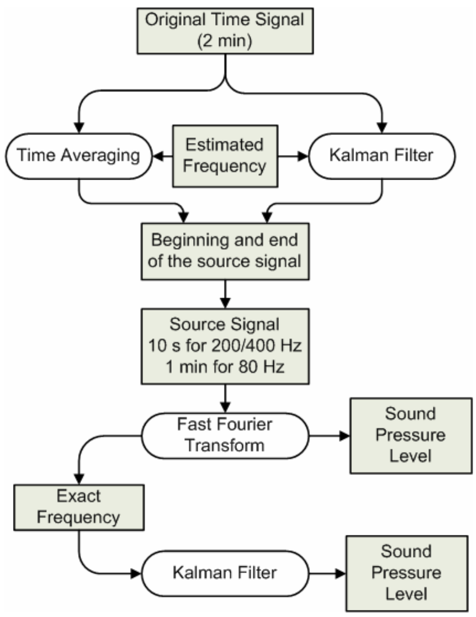

Figure 7: The post processing procedure.

Conclusion The three methods have been used simultaneously for each measurement. The procedure is depicted in Figure 7. First, an analysis by the time averaging technique and Kalman filter method using the estimated value of the source frequency is performed to locate the source signals in the measurement. Then, when the location is know, an FFT is performed in order to get the exact frequency of the sound source. The Kalman filter method is then implemented using this updated frequency in order to obtain the sound pressure level at the receiver points. This procedure is repeated for each frequency of interest.

Results and analysis

Previous atmospheric studies in the Baltic Sea have shown that the most interesting phenomena from an acoustical point of view occur in the late spring and early summer[4]. Therefore two measurements periods in June 2005 and June 2006 were performed. Wind speed, wind direction, humidity and temperature have been measured at the source at the same time as the sound pressure level. Furthermore, measurements[9] of wind profiles at the receiver point have been performed in June 2005.

From equation 4 we obtain the transmission loss due to the geometrical spreading (gs):

$$TL_{gs} = 10 \cdot \log_{10} \frac{r_0^2}{rH} = TL_{tot} + 3 - \alpha \cdot \log_{10} r - D_{shore} - D_{ground}\text{ , [dB]} \qquad (5)$$

From the measured data TL_{tot} is known. The atmospheric absorption was calculated using the meteorological conditions at the source and ISO 9613-1[12]. Then in accordance with the Swedish Environmental Protection Agency model[6] the effects of shore and ground attenuation were neglected. In the figures below the resulting statistical distributions for the transmission loss due to geometrical spreading are presented. In the data analysis all wind directions are included since a detailed analysis (see Ref. [13]), shows that a good transmission do not always correlate with a downwind condition at the source/receiver.

Figure 8 shows the relative occurrence of a specific transmission loss value based on Equation 5 for the three frequencies 80 Hz (dotted line), 200 Hz (solid line) and 400 Hz (dashed line). Figure 9 shows the cumulative distribution, i.e., in what percentage of the measurements the transmission loss is higher than a certain value. In both graphs, the bold line at 80 dB marks the theoretical transmission loss due to a spherical spreading (6 dB per doubling of distance) and 63 dB marks the case of a cylindrical spreading (3 dB per doubling of distance after 200 m) according to the Swedish recommendation[6]. The assumed propagation distance is 9750 m.

It can be noticed that the transmission loss are higher at 200 Hz than for the 2 other frequencies. This difference is almost certainly due to a peak in the ground attenuation close to this frequency. As the frequencies at 200 Hz and at 400 Hz come from the same source signal (the siren), they travel together and are subjected to the same conditions. They could therefore be expected to have the same average damping due to wave spreading. One finds that the extra ground attenuation at 200 Hz is close to 14 dB. This is in remarkable agreement with an old Danish measurement[2] at Saltholmen performed with similar set up, i.e., a long propagation distance over sea (~ 7 km) and a short distance (a few hundred meters) on land. Assuming that the average damping for the 200 and 400 Hz signals are equal one can correct the 200 Hz data for the “ground damping” effect. Figure 10 depict the cumulative transmission loss distribution with all the frequencies added and the “ground damping” at 200 Hz removed.

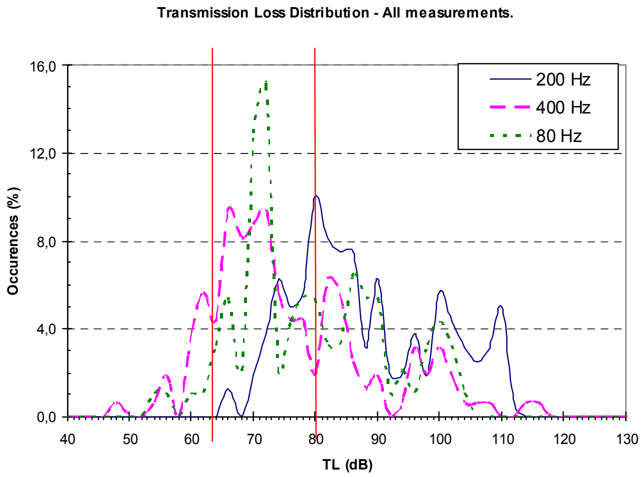

Figure 8: Relative distribution of transmission loss due to geometrical spreading. Note the 200 Hz data is systematically higher which is believed to be related to a maximum (peak) in the ground attenuation close to this frequency.

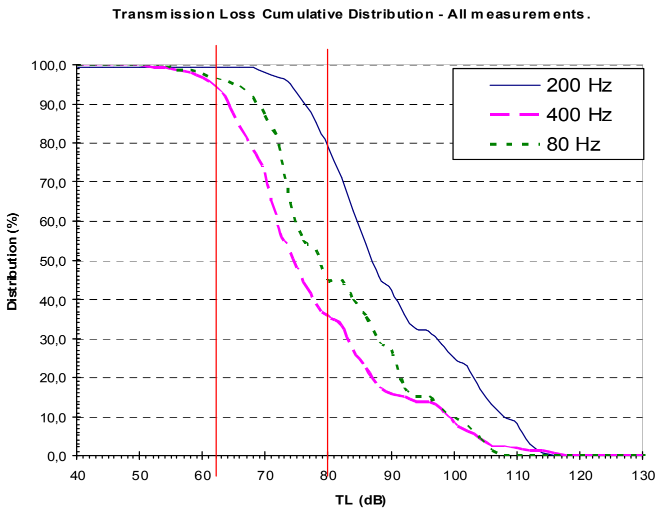

Figure 9: Cumulative distribution of transmission loss due to geometrical spreading. Note the 200 Hz data is systematically higher which is believed to be related to a maximum (peak) in the ground attenuation close to this frequency.

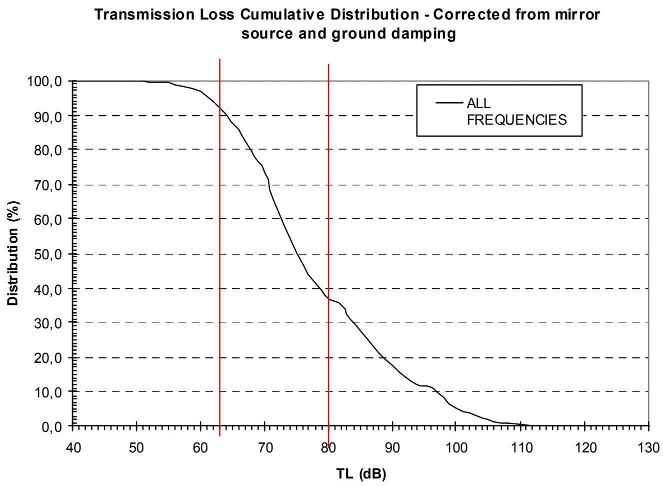

Figure 10: Cumulative distribution of transmission loss due to geometrical spreading. All frequencies added and with the 200 Hz data corrected for the ground attenuation peak. The bold line at 80 dB marks the theoretical transmission loss due to spherical spreading and 63 dB marks the case of a cylindrical spreading (after 200 m) according to the Swedish recommendation[6].

Conclusions

Measurements of transmission of sound over the sea have been performed in the Baltic region. One purpose being to obtain better data for judging the validity of the Swedish recommendation for estimating noise from sea based wind turbines[6]. This recommendation which is unique in the world assumes cylindrical wave spreading after a distance of 200 meters. Since cylindrical wave spreading compared to spherical only gives a reduction of 3 dB per distance doubling compared to 6 dB, this has large consequences on the predicted noise imission from wind turbines. Furthermore the work was intended to explore the relationship between good sound transmission and meteorological phenomena such as low level jets[9]. This work was performed in co-operation with the Meteorological Division at Uppsala University and is reported in detail in Ref. 9. One important observation from this part is that good transmission conditions for long range propagation do not necessarily correlate with downwind conditions at the source/receiver. Part of the work was also to develop procedures for the measurement of long range sound transmission and to develop modelling based on the parabolic equation. For more details on the measurement procedures and the still not finished modelling work please refer to Ref. 13.

Concerning the main results from the measurements they have been summarized as statistical distributions, see Figures 8-10. Based on the distributions one can calculate various expected values for the transmission loss or TL (compensated for atmospheric damping so that only the geometric spreading is included) as summarized in the table below. The TL (energy average) value for the propagation (geometric spreading) part only based on the Swedish model[6] and a distance of 9750 m is 63 dB. In this model the breaking point for cylindrical transmission is set to

200 m. Our data gives a value of 68.4 dB for the average transmission. Using this result and equation 5 gives a value around 700 m for the breaking point. Or as we define it here (see Eq. 1 and Fig. 1) the average height *H* of the inversion or reflecting layer trapping the sound and thereby causing a cylindrical wave spreading. It can also be noted from the table that TL_{90} (the TL value exceeded 90 % of the time) rather than the average is closest to the value predicted by the Swedish model.

Data from Utgrunden June 2005/2006	80 Hz	200 Hz	400 Hz	All frequencies
Average TL = $10\log_{10}\left(\frac{1}{N}\sum_{n}10^{-TL_n/10}\right)$ [dB]	70	67	67	68.4
TL_{10} [dB]	97	94	95	97
TL_{90} [dB]	65	62	62	64

It is difficult to state how general the results are. More measurements are needed also at other locations. This is now possible using the procedures developed in this work. However, an alternative to such long term efforts would be to combine fast simulation techniques, e.g., mainly ray-tracing, with the meteorological data base existing at Uppsala University (Dr. Hans Bergström) to simulate the transmission statistics.

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In-Home Wind Turbine Noise Is Conducive to Vibroacoustic Disease

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Abstract
Introduction. This team has systematically studied the effects of infrasound and low frequency noise (ILFN, <500 Hz) in human and animal models since 1980. Recently, yet another source of ILFN has appeared: wind turbines (WT). Like many other ILFN-generating devices, WT can greatly benefit humankind if, *and only if*, responsible measures are taken for their implementation. Vibroacoustic disease (VAD) is the pathology that is acquired with repeated exposures to ILFN environments (occupational, residential *or* recreational). This has been demonstrated in numerous scientific articles published in peer-reviewed academic journals over the past 27 years. **Goal.** To evaluate if ILFN levels obtained in a home near WT are conducive to VAD. **Methods**. Case 1: documented in 2004, in-home ILFN levels generated by a port grain terminal (GT), 2 adults and a 10-year-old child diagnosed with VAD. Case 2: isolated farm in agricultural area, four 2MW WT that began operation in Nov 2006, located between 300 m and 700 m from the residential building, 3 adults and 2 children (8 and 12-years-old). ILFN levels of Case 2 were compared to those in Case 1. In both, ILFN was assessed in 1/3 octave bands, without A-weighting, (i.e. in dB Linear). In Case 1, the lower limiting frequency was 6.3 Hz, while in Case 2, it was 1 Hz. **Results.** ILFN levels within the 6.3-31.5 Hz range in the home of Case 2 were higher than those obtained in the home of Case 1. Above, 31.5 Hz, levels varied but were comparable. **Discussion.** ILFN levels contaminating the home of Case 2 are sufficient to cause VAD. This family has already received standard diagnostic tests to monitor clinical evolution of VAD. Safe distances between WT and residences have not yet been scientifically established, despite statements by other authors claiming to possess this knowledge. Acceptance, as fact, of statements or assertions not supported by valid scientific data, defeats all principles on which true scientific endeavor is founded. Widespread statements claiming no harm is caused by in-home ILFN produced by WT rotating blades are fallacies that cannot, in good conscience, continue to be perpetuated. In-home ILFN generated by WT blades can lead to severe health problems, specifically, VAD. Real and efficient zoning for WT must be *scientifically* determined, and quickly adopted, in order to competently and responsibly protect Public Health.

Initial Disclaimer

The authors and the research team they represent would like to clarify that:

a) *No member of this team is party to anti-technology sentiments;*
b) *Large industrial plants, such as grain terminals, as well as alternative forms of renewable energy, such as wind turbines, are considered welcome additions to modern technological society by all members of this team;*
c) *The data reported herein have been scrutinized under one, and only one, agenda - that of pure scientific inquiry;*
d) *In no way can or should this report be construed as a document arguing against the implementation of wind turbines and/or grain terminals;*
e) *No member of this research team is employed by the firm that conducted the acoustical measurements reported in this article, nor are there any commercial, financial or professional agreements (contractual or otherwise) between the aforementioned accredited firm and any member of this team;*
f) *The consulting activities provided by these authors to Family R are of a purely academic and scientific nature and hence are* pro bono.

Introduction

In March of 2007, this team was contacted by an attorney-at-law representing the R. Family, in a case involving the placement of 4, 2 MW wind turbines (WT) near family R.'s property. Located between 321.8m and 642.0m from the residential building (Figs. 1, 2), the 4 WT became operational in November 2006. Two days later the R. family contacted a lawyer to begin court proceedings in order to have the WT removed.

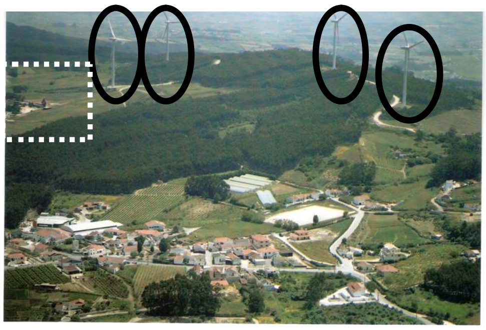

Figure 1. Aerial view of the WT home of Family R., isolated on upper left (dashed square) with the four wind turbines nearby (ovals).

Figure 2. WT home with the two of the turbines (arrows) at approximately 322m and 642m from the home.

In order for acoustical assessments to be accepted as legal documents, they must be performed by an accredited firm. In February 2007, the R. Family hired such a firm – dBLab (1) - to conduct continuous, 12-day, acoustical, wind speed, and vibration measurements. Although Portuguese noise legislation (D.L. 9/2007, January 17th) does not require acoustical evaluations of frequencies below 50Hz, nor dB Linear (dBL) measurements (without the A-weighting network), the accredited firm was additionally asked to obtain data for the entire frequency spectra, down to the lowest limiting frequency of the equipment in use, in 1/3 octave bands and in dBL. Data were made available to this team, within legal terms and with written consent on behalf of Family R., as well as the accredited firm.

This report documents the levels of infrasound and low frequency noise (ILFN, 6.3Hz-500Hz) encountered in this particular home, due to the operation of 4, 2-Megwatt WT.

Methods

dBLab used two appropriately calibrated and certified 01dB Symphonie sound level meters, equipped with ½" microphone (GRAS, model 23606). Measurements were obtained in periods of 30-min, continuously for 12 days, between Apr 5th-16th, 2007. The lower limiting frequency was 1 Hz. Simultaneous and synchronized accelerometer and wind speed data were also acquired. Measurements were taken within the Master bedroom of Family R., in accordance with the procedures stipulated by Portuguese (NP 1730, Pt 1&2, 1996 and DL 9/2007, January 17th) and International Law (ISO1996, 2003). Measurements conducted outside of the residential building and accelerometer data have not yet been fully analyzed and will not be considered in this report.

Results

Noise Analysis As Per Current Legislation

In accordance with the noise study conducted by dBLab, legally stipulated annoyance levels were exceeded during day (7am-8pm), evening (8-11pm) and night (11pm-7am) hours. dBA noise levels were also exceeded for a sensitive zone during night hours, but were within legal limits for a mixed zone. The local Municipal Authorities where the Family R.'s property is located have not yet classified the area as sensitive *or* mixed.

Wind Speed varied between 0 and 12.6 Km/h. According to the Portuguese Institute of Meteorology (Table 1), the average wind speed during the month of April 2007 was well below the average values of the previous years.

	2004	2005	2006	2007
Jan	6,6	5	6,4	4,6
Feb	7,4	8,8	8,6	6,8
Mar	11,3	12,3	10,4	11
Apr	11,4	11,5	10,7	8,9
May	11,5	13,1	10	10,7
Jun	12,6	11,9	11,7	12,8
Jul	13,1	14,3	12,2	
Aug	13,4	11,6	12,3	
Sep	9,1	10,9	10,9	
Oct	9,2	10	10,9	
Nov	5,6	6,7	6,1	
Dec	6,5	7,8	5,3	

Table 1. Monthly average wind speeds (in Km/h), from 2004 onwards, obtained at the relevant meteorological station near the property of family R, as provided and certified by the Portuguese Institute of Meteorology, on July 27th, 2007.

Acoustical Analysis of Infrasound and Low Frequency Noise

As per the request of this team, spectral analysis of 1/3 octave bands ranging from 1-500 Hz, in dBL were also obtained. Figure 3 compares the residual (no WT blade movement) and environmental (with rotating WT blades) measurements taken within the Master bedroom.

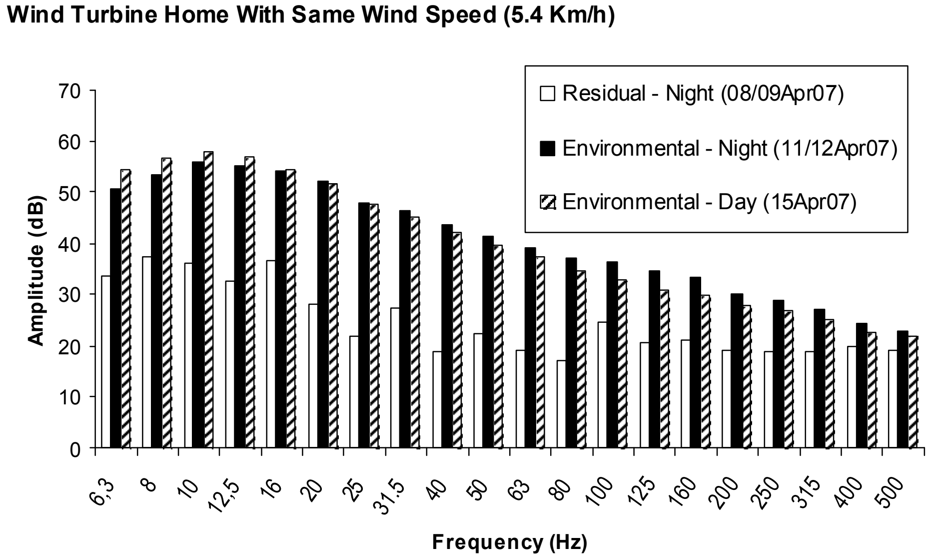

Figure 3. Comparison of 1/3 octave ILFN levels, in dBL, of the *Residual* (no WT blade movement) measurement and the *Environmental* (with rotating WT blades) measurement in the WT home Master Bedroom, with the same recorded wind speed.

Since ILFN is not yet recognized as an agent of disease, it is not covered by legislation. Therefore, permissible exposure levels for ILFN have not yet been determined, and dose-response relationships are unknown. Hence, no adequate standard exists to appropriately compare the ILFN levels in Figure 3 within the context of human health effects.

Analysis Within the Context of Vibroacoustic Disease

Although no generally accepted standard exists for linking the ILFN levels shown in Figure 3 to human health effects, the authors propose that a standard can be established by comparing WT-produced ILFN levels to ILFN levels that have been shown to be conducive to vibroacoustic disease (VAD).

Since 1980, this team has been systematically studying the effects of ILFN on human and animal models. As a result, an illness termed VAD (2-4) has been identified and can be readily diagnosed through echocardiography (5-8) and bronchoscopy (9-13) examinations.

On March 8th, 2007, the first time, the Portuguese Ministry of Labour, through its National Center for Occupational Diseases, granted 100% professional disability to a 40-year-old flight attendant, for having developed VAD during her professional activity. She was diagnosed with VAD in 2001, at the age of 34.

Within the context of VAD studies, the compilation of data on ILFN-rich environments has been ongoing since 2003. Hence, this team is uniquely positioned to provide pertinent data with which to compare the ILFN levels obtained in the bedroom of Mr. and Mrs. R.

Although VAD has been mostly studied within occupational settings (3), in 2004 this team documented (14) its first Portuguese case of environmental VAD in Family F. Residential ILFN was produced by a port Grain Terminal (GT) within line of sight of the home (Figs. 4, 5). From 1982 until 2003, this GT was allowed to operate at any time of the day or night. Operating hours were only restricted in 2003 when new legislation mandated that noisy industrial activities must cease at 11 p.m.

Acoustical measurements at the Family F. home were conducted with a Bruel & Kjaer 2260 sound level meter, equipped with a ½" microphone (B&K, model 4189). Measurements were obtained in periods of 15-min, for 3 hours, starting at 9 p.m. (evening period) on Feb 4th, 2004. The lower limiting frequency was 6.3 Hz (14).

Figure 4. Trafaria Deep Water Grain Terminal (TDWGT).

Figure 5. View from the GT home of Family F., located in Lisbon. Across the Tagus River is the TDWGT.

Figure 6 compares the ILFN levels obtained in the WT home of Family R., with those obtained in the GT home of Family F. Below 31.5 Hz, all 1/3 octave bands have higher dB Linear readings in the WT home than in the GT home. The two peaks detected within the GT home, at 40Hz and 50Hz, are specifically related to unidentified GT operations. Above 200 Hz, the GT has higher dB levels than the WT home. The remaining 1/3 octave bands showed similar levels in both homes.

Manifestation of Vibroacoustic Disease in Family F. – GT Home

"Mr. F. is apparently asymptomatic. He complains of a lack of concentration and overall irritation, and has severe bouts of rosacea. He has always lived in the suburbs of the city of Lisbon, and has been working in the centre of Lisbon for the past 10 years. Mrs. F. has been diagnosed with hepatitis A, mononucleosis and allergic rhinitis. While still a student in university, she was once diagnosed with a late-onset epileptic seizure, for which she is currently unmedicated. She complains of body aches, particularly in the right shoulder, left knee, back and neck. X-rays have not revealed any abnormalities. She has always had headaches, mostly radiating along the back of the neck. Approximately 4 or 5 years ago, while in a shopping mall supermarket, Mrs. F. suffered a violent tachycardia, with feelings of faintness. She

was taken to the hospital where a subsequent EKG did not disclose abnormalities. Mrs. F. has worked in governmental administrative offices, in the centre of Lisbon, for the past 16 years. Ten-year-old P. suffered from asthma until the age of 1 year. At 5–8 months of age, he was medicated for reflux, and then again until he was 1 year old. At 8 months he suffered pneumonia. After the age of 1, he began to develop repeated ear infections that were not responsive to antibiotics. At age 3 he underwent ear surgery. At the age of 5, at school, he suddenly lost his vision and was taken to the hospital, where the EEG revealed an epileptic seizure. Nose bleeds without an apparent cause used to be frequent, but have subsided with age. There is no history of rheumatic fever, radiation or asbestos exposure" (14).

Through echocardiography, all three members of this family showed characteristic thickening of cardiovascular structures normally seen in VAD patients (14), namely the pericardium and mitral valve (2, 3, 5-8). The most severe cardiovascular condition was observed in 10-year-old P., most probably because the mother spent the pregnancy gestation months in that same ILFN-rich home. For a more detailed description of this case, see (14).

Late-onset epilepsy, nose bleeds, tachycardia, muscular and joint pain with no imaging corroboration despite sustained patient complaints, are common in VAD patients (2, 3). Respiratory pathology has already been closely linked to ILFN exposure, both by this team (2-4, 9-13, for example) and by other authors (15-17, for example). This family continues to be followed by this team, and has chosen to remain in the ILFN-rich home, but they have relocated their bedrooms to the back of the house.

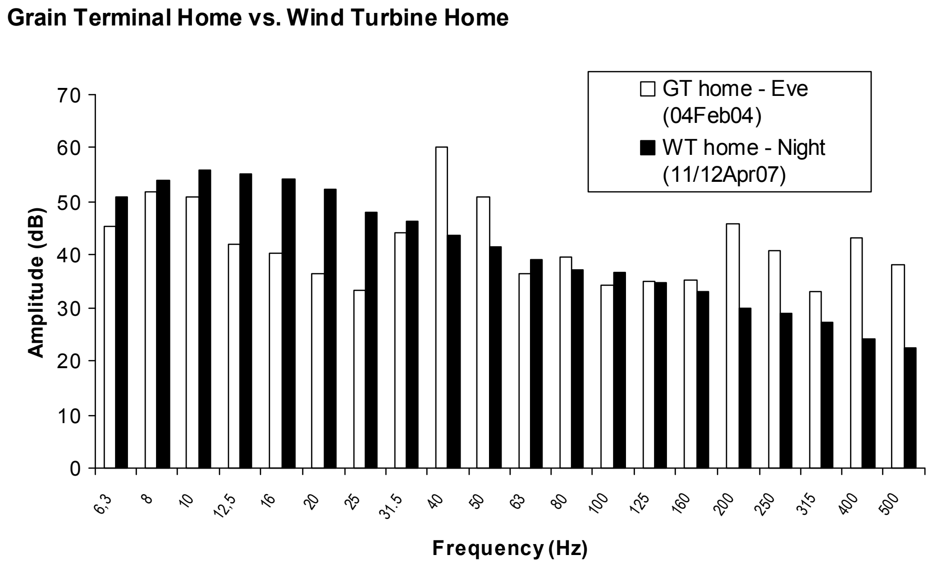

Figure 6. Comparison of the frequency spectra obtained in the GT home of Family F., in 2004, with those obtained in the WT home of Family R., in 2007. The 40Hz peak in the GT home is specifically associated with GT operations. Within the range of 6.3Hz to 31.5Hz, 1/3 octave bands disclose higher dBL levels in the WT home than in the GT home.

Manifestation of Vibroacoustic Disease in Family R. – WT Home

Mr. R has deep concerns about his memory loss, increased irritability and progressive intolerance toward audible noise, all of which he complained about at the very first meeting with this team, in March 2007. Both Mr. and Mrs. R. have developed great difficulty in sleeping continuously throughout the night, as well as non-specific body pain. Upon visiting a general physician at the local State Health Center, Mr. R was prescribed 2 analgesics (anti-inflammatory and spasmolytic) and 2 tranquilizers (diazepam-based and short-term sleep-inducer).

Echocardiograms (routine, non-invasive VAD diagnostic test) of Mr. and Mrs. R. disclosed slight to moderate pericardial thickening (between 1.7mm and 2.0mm, normal for the equipment in use: <1.2mm). Respiratory drive was below normalized values in both adults (46%-53%, normal: >60%), suggesting the existence of brain lesions in the areas responsible for the neurological control of breathing (3).

In mid-March, Mr. and Mrs. R received a letter from their 12-year-old son's school, expressing concern for the growing difficulties of an otherwise outstanding student, "*particularly in English, Humanities and Physical Education. He progressed in Mathematics, which is a field that naturally attracts his type of intelligence. However, in the above mentioned coursework, it seems that [the child] has lost interest, makes a lesser effort, as if he were permanently tired. In Physical Education, an abnormal amount of tiredness is also observed. Is [the child] leading a healthy life? Does he sleep sufficient hours during the night?*"

Given the above school information, and since cognitive and memory disturbances are common and well documented in VAD patients (2, 3), the child received neurophysiological evaluation. Brainstem auditory evoked potentials disclosed asymmetries in the right and left nerve conduction times, and the right I-V interlatency value was at the threshold of normal values (4.44ms). The endogenous evoked potential P300 recording occurred at 352ms (normal: 300ms). This measure reflects the time it takes to recognize and memorize infrequent stimuli. *"Although this result is in accordance with the child's school report indicating that cognitive processes are affected, it is not possible to state that this situation is irreversible. Moreover, in children, P300 recordings often disclose variations that are difficult to interpret. Nevertheless, initial clinical signs of Stage-I VAD are characterized by this type of cognitive impairment and, as such, may be reversible at this clinical stage provided ILFN exposure is suspended"* (18).

The R. Family income is provided by breeding bulls and raising and training horses for bullfights. Horses have exhibited an abnormal behaviour, lying down and sleeping during the day. Tissue fragments have been removed from the farm animals that have been scheduled for slaughter, and will be submitted to the light and electron microscopy analyses that this team usually conducts on ILFN-exposed tissue fragments (3,4). These procedures will be repeated every 6 months, and follow-up reports will ensue. Mr. R. has resident employees who are also receiving all medical tests.

DISCUSSION

ILFN Levels

ILFN levels within the 1/3 octave bands ranging from 6.3Hz to 31.Hz are larger in the WT home than in the GT home. Other bands have a similar dBL level with the exception of the 40Hz and 50Hz bands, and those equal or above 200 Hz. Previous studies strongly suggest that infrasound (≤ 20 Hz) exposure is specifically associated with pericardial thickening (3, 7, 19). Since the family living in the GT home has developed VAD due to in-home ILFN exposure, it is reasonable to assume that the WT family will also progressively develop VAD.

In a perfect world, designed for the most efficient and accurate scientific studies, all noise assessments ought to be conducted with the same equipment and with the same procedures. This is not feasible. So, despite on-site and factory calibrations, a legitimate question will always remain: can the differences between the ILFN levels in the homes of Family F. and Family R. be due to differences in the noise measuring equipment and procedures alone? Despite this legitimate question, these data are sufficient to warrant precautionary measures.

If and when moderate and severe VAD-related symptoms are documented in Family R., this question can be put to rest. This course of action, however, lacks any ethical basis, and could potentially result in a lawsuit, due to negligence.

Occupational vs. Residential Exposures

Occupational exposures to ILFN occur at larger dBL levels (See Fig. 7). However, residential exposure occurs over longer periods of time, affecting all family members (particularly children), and is present during sleep time. In this team's experience, residential ILFN exposures lead to accelerated progression of VAD (9).

Drama or Challenge

Neither the authors nor the team they represent are oblivious to the implications that this study brings to light. However, dramatization of a problem rarely leads to any sort of solution.

Instead of attempting to appease those who are vehement about the notion that WT are inconsequential to human health, and to avoid the useless acrimonious debate that usually ensues after these type data is presented, a challenge is offered up: *zoning laws*. And this immediately leads to the issue of safe distances from the aerodynamic pressure waves produced by rotating WT blades.

Safe Distances…

Scientists have not yet established safe distances between residential buildings and WT. Many scientists have not yet recognized that ILFN is an agent of disease. Hence, the fact that rotating WT blades (analogous to aircraft propellers, or rather, helicopter rotor blades) produce acoustic pressure waves consistent with ILFN phenomena is, to many, simply irrelevant – because ILFN is (erroneously) assumed to be harmless.

…And the Scientific Method

Following a logical rationale: If ILFN is not suspected as an agent of disease, then it does not need to be assessed or investigated as to potential health hazards. Most scientists and physicians do not, therefore, possess information regarding any aspect of ILFN. It follows that until scientific data exist on the subject, no credible claims can be made regarding safe distances between rotating WT blades and residential homes.

Some team could develop an equation that would determine, on a case-specific basis, the safe distance between a home and WT, since the amount of ILFN will depend simultaneously on several factors, including: distance to the building, blade size, wind speed and direction, geology, type of terrain, building resonance properties of both ILFN and solid-to-solid ground vibration transmission, type of vegetation as well as its quantity and distribution.

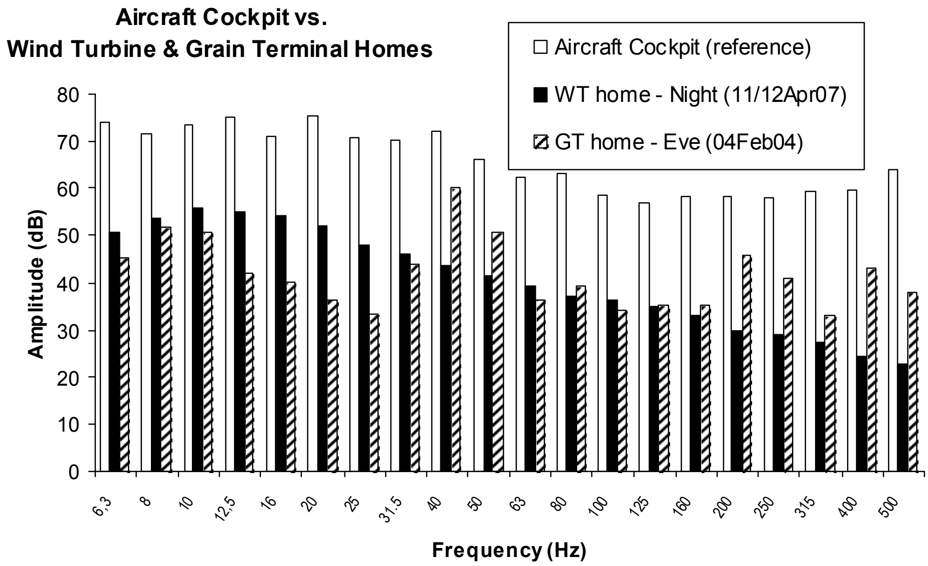

Figure 7. Comparison of 1/3 octave ILFN levels, in dBL, of the WT home, the GT home, and the reference ILFN levels used for occupational exposures by this team (Aircraft Cockpit (19)).

Prospects of New Data

As certified by the Portuguese Institute of Meteorology (Table 1), the average monthly wind speeds in August are generally higher than in April. Hence, dBLab will repeat all measurements during the month of August. WT-generated ILFN is strongly related to the acoustic pressure waves aerodynamically generated by rotating blades. This is somewhat analogous to the infrasound (≤ 20 Hz) levels in airplane cockpits, which are larger with increasing aircraft speed, due to the impact of the aerodynamic airflow on the nose of the aircraft (19).

The neurophysiology evaluation of the child will be repeated in late September, after he has spent 2 months away from the ILFN-contaminated home, and in December, non-invasive VAD diagnostic tests will be repeated on all family members and resident employees. Electron microscopy studies of animal tissue fragments are ongoing.

CONCLUSIONS

ILFN levels within the range of 6.3Hz to 31.5Hz obtained at the WT home are higher than those obtained at the GT home. Family members residing in the GT home have been diagnosed with ILFN-induced pathology, i.e., VAD. With time, it is highly probable that the family residing at the WT home will also develop severe VAD, since they are already exhibiting symptoms consistent with early VAD.

Precautionary measures regarding the placement of WT near inhabited buildings are justified. Safe distances between WT rotating blades and inhabited buildings have not yet been determined by the scientific community.

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Masking of wind turbine noise by sea waves

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Abstract
Several countries use immission guidelines which relate the wind turbine noise to the background sound assuming a masking effect from wind induced sound. Despite a thorough literature search no studies have been found that investigate the masking potential on wind turbine noise by sea waves. This effect on wind turbine noise could permit optimal energy output without risking complaints by nearby residents especially for off-shore wind farms. Field measurements of sea wave sound are reported from a number of sites along the coast of Sweden. This together with a prestudy concerning the masking potential of sea wave sound on wind turbine noise show that sound from breaking waves has a good masking potential considering an immission value of 40 dB(A) at the shoreline. The shoreline can be regarded as a

line source leading to a transmission loss of 3 dB per distance doubling which is verified for distances up to 70 m. Based on the measurements a prediction model for 1/3-octave band spectra is developed as well as a regression model for A- and C-weighted sound pressure level showing a high correlation with the significant wave height. Sea bottom inclination is found to be a determining factor for the characteristics of the sea wave sound and thus the masking potential which is frequency dependent.

Introduction

Wind energy is regarded as one of the most effective alternatives among renewable energy sources. However wind energy also introduce some problems, mainly consisting of annoyance, where one big issue is unwanted sound i.e. noise. Several countries use immission guidelines which are related to the background sound at the immission point expecting a masking effect on wind turbine noise (Almgren M (2007)). This masking effect is a result of the similarities between wind turbine noise and natural background sound. Natural background sound is often the dominating background sound were many wind farms are located.

In question of natural background sound at coastal locations the prevalent factor, except for wind induced vegetation sound, is probably background sound from breaking waves. The potential masking effect on wind turbine noise from breaking waves could permit optimal energy output without risking complaints by nearby residents especially for off-shore wind farms. Prior to this study an extensive literature study was undertaken. This resulted in no studies found concerning the background sound from breaking waves and its effects on the background sound on land, although many reports regarding underwater sound was found. It should therefore be of significant importance to investigate this matter further.

Masking of wind turbine noise is a very extensive field and the research is ongoing with many facts to consider especially psycho acoustic factors. This study will not go into detail regarding the masking effect of wind turbine noise but more generally investigate the masking potential by sea waves on wind turbine noise following present limits. The approach is to first perform measurements at suitable locations regarding wave climate and signal-to-noise ratio followed by data analysis, evaluation of the masking potential and modelling of appropriate frequency spectra models based on the measurements.

Theory

Sea waves consist of many different wave types which interact and form the sea surface. They range from small capillary waves with a wavelength of 1 cm and a time period of 0.1 s to Rossby waves in the oceans with the wavelength of 10000 km and a time period of several years (Döös K (2006)). Waves important for sea wave background sound at the coasts are the wind-driven surface gravity waves, which are divided into short and long surface gravity waves. The short surface gravity waves have a wavelength that is shorter than the water depth and hence are located at relatively deep waters. The long surface gravity waves have a wavelength that is longer than the water depth resulting in that they are dominant close to the coast. It is the long surface gravity waves that break when they reach the shore and thereby transforms some of the wave energy into acoustical energy. The total kinetic and potential wave energy is proportional to the square of the wave height and is given by equation (1) (Ranka K et al. (2003))

$$E_{wave} = \frac{1}{8}\rho_w g H^2 \tag{1}$$

where ρ_w denote the water density, g is the gravitational constant and H is the wave height. The criterion regarding breaking waves is essentially based on the water depth and the inclination of the sea bottom. When the depth is decreasing closer to the shore, the waves rise to a height of approximately 80% of the depth before they break. A simple relation between the wave height (H) and water depth (d) is given by equation (2) (Schultz U (2003))

$$\gamma = \frac{H}{d} \tag{2}$$

where γ is called wave breaking index and range from 0.6 to 1.2 with an average of 0.78. The wave height in this study is taken as the significant wave height ($H_{1/3}$), which means the average of the 1/3 highest waves from trough to crest (Schultz U (2003)).

Two models are developed which predicts the frequency spectra of breaking sea waves based on performed measurements. The first model is constructed by a basic scaling law as described by equation (3)

$$\alpha(f_t, x) = \frac{L_{p*}(f_t, x) - L_p(f_t, 1)}{\log H_{1/3}} \tag{3}$$

where α denote a dimensionless scaling constant, f_t is 1/3 octave band frequency, L_{p*} is the average sound pressure level for sea waves x m high and L_p is the average sound pressure level for sea waves 1 m high according to measurements. The average α is calculated independently for wave heights below and above 1 m in accordance with the average of all measurements for the respective wave height.

The second model is based on a more theoretical examination of the theory concerning breaking waves and wave energy. Four necessary assumptions are made prior to the modelling:

i. Attenuation coefficient (in air) $\alpha=0$
ii. Ground reflection coefficient $R=1$
iii. Constant zone x_b with respect to significant wave height $H_{1/3}$
iv. The generated sound from different waves is uncorrelated

Geometrical dimensions used for modelling are presented in figure 1.

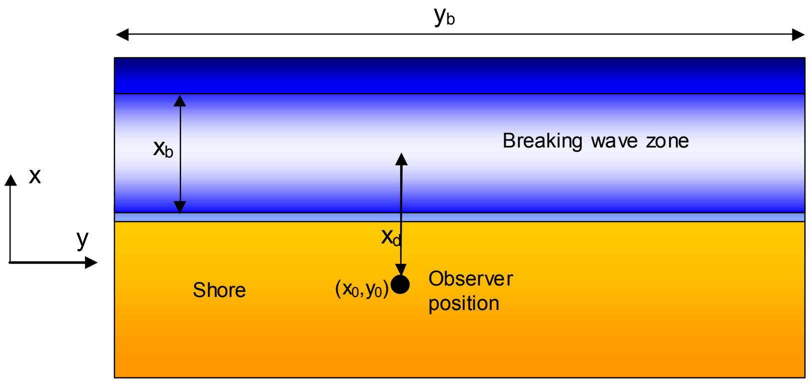


Figure 1. *Description of the coastal and wave breaking zone.*

With the above assumptions derivation results in equation (4)

Erreur ! Des objets ne peuvent pas être créés à partir des codes de champs de mise en forme. (4)

Where ρ_w is water density, ρ_a is air density, c_a is air velocity, g is the gravitational constant, $\Gamma(n,H_{1/3})$ denote a normalized frequency spectra with the dimensionless frequency $n=f\cdot(H_{1/3}/g)^{1/2}$ and $\eta(H_{1/3})$ is the acoustic efficiency dependent on the significant wave height.

If the efficiency $\eta(H_{1/3})$ is estimated by least squares method this gives a second degree equation

Erreur ! Des objets ne peuvent pas être créés à partir des codes de champs de mise en forme. (5)

The spectrum shape is estimated by a Gaussian distribution

Erreur ! Des objets ne peuvent pas être créés à partir des codes de champs de mise en forme. (6)

where the parameter $\lambda_{lu,}(H_{1/3})$ is determined by the bandwidth of the spectrum and the center frequency $n_c(H_{1/3})$ is approximated by

Erreur ! Des objets ne peuvent pas être créés à partir des codes de champs de mise en forme. (7)

Measurements

Measurements of sea wave sound have been performed at four locations, and a total of 16 measurement sites, on the coast of Sweden for a period of two weeks. The measurement sites are chosen so that a positive signal-to-noise ratio can be achieved with little or no influence from other sound sources compared to the sea wave sound. The investigated shores are categorized as sand beaches, rocky beaches, archipelago cliffs and cliff beaches. Examples of measurement sites are presented in figure 2-5. All shores have an apparent uniform bottom profile.

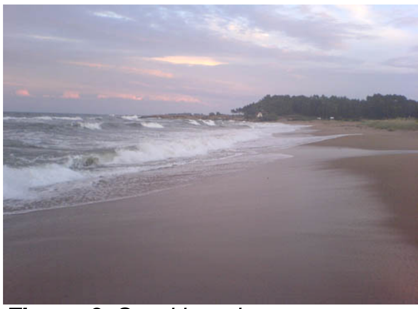


Figure 2. *Sand beach*

Figure 3. *Cliff beach*

Figure 4. *Rocky beach*

Figure 5. *Archipelago cliffs*

The main measurement equipment consists of a laptop equipped with a data acquisition card, Digigram VX-Pocket V440, and a ½-inch microphone powered by a pre-amplifier. A wind screen shaped as an ellipsoid, with major axis 20 cm and minor axis 10 cm, is used for all measurements. The microphone is placed on a tripod 1.5 m above sea level and as close to the shoreline as possible depending on wave height. Measurements are also performed for varying distances, up to 70 m, from the shoreline to investigate the transmission loss on close range. Additionally a Norsonic 118 Sound Analyser is used for some measurements.

One of the main concerns when performing measurements outside is the influence of pseudo-noise generated by strong winds especially above 5 m/s. A test of the pseudo-noise generation is carried out using controlled wind flow inside a lab at wind speeds of 0, 4, 7 and 10 m/s and a sound source of white noise. It is clear from these measurements that the wind only affects the wave sound measurements at frequencies below 100 Hz. The measured pseudo-noise curves are used to correct wind influenced measurements and the corresponding uncorrected measurements are marked with a thin dotted line in figure 6.

The significant wave height is taken from appropriate wave buoys controlled by SMHI, the Swedish meteorological and hydrological institute, which delivers hourly reports of significant wave height and wave directions. The wave height is also measured on site by a basic wave metering system consisting of a graded iron rod on a stand. To get a more accurate result wave buoys or other similar wave metering systems closer to specific sites should be used. Nonetheless the significant wave heights used for the analysis should be more or less valid based on the observations on site.

A program is written in Matlab Data Acquisition Toolbox which is used for collecting sound data at a time record of 5 minutes per trigger. The data is analyzed using an averaging time of 5 minutes with SpectraPLUS 5.0, Matlab and NorReview. All measurements influenced by for example wind induced vegetation sound, traffic, human activity and motor-boats are discarded. The average linear 1/3 octave band spectra for undisturbed measurements at respective significant wave height are shown in figure 6. The transmission loss on short range is found to be 3dB per distance doubling, see figure 7, as would be expected if the shoreline is regarded as a line source. There are also signs of a ground effect dip (Wagner S et al. (1996)) in the frequency range 200-800 Hz and for frequencies below 100 Hz the sound pressure level could be considered approximately constant up to 70 m, see figure 8.

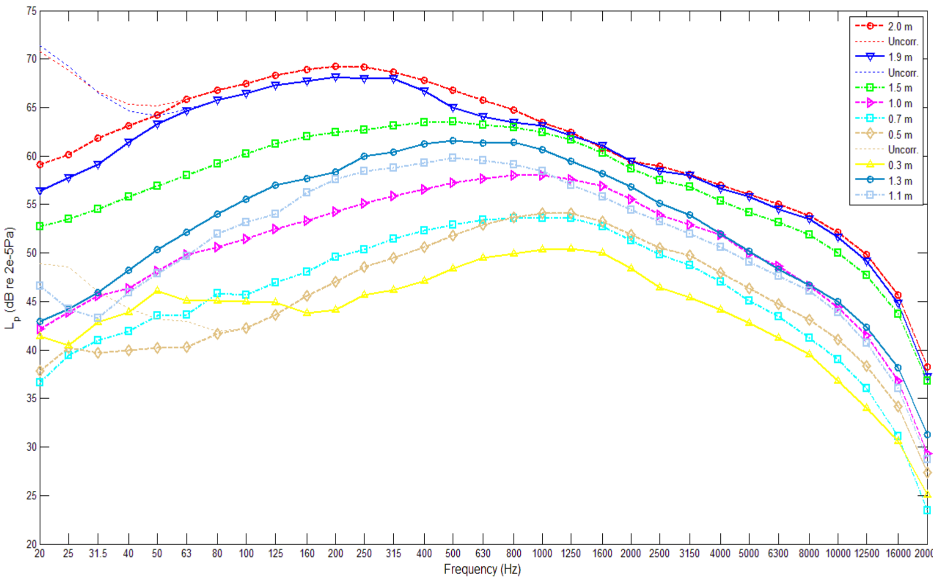


Figure 6. Average linear 1/3 octave band spectra for sound from breaking waves. The uncorrected curves are without the correction for the local wind noise, i.e. pseudo-noise, at the microphone.

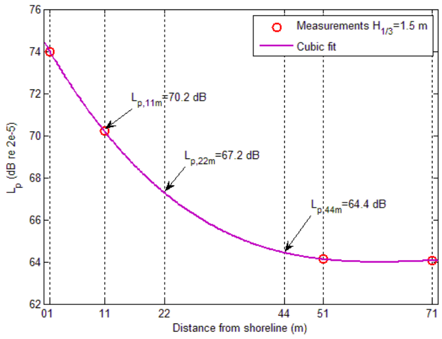


Figure 7. *Example of transmission loss for $H_{1/3}$* =1.5 m.

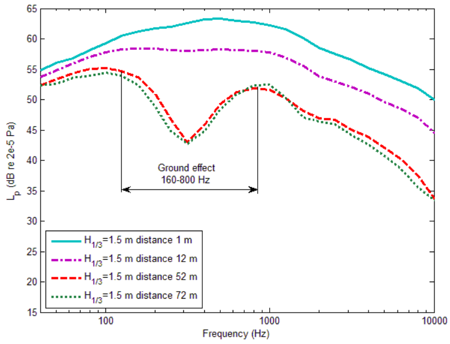


Figure 8. *Example of ground effect for $H_{1/3}$* =1.5 m.

Regression analysis

Wind energy immission guidelines usually use an approach which either set fixed limits related to the A-weighted equivalent sound pressure level of the wind turbine noise or limits related to one of the statistical percentile values, in general L_{A90} or L_{A95}, of the background sound (Almgren M (2006)). The first step to determine the possible masking by sea waves on wind turbine noise should consequently be to look at these values for different significant wave heights. A suitable method is regression analysis as long as the correlation between sound pressure level and significant wave height is high. This is the case for the performed measurements with a correlation of 0.97 for $L_{Aeq5min}$ and 0.95 for $L_{A905min}$, which makes linear regression a good choice especially as the significant wave height has a built in uncertainty as described in previously. The result is presented in figure 9 and the regression curves shows a good fit to analyzed data.

In the case of long distance sound propagation it is primarily the low frequencies that are of importance since higher frequencies to a large extent attenuates. Therefore C-weighting could be a more accurate weighting filter for showing the masking potential of sea waves as many off-shore wind farms are built at some distance from land. The dominating frequency range regarding long distance wind turbine noise is considered to be between 20-400 Hz and hence this is the frequency range analyzed with the C-weighting applied. The corresponding linear regression curve almost shows a doubling of the slope compared to the A-weighted regression curves. This could mean less masking potential for low significant wave heights and vice versa.

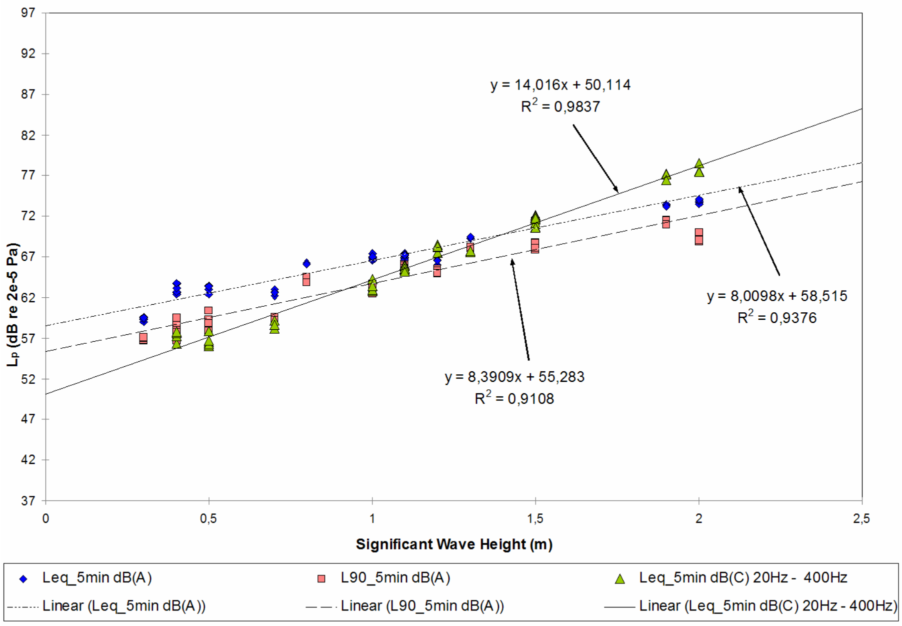


Figure 9. *Regression analysis correlating sound pressure level at the shore line to significant wave height.*

Model comparison

The two models developed are compared with each other and with the measurements in figure 10–13. They both show fairly good agreement with the measurements, especially for wave heights above 1 m which are considered most essential for the masking potential. An important note is that the frequency spectra normally vary to some extent between different measurements for the same wave height. It is also most probable that the spectra will show some differences at different locations which could only be resolved by long time measurements at numerous locations. The dominating factor determining the spectral shape is found to be the sea bottom inclination.

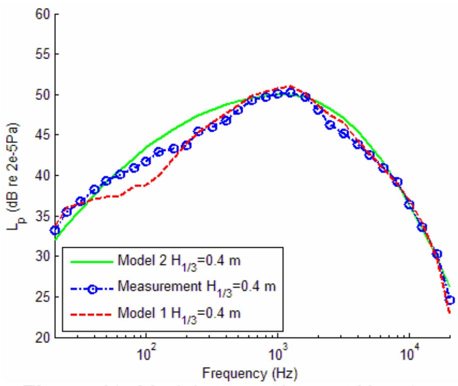


Figure 10. *Model comparison at $H_{1/3}$=0.4 m.*

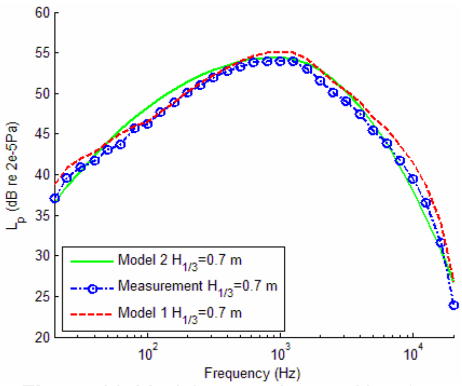
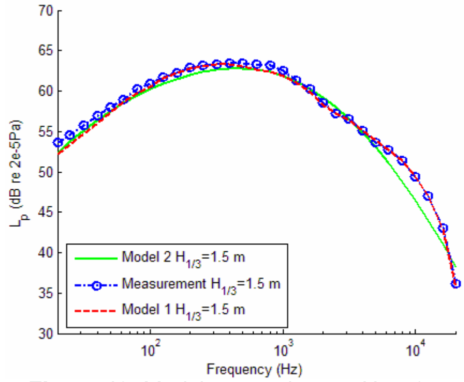


Figure 11. *Model comparison at $H_{1/3}$=0.7 m.*



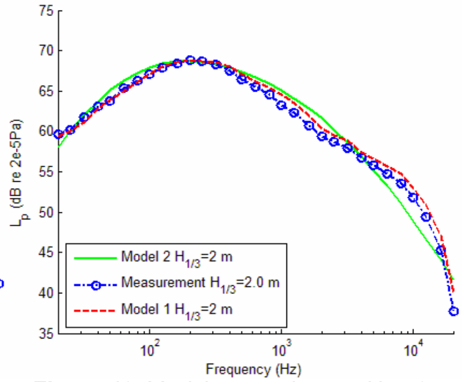


Figure 12. *Model comparison at $H_{1/3}$=1.5 m.* ***Figure 13.*** *Model comparison at $H_{1/3}$=2 m.*

Masking Potential

How could the masking potential of sea wave sound on wind turbine noise be described? Should total masking be advised or only partial as is standard in most countries which relate the wind turbine noise to the background sound, where a positive signal-to-noise ratio of 3-5 dB(A) is normal. One important characteristic of the background sound concerning its masking potential is the modulation, where large long time fluctuation results in poor masking potential. Additionally the standard deviation could be examined. For all performed measurements the top-top fluctuations are 10-15 dB(A) and the standard deviation 1.5-4 dB(A). The one minute time history for an arbitrary measurement of sea wave sound is shown in figure 14.

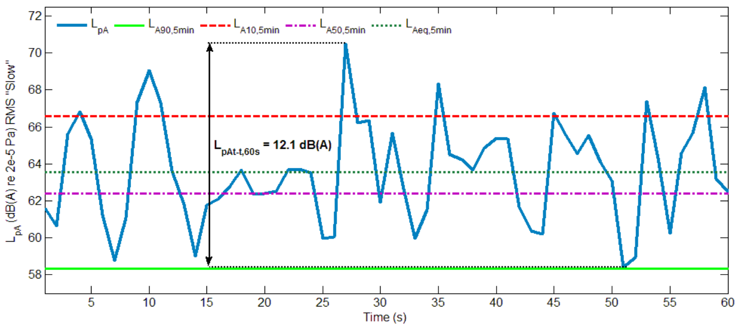


Figure 14. *One minute time history of sea wave sound, representing the A-weighted sound pressure level analyzed with time constant "slow".*

An acknowledged theory regarding the masking potential is that it is sufficient with a positive signal-to-noise ratio in only one 1/3 octave band to make the wind turbine noise audible (Stephens D.G et al. (1982)). Figure 15 shows the linear 1/3 octave band spectra from three wind turbines in relation to the linear 1/3 octave band spectra of sea wave sound for three significant wave heights. Spectra 1 is measured at sea and represents a 2 MW modern wind turbine (Plovsing B et al. (2006)), Spectra 2 shows the spectra of a land based wind turbine with unknown effect (Fégeant O (1999)) and Spectra 3 is from an old land based 2 MW prototype wind turbine (Ljungren S (1988)). Spectra 1 and Spectra 3 has furthermore been downscaled to represent the frequently used immission limit 40 dB(A).

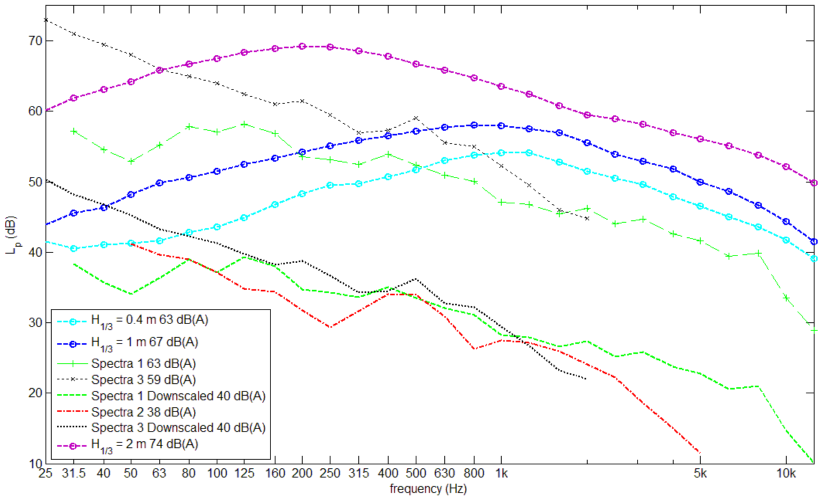


Figure 15. *Comparison of linear 1/3 octave band spectra of three wind turbines and sea wave sound representing the significant wave height 0.4m, 1m and 2 m.*

The conclusion following from figure 15 is that the masking potential considering the immission limit 40 dB(A) is good while if the sound pressure level is equal to that of the wind turbine noise the masking potential is worse. It should be noted that this is measurements of sea wave sound at the shore line.

A prestudy determining the masking threshold of sea wave sound on wind turbine noise through listening tests shows a similar result. 6 subjects listened to samples of sea wave sound and wind turbine noise resulting in the thresholds in figure 16-17, i.e. at which SN-ratio the wind turbine noise is audible. The wind turbine noises used are from a single wind turbine and a wind farm. A more detailed review of the testing procedure is given in Bolin K (2007).

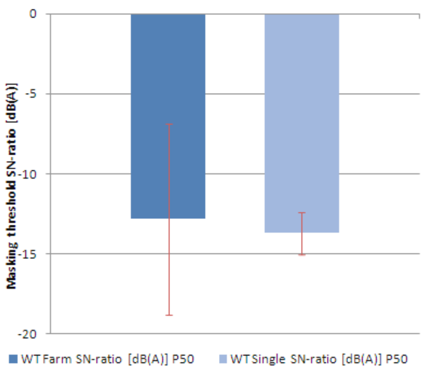


Figure 16. *Masking threshold P=50%*

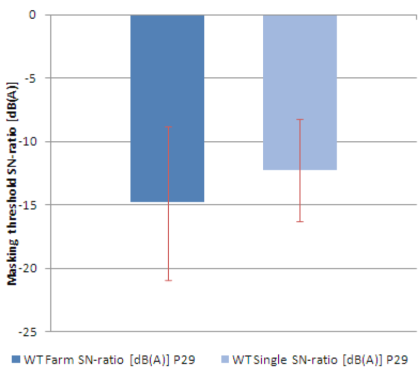


Figure 17. *Masking threshold P=29%*

Conclusions

Following the results in the previous chapters the evident conclusion is that background sound from breaking sea waves most likely will contribute to the masking of wind turbine noise. The sound pressure level from the regression analysis is by far above that of the frequently used immission limit approving 40 dB(A). The masking potential is well exemplified in figure 15 by the frequency spectra corresponding to three different wind turbines and also confirmed through listening tests. As discussed C-weighting could be more accurate describing the masking potential, but then C-weighting should also be applied to the wind turbine noise which is not presently the case. It is also necessary to realize that the wave climate and wave breaking potential could vary between different locations, where the sea bottom inclination is believed to be a determinant factor. The results presented here are based on measurements on four locations along the Baltic sea on shores where the bottom profile is uniform. To estimate the variation that can result more measurements on locations with different sea bottom inclination and other special features is advised.

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Second International Meeting
on
Wind Turbine Noise
Lyon France September 20 – 21 2007

A Variety of Wind Turbine Noise Regulations in the United States – 2007

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Abstract

Similar to other new large-scale projects, proposed wind turbine projects can produce varying reactions among community residents, including potential concerns about noise. Both state and local governments within the United States have developed a variety of noise regulations that specifically address wind turbine installations. These regulations have sought a balance of allowing for wind turbine development with protection of the public from excessive noise. A presentation at the First International Meeting on Wind Turbine Noise 2005 focused on regulation of wind turbine noise in the Western United States. Since that time, new regulations have been adopted in areas throughout the United States. This paper will identify several types of regulations and discuss their characteristics and impact on wind turbine projects and their associated communities.

Introduction

Well-balanced noise regulations aim to protect the interests of both the general public and the business community. To encourage this balance the United States chose decades ago that noise be regulated by state and local governments rather than on a national level. Although several federal agencies are concerned with noise associated with transportation systems (highway, air, and rail), interstate gas transmission facilities (gas compressor stations), and developments on federally-owned land, there are no federal noise limits that apply to either individual wind turbines or to entire wind turbine projects. Many states have also chosen to consider noise a local issue best addressed by local regulations that reflect the specific needs and wishes of a community. Consequently, few states have enacted noise regulations or siting procedures that pertain specifically to wind turbine developments. Many local communities, which are typically rural in nature, are now for the first time reviewing site applications for small, medium, and large-scale wind turbine projects. In an effort to support this review process and to provide appropriate protection for all interested parties, communities have adopted a variety of local laws since 2000 that specifically address wind turbine noise. An earlier paper[1], which was presented at the First International Meeting on Wind Turbine Noise 2005, describes the federal noise regulations and guidelines and discusses state and local noise regulations in the Western United States for wind turbines. We expect that noise and other associated wind turbine regulations throughout the U.S. will continue to evolve as wind turbine manufacturers advance the design and capacity of their machines, and as more communities gain experience in reviewing and hosting wind turbine developments. The wind industry, host communities, and government policy-makers will benefit by collecting and sharing this knowledge. The following provides examples of wind turbine noise regulations and comments on the salient features of these regulations.

Positions on Wind Power

Official statements of federal, state, and local government agencies uniformly embrace the development of renewable energy sources, including wind power. However, in practice, most regulation of a wind turbine project is at the local level, and local community attitudes and regulations can range from encouraging development to actively discouraging some development. Regulations may distinguish between private and commercial wind turbine developments, and set maximum heights and electrical ratings, number of turbines, and minimum setbacks, as well as other criteria in response to community wishes. One town's thoughts and concerns are expressed below:

Community Benefits and Concerns about Wind Power

The "Wind Energy Facility Law of the Town of Ellenburg, New York," (Local Law No. 4 of 2005)[2] states its purpose, and also, identifies community benefits and concerns, including potential noise, that are associated with wind turbine developments. The local law contains:

§2 Purpose. The Town Board of the Town of Ellenburg adopts this Local Law to promote the effective and efficient use of the Town's wind energy resource through wind energy conversion systems (WECS), and to regulate the placement of such systems so that the public health, safety, and welfare will not be jeopardized.

§4. Findings. The Town Board of the Town of Ellenburg finds and declares that:

1. Wind energy is an abundant, renewable and nonpolluting energy resource of the Town and its conversion to electricity may reduce dependence on nonrenewable energy sources and decrease the air and water pollution that results from the use of conventional energy sources.
2. The generation of electricity from properly Sited wind turbines, including small systems, can be cost effective, and in many cases existing power distribution systems can be used to transmit electricity from wind-generating stations to utilities or other users, or on-Site consumption can be reduced.
3. Regulation of the siting and installation of wind turbines is necessary for the purpose of protecting the health, safety, and welfare of neighboring property owners and the general public.
4. Wind Energy Facilities represent significant potential aesthetic impacts because of their large size, lighting, and shadow flicker effects.
5. If not properly regulated, installation of Wind Energy Facilities can create drainage problems through erosion and lack of sediment control for facility and access road Sites, and harm farmlands through improper construction methods.
6. Wind Energy Facilities may present a risk to bird and bat populations if not properly Sited.

7. If not properly Sited, Wind Energy Facilities may present risks to the property values of adjoining property owners.
8. Wind Energy Facilities are significant sources of noise, which, if unregulated, can negatively impact adjoining properties.
9. Construction of Wind Energy Facilities can create traffic problems and damage local roads.
10. Wind Energy Facilities can cause electromagnetic interference issues with various types of communications.

Of note, the Town of Malone, New York shares similar words in the Findings section of its local law, but names only large-scale multi-tower wind energy facilities in most of its statements.

Project Size and Purpose

The following paragraphs from the Town of Malone, New York Local Law of 2006 distinguish between private and commercial wind turbine developments, allowing one small tower (Wind Conversions System, WECS, no greater than 10 kW) per private party and strongly discouraging large-scale/commercial projects.

§ 80-11 Development Standards.
All small wind energy systems shall comply with the following standards. Additionally, such systems shall also comply with all the requirements established by other sections of this Article that are not in conflict with the requirements contained in this section.

1. A system shall be located on a lot a minimum of one acre in size, however, this requirement can be met by multiple owners submitting a joint application, where the aggregate size of their lots is at least one acre.

2. Only one Small WECS (plus, where authorized, a temporary wind measurement tower) per legal lot shall be allowed. Where there are multiple applicants, their joint lots shall be treated as one lot for purposes of this limitation.

3. Small WECS shall be used primarily to reduce the on-site consumption of utility-provided electricity.

§80-12 Standards
A Small Wind Energy System shall comply with the following standards:

1. Setback requirements. A Small WECS shall not be located closer to a property line than one and a half times the Total Height of the facility.

2. Noise. Except during short-term events including utility outages and severe wind storms, a Small WECS shall be designed, installed, and operated so that noise generated by the system shall not exceed the 50 decibels (dBA), as measured by an unweighted meter at the closest property line.

5. The maximum turbine power output is limited to 10 KW.

§80-14 Variances.

A. The Zoning Board of Appeals in accordance with its normal procedures may grant variances for Small WECS, but in no event shall the Zoning Board of Appeals grant a variance allowing a larger WECS than permitted by this Chapter, or a WECS primarily designed to generate electricity for off-site use, or any large-scale multiple-tower wind facilities.

B. If a court of competent jurisdiction (1) orders the Zoning Board of Appeals to consider a use variance for any Wind Energy Facility other than a Small WECS, and such use variance is granted, or (2) the prohibition on any Wind Energy Facility other than a Small WECS is invalidated, no Wind Energy Facility shall be allowed except upon issuance of a Special Use Permit issued by the Town Board after a public hearing, which Permit shall require a Decommissioning Plan and removal bond, a Public Improvement Bond to protect public roads, and shall comply with the following minimum setbacks:

a. The statistical sound pressure level generated by a WECS shall not exceed L_{10} - 45 dBA measured at the nearest off-Site dwelling existing at the time of application. If the ambient sound pressure level exceeds 45 dBA, the standard shall be ambient dBA plus 5 dBA. Independent certification shall be provided before and after construction demonstrating compliance with this requirement.

b. 1,500 feet from the nearest Site boundary property line.

c. 1,500 feet from the nearest public road.

d. 1,500 feet from the nearest off-Site residence existing at the time of application, measured from the exterior of such residence.

Although the Malone Local Law does include noise and setback standards for a commercial and/or large-scale WECS, it requires a court order for the town to even consider a variance application for this type of WECS. In addition, defining the maximum rating at 10 kW for a small-scale WECS maintains a relatively low ceiling for the size of the units. The setbacks between the small-scale and commercial/large-scale developments also differ, with 1500 ft (460 m) minimum setbacks from the Site property line, public roads, and off-Site residences required for the wind turbines of the latter projects. The noise limits for the project types differ as well; the small scale WECS has L_{max}=50 dBA at the nearest property line and the commercial/large-scale WECS has L_{10}=45 dBA at the nearest off-Site dwelling (and for an elevated ambient, relaxes the L_{10} limit to ambient plus 5 dBA).

Other local laws may recognize the size (small or large) or type (non-commercial or commercial) development, but still set uniform standards for all wind turbines. For example, the Town of Westfield, New York - Local Law No. 2 for the Year 2002 requires for all WECS projects:

c. Setback. The minimum required setback for any WECS tower from property lines, overhead utility lines, dwellings, agricultural buildings, or other WECS shall be equal to 1.5 times the proposed structure height, including blades.

d. Noise. WECS towers shall be properly maintained and operated at all times and shall be located with relation to property lines so that the noise produced during operation shall not exceed fifty (50) dBA, measured at the boundaries of all of the closest parcels that are owned by non-site owners.

Project Participants

Both acoustic and non-acoustic factors strongly influence a person's reaction to sound. High level sounds, tones, beats, significant low-frequency energy, and other distinctive acoustic factors will contribute to annoyance. However, a person's feeling about the source is a major non-acoustic factor, and indeed, may control the extent of a person's annoyance to the sound. Power plant developers have long recognized that good community relations contribute to the success of a project. Although not a standard practice for siting traditional electric power plants, proponents of several projects[3] have developed Property Value Assurance Plans where the project itself would purchase a nearby home at a fair market assessed price, should the resident decide to sell. The plant would then resell the home to a willing buyer. These programs, which were developed during each plant's permitting process, helped to gain the community's support for the project. In other cases, projects have purchased a noise easement from a resident only after considering and/or implementing other noise mitigation measures.[4]

We understand that wind power developers have also offered a Property Value Assurance Plan to neighbors as well as purchased easements from neighbors. Wind power projects are unique in that developers must typically assemble a site by negotiating land lease and easement options with many community landowners during the permitting phase. Should the project move forward, these community residents would then become economic participants, and likely, would be more accepting of any project noise or other impacts. As acknowledgement of this condition, wind turbine laws normally distinguish between participants and non-participants and allow for project noise requirements and setbacks to be waived at a participant's property.

In at least one case though, landowners' plans to become wind power project participants could not be fulfilled. Wabaunsee County, Kansas has chosen to prohibit large wind turbines [greater than 100 kW or taller than 120 ft (37 m) in total height] and to limit small turbines to one turbine per 20 acres. This ban is in response to the county's fear of large-scale wind turbine developments changing the overall character of its environment.

State Level

A few state agencies and environmental groups have published model ordinances to help guide local communities in developing local laws. The model ordinance recommended by the State of Wisconsin for local communities includes:

Wisconsin's Draft Model Ordinance (22 October 2003)

1) Audible noise due to Wind Energy Facility operations shall not exceed fifty (50) dBA for any period of time, when measured at any residence, school, hospital, church or public library existing on the date of approval of any Wind Energy Facility Siting Permit.

2) In the event audible noise due to Wind Energy Facility operations contains a steady pure tone, such as a whine, screech, or hum, the standards for audible noise set forth in subparagraph 1) of this subsection shall be reduced by five (5) dBA. A pure tone is defined to exist if the one-third (1/3) octave band sound pressure level in the band, including the tone, exceeds the arithmetic average of the sound pressure levels of the two (2) contiguous one-third (1/3) octave bands by five (5) dBA (sic) for center frequencies of five hundred (500) Hz and above, by eight (8) dBA for center frequencies between one hundred and sixty (160) Hz and four hundred (400) Hz, or by fifteen (15) dBA for center frequencies less than or equal to one hundred and twenty-five (125) Hz.

3) In the event the ambient noise level (exclusive of the development in question) exceeds the applicable standard given above, the applicable standard shall be adjusted so as to equal the ambient noise level. The ambient noise level shall be expressed in terms of the highest whole number sound

pressure level in dBA, which is succeeded for more than five (5) minutes per hour. Ambient noise levels shall be measured at the exterior of potentially affected existing residences, schools, hospitals, churches and public libraries. Ambient noise level measurement techniques shall employ all practical means of reducing the effect of wind generated noise at the microphone. Ambient noise level measurements may be performed when wind velocities at the proposed project site are sufficient to allow Wind Turbine operation, provided that the wind velocity does not exceed thirty (30) mph at the ambient noise measurement location.

4) Any noise level falling between two whole decibels shall be the lower of the two.

5) In the event the noise levels resulting from the Wind Energy Facility exceed the criteria listed above, a waiver to said levels may be granted by the Committee provided that the following has been accomplished:

a. Written consent from the affected property owners has been obtained stating that they are aware of the Wind Energy Facility and the noise limitations imposed by this Ordinance, and that consent is granted to allow noise levels to exceed the maximum limits otherwise allowed; and

b. If the applicant wishes the waiver to apply to succeeding owners of the property, a permanent noise impact easement has been recorded in the [Office of the Town/County Register of Deeds] which describes the benefited and burdened properties and which advises all subsequent owners of the burdened property that noise levels in excess of those permitted by this Ordinance may exist on or at the burdened property.

(http://www.doa.state.wi.us/docview.asp?docid=2869&locid=5)

This model ordinance limits the Wind Energy Facility (WEF) sound level to L_{max}=50 dBA at noise sensitive receptors, reduces the limit by 5 dBA for tonal sound, increases the limit to match elevated ambient sound levels, and waives the limits for landowners who participate in the project (e.g., lease or noise easement with WEF). We do not know the primary source(s) for this model ordinance and it's quite possible that Wisconsin borrowed paragraphs from elsewhere. However, since the time that this model ordinance was first published, communities from within and outside Wisconsin have adopted similar words for their own local laws. [A few sections have unfortunately propagated without revision though, such as the tonal criterion in Paragraph 2, which refers to dBA rather than dB; and of less importance, the ambient definition of the sound level exceeded for more than five minutes per hour rather than six minutes per hour (i.e., L_{10} sound level)].

In contrast to the Wisconsin Model Ordinance, the model ordinance below, which was developed by an environmental organization (PennFuture) for the State of Pennsylvania, suggests higher sound limits for the WEF, does not consider potential tonal sound of the WEF, and does not address the ambient sound environment.

PennFuture Model Wind Ordinance (21 March 2006)

13. NOISE AND SHADOW FLICKER

A. Audible sound from a Wind Energy Facility shall not exceed fifty-five (55) dBA as measured at the exterior of any Occupied Building on a Non-participating Landowner's property. Methods for measuring and reporting acoustic emissions from Wind Turbines and the Wind Energy Facility shall be equal to or exceed the minimum standards for precision described in AWEA Standard 2.1 - 1989 titled Procedures for the Measurement and Reporting of Acoustic Emissions from Wind Turbine Generation Systems Volume I: First Tier.

(http://www.pennfuture.org/UserFiles/ModelWindOrdinance_Final3_21_06_.pdf)

New York State has not developed a model ordinance for wind turbine developments, but instead, has summarized and published for general reference a document on local ordinances. This on-line publication[2] presents a wide variety of local ordinances adopted throughout New York State.

Applying another approach, the West Virginia Public Service Commission (WVPSC) has adopted a set of guidelines for noise studies for siting certificates, which they apply to wind power projects throughout that state. The guidelines require information on the existing ambient and sound estimates for the construction and operation of the proposed projects; they do not set standards. The required information includes:

Preconstruction – identify land uses and existing ambient sound levels (Ldn) in communities within one mile of the facility.

Construction – predict construction noise associated with blasting, earthmoving, pile driving, erection, traffic, and equipment installation at the nearest property boundary and within one mile and five miles from the facility. Identify noise sensitive areas within one mile and five miles of the facility. The noise sensitive areas include hospitals, schools, residences, cemeteries, parks, and churches. Describe construction equipment, procedure, and potential noise mitigation options.

Operation – predict operation noise and identify land uses and type of structures (residential, commercial, or industrial) within one mile of the facility. Describe equipment and procedures to mitigate potential noise.

The WVPSC reviews and evaluates this information, which is supplied by the project developer, during the permitting process for a wind power project.

Local Level

The noise standards in local laws can range from a relatively simple sound limit to a set of complex requirements for a wind power project. This section presents examples of local laws and comments on their various features.

Antis Township, Pennsylvania (2006)

A. Developer/Permitee shall comply with the following noise standards:
1. Developer/Permitee shall make a good faith effort to maintain a noise level attributable to the wind turbine generators of not more than 45dbC (sic) within a reasonable margin of error as measured from the property line of existing Non-Participating residences;
2. The Parties acknowledge that the Project's construction will be the source of intermittent noise. Developer/Permitee shall require all contractors to incorporate reasonable noise reduction measures in order to mitigate the amount of noise generated during the construction phase.
(http://antistownship.org/antis/lib/antis/2006_wind_turbine_ordinance.pdf)

One questions whether "dBC" was intended by the township rather than "dBA", however, of more interest here are the stated requirements of "good faith effort", "reasonable margin of error", and "reasonable noise reduction measures." These qualitative standards would require interpretation and agreement by the community and developer for a project.

Chippewa, Minnesota (2005)
12.7. Subdivision 7 — Setback Requirements
12.7.1.

Object	Setback Over 100 KW	Setback Under 100 KW
Residence (Other than applicant's residence)	750 ft (229 m)	300 ft (91 m)
Project Boundary	5 rotor diameters	5 rotor diameters
Public Roads (from right-of-way)	300 ft (91 m)	1 times height (max)
Other Structures	1.25 times height	1.25 times height (max)

12.8. Subdivision 8 — Noise Standards
12.8.1. Noise is regulated by the MPCA under Chapter 7030. These rules establish the maximum nighttime and daytime noise levels that effectively limit wind turbine noise to 50 db (A) at farm residences. However, these standards may not be sufficient for the "preservation of public health and welfare" in relation to impulsive noises. Additional local limits relative to impulsive and pure tone noises may be appropriate.
(http://www.co.chippewa.mn.us/Ordinance%20Section%2012%20Windpower%20Mgt.pdf)

The standards require greater setbacks for wind turbines rated greater than 100 kW than those rated less that 100 kW, but they apply the same noise criterion for each size machine. In addition, they also suggest the need for more limits on wind turbine projects. The Minnesota Pollution Control Agency, (MPCA, a state agency) adopted a set of receptor noise standards over 25 years ago. The sound level standards (dBA) at noise sensitive receptors (e.g., residences) are: L_{10}=65(day)/55 (night) and L_{50}=60(day)/50(night). We understand that funding has been reduced at MPCA and that enforcement of these standards has now been left to local governments.

Manitowoc County, Wisconsin (2004, 2005, 2006, & 2007)
"Large wind system" means a wind tower and turbine that has a nameplate capacity of more than 100 kilowatts or a total height of more than 170 feet, or both.

(2) Set Backs. The wind tower in a large wind system and each wind tower in a wind farm system must be set back:
(a) at least 1.1 times the total height of the large wind system from the property line of a participating property.
(b) at least 1,000 feet from the property line of a nonparticipating property unless the owner of the nonparticipating property grants an easement for a lesser setback. The easement must be recorded with the Register of Deeds and may not provide for a setback that is less than 1.1 times the total height of the large wind system.
(c) at least 1.1 times the total height of the large wind system or 500 feet, whichever is greater, from any public road or power line right-of-way.

(14) Noise. The noise generated by the operation of a large wind energy system may not exceed the ambient noise level by more than 5 dB(A) as measured at any point on property adjacent to the parcel on which the large wind energy system is located. The noise level generated by the operation of a large wind energy system will be determined during the investigation of a noise complaint by comparing the sound level measured when the wind generator blades are rotating to the sound level measured when the wind generator blades are stopped.
(http://www.manitowoccounty.com/Upload/8/Chapter%2024%20Current%20-%2005-01-2006.pdf)

The Manitowoc County regulations define large wind systems by rated capacity (greater than 100 kW) and by height [taller than 170 ft (52 m)]. The standards for large wind systems have setbacks of 1000 ft (305 m) from the property lines of non-participating properties and 500 ft (152.5 m) from public roads and right-of-ways.

The sound limit for a large-scale wind power project is 5 dBA above the existing ambient sound level, measured at any location within an adjacent property.

Benton County, Indiana

A. Noise and Vibration

1. At no point within 200 feet of a primary residence may the sound pressure levels from a wind turbine exceed the following sound levels. Sound levels shall be measured with an octave band analyzer or sound level meter and associated filter manufactured in compliance with standards prescribed by the American National Standards Institute (ANSI). This standard shall supersede any noise standard(s) set forth in Section 8-7 of the Benton County Zoning Ordinance.

Octave Bands (Hz), per ANSI	Maximum Permitted Sound Level (dB) measured 200 feet from the edge of any Primary Structure
63	75
125	70
250	65
500	59
1000	53
2000	48
4000	44
8000	41

(http://www.ces.purdue.edu/Benton/files/noise%20and%20vibration.pdf)

This standard attempts to address the spectral content of the wind turbine sound. We note that a sound that matches the maximum permitted level for each octave band would result in an overall A-weighted sound level of 62 dBA; this overall sound level is significantly greater than limits in other wind turbine laws that we have reviewed.

Summary - Features in Wind Turbine Regulations

The list below summarizes the numerous features that we have found in the variety of wind turbine noise regulations:

Project Type

- Small-scale/large-scale (10 kW, 20 kW, 100 kW)
- Single tower/multi-tower
- Private/commercial

Overall Sound Level (dBA)

- Absolute (Lmax, L10, L50; 45, 50, 55, 60 dBA)
- Relative to ambient (equal, +5 dBA)

Spectral Content

- Tone (qualitative, quantitative criterion)
- 1/3 or 1/1 octave band limits
- dBC

Other Characteristics

- Impulsive
- Low frequency

Measurement Location

- Site property line
- Non-participant’s property line
- Noise-sensitive non-participant’s structure (e.g., residence)

Related Standards

- Setback (300, 750, 1000, 1500 ft) – 90 m to 460 m
- Height (65, 80, 120, 125, 170, 350, 400, 440 ft) – 20 m to 135 m
- Participants (easement, waiver)

Conclusions

Most regulation is performed on the local level, with the noise standards and related size and setback standards reflecting the different positions of communities on wind turbine development. As wind turbine designs evolve and as communities gain more experience in reviewing and hosting wind power projects, we expect that the regulations will also evolve in a continuing effort to balance the interests of all parties.

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Second International Meeting

on

Wind Turbine Noise

Lyon France September 20 – 21 2007

Investigating the audibility of wind turbines in the presence of vegetation noise

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Abstract

This paper describes a prediction method of vegetation noise and shows comparisons between simulations and measurements of steady as well as time fluctuating vegetation noise. The results indicate that both the vegetation spectrum as well as the time variations can be accurately predicted. A psycho-acoustic study with six subjects has been performed to establish masking thresholds for wind turbine noise in vegetation noise. Two types of wind turbine noise (with and without modulation) were used in this experiment and coniferous as well as deciduous noise was for masking. The masking thresholds were compared to theoretical calculations and showed good agreement in the deciduous masker case the coniferous masker showed threshold differences between calculations and test results.

Introduction

The growing height of wind turbine (WT) towers gives rise to increasing efficiency in woodland areas earlier considered unsuitable due to the high surface roughness above forests. However, the sound environment at nearby dwellings could be negatively effected by introducing noise polluters in regions earlier unaffected by industrial noise. In [1] Fégeant proposed a semi-empiric prediction model for vegetation noise. Although Fégeant´s work was pioneering the wind turbulence was only briefly taken into account [2] and no general prediction method was presented. In [3] and [4I a more general prediction model was proposed which allowed a more advanced turbulence model than what is possible with Fégeant model [1]. Comparisons between the model and measured results were also presented in these references. In [4] masking of WT noise by vegetation noise was also addressed.

However, the percentile values of vegetation noise were not presented. This is important since short periods of high S/N ratios between WT noise and background noise can lead to audibility, although the equivalent sound pressure level completely masks the WT noise. Therefore percentile values like L_{A90} might be preferable to evaluate the masking potential. Furthermore, a psychoacoustic test to determine the masking threshold of WT noise in vegetation noise is an interesting issue and has not been performed before.

The purpose of this paper is to examine if the proposed vegetation noise model in [4] could predict percentile values. The results indicate how different WT noises are audible in the presence of natural background noises and could be used as a tool to optimize the power generated from WT as well as avoiding disturbance among nearby residents. A prediction model for noise from vegetation including the deleafed state is described. This has been coupled to wind turbulence and therefore percentile values such as $L_{A,90}$ and $L_{A,10}$ can be predicted. Thereby it is the author's opinion that the model can be used to determine the background noise level instead of extensive measurement campaigns. In this paper preliminary results from psychoacoustic tests with six subjects are also presented. These are compared to a loudness model to examine if this is applicable to the sounds in question. Two different WT sounds have been used as stimuli. The first sound is recorded from a single WT with distinctive amplitude modulations. The second sound is from a WT park.

Prediction model

The model proposed in [4] calculate the frequency dependent sound pressure level $\tilde{p}_{eff}(f)$ by

$$\tilde{p}_{eff}^{2}(f) = \frac{\rho c}{4\pi}\sum_{x}\sum_{y} J(f,x,y)\Delta x \Delta y \int_{z} C_R M(z)^{2\chi}\Gamma(f)\,dz \,, \qquad (1)$$

where ρ is the air density c the sound speed, x *and* y represent the dimensions in a horizontal plane, J is a propagation factor, z is the vertical dimension, C_R is a species dependent radiation constant, M the Mach number, $\Gamma(f)$ is the normalized frequency spectrum and f is the centre frequency of a third octave band, for further explanation of these parameters see [4].

With the discrete horizontal dimensions the Sandia model [5] can be used to calculate space and time correlated time series of turbulent wind velocities. These sequences are then inserted in Equation (1) which gives time dependent sound pressures. For further description, see [4].

A graphical user interface (GUI) of this prediction model has been created and examples of input data windows are shown in Figure (1). These windows allow for specifying different meteorological parameters influencing the average wind as well as the turbulence. Results from this program can be viewed as third octave band spectrums as well as distributions of A-weighed sound pressure levels.

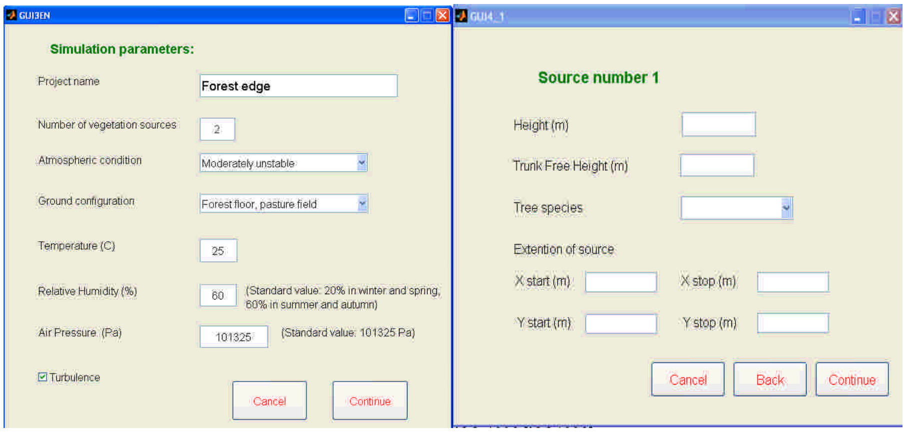


Figure 1: Examples of GUI input data windows from the software predicting vegetation noise.

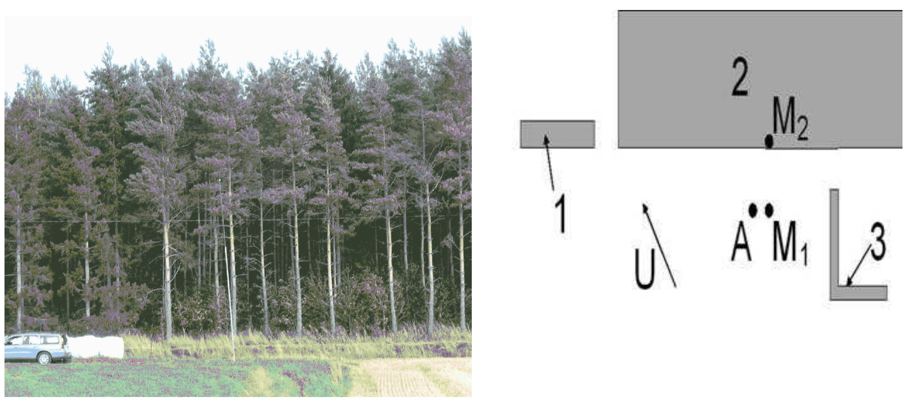
Measurement

To investigate the sound generated by vegetation for conditions not reported by Fégeant [1], i.e., at higher wind speeds and different meteorological conditions new measurements were considered necessary. These measurements were conducted in agreement to the procedure described in ISO 1996 [6].

The measurement setup consisted of a cup anemometer mounted on a 10 m high pole, and a weather station registering humidity and temperature. The sound measurement equipment consisted of 1/2" microphones at 1.2 m height above ground connected to a digital analyzer SONY PC216Ax with 44 kHz sampling frequency. In order to decrease the pseudo-noise generated by wind the microphones were protected by foam windscreens 10 cm in diameter, the sound damping produced by the protection are corrected in the analysis of the measurements. A high pass filter with a cutoff frequency of 20 Hz was used to further reduce the pseudo-noise.

Description of site

A hedge of birches (1) in Figure 2b with a depth of 5 m and a length of 45 m were located a distance of 100 m from the measurement equipment. The height of the birches was estimated to H_1=20 m and the trunk free space to h_1=1 m. The site was dominated by an edge of mixed conifers region (2) consisting of both pines and spruces as can be seen in Figure 2a with tree height H_2=20 m but the trunk height differed $h_{2,p}$=7 m and $h_{2,s}$=2 m for pine and spruce respectively. The width of the forest was 155 m and the depth was several hundreds of meters thereby the approximation that only the region between the forest edge and two tree heights inward contribute to the noise generation [1] is used. There were shrubberies of hazel below the trees; these are however not modeled in the simulations. By the side of the forest edge there was an L-shaped hedge, region (3), of birches at a distance of 40 m from the microphones. These trees were 20 m high and had a trunk height of 1 m. Both legs of the hedge were 30 m long and with a width of 3 m. The ground was covered with short grass. The microphone position (M_1) was 10 m upwind of the forest edge and the anemometer position (A) was at the same distance from the edge. The temperature was T=25ºC and the relative humidity H_R=50%. A wind turbine type Vestas V52 was standing at a distance of 0.8 km from the site in the direction of hedge 1 which might contribute to the low frequencies in the measurements although it was not audible to the author.



(a) (b)

Figure 2: Photography (a) and sketch (b) of measurement site. The symbols are explained in the text.

Results

The third octave band spectrum in Figure 3 shows good spectral resemblance between measurements and model calculations. This shows that the time averaged data can be predicted by the model proposed in [4]. For further comparisons see [4]

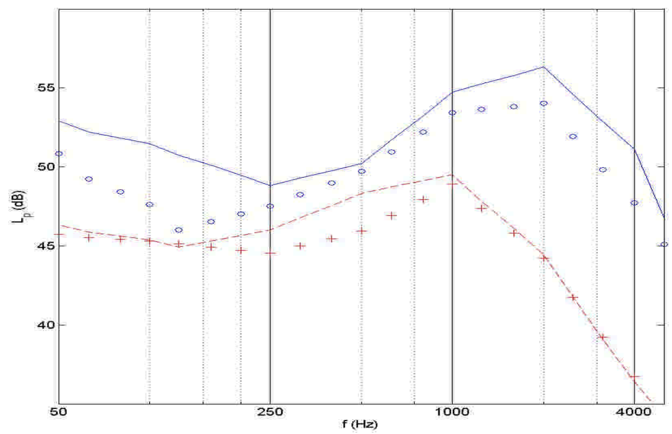


Figure 3: Third octave band spectrums of predictions (- - -) (——) and measurements (+) (o) for wind speeds 4.6 m/s (red) and 8.3 m/s (blue).

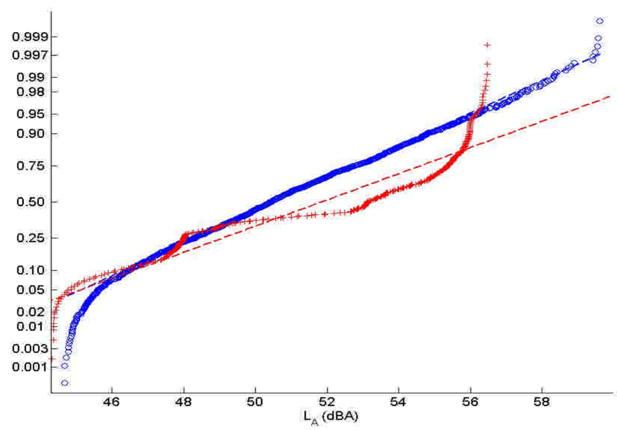


Figure 4: Cumulative distribution of A-weighed sound pressure levels. The y-axis is scaled so that a line corresponds to a Gaussian distribution. Measurement values are denoted (o) and prediction values (+). The dotted lines show the least square fits of normal distributions to the two data sets.

Cumulative distributions of measurements and predictions are shown in Figure 4. This graph shows that the measured time series of vegetation sound are nearly completely Gaussian distributed, shown by the tight fit to the dotted line. Larger deviations from the Gaussian distribution are shown in the simulated sound levels; this might be due to the relatively short simulated time series of 5 minutes compared to the measurement of 20 minutes. However, the two lines are nearly parallel and hence the properties of the Gaussian distributions are similar.

Psychoacoustic test

Test sounds

Two target sounds, the first from a single WT and the other from a wind turbine farm were used in the experiments. Spectrograms of the WT sounds are presented in Figure 5 and 6. The first wind turbine noise was recorded from a single wind turbine Wind World 100 kW with the same measurement technique as for the vegetation recordings. This is a relatively old wind turbine (erected 1991) and the noise contains both aero-acoustic components from the blades as well as mechanical noise from the hub. This sound has characteristic 1.8 Hz amplitude modulations (AM) of 1.8 dBA between top and bottom values caused when the blades pass the tower. These can clearly be seen in the frequency bands between 500 Hz and 2 kHz in Figure 5. The second wind turbine noise was recorded at a distance of 400 m from the Rhede wind turbines park at nighttime [7]. The microphone was mounted on a pole 4.5 m above the ground level. The park consists of seventeen 1.8 MW wind turbines with a height of 98 m and 35 m blade radius.

The natural ambient noises considered of coniferous and deciduous trees, see Figure 7 and 8 for spectrograms of the sounds. The vegetation noises were from coniferous and deciduous trees as these two types emit different noise types. These noises were recorded on a digital analyzer SONY PC216Ax using an Omni-directional 1/2" microphone. The microphone was placed 1.2 m above the ground level [6]. In order to decrease the pseudo-noise generated by the wind into the microphone a foam windscreen 10 cm in diameter was used to enclose the microphone. Both recordings were performed at times with high wind speeds, around 8 m/s, contributing to relatively high signal to noise ratios when vegetation noise levels are compared to the levels of other ambient noises. All stimuli were normalized to a constant A-weighed sound pressure level of 40 dBA. This was due to the fact that the Swedish emission guideline for wind turbine noise is set to 40 dBA at wind speeds of 8 m/s. Each test signal was 4 s long with a fade in and fade out of 40 ms.

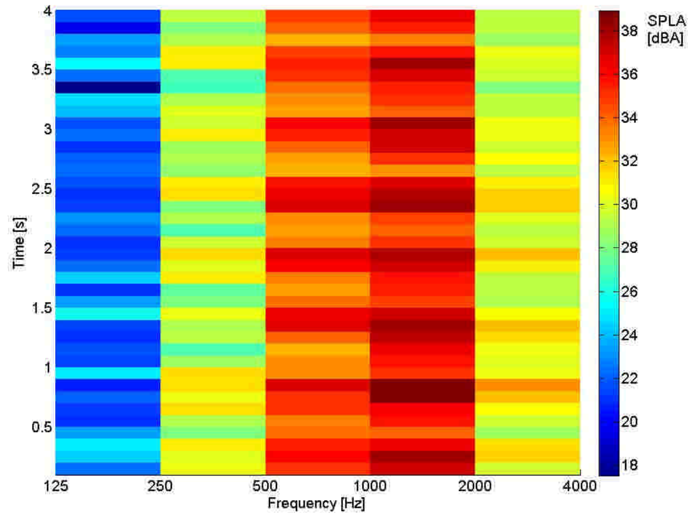


Figure 5: Octave band spectrogram of single WT sound.

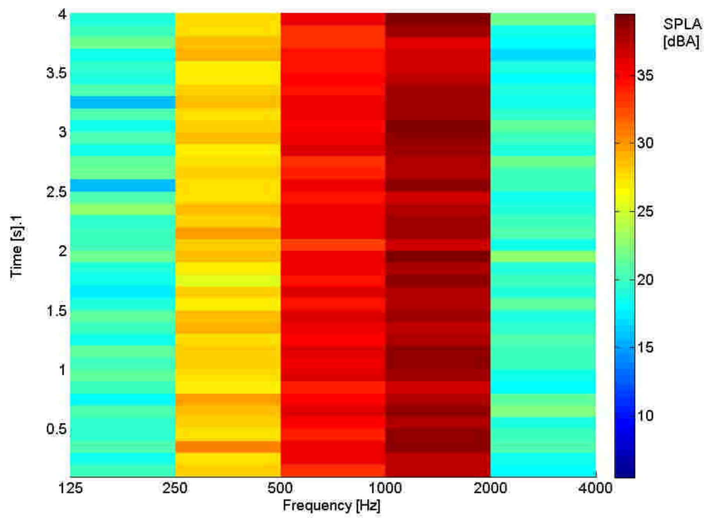


Figure 6: Octave band spectrogram of WT farm sound.

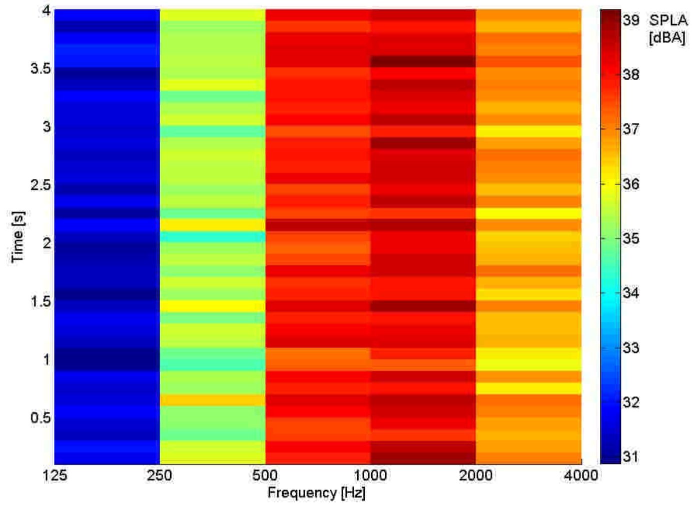


Figure 7: Octave band spectrogram of coniferous natural ambient noises.

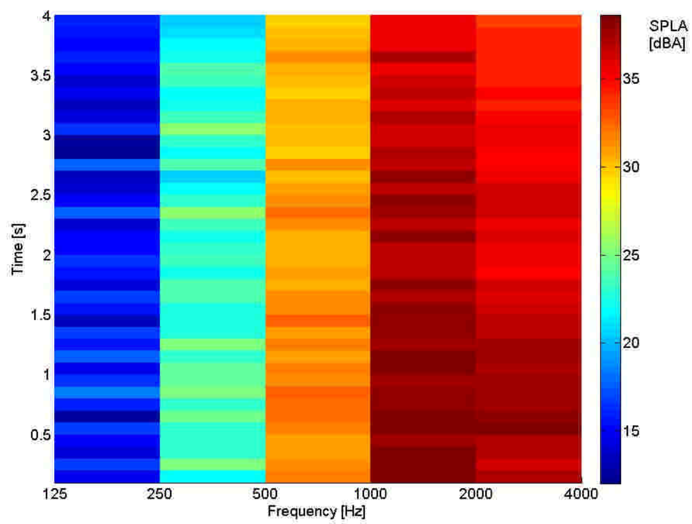


Figure 8: Octave band spectrogram of deciduous natural ambient noises.

Masking theory

A partial loudness model by Moore et al [7] is compared to the test results. Third octave band spectrums from the target sound and the masker is used as input and from these data a partial loudness value is calculated. The masking thresholds in these calculations are the 3 phon levels [8]. These calculations were performed in the software AESLOUD developed at Cambridge University. In table 1 the signal-to-noise (S/N) ratio for the masking thresholds are shown. The S/N ratio is defined as the difference of the A-weighed sound pressure levels between the targets and the maskers. Although the audibility of AM sounds has been investigated in several articles [9], [10] and [11] the conclusions regarding the effect on masking are not unanimous, furthermore artificial sounds with 100% amplitude modulations are commonly used in these tests. However, it has not, to the author's knowledge, been performed masking tests with the relatively low amplitude modulation in the single WT sound. Consequently it is considered interesting to investigate if this modulation has any effect on the masking possibility.

	Single WT	WT farm
Coniferous	-10.9	-11.9
Deciduous	-13.8	-13.1

Table 1: Calculated S/N ratios [dB] of masking threshold of the target sounds in the maskers.

Subjects

Six subjects participated in the study. They consisted of staff and students from the Kungliga Tekniska Högskolan (KTH), Stockholm. Their ages varied between 20 and 63 years. Four subjects were females and two subjects were men.

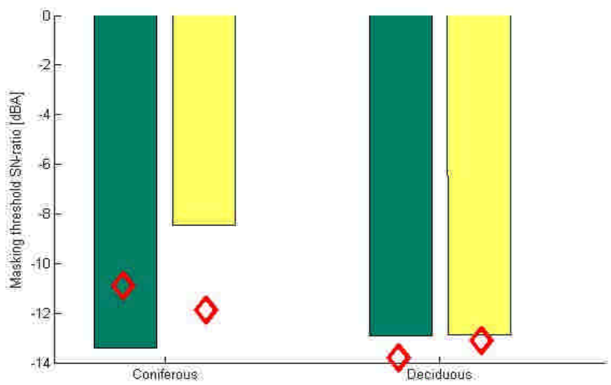
Procedure

All the listening tests were performed in a hemi-anechoic room where all monaurally recorded signals were presented through headphones AKG k-501 [12]. An audiometric test was administered to each subject prior to the listening test. All the subjects exhibited normal hearing abilities from 125 Hz to 8 kHz [13].

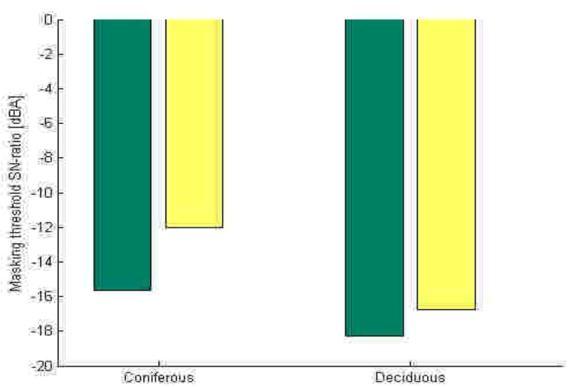
A two alternative forced choice task was used. The noise alone or the target and noise were presented in random order with a 0.5 s pause between the sounds. The subjects had options to hear wind turbine noise during the test. The subjects were instructed to determine which of the samples contained the target. An up-down procedure [14] was used, this was repeated two times and the average value was defined as the masking threshold. Furthermore a transformed up-down procedure [14] was used to determine the point corresponding to the 29.3% point on the subject's psychometric function. The tests started at S/N ratio of 8 dBA and the step size was 5-dB in the first step, 3-dB in the second and 1-dB thereafter.

Results

As only six persons have performed the test no analysis regarding the statistical significance of the results is performed in this paper. The masking thresholds of the different targets and maskers are shown in Figure 9. As expected the 50% psychometric test Figure 9(a) shows higher values than the 29% test Figure 9(b). The results in both tests indicate that the coniferous masker conceal the targets at higher S/N ratios than the deciduous masker in three out of four tests.



(a)



(b)

Figure 9: S/N ratios [dB] of masking thresholds P=50% (a) and P=29% (b). Green bars show the single WT sound and the yellow bars show the wind farm target. The red diamonds (◊) indicate the theoretical masking thresholds from Table 1.

The threshold differences between the single WT target sound and the wind farm sound are small but with a tendency that the single WT sound has lower thresholds. This indicates that amplitude modulations increase the audibility of wind turbine noise. Comparisons between the theoretical values, denoted by the red diamonds in Figure 9(a) and test results show good agreement with the deciduous masker but the coniferous noise differ and this might be due to the few test persons used. Furthermore the difference seen in both Figure 9(a) and 9(b) by the coniferous masker between the single WT and WT farm indicate that the low frequency components between 125-500 Hz in the WT farm sound is well concealed by the coniferous noise, see Figure 5-7. The deciduous masker shows smaller difference between single WT and WT farm targets.

Conclusion

The utilized prediction method discussed in this paper shows good spectral resemblance to measurements. Turbulent wind time series from the Sandia model can easily be used as input parameters but the available computer power prevents long time series to be computed in large vegetation areas. However the measured and simulated vegetation noise shows similar normalized distributions.

The graphical user interface is fairly easy to use for a person with some experience in meteorology but no extensive knowledge of the prediction model is considered necessary to operate this program.

The study concerning the masking threshold shows that large differences between the masking thresholds of different WT noise might be expected in coniferous background noise. If these deviations are statistically significant or occur because too few subjects performed the test can unfortunately not be established.

A possible application for the masking threshold could be a limit for wind turbine noise emission in areas where special concern to an undisturbed soundscape is desired, for example in recreational areas, national parks and nature reserves. However, the masking threshold should not be confused with the annoyance threshold that requires other psychophysical methods to determine.

Future work

More persons should participate in the psycho-acoustic test in order to increase the statistical significance of the results. Investigation of the masking potentiality of time varying sounds, theory and tests with sounds with duration around one minute could be a better measure of the audibility.

Acknowledgements

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What is the Real Background Noise?

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Abstract

A test that relies on background noise measurements related to wind speed may stand or fall on one or two decibels difference, yet the reality is that unattended outdoor measurements are highly variable and unpredictable. Measurements taken almost next to each other and at more or less the same time have been quite different. This paper considers what the noise v wind curve should look like and how it is made up of two separate data sets, one related to the wind and the other not. The paper considers exposure and shelter at noise measurement locations, noise sources and the effect of non-wind related noise. It also considers what the differences should be between night and day. Finally the paper looks at the limitations of the recorded data. Limitations of the equipment, results that are not typical of the measurement location and results that are typical of the measurement location but not elsewhere.

Introduction

A planning application assessed under ETSU-R-97 [1] or any test that relies on background noise measurements may stand or fall on one or two decibels difference in the background noise. So it is important both for developers (so that they can properly plan the development) and for residents (so that they can have adequate protection from noise) that the measurements are not only accurate but that they truly represent the “real” conditions at each location.

What is real is not so much a technical matter as a philosophical one. What is real can only be determined within the context of the question. Perhaps the best that can be done is to look at the technical background and describe a variety of “real” background noise levels and some that are clearly not real and many in between. It will be for the reader or perhaps the Inquiry or the court of law to decide which is the real background noise in the context of the particular circumstance being considered.

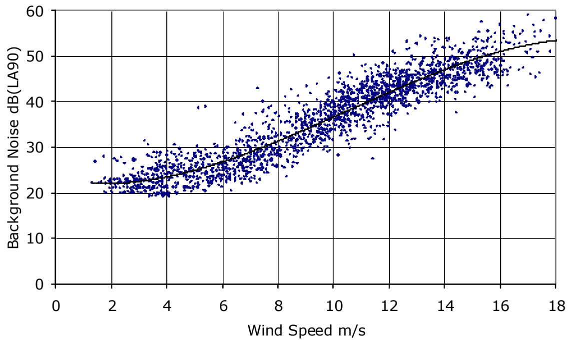
All the examples in this paper are taken from Environmental Statements for wind farms submitted in the belief that they represented the real noise level and its relationship to wind speed. All the noise levels in this paper are decibels as 10 minute LA90.

The Reality

In order properly to assess the impact of wind farm noise on noise sensitive neighbours the background noise has to be measured at a range of wind speeds and a graph of background noise level plotted against wind speed. The normal procedure is to measure wind and noise in 10 minute periods, the noise being measured at the sensitive properties and the wind measured on the wind farm site at a height of 10m above the ground.

The graph below in Fig 1 shows a typical result together with the best fit curve.

Fig 1



This all looks very neat and simple. The reality is that unattended outdoor measurements such as this are fraught with difficulty and can easily be affected by unexpected and unwanted data. In practice the results of these background noise measurements are highly variable and unpredictable.

The table below shows a summary of the background noise levels at the same residential location measured by two developers at different times.

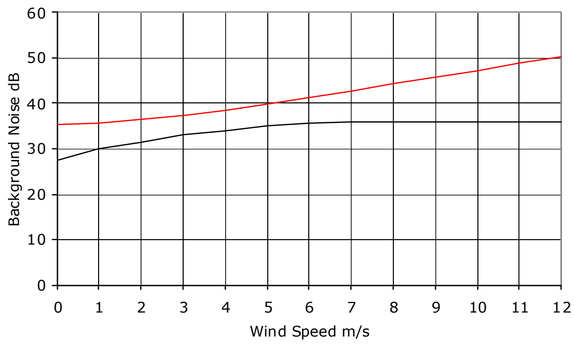
Table 1

Location II	6m/s	8m/s
Developer 1	38	42
Developer 2	32	34

Developer 1 might well have relied on its background noise measurements to design turbine noise levels of, say, 42dB at 6m/s and 44dB at 8m/s on the grounds that the background noise was not exceeded by more than 5dB. If the real background noise level is represented by Developer 2's measurements then the turbine noise levels would exceed the background noise by 10dB and, if ETSU-R-97 was the standard in use, then it would not meet either the day or night time requirements resulting in a significant loss of amenity and perhaps nuisance to residents. On the other hand if Developer 1's measurements are the real ones then Developer 2 might have unnecessarily removed turbines from the preferred design to comply with the lower background noise so reducing the viability of the development.

At another residential location the noise levels are shown below. The graph shows two best fit curves for the location made by two developers.

Fig 2

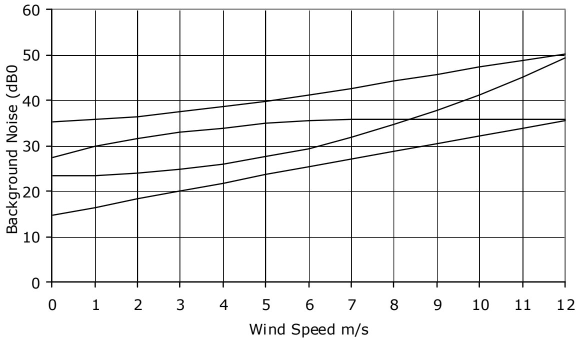


The interesting thing here is not only that this is the same site but the measurement positions were within a few metres of each other and the measurements were taken over almost the same period of time. They were taken over two week periods but were staggered by four days. In other words 72% of the measurements covered exactly the same period. The only differences are the equipment and the operator and the location of the anemometer mast.

How can it be possible that measurements taken almost next to each other and at more or less the same time are so different? It cannot be attributed to the anemometers being located on different hills because, even though the anemometers may be recording different wind speeds the measured noise levels must be almost identical. In fact, a closer examination shows that the noise levels reported at the same time were quite different. In one case about 10% of the noise levels were below 35dB and in the other about 50% were below 35dB.

The story of this unfortunate property does not end there because there were two other measurements taken at the same location about six months before in connection with two other wind farm applications. Fig 3 shows four curves, three of them taken at the same property and the fourth (the lowest curve) at the neighbouring one that was considered to have the same characteristics.

Fig 3



This shows an even wider divergence so that, at the wind speed likely to be the most sensitive for turbine noise (usually about 6m/s), there is a spread of around 15dB.

Regrettably such differences are the norm. At the six locations for which duplicate data is available only one has similar noise levels for two sets of data. To have such large discrepancies is not acceptable where decisions on whether a development should go ahead or not are at stake.

What Should The Curve Look Like?

The background noise graphs of the type shown in Fig 1 are familiar. The best fit curve has the flat S-shape.

The curve can be considered as being made up of two separate noise sources each consisting of a set of data. The first is a horizontal line consisting of noise that is not wind related (the NWR element). It may be inherent meter noise, streams, road traffic or any other continuous or varying noise other than that associated with the wind. Because it is not wind related the best fit curve for this first set of data must be horizontal.

The second noise source produces a set of data that is related to wind speed (the wind generated element).

Fig 4

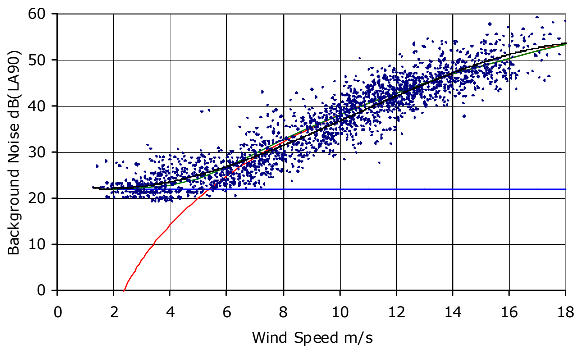


Fig 4 shows how these two elements go together to produce the typical best fit curve. Because of the way the curve is made up a second order polynomial is probably not sufficient to describe the position properly and a third order polynomial would be better.

The wind generated element can be described by:

$$L_1 = A \times \log(V) + C \,.\,.\,.\,.\,.\,.\,.\, \{1\}$$

Where L_1 is the 10 minute measured sound pressure level in dB(LA90), V is the wind speed at the noise measurement location and A and C are constants whose values depend on various factors to be discussed later in this paper. It is not proposed to define what “the wind speed at the noise measurement location” means in any further detail.

The NWR element can be described by:

$$L_2 = D. \,.\,.\,.\,.\,.\,.\,.\,..\,.\,.\,.\,.\, \{2\}$$

Where L_2 is the 10 minute measured sound pressure level in dB(LA90) and D is a constant.

Exposure and Shelter

Background noise measurements for wind farms are complicated by the fact that the wind measurement is made at a different place from the noise measurement. Taking two noise sensitive locations and assuming that the noise generating objects (trees, shrubs, grass and so on) are similar, if the wind speed were measured at the noise measurement locations there would be no difference in the graphs for a sheltered location down in a valley and for an exposed location on a hill. The fact that noise levels are, in practice, less at sheltered locations than at exposed locations is because of the difference in wind speeds between the two sites compared with the anemometer wind speed at the development site. The degree of exposure could be defined as the ratio of wind speed at the noise measurement location to the wind speed at the anemometer site. The smaller the ratio the less exposure or, conversely, the more the shelter.

For example if the degree of exposure is 0.75 then we can re-write equation 1 as:

$$L_1 = A \times \log(0.75 \times V_A) + C \ldots\ldots\ \{3a\}$$

or

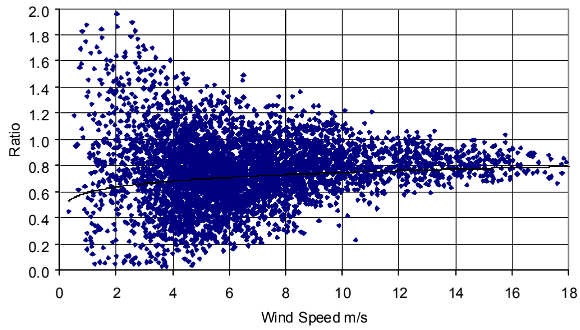
$$L_1 = A \times \log(V_A) + C - 0.125 \times A \ldots\ldots\ \{3b\}$$

Where V_A is the 10m wind speed at the anemometer.

So the wind generated part of the curve can be considered as moving to the right with increasing shelter (as described by equation 3a) or moving down (as described by equation 3b). To be precise the left to right shift is only a linear movement if the X-axis is logarithmic. As the X-axis here is linear by convention the left and right shift is constrained by the Y-axis – data shifted to the left is "squashed" against the Y-axis.

In passing, it is worth considering an alternative possibility. It is well documented that the atmosphere becomes less stable at higher wind speeds – for example van den Berg [4] and van Lieshout [5] – so the relationship between wind speed at the noise measurement location and wind speed at the anemometer mast is velocity dependent. The graph in fig 5 shows the result of comparing the wind speed at a development site with that at another more sheltered location 3km away. The vertical axis is the ratio of the wind speed at the sheltered location to the wind speed at the development site.

Fig 5



The power trend line has the relation:

$$V/V_A = 0.6 \times V_A^{0.1} \ldots\ldots\ \{4\}$$

showing increasing instability with wind speed. We can substitute the relationship in equation {4} into equation {1} as follows:

$$L_1 = A \times \log(0.6 \times V_A^{1.1}) + C \; . \; . \; . \; . \; . \; . \; . \; \{5a\}$$

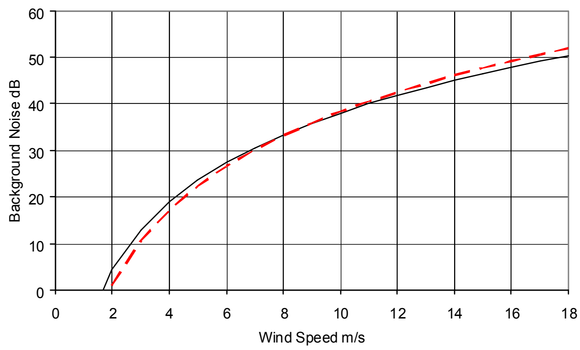
or

$$L_1 = 1.1 \times A \times \log(V_A) + C - 0.222 \times A \; . \; . \; . \; . \; . \; . \; . \; \{5b\}$$

As the degree of shelter increases the curve is therefore shifted down and becomes steeper – contrary perhaps to intuition.

Fig 6 below shows a comparison of the linear and power relationships for the set of data in Fig 5 The linear relationship (solid line) is 0.75 (as equation 3a) and the power relationship (broken line) is 0.1 (as equation 5a).

Fig 6



The differences here are small and there would be very little error if the shift were considered to be simply a shift of the wind generated curve up or down or right and left. However, that might not be the case in every circumstance.

Noise Sources

The value of C in equation 1 must also be dependent on the size, type and quantity of noise generating objects and how they are exposed to the wind. For example, trees might have a more significant quantity of noise generating components than grass but they might also be more exposed to the wind. To approach it with a broad brush the value of C will be higher for a location with trees and hedges than it will for an area with mown grass.

However, as with the degree of exposure, a shift of the wind generated curve up and down due to a change in the type and location of vegetation can be described alternatively as a shift to the right or the left.

VALUE OF A

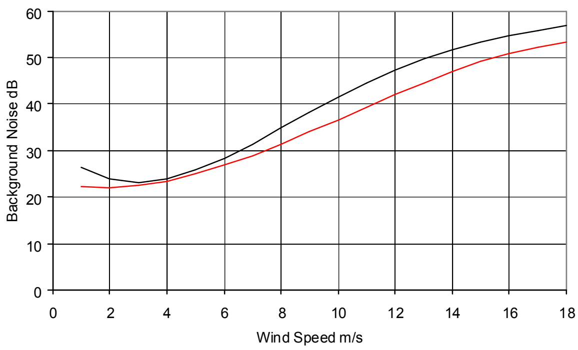
There does not appear to be any firm evidence to establish the value of A in equation 1 and indeed it may be dependent on the noise sources. In practice it is difficult to read from graphs of measured noise because of the flattening effect of the NWR element. An examination of a large number of graphs with low NWR elements suggest that it is normally between 40 and 60.

As described above and later, it may be that the curve is steeper in more sheltered or at night but the difference is probably small.

THE EFFECT OF THE NWR ELEMENT

Fig 7 shows the polynomials for two locations where noise has been measured simultaneously. One is exposed on the hill at an elevation only a little below the anemometer mast (the top, black, line) and the other is further down in the valley.

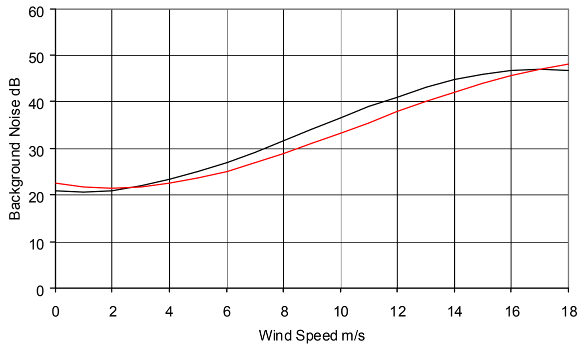
Fig 7



The measurements suggest that the NWR elements are similar in each case. The wind element simply moves up and down or right and left on the graph reflecting both the degree of exposure and shelter and the nature of the noise generating components. Because the NWR element does not move up or down and shifting it to the left or right makes no difference to it, it is better to consider that the whole curve moves horizontally.

Another example in Fig 8 shows why it may be better to consider that the wind curve moves horizontally. The graph below shows two polynomials of exactly the same set of noise data but plotted against wind speeds from two different anemometers that were 3km apart. The noise measurement location can be considered as more sheltered from one wind farm site than from the other.

Fig 8



Because the noise data is exactly the same for both curves, the position of the individual points in the scatter diagram can only move horizontally from left to right or vice versa. One best fit curve must therefore be considered as derived from the other by shifting to the right or left.

In summary the polynomial curve can be considered as shifting left or right according to:

> The degree of shelter at the noise measurement location as compared with the anemometer location.
>
> The nature and position of the noise generating objects at the noise measurement location.

Night and Day

Leaving aside the question of the difference in wind shear during the day and during the night for the moment, if the day and the night time noise graphs for a site are compared then the Wind generated element must be the same. Figure 9 is day time and figure 10 is night time at the same location. The NWR element of the graph alters the shape and height of the graph at lower and middle wind speeds. Unless the NWR element is particularly high it would not therefore significantly affect the curve at higher wind speeds.

Fig 9

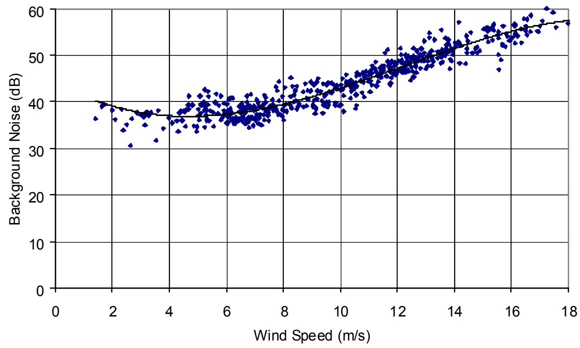
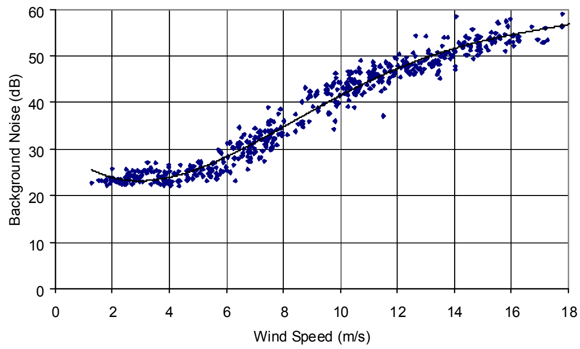
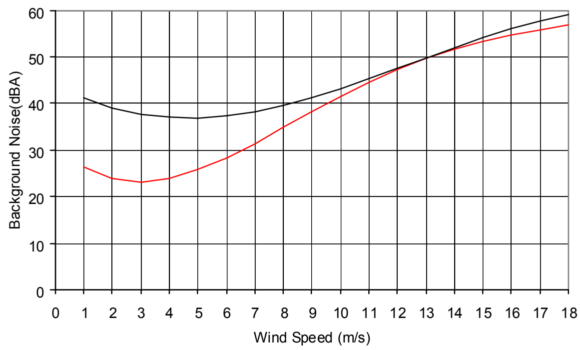


Fig 10



The differences are at the lower wind speeds. Where the wind element dominates there is little difference. This can be seen more clearly in Fig 11 which shows the day and the night measurements together.

Fig 11



This is as the measurements should be since the site is several hundred metres from a medium trafficked road.

If the wind shear is greater at night then the effect of this would be exactly the same as increasing shelter. That is to say there will be a tendency for locations to be more sheltered at night than during the day and so the night time wind generated element will tend to be shifted to the right compared with the day. Furthermore, if the power relationship in equation 5 is valid then the night curve could be steeper than the day curve.

Some Practical Examples

This section discusses some of the reasons why the actual or apparent measured noise levels may not be the real ones depending on the context and gives examples.

RESULTS THAT ARE NOT THE REAL NOISE LEVEL

Sometimes the noise levels apparently recorded by the equipment are not the actual environmental noise levels present at the time. Essentially this is a question of whether the equipment is the right equipment, whether it is being used correctly and whether it is operating without fault. All these issues ought to be obvious to the professional consultant. Nevertheless, because of the particular difficulty of this type of measurement, about one third of those submitted in Environmental Statements are probably faulty due to problems with equipment.

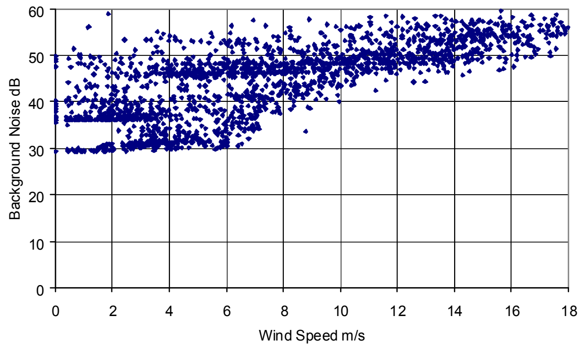
The first question is whether the equipment is fundamentally right for the job.

> What is the noise floor in dBA? It may not be enough to rely on the manufacturers data and, where possible, it is better to keep a record of the performance of individual items of equipment. Not only does this identify any shortcomings in the equipment but allows any changes in performance to be monitored. The actual noise floor of the instrument needs to be as low as possible but certainly it needs to appear to record noise below 20dBA to reduce distortion of the polynomial in low noise situations.
>
> The right windshield is essential. A study on improved windshields by Davis [2] was published at much the same time as ETSU-R-97. It recommends types of enhanced windshields that can be used. Such windshields are available commercially. A standard windshield has a self noise level proportional to the sixth power of the wind speed when measured in laminar flow [3]. What is more the self noise at a wind speed of 8m/s is 48dBA so that measurements in exposed places could easily be affected by wind on the windshield. It is almost impossible to identify the problem from the measurements because the wind shield noise can be considered as just another noise generating object at the measurement position. Perhaps an indicator is a steep curve close to the sixth power of velocity, but that might also be the real background noise in some circumstances.

The final issue here is that of faults in the equipment. All equipment develops faults at times and it is important to go through all the data sets when measurements are complete to look for anomalies that might indicate equipment faults. Anything showing unusual features would warrant further investigation.

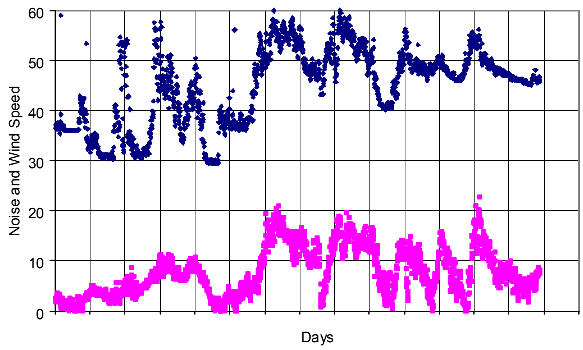
Figure 12 shows a curve containing banding.

Fig 12



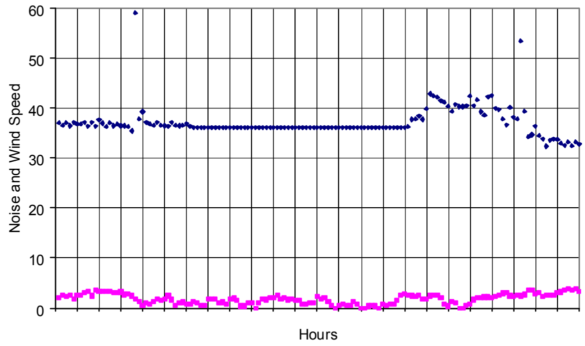
The banding may be due to a boiler flue, to plant or machinery in a farm. But it could also be an equipment problem. It is useful to plot all the data as a time series as shown in Fig 13.

Fig 13



There are a number of “suspicious” indicators here. On some of the first few days of the period when the wind was low the noise level dropped to 30dB at night. After day 6 when there was a big rise in wind speed the noise level never came back down to 30dB again even when the wind speed reduced to zero in the middle of the night. What seems to have happened is that the entire curve has shifted up by about 10dB. It cannot be that the wind shield was blown away because the noise level would still drop to 30dB when there was no wind. Further examination might suggest a problem with the meter. Fig 14 shows a closer look at day 1.

Fig 14



It can be seen that for ten hours the recorded level was exactly 36.1dB. The probability of this being the real noise level is very small and it is almost certainly some fault of the meter. Since this happened on the first day it puts the rest of the measurements under suspicion.

RESULTS THAT ARE REAL BUT NOT TYPICAL OF THE MEASUREMENT LOCATION

These can be the result of insufficient data or more particular a data set covering an insufficient range of wind speeds and wind directions. Alternatively it can be the result of noise sources measured at the measurement location that do not exist for the whole year or even for a substantial part of it. For example, measurements taken near sheep enclosures in the lambing season have resulted in raised noise levels.

Fig 15 shows an example where the amount of data at higher wind speeds is small. There is no way of knowing whether the polynomial is accurate or not but more measurements are needed over a larger range of wind speeds to be certain that something approaching the real noise level has been obtained.

Fig 15

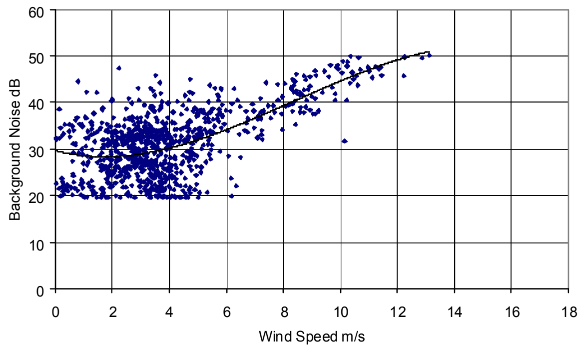
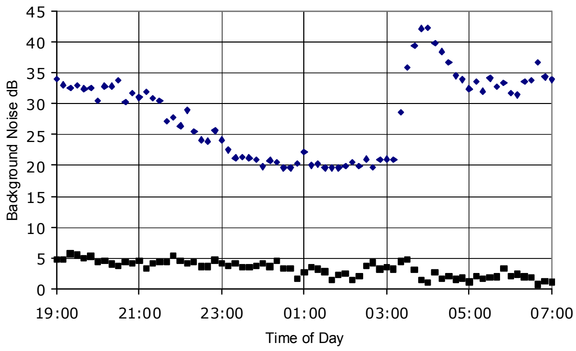


Fig 15 also shows another problem with the measurements. The thing that draws attention is the large spread at low wind speed. It is a night time measurement and this is unusual at night. It is instructive to look at the low wind speed data in a time series. This shows a picture of what is happening without the influence of wind. Fig 16 shows a detail of one typical night time period from early evening to morning. The bottom set of data is the wind speed.

Fig 16



From about 9 o'clock in the evening the noise level falls gradually to a minimum at 11pm and stays constant until 3.20 in the morning when it rises 22dB in the space of 30 minutes. This happens at the same time every morning unless it is particularly windy. Sunrise is about 4.15 at this location on this day. This is clearly the dawn chorus. The measured noise levels here are the real noise levels for period of the measurements but do not necessarily represent the normal night time situation throughout the year.

Boiler or other plant noise is another common source picked up. Boiler noise may be representative at a house (even in the summer hot water is required) but not necessarily all parts of the house.

Figure 17 shows an extreme case that was nevertheless presented as the real background noise level at a property.

Fig 17

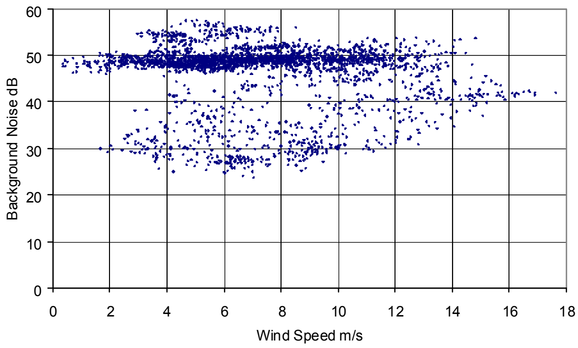
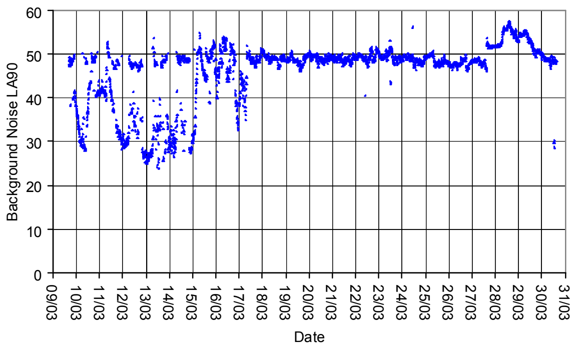


Fig 18 shows the same data as a time series.

Fig 18



On further investigation it was found that there was a generator at the property that was used at times during the day but turned off at night as can be seen in the first six days. A week into the measurement period the generator developed a fault and stayed on all the time.

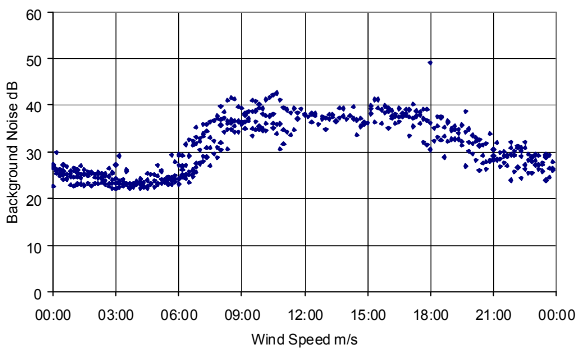
There is a further factor that is more unpredictable than anything else as far as measurements at a specific location are concerned. That is the variation of background noise with time of year. There is not enough information to be able to quantify this. There is no doubt however that variation does take place. Some trees and shrubs are more noisy in the autumn – like the beech. Others, like the Scots pine can be more noisy in the spring. But that is only part if the story because one group of trees can screen wind from another group in certain conditions so that the presence of some trees at certain times of year may reduce background noise. The location in Fig 8 has relatively low noise levels but is surrounded by deciduous trees and located on the edge of a large mature conifer plantation. In most conditions, the deciduous trees are sheltered from the wind by the coniferous forestry.

RESULTS THAT ARE TYPICAL OF THE MEASUREMENT LOCATION BUT NOT ELSEWHERE

Because it is usually impossible or unreasonable to make background noise measurements at every property likely to be affected by a wind farm development, measurements made at one location are regularly used as a proxy for another location. The fundamental questions to be answered in considering whether a set of data can be used as a proxy are "is the degree of shelter similar?" and "is the nature of noise generating objects similar?" This has to be a matter of individual judgement but the mere proximity of one location to another is not sufficient reason.

Many differences are obvious such as streams or livestock on farms. Another common difference is exposure to road traffic noise. This noise can usually easily be identified. At the location on Figs 9 and 10 the reason for the higher day time level is road traffic. If it is not certain whether this is the case all the data at wind speeds less than 4m/s can be plotted against time of day. The result is shown in Fig 19.

Fig 19



This shows the standard pattern of road traffic with a fairly constant noise level between 0900 and 1800hrs. The traffic then eases off gradually over the evening period and into the night until it rises quite steeply over about two hours in the morning.

A Special Case

Apart from the NWR and Wind generated elements there is another factor in some background noise measurements that is partly wind related but not wholly. This is water noise where the location is near the sea. Water noise in places such as the Atlantic coast of Europe whilst linked to local wind can also be significant even when there is no wind. Water noise from inland lakes or estuaries is largely related to the wind because it dies down quickly as the wind drops.

Is the Average the Real Background Noise?

All the above has tacitly assumed that the “real” background noise is defined by the best fit polynomial. This in itself is a considerable assumption. The normal practice with local authorities when assessing non wind related noise from industrial developments is to take a time of lowest background noise.

The most common example of this is when background noise is required at night in an area substantially affected by road traffic noise. The normal method of assessment is to compare the noise from the industrial development with the background noise level at the quietest part of a quiet night, that is to say a calm night when wind and weather conditions do not affect the noise level. It is not normal practice to average the background noise level over the whole eight hour night time period or over a range of weather conditions.

Similarly it would be more in accordance with normal practice to compare turbine noise at each wind speed with the lowest background noise at that wind speed. In practice the lowest 10 minute measured value would probably be unreasonable. It has been suggested that the level adopted should be the “L90 of the L90 readings”. That is perhaps too extreme but more realistic might be one standard deviation below the average line.

Conclusions

Making the measurements is only half the task. Careful analysis of the results is essential to make sure that they are robust.

- Always plot and examine a time series.
- Does the data cover a large enough range of wind speed and direction?
- Does the polynomial produce a flat S that can be shown to be composed of a NWR component and a wind generated component?
- What is the level of the NWR element of the curve? Why is it at the position that it is?
- If it is not significantly affected by the NWR element, what is the noise level at 10m/s? Generally this will range from 35dB in a well sheltered area without many noise generating objects to 45dB in an exposed area with trees - bearing in mind that exposure is relative to the anemometer position. If it is outside this range is there a good reason?

Going back to Fig 3 it is of considerable concern that probably none of the four polynomial curves represents the real noise level in any useful sense.

Rules for Proxies

- The NWR element (streams, traffic, farm noise etc) should be similar.
- The nature and number of noise generating objects should be similar.
- The degree of shelter should be similar.

References

[1] ETSU-R-97 – The Assessment and Rating of Noise from Wind Farms
[2] Davis R (1996). Noise Measurements in Windy Conditions. ETSU-W-13-00386.
[3] Bruel and Kjaer data on UA0237
[4] G.P. van den Berg Effects of the wind profile at night on wind turbine sound JSV 2003
[5] Paul van Lieshout - Time Dependent Energy Calculations, BWEA 2004

Acknowledgements

The data used in this paper is all in the public domain and forms part of some of the many Environmental Statements that I have analysed over the last few years. I would like to thank all those who were out with their equipment in all weathers gathering the data in good faith only to have me pick it apart. Most of them probably know who they are but I have decided not to credit them individually for obvious reasons.

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Wind Farm Noise Predictions: The Risks of Conservatism

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Abstract

Conservative approaches to the prediction of noise immissions from wind farms reduce the risk of compliance failure. However, overly conservative approaches introduce the risk of not capturing the true energy generating capacity of a given wind farm site. Unlike other forms of development, conservative planning of wind farms cannot be offset by increased mitigation without incurring such lost energy generating potential. The large scale of modern wind farms means that seemingly small conservatisms in the prediction of noise immission levels can translate to substantial lost development opportunities.

A worst case assessment methodology assumes that a receiver is located downwind of every turbine, all turbines experience the same wind conditions as the first upwind turbine, the ground acts as a hard reflective surface, and all turbines are emitting sound power greater than test levels. Minimal reductions, if any, are factored for the excess attenuation provided by the atmosphere and barrier effects. Whilst this scenario is possible, it is unlikely that all these factors will transpire simultaneously in practice. To gauge the pessimism of this approach, long term measurements were carried out near operational wind farms and compared to noise levels predicted using several techniques. This paper presents an initial analysis of these measurements, which are still ongoing at a number of wind farm sites, and discusses the opportunities for more realistic prediction techniques. The paper then continues to discuss the potential impact that the use of more realistic prediction techniques may have on increasing the potential generating capacity of wind farm sites.

Introduction

It is common practice in many countries to control the noise impact of proposed wind farm developments by setting limits for the maximum level of noise that may occur at surrounding noise sensitive receptor locations. An important distinction in this practice is that the test of compliance in some countries may be based on predicted noise levels alone, whilst in others the test is based on the actual noise levels that occur in practice, as demonstrated by measurements. The latter method offers benefits for regulators in that there is a definitive limit for the noise that may occur in practice. However, measurement based compliance places the onus on developers and their advisors to plan and design wind farms in a way that adequately addresses the risk of a failed compliance test and the subsequent power generation losses that could be incurred to address the failure. The prediction of wind farm noise immission levels (i.e. the noise occurring at the receiver location, in contrast to the emission level that defines the sound power output of the sources) is therefore an integral element of the planning process for measurement based noise compliance regimes. However, prediction of environmental noise immissions from wind farms is influenced by a range of variables. This means that choices have to be made in the calculation parameters adopted for these variables in any assessment, and these choices can have a significant bearing on the outcome results.

The propagation of environmental noise immissions, and therefore its prediction, is influenced by a number of variables. This is evident in the measured noise levels observed around wind farms. Such noise levels tend to show a relatively wide range of temporal variation, even under relatively stable downwind propagation conditions. The key focus of a prediction exercise is usually the upper noise level that will occur under such downwind conditions, for which the following factors must be addressed:

- the turbine sound power and any associated uncertainties;
- the source height;
- the receiver height;
- the wind speed experienced by the turbine rotors, how this may vary across the rotor diameter, how it may vary between individual turbines across a multi-turbine site, and how these variations relate to reference wind speeds derived at other heights or locations;
- the wind direction, and the range of angles to the direct line between the source and receiver for which downwind conditions are considered to occur, along with the portion of an expansive site that can simultaneously lie within these angles;
- temperature and humidity;
- the terrain profile with respect to intervening ground height and noise screening features;
- the ground characteristics of the surrounding area and any regional or seasonally varying changes to its composition;
- the selection of noise index adopted to quantify the calculated noise immission levels (L_{Aeq}, L_{A90}, L_{A50}, etc.).

These variables, and the manner in which they are accounted for, will impact on the likelihood of the predicted noise immission levels being higher or lower than the actual immissions that occur in practice. Understanding the nature of these factors to enable informed selection of prediction input parameters is therefore vitally important for designers and developers alike if they are to make truly informed selections of their noise prediction methodologies and likewise the relevant input parameters for their selected methodology. Ultimately, there will be a trade-off of considerations that involves the choice of appropriate methodology and input parameters. This trade-off will need to strike the appropriate balance between the potential generating capacity losses of conservative approaches and the compliance risks of more optimistic approaches.

In most instances, environmental noise predictions are made on the basis of established engineering methods such as ISO 9613[1]. The use of these methods has been supported by various studies such as the EU Joule report[2] which found that such methods offered a robust means of estimating downwind noise levels that would not generally be exceeded in practice, and generally offered a margin of conservatism depending on the choices made regarding input parameters. However, despite the relative simplicity of such prediction methods (when compared to advanced numerical or analytic methods), informed choices still need to be made on a site by site basis. Experience suggests, however, that these choices can have a significant effect on the outcome findings of individual noise assessments and thus can often become the focus of considerable dispute between developers/designers and other interested parties.

To demonstrate the potential significance of such choices, consider the following two example scenarios. Both depict a simple generic turbine layout with four equidistant receivers in all directions. The first image shows the number of turbines that can be operated within a 40 dB(A) limit at each property if a mixed ground cover (ISO 9613 G=0.5 for source, middle and receiver ground) is adopted in predicting the noise levels. The second scenario represents the number of turbines that can be adopted if the calculation reverts to a pessimistic hard ground (ISO 9613 G=0 for source, middle and receiver ground) model. In both instances, the presumption is that the design is to be based on un-curtailed turbines, and thus the only method of reducing the level is to remove turbines from the design. Comparing the two scenarios demonstrates an 80 turbine layout to be feasible in the first scenario, reducing to a 46 turbine layout in the second scenario. Thus, the choice of mixed ground or hard ground in the prediction model translates to a very substantial 42% reduction in the energy generating potential of the site. This huge difference in energy generating potential occurs even though the difference between calculated noise immission levels for the mixed ground and hard ground scenarios is less than 3dB(A) – a level typical of ‘safety margins’ that are frequently applied in other areas of acoustics. Further, this generating loss is incurred for an order of level difference which is commonly regarded as the smallest subjectively discernible change in noise level. Whilst the above is clearly a simplified scenario, and in practice there may be alternative design and curtailment measures that could be employed to reduce the lost energy capture, the example serves to demonstrate the potential value to be gained from a better understanding of the true uncertainty of current prediction practices.

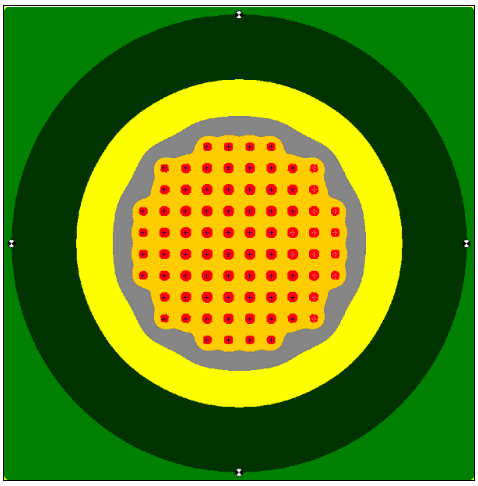


Figure 1: Noise contours for a regular layout of 80 Vestas V90-3.0MW turbines operating in their 109dB(A) mode at a 10m height wind speed of 8ms^{-1}. Four receivers are shown, each located on the calculated 40dB(A) noise contour. Propagation losses have been calculated using ISO9613-2 with a hub height of 90m, a receiver height of 4m, RH=70%, T=10 degree C and G=0.5.

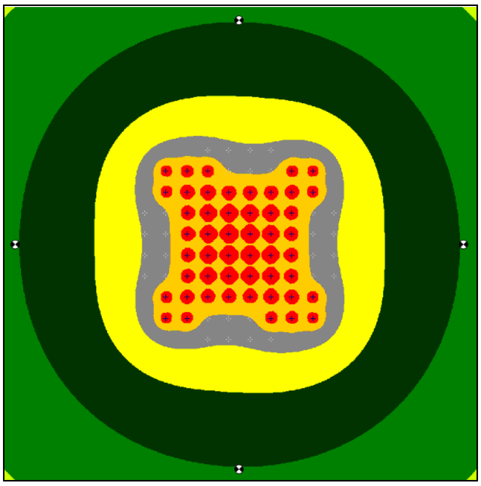


Figure 2: Plot showing the turbines that have to be switched off to achieve 40dB(A) at all the receiver locations when assuming G=0, or hard ground. Note that 40dB(A) is achieved at all receiver locations with all 80 turbines operating when G=0.5, or mixed ground, is assumed. The result shown is the noise contours calculated assuming G=0, hard ground, for 46 Vestas V90-3.0MW turbines operating in their 109dB(A) mode at a 10m height wind speed of 8ms-1. The resultant loss in generating capacity is therefore 42% for this particular condition assuming the only noise control option is to turn off turbines.

This example highlights the effect that seemingly minor assessment choices can have on national wind energy potential. To provide an improved basis for making noise prediction choices, Hoare Lea Acoustics are conducting noise monitoring exercises around a number of UK wind farm sites for the purpose of comparing predicted and actual noise immission levels. A key element of this investigation was to compare predicted noise levels that are derived from techniques that are normally used during the design phase of a wind farm with the actual immission levels that occur in practice. This investigation has considered predicted and measured turbine noise levels that occur for the wind speed experienced at the turbine rotors, thus focussing the analysis on sound power and propagation effects by limiting the influence of uncertainties related to reference wind speeds and wind shear.

This paper presents the findings of the measurements and analysis completed to date and sets out the requirements of any further studies.

Site Descriptions

For commercial reasons, it is not possible to disclose the full details of the wind farms chosen for this study, and thus the following general descriptions are provided. Both sites were located in rural areas and comprise wind farms with more than 20 turbines. At both sites, the turbines were two speed active stall regulated machines rated at over 2 MW generating capacity per machine.

At Site A, the wind farm is located on a relatively high plateau characterised by moderately undulating terrain and minimal vegetation. Ground conditions were a mix of partly grassland and mainly peat bog, but given the undulation, the land was not prone to complete saturation.

At Site B, the wind farm is located in reasonably flat terrain with minimal vegetation. The ground surrounding the wind farm was almost entirely composed of peat bog. These ground characteristics, coupled with the very high rainfall in the area, meant that the ground is believed to have been totally water logged for the entire duration of the survey, thus providing effectively hard ground propagation conditions.

Survey Description

At each site, automated Type 1 sound logging meters were positioned at varying distances from the nearest turbine. The equipment comprised Svantek SVAN949 logging sound level meters (SLMs) housed in environmental enclosures with battery power. The enclosures have an integral pole to provide a mounting for the microphone and windshield system with an installed microphone height of 1.5 m above ground. A two layer windshield system was used to reduce wind induced noise on the microphone. The primary windshield and rain protection were provided by a 01dB BAP21 outdoor microphone adaptor which enclosed the standard microphone and pre-amplifier. The secondary windshield was custom made from open cell foam approximately 10mm thickness formed as a domed cylinder 170 mm diameter and 300 mm high. A lower disc of 40 mm thick open cell foam formed total enclosure of primary windshield. The outer windshields were custom designed following the guidance given in the report Noise Measurements in Windy Conditions[3]. The report indicates that the insertion loss of this type of windshield assembly is likely to be less than ±1 dB between 50 Hz and 5 kHz. A total measurement period of approximately 47 days was obtained at this site.

At Site A, 3 sound level meters were positioned to the northwest of the wind farm at distances ranging from 415 m to 920 m. The positioning of the meters was largely driven by practical access constraints.

At Site B, 5 sound level meters were positioned along a single line directed just to the west of north. The alignment of this array of meters was chosen for the availability of stable ground conditions and to avoid local streams to the north east of the site which would have been sufficient to contaminate the measurements with water flow noise. The measurement distances were 101 m, 270 m, 466 m and 754 m. At the 466 m measurement location, a 1.5 m and 4 m measurement height was used to enable the influence of ground conditions near the microphone to be investigated. The equipment was the same as that used at Site A. A total measurement period of approximately 34 days was obtained at the 100 m location and more than 57 days at the other locations.

Whilst the northwest positioning of the meters for both sites was out of the direct down-wind line according to the prevailing UK south westerly wind direction, it offered a broader mix of wind directions to be acquired enabling both downwind and crosswind noise propagation conditions to be investigated.

For both sites, the SLM's were set to log continuous periods of 10 minute noise levels, recording statistical and equivalent noise level parameters. The internal clocks on the SLM's were synchronised with the wind farm control system. All systems were calibrated on deployment, during interim data collection and following collection from site, no significant drifts in sensitivity were found (typically below 0.5 dB(A)).

Supplementary non-acoustic data was obtained from the Supervisory Control & Data Acquisition (SCADA) System of each wind farm for the operation of the turbines and met mast during the period of noise monitoring. The SCADA data provided the following information:

- date/time at the end of each 10 minute period;
- primary wind speed from the turbine nacelle (mean);
- turbine power output (kW) (mean);
- turbine rotor speed (min/mean/max);
- turbine nacelle orientation (mean);
- met mast wind speeds at hub height (mean);
- met mast wind direction at hub height (mean);
- rainfall indication;
- temperature and humidity (not used in the present assessment but effects to be studied).

Analysis

The first element of the data analysis was to correlate the measured noise level information with the prevailing wind conditions. At the design stage of a wind farm, predictions would normally be based on a single reference 'free condition' wind speed value which is taken to be experienced simultaneously by all wind turbines (with the exception of very large sites where more than one reference may be used). Thus, for this study, it was initially chosen to relate the measured noise levels to a single wind speed and direction representation for the site. Generally, this information was acquired from the site meteorological masts. However, at Site B it was known that under certain directions, the reference meteorological masts would be downwind of the wind farm and the wind speed measurement would therefore be influenced by the wind farm's presence. For these directions, the wind speed was taken from turbine locations that were upwind of the remainder of the site. The wind speed data at the turbines were deduced from the nacelle anemometer readings, subsequently corrected to free-flow conditions (using site-specific nacelle corrections supplied by the site operators). In all instances, the wind speed reference for the correlation related to hub height wind speeds. Due to differing client requirements for the two sites, the Site A wind speed data were then corrected to 10m wind speed heights assuming reference roughness conditions (z=0.05), whilst the raw hub height wind speed data was referenced for Site B.

The correlated noise and wind speed data were then filtered to eliminate any periods in which rainfall was indicated to have occurred, or during the times when service personnel were known to have been near the sound level meters.

At Site A, additional data filtering comprised reduction of the data set to wind directions from 90 to 200 degrees to provide a 110 degree wide arc of downwind propagation conditions (require at Site A to encompass the distributed measurement locations).

At Site B, the raw datasets were reduced to include only those periods in which all turbines were generating in high speed mode. Additional data filtering then resulted in the production of two datasets for downwind angle ranges +/-15 degrees from directly downwind and +/-45 degrees from directly downwind. The former angle range is specified in the relevant turbine sound power output standard (BS EN 61400 Part 11:2003[4]) whilst the latter represents an extended range often regarded as still representing downwind conditions (although downwind propagation can ultimately occur for wider angles due to the range of wind speeds considered for wind farm sound propagation). An additional dataset was also formed for wind directions within +/-15 degrees of directly upwind conditions for the nearest turbine and the measurement line.

For each of these correlated 10 minute records, predicted noise levels were generated using the ISO 9613 prediction methodology according to the following parameters :

- source height equal to hub height for both sites;
- receiver height equal to 4 m and free-field conditions;
- 10 degrees Celsius and 70% relative humidity;

- flat and level ground cover for two separate scenarios; G = 0 and G = 0.5 (for source, middle, and receiver ground) to consider hard and mixed ground cover conditions;
- turbine sound power data provided by the manufacturers and measured according to BS EN 61400 Part 11:2003, excluding any margin for test uncertainty or manufacturers warranties (i.e. raw measurement turbine noise levels). The turbine sound power data was converted to hub height wind speeds (assuming reference ground roughness of 0.05 m) and plotted to obtain a 3rd order polynomial best fit curve. This curve was then used to obtain the sound power value for non-integer wind speeds;
- in the case of Site A where the number of operational turbines varied during the survey, the predictions for each 10 minute period only included for the turbines which are known to have been operating;
- the subtraction of 2 dB(A) to correct for the use of the L_{A90} rather than L_{Aeq} index, according to ETSU-R-97[5].

Results & Discussion

The results obtained from the study and analysis completed to date has enabled interim findings to be produced which will guide subsequent further analysis and measurement studies. A sample of some of the key results and findings are presented in this section.

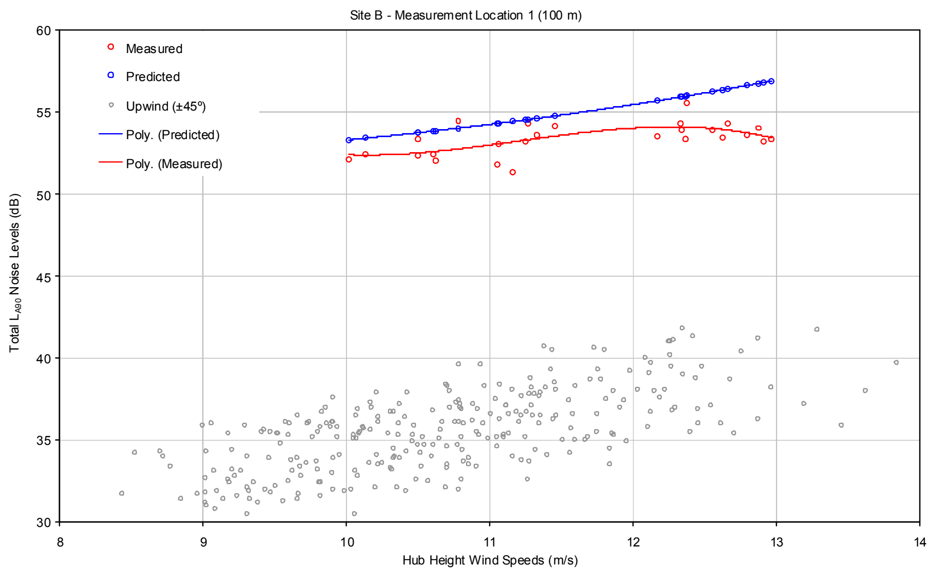
Comparison of the findings for the two sites indicated similar margins between measurement and predictions for the various approaches. Using conservative approaches where the predictions tended to be greater than the measurements, Site A generally showed a slightly greater level of conservatism. However, the analysis of Site A was subject to a greater degree of complexity due to factors such as ground terrain profile and the varied orientations of the measurement locations relative to the wind farm. Thus, whilst the analysis of Site A was supportive and consistent with Site B, the discussions here are focussed on Site B for the purposes of simplicity and clarity in conveying the interim findings.

The group of charts presented in Figures 3a to 3d relate purely to the Site B measurements, with associated noise immission predictions presented for a single prediction methodology. The indicated upwind measurements for all four sites are the +/-15 degree upwind measurements taken from the furthest position (where upwind noise levels are more likely to relate to background noise levels). The indicated downwind measurements are for the +/-15 degrees angle only. The prediction methodology for this set is based on hard ground cover (ISO 9613 G=0 for the source, middle and receiver ground) with a single reference free-field wind speed for each ten minute period being assumed to occur at all of the turbines. Comparison of the results for the four separate measurement locations indicates the following:

- The upwind and downwind measurements show a very clear noise level difference which supports the view that downwind measurements have been strongly influenced, if not controlled by, the wind farm's emissions. At the furthest location, the difference between the downwind measurement trend line and the general trend of the upwind values is around 6 to 7 dB(A). Previous studies such as the EU Joule project have indicated differences between upwind and downwind turbine noise levels of the order of 10 dB(A) to 15 dB(A) at distant locations. The observation of a lower difference at the furthest position may indicate that either the 10 dB(A) to 15 dB(A) reduction has not been realised at this site, or more likely, that the background noise is dominating the upwind measurements, thus limiting the observed difference.
- At all locations, the predicted immissions trend line generally exceeds (by up to approximately 1 dB(A) at the nearest measurement location) or just equals the downwind measured data trend line. The exact background noise level influence at each measurement location for each 10 minute period cannot be known. It is however likely that the background noise level may have contributed 1 dB(A) or more to the total measured noise levels. The margin between actual turbine contribution and the predicted immission levels will therefore be greater than indicated by the total measurement comparison represented in the charts.
- At hub height wind speeds up to approximately 12 m/s, the margin between the prediction trend line and measurement trend line is relatively constant for

increasing wind speed at each site. At higher wind speeds, the prediction and measurement trend lines diverge at each site, with the predictions showing an increasing margin above the measured noise levels. Subsequent results discussed later tend to suggest this is due to the increased significance of wind speed variations across the wind farm at higher wind speeds.

- The margin between the prediction trend line and measurement trend line tends to progressively decrease with increasing distance from the turbines. The most obvious potential cause of this effect is the increasing influence of background noise at increasing distance. However, another important consideration is the changing angle between the turbines and the measurement locations relative to the wind direction with increasing distance from the turbines. As the receiver location approaches the turbine locations it becomes increasing unlikely that the receiver location could lie downwind of every turbine simultaneously. This means that some turbines at peripheral positions may contribute less than the directly downwind propagation assumed in the prediction. At increasing distance, this effect is reduced, and the turbines located at the periphery of the site will then increasingly contribute to the total wind farm noise level (i.e. a greater portion of the turbines at the wind farm site will be propagating sound under conditions closer to direct downwind propagation).



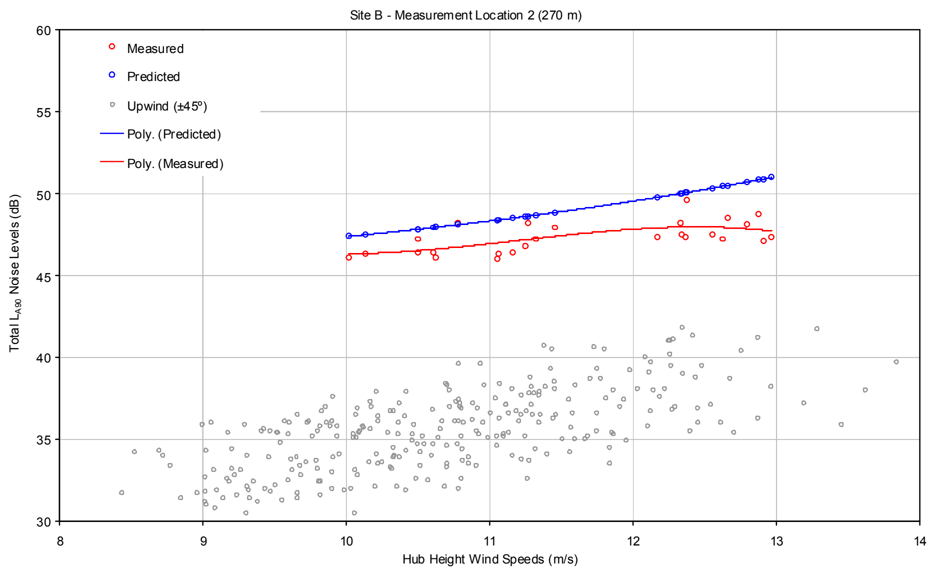
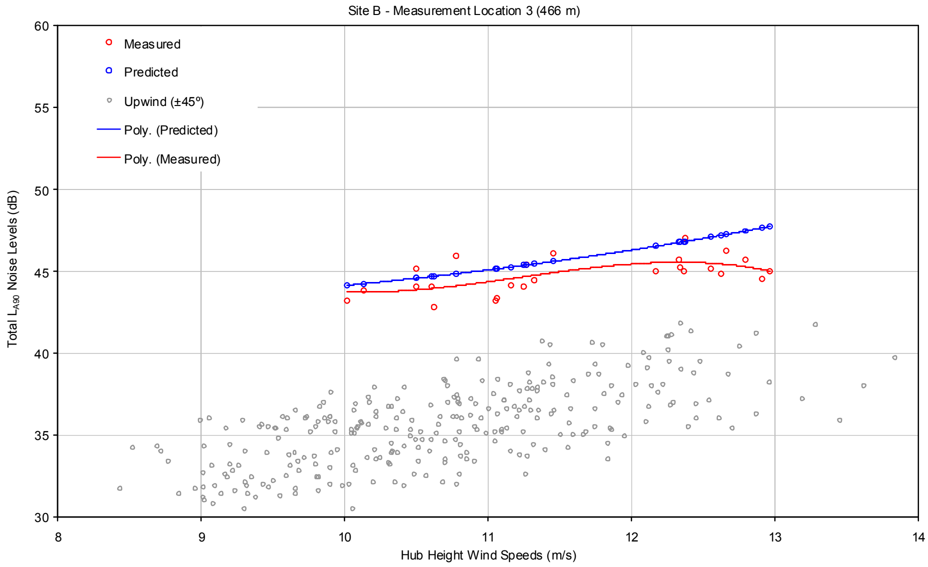


Figure 3(a & b): Sample analysis group set to compare Site B measured and predicted noise levels at the 4 measurement distances. All downwind angles restricted to +/-15 degrees. Predicted noise levels based on a single site wind speed reference and G = 0.



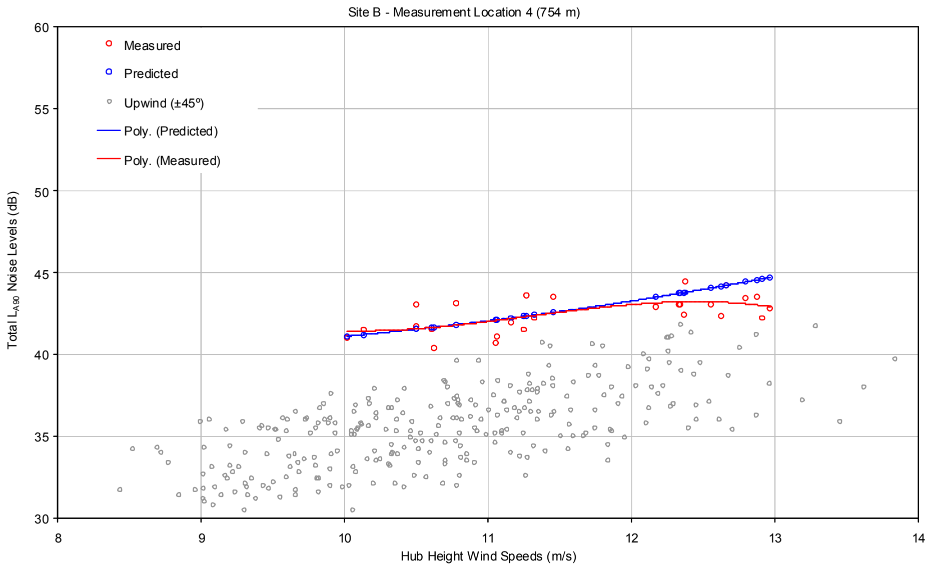


Figure 3 (c & d): Sample analysis group set to compare Site B measured and predicted noise levels at the 4 measurement distances. All downwind angles restricted to +/-15 degrees. Predicted noise levels based on a single site wind speed reference and G = 0.

The group of charts presented in Figures 4a to 4d relate only to measurement location 4 (754 m) of Site B. The 4 charts for this location differ in terms of the downwind angles considered (+/-15 degrees and +/-45 degrees downwind conditions are presented), the wind speed reference used for the predictions (initially a single wind speed reference as presented in figure 3, but then modifying the predictions to account for the actual wind speed seen by each individual turbine in each 10 minute period), and the ground cover characterisation used in the ISO 9613 prediction (G=0 and G=0.5 presented). Comparison of the results for these different analysis scenarios indicates:

- Expansion of the range of downwind angles from +/-15 degrees to +/-45 degrees indicates the predictions exceed the total measured noise levels by a slightly greater margin for the widened downwind angle. This may be due to the increased number of data samples offering a better representation of the true relationship between measurements and predictions. Alternatively, this may indicate that the contribution of the dominant/nearest turbines to the measured levels is progressively reduced as the wind direction moves away from directly downwind conditions and this effect is not represented in the predictions.
- The predictions derived using a mixed ground cover correction (G=0.5 for source, middle and receiver ground) indicate predicted noise levels slightly below the total measured noise level trend line. This is consistent with the total noise level being composed of 1 dB(A) or more contribution from background noise, which would then suggest the G=0.5 calculation with single wind speed reference offers a reliable representation of the actual turbine noise component of the total measured noise levels. However, as the actual background noise contribution cannot be precisely known, it cannot be totally dismissed that the use of G=0.5 results in predictions that slightly underestimate the actual turbine noise contribution. In this respect, site observations indicated the soil to be almost totally submerged by ground and surface water for which G=0 would be expected to be the appropriate ground characterisation.
- The predictions made on the basis of the individual wind speed experienced by each turbine rather than a single site wind speed reference indicate immission levels which no longer diverge from the measurement trend line at higher wind speeds. This tends to suggest that the margin of conservatism demonstrated at higher wind speeds is strongly related to the reduced level of wind seen by the nearest turbines to the measurement location which may be due to sheltering and/or wake effects of upwind turbines. To investigate this further, a statistical analysis of the difference between the single wind speed reference and the wind speed of each of the turbines indicated the following key figures:

  - *Mean difference = -0.5 m/s*
  - *Standard deviation of differences = 1.2 m/s*
  - *Maximum decrease = -5.1 m/s*
  - *Maximum increase = 4.3 m/s*

  In terms of the sound emissions of the turbines, wind speed changes of this order equate to sound power level variations of:

  - *Mean difference = -0.4 dB*
  - *Standard deviation of differences = 1.1 dB*
  - *Maximum decrease = -3.9 dB*
  - *Maximum increase = 7.6 dB*

  [Values shown are derived from the individual turbine specific wind speeds minus the single site reference wind speed. A negative number indicates the reference wind speed is overestimating the wind speed at each individual turbines.]

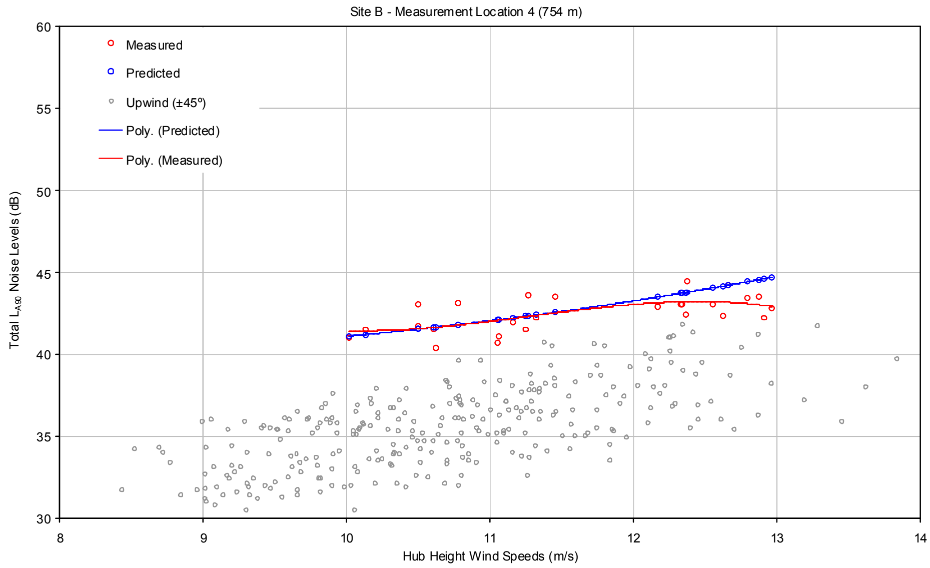


Figure 4a: Comparison of Site B measured and predicted noise levels at measurement location 4 only. All downwind angles restricted to +/-15 degrees. Predicted noise levels based on a single site wind speed reference and G = 0.

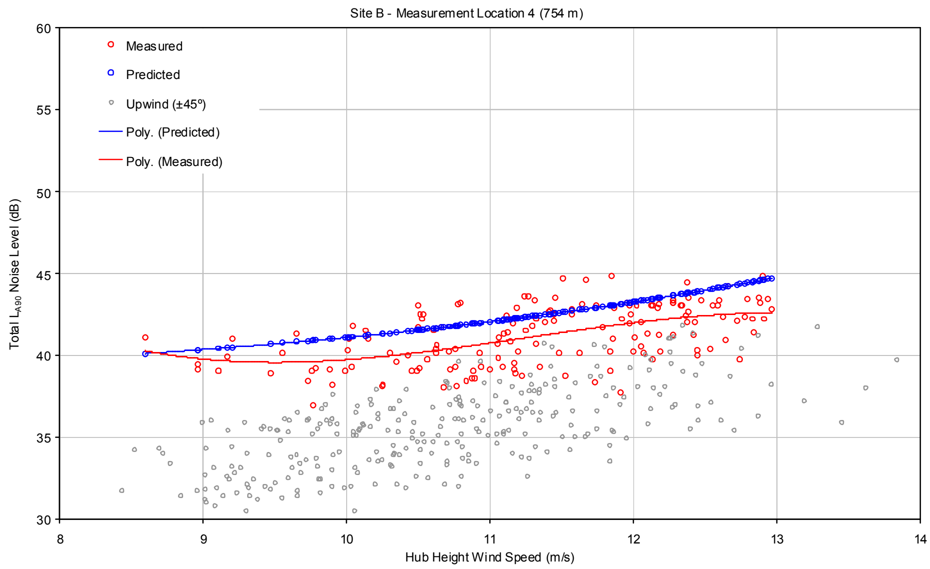


Figure 4b: Comparison of Site B measured and predicted noise levels at measurement location 4 only. All downwind angles restricted to +/-45 degrees. Predicted noise levels based on a single site wind speed reference and G = 0.

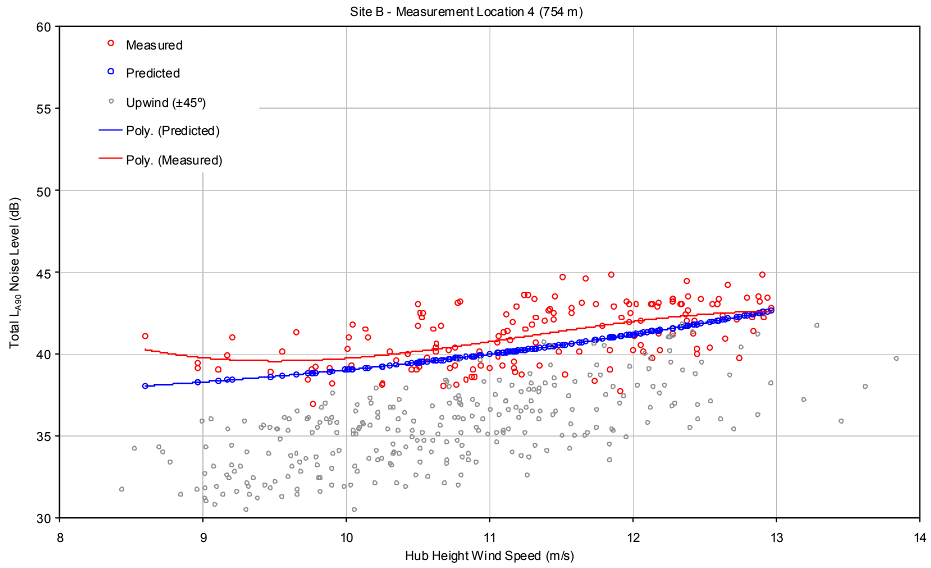


Figure 4c: Comparison of Site B measured and predicted noise levels at measurement location 4 only. All downwind angles restricted to +/-45 degrees. Predicted noise levels based on turbine specific wind speeds and G = 0.5.

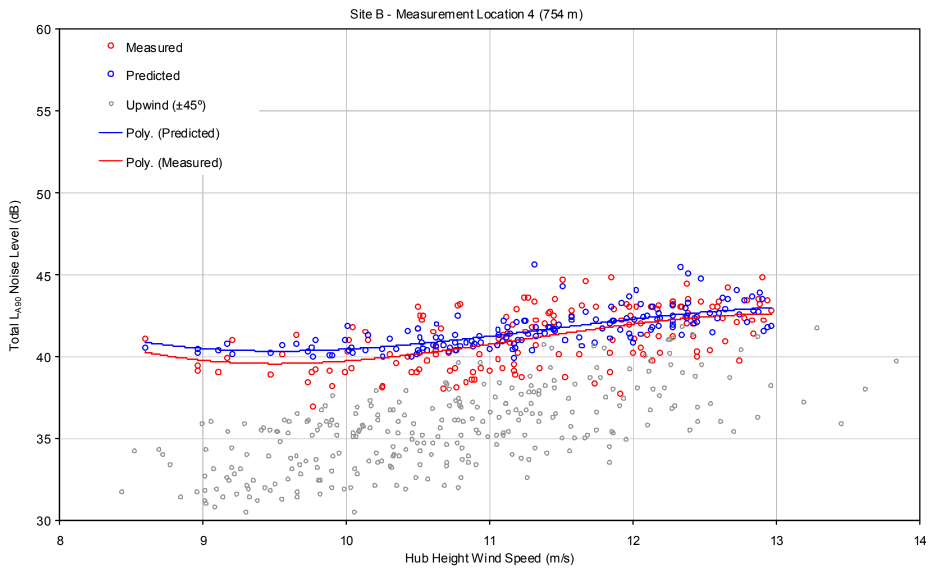


Figure 4d: Comparison of Site B measured and predicted noise levels at measurement location 4 only. All downwind angles restricted to +/-45 degrees. Predicted noise levels based on turbine specific wind speeds and G = 0.

Conclusions

The interim results of the two sites studied to date have supported the view that engineering methods such as ISO 9613 offer a robust means of determining the upper turbine immission levels that may occur in practice.

To fully quantify the extent of conservatism that may be inherent to certain prediction methods and choices, further detailed analysis of the completed and ongoing measurement studies is required to better understand the measurement contribution directly attributable to turbine immissions alone.

The findings have shown that the assumption of a single wind speed reference for all turbines that form a large wind farm site may overestimate the actual wind speed seen by each individual turbine. This is particularly the case for the turbines nearest to a location of interest which may be partly shielded by the furthest upwind turbines which experience uninterrupted (by the wind farm) and higher wind speed conditions. This means that a single wind speed reference will likely overestimate the sound emissions of the turbines nearest to a location of interest. This effect appears to be most significant at higher wind speeds for the sites studied.

The prediction and measurement comparisons presented in this paper were based on measured sound power data without inclusion of any margin for test uncertainty or manufactures warranties. It is common practice for manufacturers to add approximately 2 dB (although actual values may be considerably different to this according to commercial factors). Given that the study to date has shown that predictions using relatively conservative methods tend to equal or exceed total measured noise levels in practice (in particular, without correcting the measured noise levels for likely background influence) based on measured sound power data, the use of these same prediction methods with warranted sound power data has the propensity to result in significant design conservatism. Whilst these conservatisms may seem numerically small, and may be of limited significance subjectively, the consequences in power generating losses are substantial.

In summary, better knowledge of the relationship between predicted and actual noise immission levels has the potential to enable substantially enhanced generating capacity during the design phase of a wind farm. This requires that careful account is taken of the specifics of each site under consideration and that compatible design choices are made to avoid cumulative pessimism which may be unlikely to simultaneously occur in practice. Further works will likely be focussed on the influence of wind speed variations across large wind farms, the influence of ground conditions, and the relationship between rated sound power emissions and those which actually occur in practice.

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Lyon France September 20 – 21 2007

NOISE POLLUTION FROM WIND TURBINES - Living with amplitude modulation, lower frequency emissions and sleep deprivation

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Abstract

Although wind energy has a role to play in the renewable energy sector, when wind turbines are sited too close to people's homes, the noise pollution has dire consequences on those who live nearby. The authors, who live within 930 metres of the nearest wind turbine of a wind farm, document their personal experiences that underscore research findings on the adverse impact of wind turbine noise on human well-being, as well as present the results of sound data measured by acousticians at their home. The paper describes the nature of the noise – with its pulsating character, the vibrations felt by the body, and its intrusiveness, as well as the impact of the noise on them physically and psychologically. Most serious is the sleep deprivation and the ensuing adverse effects, and the inability to pursue or sustain normal family and social activities. Indeed, the authors recently abandoned their home because of the unremitting character of the noise and its adverse impact on their lives. The authors note that rural environments, which are attractive to the wind energy industry, are especially challenging because background noise is low or virtually non-existent, particularly at night. Yet current UK guidelines, set by the Government in 1997 with significant input by the wind energy industry, offer no respite to those who live near wind turbines or those communities analysing current wind turbine applications from developers. The authors suggest that the wind energy industry would gain credence by acknowledging that there are gaps in the ability to

predict with accuracy whether wind turbines will create noise pollution. Moreover, the industry could avoid the issue altogether by placing wind turbines further from homes. This solution would simultaneously contribute to the credibility of the wind energy industry while protecting the public's health and their right to the amenities of their homes.

Introduction

We are Julian and Jane Davis. We live on a farm on the Fens in Lincolnshire, England, an area known as South Holland. In May 2006, the construction of a wind farm consisting of eight 2 megawatt turbines, each approximately 100 metres tall, was completed, located south from us with the nearest turbine 930 metres away. Even though we live on the Lincolnshire Fens, our house is well-shielded by mature trees and large agricultural buildings, so for most of the year, we cannot actually see the turbines. As soon as the wind farm became operational, we noticed subtle acoustic abnormalities. At this point we assumed NO connection with the turbines. But as a few days passed, the full extent of the noise pollution from the wind farm became apparent.

We had supported wind energy and the construction of wind farms and were naïve enough to believe the literature issued by the developers. We had thought that normal background noise would mask any emissions from the wind turbines and that if there was not enough wind to make any background noise (e.g., trees rustling), then the turbines would not have enough wind to operate. We had also done limited research on complaints against wind farms; besides, many objections were based on the visual effects on the landscape. To us at this time, any visual impairment caused by the erection of the wind farm was a fair trade for the supposed environmental benefits.

We are presenting this paper to illustrate the devastating effects of wind turbine noise pollution when wind farms are sited too close to homes or otherwise inappropriately sited. We have since learned that even engineers and designers within the wind energy industry cannot accurately predict how the wind turbines interact within a given environment and climate, even with the most current computer modelling. [1]
(Barbara J Frey, BA, MA and Peter J Hadden)

Moreover, the developers certainly do not publicise that noise pollution from wind farms is a significant issue. As we have learned, it is an issue that cannot and should not be dismissed because of its varied, unpredictable, and sometimes elusive yet damaging nature.

It may be said that wind turbines create pollution during their construction, and that is true of any industrial construction, but once in operation, wind turbines may continue to emit unprecedented levels of pollution in the form of sound pressure waves, some of which are interpreted by humans as noise. Having been exposed to over 10,000 hours of sound pressure waves emitted by a wind farm sited 930 metres from our home we have a reasonable grasp of the "nuisance" caused by the varied emissions of wind turbines.

To date many people have been somewhat dismissive about wind farm noise pollution. The combination of the inability of the general public to understand the mechanisms, by which sound pressure waves with various characteristics are emitted from turbines, and the varied and sometimes subtle nature of the noise pollution they create, make it very easy for those who wish to diminish its importance. In fact, for many people, merely standing at the base of a turbine and hearing a gentle swish of the blades comprises all the research that they consider necessary to form an opinion.

We had welcomed the construction of a nearby wind farm naively believing wind turbines to be a legitimate alternative energy source. Yet, for some, wind turbines seem to hold a near religious or romantic value (as opposed to simply being large industrial generating units), and this attitude appears to influence some of the research and media coverage to date.

Within the UK the guidance on wind farm construction has not kept up with the developments of wind turbines. The techniques chosen by the Government to predict and assess noise pollution from wind farms, published in ETSU-R-97, are now unreliable and inappropriate, and extrapolations to increasingly taller turbines appear not to hold true in a number of cases. [2] (Bowdler) This, in terms of noise pollution control, has lead to a situation where developers use this to their advantage. For under UK guidance if the amplitude of the emitted noise modulates at short periodic intervals it is almost impossible to breach the imposed conditions (no matter what the peak dB level is).

The result, under certain circumstances is no control or limit at all. In the UK, if the noise of a wind farm was replicated electronically next to a domestic dwelling, under nuisance law an enforcement notice would be issued to stop it. Yet if the very same noise comes from the actual wind farm, then the UK guidance (ETSU-R-97) is used to impede nuisance law that in other circumstances protects the public.

To compound this our house is set in secluded, quiet countryside, and probably being the quietest, nearest property to the wind farm, is surrounded by trees and large agricultural buildings. An approximation to our normal background noise with the turbines (but not in operation) would be around 18 – 20dB (A) (this was only recorded after the wind farm was constructed).The difference between our normal rural quietitude and peaks of the amplitude of aerodynamic modulation occurring between 55 and 66 dB(A) are therefore far more noticeable. The “normal” operating noise levels from the turbines are double our ambient noise at 36 - 40 dB (A).

Turbine noise is only measured as background noise, but the effect on human life and health can be devastating. Studies carried out on the health of communities living around existing wind farms are starting to uncover some unpleasant facts. Lower frequency sound pressure waves emitted by some turbines have been connected with similar physiologic changes associated with Vibro-Acoustic Disease (VAD) [3] (Ref – Mariana Alves-Pereira & colleagues). Noise can adversely affect mood and health, for example, it can cause measurable changes of physiological stress (like cortisol). There is a substantial body of research that documents the ill-effects of noise and sleep deprivation on human health.

There are other aspects that shape peoples perception of the nuisance caused by noise pollution from wind farms. [4]Pedersen (2005), reports of the possibility of a complex relationship between audio and visual stimuli, for example, the blade motion and/or shadow flicker. Preconceptions of the impact of turbines on the landscape may influence sensitivity to noise from a wind farm. Conversely, the visual aspect of the turbines may just remind people of the devastating effects they have on their lives. Remarkably the solution is so simple: site wind turbines away from homes.

Methodology

Noise pollution can be viewed as comparative only to an extent, and can be put down to personal perception, annoyance and irritation. A better aim is to identify the noise pollution and correlate it with influencing factors and to explain how the combination affects day to day living by:

1) Identifying and naming specific repeatable noise characteristics. This has been done without reference to other published works so as to maintain our personal perspective on the noise pollution.
2) Identifying any relationship of noise source to point of perception.
3) Identifying any physical factors affecting the perception and annoyance of noise pollution emitted from the wind farm.
4) Describing and recording the effects that noise pollution from the wind farm have on day to day living.

All observations are based on personal perception. Where indicative values are given for noise levels these are generally given as "real time" values for approximate comparative guidance (although they are based on actual data recorded at our home).

Results

SOUND PRESSURE WAVES EMITTED BY WIND FARMS (ACOUSTIC ARTEFACTS)

1) **Whooomph:** one of the louder aerodynamic noises emitted, it modulates like the sound of a slow helicopter blade rotating. With varying amplitude of this aerodynamic modulation it can take on a slight whipping sound. Normal sound levels of the Whooomph is approximately 45 to 55 dB (A). Indoors this results in a pulsating THUD or beat, that is both heard and felt.
2) **Swish**; general sound of the blade whipping the air (35-45dB (A)).
3) **Roar/Grind/(WD40**) like a speeded up recording of the sea or intense distant road noise (35 – 45 dB(A))
4) **Hum:** (perceived at approximately 80 – 250 Hz) very subtle but impossible to get away from, exceptionally penetrating.

5) **Amplitude Modulation (AM)**: Most dramatically effects the Whooomph, synchronisation of noise from the wind farm causing reinforcement of the waveform – adds 5 to 10dB (A) to the level of the Whooomph.

PERCEPTIONS

1) For Swish and hum the amplitude is proportional to distance from turbines. The hum appears to cross from audio to physical. It is almost as if you can feel the noise as a sensation in the ear. The amplitude of the swish decreases greatly when the observer moves a short distance from the turbines. The amplitude of the hum does not and is detectable at more than 2000 metres from the turbines.
2) Whooomph, Roar and AM projects AWAY from the turbines, i.e the nearer you get the less the effect or amplitude. Once you get closer than approximately 600 metres detection becomes difficult. Conversely, the three types of emission can easily be detected up to 1500 – 2000 metres from the wind farm.
3) Because the source of the noise pollution is so large and high it engulfs or encompasses affected properties.
4) The sensation is felt in the body as well as being “heard” in the conventional sense. For instance when putting ear defenders on to work on a car with a defective alarm, the defenders blocked out the car alarm sound, but the turbine “noise” could be clearly heard and felt even with the defenders in place. Within our home (as was) the fabric of the house insulates against audible sounds but you can still sense the rhythm of the turbines. This is particularly noticeable when trying to relax or sleep.

FACTORS THAT EMPHASISE TURBINE EMISSIONS

1) Shelter – trees tend to filter out other sounds, making the sound of the turbines clearer.
2) Reflective Surfaces – Buildings reflect the sound, increasing the annoyance and making the enveloping of the area even more complete.
3) Insulation from other sounds (double glazing, wall insulation, ear plugs etc) leads to greater selection for lower frequency sound pressure waves as they

have a much greater ability to penetrate and are practically impossible to protect against in a domestic situation.

4) Wind direction: All effects are worst when the wind is from a southerly direction, blowing through the wind farm toward our home. Whooomph and AM only occur with this wind direction. However, the other aspects of the noise are always present to some extent regardless of wind direction. Lower frequency emissions vary little in perceived amplitude irrespective of wind direction or turbine operation.
5) Stable air conditions associated with temperature inversion on summer evening, i.e., still air and quiet at ground level but strong wind at 100 metres above ground level. [5] (Van den Berg).

THE EFFECT ON LIVING

Noise Characteristics influence:

1) Sleep
2) Rest
3) The ability to enjoy the amenity that is your home (or was)
4) Health issues
5) Loss of value to home because prospective purchasers will avoid noisy, unhealthy locations (unrelated to landscape value)
6) Concentration making using complex equipment potentially dangerous.
7) Impairing cognitive ability, which may have adversely affected Jane and our daughter's ability to achieve high grades in her exams.
8) Social lives, e.g. it is no longer possible for our daughter to have "sleep-overs".
9) Moods,,,, constant tiredness leads to increased irritability and feelings of despair, and feelings of inability to cope with normal day to day activities.

<u>Sleep</u>

Much has been written about the alleged fact that noise from wind turbines does not cause you to wake up – but that the noise may prevent you returning to sleep once awake. Many acoustic reports make reference to the fact that external ambient noise such as "the wind rustling the leaves in the breeze", the trickle of a nearby stream, or a vehicle passing on a distant road, will mask the noise of the turbines.

Well. We are here to tell you that this is not always the case. I suppose that in our situation, we have no convenient trickling stream – where we live in the flat East Anglian Fens, the dykes or drains don't do "trickling", also where we live there are no roads that vehicles pass along that could wake us up – and the leaves mask any background noise, which leaves only the pure wind turbine "Acoustic Artefacts" to impinge on our previously undisturbed sleep. As humans sleep in cycles usually of about four hours, then what we have found – repeatedly, is that our brains have subconsciously heard the noises coming from the turbines – or possibly, our bodies are responding to the disturbance, because one hears with more than one's ears, sound is processed by the brain, and our auditory processing operates even while sleeping. When we are in a lighter phase of sleep – and thus we get startled awake – in much the same way that you do when your alarm clock goes off when you have set it wrongly for 3.44 am – and having been shocked awake like that – it is almost impossible to go back to sleep again.

Two or three weeks of this happening night after night leads to symptoms of sleep deprivation – used in some cultures as a form of torture.

Rest

If a body can't rest then a body can't work…or function properly – and that is what we found. A tired mind and body become more prone to accidents, not ideal in any circumstance but dangerous on a farm. The peculiar noises that the wind turbines emit can not only be heard, they can also be felt by the body, and thus trying to rest becomes impossible. We tried: fans, white noise machines, sleeping tablets, red wine and ear plugs. The latter again masks background noises but allows the low frequency that we get to penetrate so that it feels part of your body and the beat – the pulsation -- that is slightly faster than our human hearts beat, means that you feel as if you are constantly trying to get your heart to catch up with this external rhythm that is felt by the body rather than heard ... so rest is impossible.

The ability to enjoy the amenity that is your home (or was)

The biggest problem with the noises from the wind turbines is that they are so unpredictable. You can plan a BBQ for an evening where the weather looks appropriate, warm and sunny, and the evening will be still with no wind at ground level and then – just as the food is ready comes the THUMP, THUMP, THUMP that indicates AM is back … and when that happens, it's really difficult to even find out if someone wants a sausage or a beef burger – and conversations become stilted as the noise draws people's attention and diverts and distracts them. We now know that these weather conditions – so right for BBQs or sitting out enjoying the rural quietitude – are a result of low level stable atmospheric conditions but strong winds at 100 meters above ground. [6](Van den Berg) In these so- called stable atmospheric conditions, AM is disturbing and disruptive.

Because we have farm buildings that the noise can reflect off, during a night when the noise is really bad, you can even get a harmonic going in the farmyard with all buildings pulsating and vibrating – sometimes causing some people with existing ear disease to feel nauseous.
The problem became so bad last summer 2006 – the noise forced us to evacuate our home and to sleep out with friends, on bed settees, spare beds, settees, hotels by main roads – anywhere that gave us some peace away from the noise and low frequency sensations. The hum, incidentally, does not travel with us!

Health Issues.

Other speakers at this Conference will present scientific evidence about the definite links between wind turbine noise pollution and health, in a far more scientific form than we can.
What we do know is that right from the commencement of the wind farm operations we all started suffering from headaches and a horrible sensation in the ears. Friends staying with us said it was "as if someone is using a pipe cleaner to clean out my ears", and other descriptions include someone "blowing down my ear drums".
House guest's complained of being suddenly awoken at 4am with a sound that they described as being equivalent to a motorcycle revving outside the bedroom window. But there was no bike, and they found this noise from a unseen source very eerie and unsettling. We experienced ear infections – something that certainly in my case I had managed to live 50 years without, stomach upsets, general feelings of jitteriness and depression. We were permanently tired, our cognitive skills were impaired, and our ability to concentrate on anything for even a short period of time was dramatically

reduced. For our daughter studying for vital AS exams this was extremely challenging, and for Jane also studying for her Diploma it was disconcerting, and interfered greatly with the processes needed to write complex papers. When watching television the noise was distracting because the “THUMP”, “THUMP” could be heard alongside, and significantly interfered. Because of its nature, the ability to follow conversations is impaired, yet alone understanding the story line.

It was difficult to fall asleep, or stay asleep, and when you woke – it was always with a sense of not having slept.

The only good effect that we can report is that of having completely flat lawns for the first time in three decades, the moles having left any of our land within 200 metres of any building within 3 days of the wind farm having started operations. However we too have found the low frequency hum impossible to live with, and eventually we too left our home.

WHEN A NOISE ANNOYS.

Finally, in December 2006, we decided that we could not carry on with the half life that we had been living and that we needed a more permanent resolution than the itinerant traipsing from friend to friend with sleeping bags and pillows. We effectively rented a “sleeping house”. Erroneously, we thought that by then, the Authorities were going to take action to resolve our awful situation soon. We had got better – nae even expert – at predicting when the worst noises would occur, so that we could flee our home.

On May 27th, this year – almost exactly one year after the wind farm commenced operating – we effectively abandoned our home for the purposes of living in it. We now know that we are the fourth family in the UK to take what we consider to be drastic and devastating action, that is, we have been forced from our homes.

Some of you will have been at the Institute of Acoustics meeting in Swaffham earlier this year where reference was made to our plight, and we know that some of you disbelieved so much that you found the situation funny.

All I ask of you who disbelieve as you listen or read this: Do you really think we would leave our home and use our savings to rent a house 5 miles away just for fun? If you are a disbeliever, come and stay in our home, with your families, and experience for yourselves the inhumane circumstances imposed on my family by the wind turbine developers.

Think of us when you go home, have your dinner, perhaps a glass of wine ... and then go upstairs to your own beds in the comfort and peace of your own home, and spare a thought for the families whose lives have been torn apart when wind turbines are built too close to people's homes.

We know that we can "hear" the noise in our home under the right set of circumstances because the low frequency noise has an impulsive, pulsating characteristic. We accept that it is not clear with low-frequency noise if we are hearing or feeling it or some combination of both stimuli. Because of the impulsive nature of the acoustic low-frequency energy being emitted, there is an interaction between the incident acoustic pulses and the resonances of our home which serves to amplify the stimuli creating vibrations as well as redistributing the energy higher into the audible frequency region. Thus the annoyance is often connected with the periodic nature of the emitted sounds rather than the frequency of the acoustic energy.

Oh – and just as a reminder – we can't actually see the turbines from our house at all and we didn't object to the wind farm as we believed all the reviews that said "Modern Wind Turbines are Quiet"………..

MOST RECENT FINDINGS.

The DTI has recently investigated the incidence of low frequency noise and Aerodynamic Modulation at wind farms in the UK. It is hoped that the full report will be available before the conference.

A summary of the report concludes that the incidence of AM at wind farms is very limited in terms of the number of people affected.

So those attending the windturbinenoise2007 Conference should consider themselves privileged to be able to listen to the experiences of one of the very few families that are affected by AM, though the numbers are higher for those disturbed by wind turbine noise more generally. (Though if that rare, one does wonder about entire conferences devoted to wind turbine noise, and research articles within the industry consumed with the same issue.)

The report also concluded that the causes of AM are not fully understood and that AM cannot be predicted using current state of the art methods.

Conclusions

Many aspects of windfarm noise pollution are a direct and obvious intrusion to day to day life. Sleep deprivation, with its associated health deficits is probably the worst aspect and the facilitator of many other problems.

The lower frequency sound wave pollution from the turbines appears unstoppable in terms of penetration through buildings and the likely health effects of such pollution are only now becoming evident.

We support the recommendations of the French Academy of Medicine, and the UK Noise Association, that industrial wind turbines should not be sited near homes, with a separation of **at least 2km**, though in some circumstances, a greater separation may be necessary to protect the health, well-being, and the amenities of one's home for those living nearby.

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[6] **Effects of the wind profile at night on wind turbine sound** G.P. van den Berg* Science Shop for Physics, University of Groningen, Nijenborgh 4, 9747 AG Groningen, Netherlands Received 22 January 2003; accepted 22 September 2003

Second International Meeting
on
Wind Turbine Noise
Lyon France September 20 – 21 2007

Review of post-construction noise compliance assessment conditions included in various wind farm planning permits in Victoria, Australia

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ABSTRACT

The New Zealand Standard 6808:1998 *Acoustics - The assessment and measurement of sound from wind turbine generators* (the "New Zealand Standard") is currently used in the State of Victoria (Australia) to assess noise emissions from wind farms. Section 5 of the New Zealand Standard, related to the post-construction compliance assessment, details the methodology to determine compliance with the limits, but does not detail practical measures to undertake the noise monitoring.

In Victoria, the planning permit conditions for a proposed wind farm are determined by an independent panel appointed by the Minister for Planning, when the project's power output exceeds 30MW, or by the local council for smaller projects.

These planning permit conditions usually outline the post-construction compliance assessment requirements and may be more or less stringent for different wind farm projects.

This paper presents a general review of planning permit conditions for a number of approved Victorian wind farms. It highlights various conditions regarding noise compliance assessment of wind farms and discusses their practicability and limitations.

1. INTRODUCTION

This paper presents a general review of planning permit conditions pertaining to post construction noise compliance assessment for a number of approved Victorian wind farms. The practicalities and limitations associated with the method proposed for compliance assessment are examined and discussed.

This paper will attempt to develop a post-construction noise compliance method that could be used for all future wind farm projects in Victoria and beyond.

The sites included in this study are presented in Figure 1.

Figure 1 – Reviewed sites

2. PLANNING PROCESS

In Victoria, the planning permit conditions for a proposed wind farm are determined by an independent panel appointed by the State Minister for Planning, when the project's power output exceeds 30MW, or by the local council for smaller projects.

During the panel hearing, the community, local council and technical experts provide submissions to assist the panel in making its decision. The panel members usually consist of lawyers, planners and engineers. During this process planning permit conditions can be proposed by any submitters and the panel will then decide on the final set of conditions to be included in the planning permit.

An indicative flowchart of the process is presented in Figure 2.

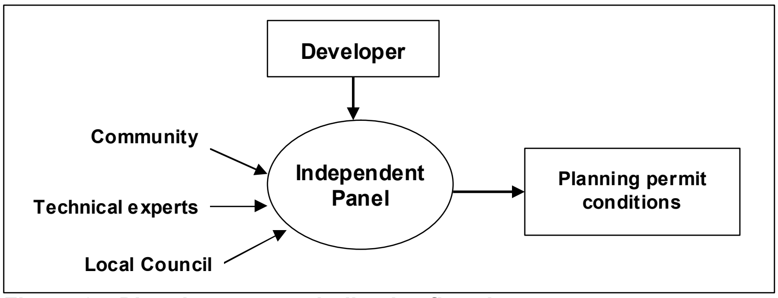

Figure 2 – Planning process indicative flowchart

3. THE NEW ZEALAND STANDARD

The New Zealand Standard 6808:1998 *Acoustics - The assessment and measurement of sound from wind turbine generators* is currently used in the State of Victoria (Australia) to assess noise emissions from wind farms. Section 5 of the New Zealand Standard, related to the post-construction compliance assessment details the methodology to determine compliance with the limits and is presented in Appendix A.

The New Zealand Standard is currently under review; therefore it is possible that a method for post-construction noise compliance monitoring such as that proposed in this paper may be included within the Standard.

4. PLANNING PERMIT CONDITIONS

The conditions of the planning permit relating to the post-construction noise assessment for each of the wind farms included in this study are presented in Appendix B.

A summary of requirements is detailed in Table 1.

Table 1
Summary of requirements

Wind Farm	Compliance with NZ Standard	Post-construction noise monitoring program Required?	Commencement	Duration	Comments
Challicum Hills	Yes	No	n/a	n/a	To the satisfaction of the responsible authority
Wonthaggi	Yes	Yes	Not specified	Not specified	At any existing dwelling at the time of the application To the satisfaction of the responsible authority
Yambuk	Yes	Yes	2 months from the commissioning of the first generator	A minimum of 12 months after the commissioning of the last generator	Monthly results must be forwarded to the Minister for Planning within 30 days of the end of each month
Waubra	Yes	Yes	2 months from the commissioning of the first generator	A minimum of 12 months after the commissioning of the last generator	Report summarising the results of the monitoring program must be forwarded to the Minister for Planning within 45 days of the end of the monitoring period

Table 1 (cont.)
Summary of requirements

Wind Farm	Compliance with NZ Standard	Post-construction noise monitoring program Required?	Commencement	Duration	Comments
Macarthur	Yes	Yes	Initial program: within 2 months of the commissioning of the last turbine (or group of turbines if staged construction) Second program: between 10-12 months of the start of the initial program for the whole site		Monitoring starting date and extent to be agreed between the responsible authority and the facility operator Concurrently monitoring at all dwellings where background noise monitoring was undertaken If compliance was demonstrated by the initial program, a second noise compliance monitoring program is to be undertaken No further noise compliance monitoring program is required if compliance is demonstrated by the second program Further noise compliance monitoring may be required by the responsible authority at any dwelling on the basis of a reasonable belief that the noise limits are exceeded.

In addition to these requirements, most planning permits will ask for a noise management plan which includes methods in which to respond to complaints.

5. DISCUSSION

It can be seen from this selection of planning permits that the conditions relating to post-construction noise assessment may be either very brief or very detailed depending on the project and also go beyond the requirements of the New Zealand Standard. The level of detail and extra requirements are usually related to the level of opposition to the development of the project in order to increase the level of security for the neighbouring residents.

The New Zealand Standard provides a generic methodology to assess post-construction noise compliance, but does not detail practical measures to undertake the noise monitoring. The New Zealand Standard leaves the relevant authority to deal with the following issues:

- The best time to start the noise compliance monitoring program
- The duration of the noise compliance monitoring program
- The wind conditions under which the monitoring should be performed

The following section attempts to identify the fairest and most practical ways to address the issues above by reviewing the planning permit conditions for the Victorian wind farms included in this study.

5.1. Challicum Hills

Owned by Pacific Hydro Limited
Completed in August 2003
35x1.5MW (Total 52.5MW)
68m hub height

The Challicum Hills wind farm is located to the north-west of Melbourne near Ararat. The conditions of the planning permit relating to the post-construction noise assessment are presented in Appendix B1.

The planning permit requires that the operation of the wind farm must comply with the New Zealand Standard to the satisfaction of the relevant authority, but does not provide any guidance on when or how to demonstrate compliance. This condition does not specify that the post-construction noise monitoring should be undertaken at the most appropriate time to allow for worst-case wind conditions.

A post-construction noise monitoring program was undertaken in early 2004 at the four residential properties where pre-construction background noise levels were monitored as required by the New Zealand Standard. Compliance was demonstrated at the Challicum Hills wind farm and, to my knowledge, no complaints regarding noise have been received.

5.2. Wonthaggi

Owned by Wind Power
Commissioned in December 2005
6x2MW (Total 12MW)
65m hub height

The Wonthaggi wind farm is located to the south-east of Melbourne near the township of Wonthaggi. The conditions of the planning permit relating to the post-construction assessment are presented in Appendix B2.

The planning permit requires that the wind farm must comply with the New Zealand Standard to the satisfaction of the responsible authority (the Minister for Planning) at any existing dwelling at the date of the approval of the planning permit. This additional detail provides little guidance on where compliance is to be achieved to protect the wind farm operator from having to comply with the New Zealand Standard noise limits at dwellings which did not exist at the time when the wind farm was designed.

The planning permit also requires that a post-construction noise monitoring program be undertaken in accordance with the New Zealand Standard to the satisfaction of the relevant authority.

A post-construction noise monitoring program was undertaken June 2006 at two of the three residential properties where pre-construction background noise levels were monitored as required by the New Zealand Standard (permission to monitor noise levels was not granted by the owner of the third property). Compliance was demonstrated at the Wonthaggi wind farm and, to my knowledge, no complaints regarding noise have been received apart from entrenched opponents to the project.

5.3. Yambuk

Owned by Pacific Hydro Limited
Completed at the end of 2006
20x1.5MW (Total 30MW)
70m hub height

The Yambuk wind farm is the first stage of the Portland Wind Project located on the coast of south-western Victoria. The Yambuk wind farm is located to the west of Melbourne near Portland. The conditions of the planning permit relating to the post-construction assessment are presented in Appendix B3.

In a similar way to the Wonthaggi wind farm, the planning permit requires that the wind farm must comply with the New Zealand Standard to the satisfaction of the responsible authority (the Minister for Planning) at any dwelling existing or approved at the date of the approval of the planning permit.

The planning permit also requires the following in Condition 17(a):

> *post-construction monitoring must commence two months from the commissioning of the first generator and continue for a minimum of 12 months after the commissioning of the last generator.*

The post-construction noise monitoring must be undertaken in accordance with the New Zealand Standard and results of each calendar month must be forwarded to the Minister of Planning within 30 days of the end of that month.

As part of section 5.1.2, the New Zealand Standard states the following:

> *Once the WTG (or windfarm) is installed and operational, it may be necessary to monitor the sound level in the surrounding area (…)*

Condition 17(a) contradicts the above by requiring the noise monitoring program to start before the whole wind farm is operational.

It is my understanding that this condition was introduced to protect residents' amenity against staged wind farms and to avoid excessive noise emissions during operation of the potential first stages. Monitoring noise levels from within 2 months from the commissioning of the first turbine will not prove compliance or otherwise of the New Zealand Standard noise limits as these measurements will not be representative of the whole wind farm and are likely to be affected by construction noise.

A monthly noise monitoring program over a period of at least 12 months will provide noise emissions from the wind farms under a large number of wind directions and may show non-compliance under certain wind conditions.

The worst case scenario is when the dwelling is located downwind from the wind farm, and it is possible to determine an appropriate period for noise monitoring at each affected dwelling using recorded wind patterns on site. Noise monitoring should be undertaken during a period where the monitored dwelling is located downwind from the wind farm. If compliance is achieved during this worst case scenario, it is very likely that compliance will be achieved at all times.

Complying with such conditions is very expensive and time consuming for the wind farm operator and may not be necessary to demonstrate compliance.

Post-construction noise monitoring is currently being undertaken at Yambuk and, to my knowledge, no complaints related to noise have been received.

5.4. Waubra

Owned by Acciona Energy Oceania
Expected to be operational by mid 2008
128x1.5MW (192MW)
80m hub height

The Waubra wind farm is located to the north west of Melbourne near Ballarat. The conditions of the planning permit relating to the post-construction assessment are presented in Appendix B4.

The conditions set in the planning permit are very similar to those for the Yambuk wind farm. The only difference is that results are to be forwarded to the Minister for Planning within 45 days of the end of the monitoring period.
Similar comments as for the Yambuk conditions can be made for these conditions.

The Waubra wind farm received approval from the Minister of Planning in June 2005 and construction started in November 2006.

5.5. Macarthur

Owned by AGL Energy Limited
Planning approval in October 2006
Proposed 183x1.8MW (330MW)

The Macarthur wind farm is proposed to be located to the west of Melbourne near Portland. The conditions of the planning permit relating to the post-construction assessment are presented in Appendix B5.

Unlike the other reviewed planning permits, Condition 21 allows for a potential staged wind farm and provides a sound methodology to determine compliance or otherwise with the New Zealand Standard noise limits. Furthermore, this condition allows the responsible authority to determine the date at which the post-construction noise monitoring program should start. In this case, it would be reasonable that a period when worst-case wind conditions are likely to be experienced should be selected for each of the dwellings to be monitored.

Condition 21 is presented below:

> *The initial compliance noise monitoring program must commence within 2 months of the commissioning of the last turbine in the wind energy facility or, if the facility is constructed in groups of turbines, separate programs within 2 months of the commissioning of each group. The date at which 'commissioning' has been deemed to occur and the extent of the noise compliance monitoring shall be agreed between the responsible authority and the wind energy facility operator.*

If compliance has been demonstrated during the first period of noise monitoring, Condition 26 of the same planning permit requires for a second period of noise monitoring to be undertaken at approximately the same time of year as the first noise monitoring period.

This condition reads as follows:

> *Should compliance be demonstrated by the program above the compliance noise monitoring program must be repeated commencing not less than 10 months and not greater than 12 months after the commencement of the initial compliance noise monitoring program for the whole site.(…)*

If the second noise monitoring program demonstrates compliance with the New Zealand Standard noise limits, then no further monitoring is required unless requested by the responsible authority at any dwellings on the basis of a reasonable belief that the New Zealand Standard noise limits are being exceeded.

The Macarthur wind farm received approval from the Minister of Planning in October 2006.

6. RECOMMENDATION

After reviewing a selection of planning permit conditions related to post-construction noise assessment, it was found that the level of complexity and detail varied significantly between projects. The New Zealand Standard provides only the methodology for determining compliance and limited details regarding the way the post-construction noise monitoring program is to be undertaken

It is considered that permit conditions requiring measurements to be performed once the first generator is completed will not prove compliance or otherwise of the New Zealand Standard noise limits as these measurements will not be representative of the whole wind farm and are likely to be affected by construction noise.

In addition, guidance regarding the wind conditions required during the measurement period must be provided as well as the duration of the monitoring period.

The following recommendations are proposed and could be included in the New Zealand Standard as part of the revised version:

- Post-construction noise monitoring should be undertaken during a period of worst case wind when the monitored property is located downwind from the nearest turbines

- Compliance should be demonstrated during two periods of noise monitoring separated by at least ten months and no more than twelve months

I propose that the following post-construction noise assessment conditions, based on the Macarthur wind farm conditions, be used as a model for wind farms assessed in accordance with the New Zealand Standard:

> *The operation of the wind energy facility must comply with the New Zealand Standard 'Acoustics – The Assessment and Measurement of Sound from Wind Turbine Generators' (NZ 6808:1998) (the 'New Zealand Standard'), in relation to any dwelling existing or approved in the vicinity of the wind energy facility at the approval date of this document.*
>
> *A post-construction noise monitoring and compliance assessment program must be undertaken by the wind energy facility operator. This must be to the satisfaction of the responsible authority with regard to timing, program design, determination of compliance, any necessary remedial action and information dissemination.*

The initial compliance noise monitoring program must commence within 2 months of the commissioning of the last turbine in the wind energy facility or, if the facility is constructed in groups of turbines, separate programs within 2 months of the commissioning of each group. The date at which 'commissioning' has been deemed to occur and the extent of the noise compliance monitoring shall be agreed between the responsible authority and the wind energy facility operator.

After the complete wind energy facility is commissioned, noise monitoring shall be carried out at all dwellings used to measure background sound levels, subject to the approval of their owners. The wind turbines shall be operating in their normal mode.

The design of the program and the evaluation of the acoustic data must be undertaken by an independent expert who has had experience in the analysis, interpretation and presentation of acoustic data from wind turbines, and who is preferably a member of a recognised professional association in that field.

Should compliance be demonstrated by the program above the compliance noise monitoring program must be repeated commencing not less than 10 months and not greater than 12 months after the commencement of the initial compliance noise monitoring program for the whole site. Should the further monitoring program demonstrate compliance with the noise criteria no further noise compliance monitoring shall be required at those locations unless otherwise determined by the responsible authority.

The responsible authority may require noise compliance monitoring at a dwelling or dwellings other than the reference dwellings on the basis of a reasonable belief that noise criteria may not be being complied with.

7. FURTHER WORK

As the New Zealand Standard was primarily written to assess noise from wind farms in New Zealand, a review of planning permit conditions for wind farm projects in New Zealand could lead to adopting the same model of conditions for all wind farms assessed in accordance with the New Zealand Standard. This study could then be undertaken for wind farms throughout other Australian states as they use different noise guidelines.

Acknowledgments

I would like to thank Acciona Energy Oceania, Pacific Hydro and Wind Power for providing copies of the planning permits.

APPENDIX A

SECTION 5 OF NZS6808:1998

5. Post installation sound compliance testing

5.1. Section overview

5.1.1.
This section outlines the precise method for the post installation compliance testing of sound from WTGs in the far field, i.e. at distances where the cyclic variations in sound due to blade rotation are no longer discernible. The procedure is based upon the method outlined in 4.5 with the exception that the WTGs will now be operational. Acceptable limits are outlined in 4.4.2.

5.1.2.
Once the WTG (or windfarm) is installed and operational, it may be necessary to monitor the sound level in the surrounding area. If so, measurements shall be taken of the sound level, and in addition, consideration needs to be given as to whether there are any special audible characteristics of the sound which may justify analysis and possible application of a penalty which must be taken into account when determining acceptability (see 4.4.3).

5.2. Compliance level testing
(NOTE – The procedure outlined below should be followed whether or not background sound levels have been measured.)

5.2.1.
Sound from the WTGs shall, where practical, be measured at the same locations where the background sound levels were determined. The method of measurements shall be consistent with the measurement of background sound levels as described in 4.5 with the exception that the WTG (or complete windfarm) will now be operational.

5.2.2.
Compliance level testing shall take place at the same positions and across a similar range of wind conditions for which background sound level data has been previously collected.

5.2.3.
As with the background sound level measurements, the compliance level testing shall take place at known windspeeds in the range 0m/s to rated windspeed (typically 13m/s-15m/s) measured at an anemometer height consistent with the background level measurements. As a check on sound levels generated at higher windspeeds, it is necessary to obtain measurements at windspeeds in excess of 15m/s. For dual speed WTGs, this shall be above the cut-in speed for the higher generating capacity.

NOTE – WTG sound measurements should be taken over a representative range of windspeeds and directions, each measurement being typically 10 minutes in time duration, as described above for background sound level determination. If typically 1440 data points were collected over the required windspeed range, it would be possible to repeat the regression analysis.

An assessment of any special audible characteristics should be undertaken.

5.3. Special audible characteristics

5.3.1
Sound from a WTG that has special audible characteristics (clearly audible tones, impulses, or modulation of sound levels) is likely to around adverse community response at lower levels than sound without such characteristics. At present, there is no simple objective procedure available to quantify special audible characteristics, and subjective assessment is therefore necessary, supported by objective evidence (e.g. frequency analysis) where appropriate.

5.3.2
When sound has a special audible characteristic, the measured sound level of the source shall have a 5dB penalty applied. This is because the subjective reaction to a sound containing a special audible characteristic is generally found to be similar to a sound 5dB louder, but without the special audible characteristic. A maximum penalty of 5dB shall be applied by adjustment of the measured sound level by arithmetic addition of +5dB.

NOTE – The objective method for determining whether a sound exhibits a tonal character shall be that used in IEC DIS 1400-11 for assessing wind turbine tonal character close to the turbine, i.e. The Joint Nordic Method. The method takes a number of narrow band spectra over a period of 2 minutes and compares the sound level of the tonal frequency to the 'masking sound level' in that of a critical band positioned around the tonal frequency. As the method takes the five highest tonal values within the 2 minute monitored period, it automatically considers those cases where the sound level of the tonal frequency is fluctuating.

5.4 Compliance assessment

To determine conformance with the limits set out in 4.4.2, a comparison shall be made between the best fit regression line of the background sound levels and the regression curve of the operation windfarm corrected for any special audible characteristics. If the background levels were not measured prior to installation (4.5.1), it may be necessary to obtain background sound level measurements for limited periods at critical windspeeds to satisfy 4.4.2 (e.g. if wind turbine or windfarm sound levels exceed 40dBA L_{95}). This may be for a limited range of windspeeds and directions, with the WTG(s) non-operational.

5.5 Further monitoring

When sound levels from WTGs have been established as complying with the criteria for acceptability set down in 4.4.2 of this Standard, nothing in this Standard shall prevent further monitoring at any later date as a further check on compliance. All such follow-up testing shall be carried out in accordance with the procedures set down in this Standard. Such testing may, for example, be conducted at a later date when investigating noise complaints, as provided for under procedures set down in relevant legislation.

APPENDIX B

EXTRACTS OF PLANNING PERMITS

B.1 Challicum Hills

Planning permit No. 1107 by the Ararat Rural City Council
Part of the Ararat Planning Scheme
Dated 8 October 2001

11. *The operation of the windfarm must comply with the New Zealand Standard "Acoustics - The assessment and measurement of sound from wind turbine generators" (NZ 6808:1998) (the "New Zealand Standard") to the satisfaction of the responsible authority.*

B.2 Wonthaggi

Planning permit No. 0266 by the Minister for Planning
Part of the Bass Coast Planning Scheme

13. *The operation of the wind energy facility must comply with the New Zealand Standard 'Acoustics – The Assessment and Measurement of Sound from Wind Turbine Generators' (NZ 6808:1998) (the 'New Zealand Standard'), in relation to any dwelling existing at the date of approval of this document to the satisfaction of the Minister for Planning.*

    Note: As a guide to acceptable limits consistent with the New Zealand Standard, the sound level from the wind energy facility, when measured outdoors within 10 metres of a dwelling at any relevant nominated wind speed, should not exceed the background level (L_{95}) by more than 5dBA or a level of 40dBA L_{95}, whichever is the greater.

14. *An independent post-construction noise monitoring program must be undertaken by the proponent to the satisfaction of the Minister for Planning in accordance with the New Zealand standard and in consultation with the Environment Protection Authority.*

B.3 Yambuk

Portland Wind Energy Project – Yambuk Wind Energy Facility
Incorporated document as part of the Moyne Planning Scheme
Dated April 2003

13. *The operation of the wind energy facility must comply with the New Zealand Standard "Acoustics – The Assessment and Measurement of Sound from Wind Turbine Generators" (NZ 6806:1998) the ("New Zealand Standard"), in relation to any dwelling existing or approved (by way of a planning permit or a building permit) at the date of approval of this document, to the satisfaction of the Minister for Planning.*

    Note: As a guide to acceptable limits consistent with the New Zealand Standard, the sound level from the wind energy facility, when measured outdoors within 10 metres of a dwelling at any relevant nominated wind speed, should not exceed the background level (L_{95}) by more than 5dBA or a level of 40dBA L_{95}, whichever is the greater.

    (…)

17. *An initial post construction noise monitoring program must be undertaken to the satisfaction of the Minister for Planning as follows:*

(a) *post-construction monitoring must commence two months from the commissioning of the first generator and continue for a minimum of 12 months after the commissioning of the last generator;*

(b) *measurement must be undertaken in accordance with the New Zealand Standard;*

(c) *the results of the monitoring program of each calendar month must be forwarded to the Minister for Planning within 30 days of the end of that month; and*

(d) *the Minister for Planning must make a copy of the monitoring program from each month available without delay at its office during office hours for any person to inspect free of charge.*

B.4 Waubra

Planning permit No. PL-SP/05/0152 by the Minister for Planning
Part of the Ballarat Planning Scheme
Dated 26 May 2005

17. *An independent post-construction noise monitoring program must be commissioned by the proponent within 2 months from the commissioning of the first generator and continue for 12 months after the commissioning of the last generator all to the satisfaction of the Minister for Planning. The program must be carried out in accordance with the New Zealand standard as varied by condition 14(a), (b) and (c) above. The permit holder must pay the reasonable costs of the monitoring program.*

18. *An independent report summarising the results of the monitoring program, and the data collected, and indicating compliance or non compliance with the New Zealand Standard, must be forwarded to the Minister for Planning within 45 days of the end of the monitoring period. The results must be written in plain English and formatted for reading by lay people.*

B.5 Macarthur

Planning Permit No. PL-SP/05/0283 by the Minister for Planning
Part of the Moyne Planning Scheme
Dated 26 October 2006

16. *The operation of the wind energy facility must comply with the New Zealand Standard 'Acoustics – The Assessment and Measurement of Sound from Wind Turbine Generators' (NZ 6806:1998) (the 'Standard'), in relation to any dwelling existing in the vicinity of the wind energy facility as at 7 February 206. In determining compliance with the Standard, the following shall apply:*

    a) *The sound level from the operating wind energy facility, measured outdoors within 10 metres of a dwelling at any relevant nominated wind speed, shall not exceed the background level (L_{95}) by more than 5dBA or a level of 40dBA $L_{95,}$ whichever is the greater. This 'background sound level' shall be determined by the method specified in NZS 6806:1998. Compliance shall be determined separately for all time data and for night time data. Night time is defined as 10pm to 7am. For sleep protection purposes, a breach of this standard, for 10% of the night, amounts to a breach of the condition.*

    b) *If sound has a special audible characteristic the measured sound level of the source shall have a 5dB penalty applied. The EMP must provide details on how special audible characteristics are to be determined and penalty is to be applied.*

20. *A post-construction noise monitoring and compliance assessment program must be undertaken by the wind energy facility operator. This must be to the satisfaction of the responsible authority with regard to timing, program design, determination of compliance, any necessary remedial action, and information dissemination. The PEMP provides more detailed requirements on this.*

21. *The initial compliance noise monitoring program must commence within 2 months of the commissioning of the last turbine in the wind energy facility or, if the facility is construction in groups of turbines, separate programs within 2 months of the commissioning of each group. The date at which 'commissioning' has been deemed to occur and the extent of the noise compliance monitoring shall be agreed between the responsible authority and the wind energy facility operator.*

22. *After the complete wind energy facility is commissioned the monitoring shall be carried out at all six reference dwellings used to measure background sound levels, subject to the approval of their owners.*

23. *The locations shall be monitored concurrently, and with the wind turbines operating in their normal mode. As far as possible the noise meter calibration and noise monitoring program shall be carried out by organisations accredited with the National Association of Testing Authorities (NATA).*

24. *The design of the program and the evaluation of the acoustic data must be carried by an independent expert who has had experience in the analysis, interpretation and presentation of acoustic data from wind turbines, and who is preferably a member of a recognised professional association in that field.*

25. *Compliance at noise reference locations is determined by comparing the curve of the operation wind farm noise results to which has been arithmetically added the 5dB penalty for any special audible characteristics should such be required, with the noise criterion curves for each site and for each time period. Compliance is demonstrated by the noise curve for the operational wind farm falling below the noise criterion curve at all wind speeds.*

26. *Should compliance be demonstrated by the program above the compliance noise monitoring program must be repeated commencing not less than 10 months and not greater than 12 months after the commencement of the initial compliance noise monitoring program for the whole site. Should that further monitoring program demonstrate compliance with the noise criteria no further noise compliance monitoring shall be required at those locations unless otherwise determined by the responsible authority.*

27. *The responsible authority may require noise compliance monitoring at a dwelling or dwellings other than those reference dwellings of condition 22 above on the basis of a reasonable belief that noise criteria may not be being complied with.*

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Applicability of TLM to Wind Turbine Noise Prediction

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Abstract

Wind turbine noise propagation takes place in an anisotropic sound speed gradient due to the presence of wind. In the general case of propagation, it is desirable to be able to address upwind configurations. Modelling upwind propagation implies to introduce atmospheric turbulence. Such refinements are not so easy to take into account in current methods like ray tracing or parabolic equation. The present paper shows that the Transmission Line Matrix method (TLM) might be a tool of choice when dealing with an inhomogeneous atmosphere. A novel intensity-based procedure for propagation in an anisotropic gradient is derived. The possibility of introducing turbulence be it thermal or dynamic is investigated on the basis of effective sound speed and sound intensity.

Introduction

Compared to road traffic noise, the most striking difference with wind turbine noise is that it implies the presence of wind. So wind turbine noise propagation takes place in an anisotropic sound speed gradient, i.e. whether downwind or upwind. Therefore, noise prediction methods that can take an atmospheric mean flow into account are certainly of interest in this area. Although downwind configurations are the most critically exposed to wind turbine noise, the ability to assess the noise impact upwind can help decide where to locate a wind turbine.

It is well known that upwind configurations are more difficult to handle than downwind ones. In particular, atmospheric turbulence has to be introduced in propagation. If not, purely coherent propagation leads to large underestimation of noise levels in the shadow zone.

Among the current noise prediction methods, the implementation of upwind conditions in ray-tracing is quite complex. The Parabolic Equation (PE) is well suited for handling upwind conditions. Unfortunately, the strong underlying hypotheses regarding symmetry make it difficult to handle real world geometries. Moreover propagation in PE is essentially one-way although workarounds exist.

The purpose of this paper is to show that the so-called Transmission Line Matrix method (TLM) must be considered in the development of advanced wind turbine noise prediction codes because it can embody most of the complexities of outdoor sound propagation, this with little mathematics. In the following, the basics of TLM are first presented in the 2-D homogeneous case. A short review of the state-of-the-art of TLM with respect to wind turbine noise requirements is provided. The 2-D inhomogeneous TLM is formulated. A novel way of taking an anisotropic sound speed gradient is derived. The possibility to introduce turbulence is investigated.

TLM basics and state of the art

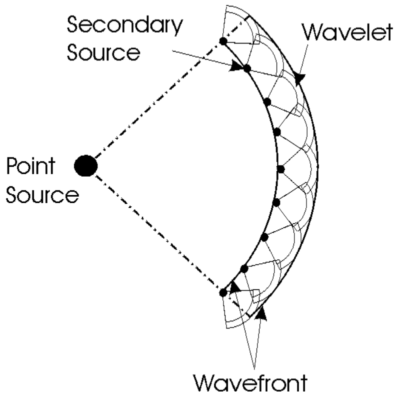


Figure 1 : Huygens' principle

The TLM method [Joh-1971] is based on the Huygens' principle. Given a point source that radiates spherically in a propagation medium, the wave front consists of a set of secondary point sources which in turn emit spherical wavelets whose envelopes form a new spherical wavefront which again gives rise to a new generation of spherical wavelets (cf Figure 1).

Let us first assume a 2D propagation with no loss of generality. For acoustics, the natural translation of the principle above on a digital computer is to discretize the propagation medium as a cartesian grid made of channels filled with air that connect at nodes or junctions, as shown on Figure 2. All channels have the same length Δl and acoustic impedance Z. A wave pulse arriving at a junction will be reflected and transmitted according to a local rule which is defined by computing the plane wave reflection coefficient at an impedance discontinuity (cf. Figure 3) and the energy conservation principle.

Considering the different possible incidences at a given junction reference as in a matrix by a row and a column index (i, j), one can establish a scattering matrix, which gives for incident waves at instant t the resulting waves in the 4 channels connected to this point at instant $t+\Delta t$:

$$_{t+\Delta t}\begin{bmatrix} R^w \\ R^n \\ R^e \\ R^s \end{bmatrix}_{i,j} = \frac{1}{2}\begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix}_t \begin{bmatrix} I^w \\ I^n \\ I^e \\ I^s \end{bmatrix}_{i,j} \tag{1}$$

Where R stands for reflected pulse and I for incident, *w,n,e,s* for the cardinal directions West, North, East and South.

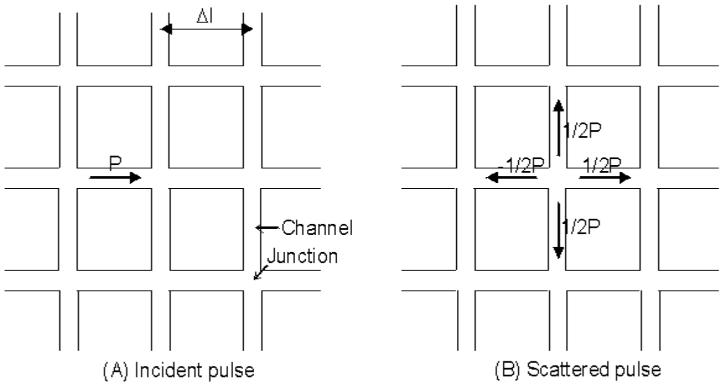


Figure 2 : 2D TLM model for acoustics

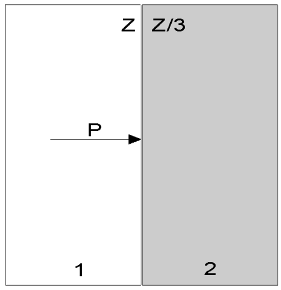


Figure 3 : impedance discontinuity at a node

The pressure at node (i, j) is evaluated as :

$$P_{i,j} = \frac{1}{2}(I^w + I^n + I^e + I^s) \tag{2}$$

For the pulse to move from one node to its neighbours, one must add a series of propagation rules. For instance, in the case of two connected east and west channels of adjacent nodes the propagation rules are expressed as follows :

$$\begin{aligned} {}_{t+\Delta t}I^{w}_{i,\, j+1} &= {}_{t}R^{e}_{i,\, j} \\ {}_{t+\Delta t}I^{e}_{i,\, j} &= {}_{t}R^{w}_{i,\, j+1} \end{aligned} \tag{3}$$

With this combination of a scattering matrix and propagation rules at the microscropic level, the normal wave motion in free-field can appear at the macroscopic level. It is of course possible to introduce boundaries in the propagation medium by defining particular propagation rules for the nodes in contact with boundaries. For instance, if one assumes that node (i, j) is at the vicinity of a vertical border with reflection coefficient r, the propagation rule above rewrites :

$${}_{t+\Delta t}I^{e}_{i,\, j} = r\, {}_{t}R^{e}_{i,\, j} \tag{4}$$

From a numerical point of view, the accuracy of the TLM scheme is close to the one of a second order finite difference scheme, but with a much better stability [Kag-1998]. Propagation at the macroscopic level is dispersive, i.e. speed of sound is frequency dependent, but when properly meshed the propagation speed can be kept constant over frequency.

Reference [Kag-1998] derives the expression of the scattering matrix for inhomogeneous media. It requires the introduction of a 5th branch. The latter is open-circuited. It increases the equivalent local compressibility :

$${}_{t+\Delta t}\begin{bmatrix} R^w \\ R^n \\ R^e \\ R^s \\ R^{st} \end{bmatrix}_{i,j} = \frac{2}{4+\eta} \begin{bmatrix} -1-\eta/2 & 1 & 1 & 1 & \eta \\ 1 & -1-\eta/2 & 1 & 1 & \eta \\ 1 & 1 & -1-\eta/2 & 1 & \eta \\ 1 & 1 & 1 & -1-\eta/2 & \eta \\ 1 & 1 & 1 & 1 & -2+\eta/2 \end{bmatrix}_{t} \begin{bmatrix} I^w \\ I^n \\ I^e \\ I^s \\ I^{st} \end{bmatrix}_{i,j} \tag{5}$$

In the above equation the exponent *st* stands for stub and η is the normalized characteristic admittance of the stub. The sound speed is then :

$$c=\sqrt{\frac{2}{\eta+4}}c_0 \text{ with } \eta\geqslant 0 \quad (6)$$

The first published application of TLM to outdoor sound propagation seems to be [Kri-2000]. It considers propagation over non flat ground in the presence of a temperature-like isotropic sound speed gradient modelled with a 5-branch scattering matrix (Cf Eq. (5)). Good agreement is found with respect to measurement data. An axisymmetric TLM is proposed in [Kag-1998]. It allows for reproducing a 3-D geometrical divergence in a 2-D domain. Recently [Hof-2007] proposed a modelling of ground impedance compatible with the TLM framework. Absorbing boundary conditions for limiting the fluid domain are available. [Mas-1998] contains a quite effective one with little computational cost. A scattering matrix for absorbing media is provided in [Kag-1998]. Atmospheric absorption has also been introduced in TLM in the field of ultrasound [Tsu-2006]. As TLM is a time-domain approach, it is not difficult to simulate moving sources [deCogan-2006] and a broadband spectrum can be used as an excitation signal.

There is no miracle method and the weak point of TLM is that it requires a volumic discretization of the simulated domain, just like in FEM. Therefore, the computational burden implied by a TLM simulation is high, compared to PE for instance. But a striking feature of TLM is that this method is distributed in essence. Therefore a simulation can be split into smaller simulations and supercomputers can be replaced by a network of standard computers. A distributed implementation of TLM is presented in [Dut-2004].

The next section proposes a new and more general approach for defining wind-like anistropic sound speed gradients in TLM.

Dealing with anisotropic gradients in TLM

Reference [Kag-2001] is the first to give a solution for the 2-D case with mean flow u parallel to one axis of the mesh where sound speed is c_0. The solution involves *one-way* additional branches parallel to the mean flow. The electronic analog of the one-way branches uses diode-like devices, not only passive components. The scattering matrix is the same as Eq. (5) but the propagation rules are more complex. The major drawback of this approach is that it implies that :

$$u=\frac{\eta}{2\eta+8}c_0 \quad (7)$$

Where η has the same meaning as in Eq. (5). Relation (7) is not at all implied by physics but by the connections of the additional branches. Furthermore, it seems difficult to handle a mean flow with a direction not parallel to a grid axis.

A new approach is described below. Let us start from the definition of the effective sound speed in air at point M where temperature (resp. wind) is defined by T (resp. $\vec{u}$) (see for example [Gau-1999]) :

$$c_{eff}(M)=\sqrt{\gamma R T(M)}+\vec{u}(M)\cdot\vec{i}(M) \quad (8)$$

where γ is the ratio of specific heats for air, R the perfect gas constant, $\vec{i}(M)$ is a unit vector defining the direction of propagation at point M.

From (6) we search for η so that :

$$\frac{2}{\sqrt{\eta+4}}c_0=c_{eff} \quad (9)$$

This leads to :

$$\eta(M)=4[(\frac{c_0}{\sqrt{(\gamma RT(M))}+\vec{u}(M)\cdot\vec{i}(M)})^2-1] \quad (10)$$

In order to ensure that $\eta\geqslant 0$ the TLM grid must be defined so that sound speed in free space complies to :

$$c_0\geqslant\sqrt{\gamma RT_{max}}+\|\vec{u}\|_{max} \quad (11)$$

where the maximum values are taken over the whole simulated grid.

An approximation of the local direction of propagation vector $\vec{i}(M)$ can be provided by a quantity related to the instantaneous sound intensity vector $\vec{I}(M,t)=p(M,t)\vec{v}(M,t)$ where $\vec{v}(M,t)$ is the local instantaneous velocity whose components are provided by [Kag-1999] :

$$v_x=\frac{I^w-I^e}{\rho_0 c_T} \text{ and } v_y=\frac{I^s-I^n}{\rho_0 c_T} \quad (12)$$

The possibility to use sound intensity in TLM has been validated in previous work [Dut-2003].

Here a purely local definition :

$$\vec{i}(M,t)=\frac{1}{\|\vec{I}(M,t)\|}\vec{I}(M,t) \quad (13)$$

is not usable directly because it does not describe properly the direction of propagation. This may be related to numerical errors. Such errors can be minimized by spatial filtering [Kag-1998]. Another interpretation is that the direction of propagation is a macroscopic information that cannot be obtained from a single local information. Qualitatively correct results are obtained when using an averaged intensity vector :

$$\vec{i}(M,t)=\frac{1}{\|\vec{I}_{mean}(M,t)\|}\vec{I}_{mean}(M,t) \quad (14)$$

on a square grid centered on the point of interest. The filter used is the arithmetic mean :

$$\vec{I}_{mean,i,j}=\frac{1}{(2a+1)^2}\sum_{j-a}^{j+a}\sum_{i-a}^{i+a}\vec{I}_{i,j} \quad (15)$$

where (i,j) are the coordinates of M on the TLM grid and a defines the span of the average around the central point. Thus $\vec{u}(M)\cdot\vec{i}(M)=\|\vec{u}\|\cos(\theta)$. Table 1 b) shows a map of θ that is based on intensity, Table 1 c) the effect of spatial filtering. By the way, b) illustrates that albeit propagation is faster along the main directions of the TLM grid (oblique square), a circular wavefront is properly reconstructed (see Table 1 b) and a)).

A comparison of a TLM simulation with or without a constant homogeneous wind is given in Table 2. With wind, it is readily seen that the wave propagation is slower upwind than downwind. This demonstrates at least qualitatively that an anistropic sound speed gradient can be implemented in TLM.

Due to the fact that the effective speed depends on the angle between wind and the direction of propagation, winds of arbitrary direction can be addressed.

The figures in Table 2 remind us a constraint of TLM : the effective speed can not exceed the speed in free space. Therefore, in the presence of wind, the propagation is globally slower.

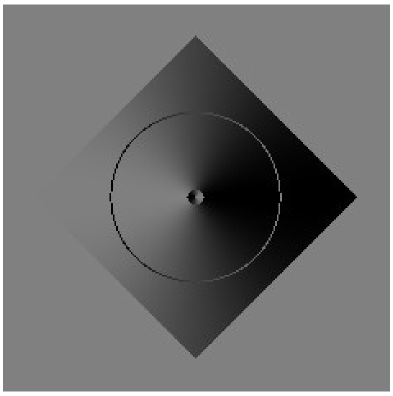
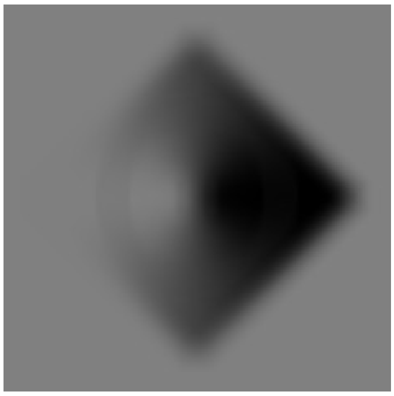
Pressure	Local intensity (Eq. (13))	Averaged intensity (Eq. (14))
 a)	 b)	 c)

Table 1: Pressure and intensity maps for the radiation of a transient signal from a point source. a) : Pressure - No wind . The grey level of the sides corresponds to zero pressure. Darker levels are positive and lighter negative. b) and c) : A constant horizontal flow $\vec{u}$ is defined for each point of the grid. The data displayed is $1+\cos(\theta)$. The grey level of the sides corresponds to amplitude 1.

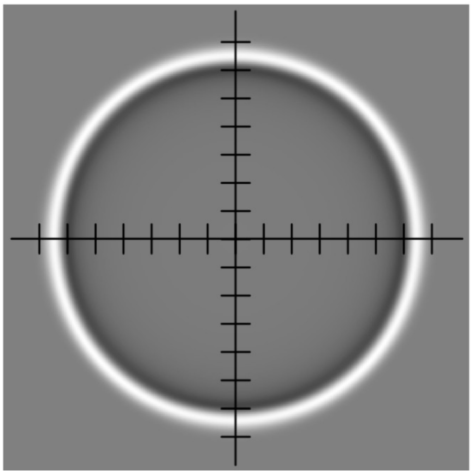
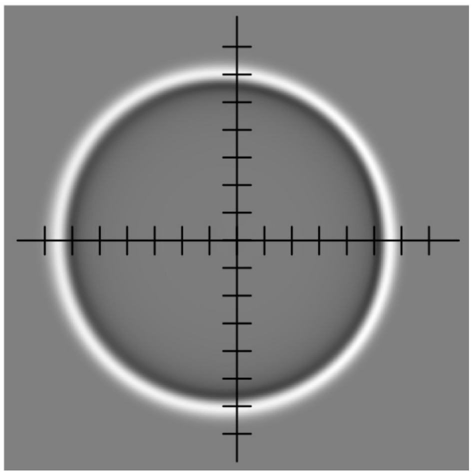
No wind	Constant wind from the right
a) 	b) 

Table 2: Effect of a constant uniform wind on propagation. The source is centered and radiates a transient signal. Pressure maps for iteration 200. On b) the progress of the wavefront is faster on the left than on the right side.

Introducing turbulence in TLM

Taking turbulence into account is mandatory for upwind configurations. Otherwise the long range noise levels are likely to be highly underestimated [Wie-1959]. Another well known effect of turbulence is to reduce interferences by decorrelation of direct and reflected waves [Emb-1996]. At a local scale, the effect of turbulence is to modify the refraction index n which is usually split into a mean part and a random part depending on the fluctuations of the medium :

$$n=\langle n\rangle+\mu \tag{16}$$

where $\langle\rangle$ stands for ensemble average.

Atmospheric turbulence can be both thermal (isotropic) and dynamic (anisotropic). In both cases turbulence is described by an intensity $\langle\mu^2\rangle$ and a spectrum of scales $G(\|\vec{K}\|)$, where $\vec{K}$ is the turbulent wave vector. Temperature and flow fields are generated from these turbulence spectra. At least two approaches exist at this stage to generate turbulence fields [Gil-1990][Bla-1990]. The latter seems to be the more elegant. It builds the turbulent field on a basis of Fourier random modes. For instance, the temperature field is defined like this :

$$T'(M)=\sum_{j=1}^{n} G(\vec{K}_j)\cos(\vec{K}_j\cdot\vec{OM}+\phi_j) \tag{17}$$

Where ϕ_j is the relative phase of a mode. The orientation of $\vec{K}_j$ is defined by a uniform random deviate over [0, 2π [, its magnitude by the spectrum of turbulent scales. See [Che-1996] for more details on the Fourier random modes technique.

On the TLM side, generalizing Eq. (8) to :

$$c_{eff}(M)=\sqrt{\gamma R(T(M)+T'(M))}+(\vec{u}(M)+\vec{u}'(M))\cdot\vec{i}(M) \tag{18}$$

and solving Eq (9) with the expression of Eq. (18) gives :

$$\eta(M)=4\left[\left(\frac{c_0}{\sqrt{\gamma R(T(M)+T'(M))}+(\vec{u}(M)+\vec{u}'(M))\cdot\vec{i}(M)}\right)^2-1\right] \tag{19}$$

As before, the TLM grid must be defined so that :

$$c_0\geqslant\sqrt{\gamma R(T_{max}+T'_{max})}+\|\vec{u}\|_{max}+\|\vec{u}'\|_{max} \tag{20}$$

Common practice with frequency-domain prediction methods is to assume “frozen” turbulence or Taylor hypothesis [Gau-1999]. The turbulent temperature and/or dynamic fields are computed once for all at the beginning of the simulation. Several simulations with different turbulence fields can be averaged to obtain a long term average. In the case of TLM, the turbulence fields can be updated during propagation. This is obviously closer to reality. Due to the low frequency nature of turbulence [Dai-1978], the celerity field updates should take place at a slower pace than the updates of the pressure field.

Conclusions

A promising intensity-based way of simulating wind-induced anisotropic sound speed gradients has been proposed. Compared to previous work it does not link unrelated physical quantities and it can deal with winds of arbitrary directions. Qualitative simulation results have been provided. The next step is to provide a thorough validation of the intensity-based procedure with respect to literature.

Regarding upwind conditions, the principle of the integration of isotropic turbulence in TLM (temperature fluctuations) has been outlined. One can indeed compute a 5-node scattering matrix from turbulence spectra. The extension to anisotropic

turbulence (wind fluctuations) can be addressed the same way as anisotropic sound speed gradients with the use of the effective celerity and the computation of the sound intensity vector.
Virtually all elements are available now to apply TLM to real world wind turbine noise problems. The point is now to develop an easily configurable distributed simulation code. This question may benefit from ongoing research on TLM for urban acoustics and propagation in complex sites at LCPC Nantes and LRPC Strasbourg.

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Recommendations for improved acceptance of wind farm projects in France with regard to acoustic noise

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1. Abstract

From the consideration of the various acoustic issues that are raised by wind farm projects, the similarities and differences of approaches and methods used in France and in Germany are reviewed. At each step of this review, advantages and drawbacks of each method are underlined. Recommendations to the acousticians, to the wind turbine manufacturers, to the developers and to the operators are derived with the objective of improving the acoustic quality of wind farm projects and their acceptance by the population.

2. Introduction

One of the arguments which are used by opponents to wind farm projects is the amount of noise nuisance that they can generate. Although this issue is considered during the permitting process both in Germany and in France, more difficulties have been reported in France than in Germany by experienced wind farm project developers and operators. Whereas many projects have been accepted in Germany, many cannot proceed in France because of acoustic problems. Looking for an explanation for the different situation in the two countries, we will focus in this paper on differences that we have noted in the handling of the acoustic issues from a regulatory point of view.

From the wind turbine, as a source of acoustic noise, to the wind farm neighbour, as a receptor of an acoustic signal, there is usually a complex propagation path and additional sources of noise often interfere at the receptor's position.

In this paper we will consider the following issues:

- The source should be known and described as accurately as possible
- The propagation model should be suitable for the purpose and for the topographic as well as for the climatic conditions
- The initial state under consideration of the various climatic conditions should be known
- The relevant perceptive issues should be known

and the decision criteria should be related to them.

We will not discuss in this paper the development process itself where a wind farm is designed under consideration of the topography, of the wind statistics and of the other users of the planning area although country-specific design rules could be derived from the regulatory framework.

3. Legislative framework

The protection of the acoustic environment is regulated by laws passed by the governments of the respective countries e.g the so-called *BImSchG* in Germany [1] or the decree on the limitation of community noise in France [19].

The implementation of these laws then relies on administrative directives such as the *TA Lärm* [7] in Germany or published by the regional administrations in France [11] which are derived from ministry studies [12].

The decisions are based on levels and measurements which are defined or recommended on the basis of the experience gained by the professional acousticians. This experience is, to some extent, represented in the standards.

The issues of source characterization, propagation calculation methods, characterization of the initial acoustic situation, level and tonality are dealt with in various standards.

4. Source characterization

The international standard IEC 61400-11 defines a method for the determination of the acoustic characteristics of a wind turbine which is described as a sound source with an apparent sound power level, a one-third octave spectrum as well as narrow-band spectral components. Optionally, the directivity of the source can also be determined [8][9]. This standard has taken over several of the propositions made by the International Energy Agency (IEA) in 1997 for the measurement of noise immission from wind turbines [6]. Further on, the method chosen for the determination of the tonality builds up on the work done during the development of the German standard DIN 45681 [14].

The standard IEC 61400-11 has an international character but its update cycle can be fairly long. Other professional organizations, such as MEASNET or FGW, develop alternative methods or recommendations which allow to implement at a faster update rate the latest findings [13][15]. These recommendations can then be used as a basis for revisions of the international standards.

The IEC 61400-11 standard has been designed with the practical application in mind of predicting the sound pressure levels at the receptors location. In order to provide the required input parameters to the intended prediction methods, the sound power level of the wind turbine as a whole had to be determined. Because of the size of the object under investigation, usual standards for the measurement of the sound power level of a source, such as the ISO 3744 [9], are not applicable. A practical method using a microphone on a plate in the vicinity of the wind turbine has been designed instead and has been laid down in the IEC 61400-11 standard.

The source as measured according to IEC 61400-11 will be considered as a point source positioned at hub height. However detailed investigations show that most of the noise is produced towards the end of the blades during their downwards movement [16].

5. Propagation model

Once the sound source is known, the use of a sound propagation model allows estimating the sound pressure level at the receptors location. The choice of the suitable model raises however many questions. In Germany, an engineering method has been laid down in 1988 as the VDI 2714 [2] and has provided a basis for the international standard ISO 9613-2 [5].

This method is widely used around the world although the uncertainty of its prediction, in the range of +/- 3dB, often leaves issues open for discussion, one of these being whether it is useful for sources higher than 30 m or not. In the acoustic community, alternative methods are actively searched for, proposed and discussed but reducing the aforementioned +/- 3dB uncertainty window proves to be difficult.

Although France is generally not favorable to ISO 9613-2, this standard is mentioned in the French developers guide to wind farm projects [12] as a method for prediction of noise levels at the receptors location.

6. Measurement of noise in the environment

Whether or not a wind turbine noise will be annoying depends very much on the background noise level in the absence of the wind turbine. Hence it is interesting to consider the methods which are suitable for its assessment.

The International Energy Agency (IEA) has published in 1997 recommendations for the measurement of noise immission at receptor locations [6]. The proposed techniques have been selected with the objective of improving the measurement reproducibility. In order to avoid air flow noise at the measurement microphones, secondary wind screens are recommended. Figure 1 shows that the use of a secondary wind screen allows to measure reliably the background noise even at high wind speeds. Further on, owing to the fact that the level of the wind turbine noise is often similar to that of the background noise, the mounting of the microphone on a large plate is recommended since it can improve the signal to noise ratio by 6 dB.

In application of the IEA recommendations, the German administrative directive *TA Lärm* allows to use secondary wind screens for the measurement at high wind speeds.

In France, the method for the assessment of noise in the environment is laid down in the NF S 31-010 standard [4]. According to this standard, the wind speed range for which measurements are valid is limited to 5 m/s. This might be appropriate when the receptor location is protected from the prevailing wind direction at the wind farm. If the receptor location is in direct view and down-wind of the wind farm, chances exist that it will be subject to annoyance. This location would be worth to investigate but measurements might not comply to the French standard because the wind speed at the microphone will probably exceed the 5 m/s limit.

One may argue that since the microphone is placed at a height of 1.5 m above ground, the wind speed at the microphone will be much lower than at the 10 m height of the wind measurement mast at the wind turbine site. In practice however, many situations will be found where the wind speed at 1.5 m height is higher than the 5 m/s limit and where flow noise could develop at the microphone even though the standard wind screen is in place. This would be the case in a turbulent wind field close to the ground where gusts would ruin the measurements although the average wind speed would remain below 5 m/s.

Hence we recommend the use of a secondary wind screen because it allows to perform measurements under most of the practical situations. The question whether or not these measurements may be taken into account within a measurement report complying to NF S 31-010 may be discussed later but the measurement itself will provide interesting insight about the noise immission during the operation of the wind turbine(s).

7. Secondary sources

The acoustic situation at the immission points depends not only on the contribution from the wind farm but also from the wind-induced background noise sources such as surrounding trees or buildings. In order to take theses sources under consideration, the German procedure allows the measurement at wind-exposed locations. In this case the secondary wind screen comes at hand to prevent flow-induced disturbing noise at the microphone.

In France, the wind speed at the microphone must not be larger than 5 m/s [4]. This rules out the measurements at wind-exposed locations. Measuring at a position in the wind shadow helps to comply to the max 5 m/s rule but leads usually to lower sound pressure levels than at wind-exposed locations.

The issue of comparing the predicted level with the measured one has to be raised here. The prediction of the sound level behind a building using the standard propagation models such as ISO 9613-2 leads to high uncertainties. Furthermore it is very difficult to estimate the contribution from the wind-induced secondary sources at these locations.

In Germany, the measurement at a wind-exposed location is preferred because it can be better compared to the prediction of the propagation model which performs reasonably well in such situations.

In order to characterize the acoustic situation between the wind turbine site and the immission point, we recommend to show the correlation of the sound pressure level at the site with the level at the immission point in relation to the wind speed at the wind turbine site.

8. Administrative criteria

In Germany, the *TA Lärm* recommends day-time and night-time noise limits depending on the type of the considered zone (commercial area, mixed area, general residential, pure residential). For example, the night-time noise limit for a mixed area is 45 dB(A). This is a noise budget which must not be exceeded by all the contributors to the noise level. This limit is the same for all the wind speeds and since the sound power level of wind turbines increases with the wind speed, the limit according to *TA Lärm* imposes a limit on the maximum sound power level of the wind turbines. That is why the most relevant parameter for the assessment of wind turbines in Germany is their maximum sound power level. The available budget for a new wind farm will be the difference between the noise limit and the background noise level before construction.

When wind turbines operate beyond the rated wind speed, the sound power level of stall-regulated wind turbines tends to increase with the wind speed whereas it stabilizes and sometimes decreases with pitch-regulated turbines. That is why a pitch-regulated wind turbine fits usually better within a given noise budget than a stall-regulated one [17]. Experience shows that the critical wind speed for a wind farm project using pitch regulated wind turbines is in the range of 8 to 10 m/s.

In France, the noise limit depends on the background noise level. The wind farm is allowed to increase the ambient noise level by 5 dB at day-time but only by 3 dB at night-time. This increase is named *émergence*. The French standard NF S 31-010 allows measurements of background noise only during periods when the wind speed is below 5 m/s at the microphone. In the absence of wind-induced noise, the background noise level depends on the activity of neighbours and other users of the area. It varies according to the time of the day as well as of the season. Hence the noise limit for a given wind farm is variable. To be on the safe side, the project developer should evaluate the lowest background noise level over the year. It can be extremely low, in the range of say 26 dB(A) e.g. during a calm and cold winter night. This is a worst case situation for the project developer and searching for the quietest 30-minutes night period of the year can be a very time consuming project.

Fortunately, the wind farm developer counts on the wind-induced background noise since his future wind farm will operate only if wind is blowing. The trees, the structures and the buildings in the surroundings will usually produce wind-induced noise. How significant these sources are, depends very much on the topography of the area, of the layout of the wind farm and of the wind direction. Reliable measurements of wind-induced noise are however usually missing.

Hints on the characteristics of wind-induced noise can be provided by existing wind turbine measurements according to IEC 61400-11. The reports include the measurement of the background noise in the surroundings of the wind turbine (Figure 1) but these measurements are usually not directly applicable to the immission points of interest because the microphone, mounted on a plate in the vicinity of the wind turbine, is more sensitive to the noise coming from the wind turbine than from the environmental sources which are close to the ground.

The acoustician usually makes an assumption for the wind-induced background noise. By comparing the level of the assumed or measured background noise with the expected noise of the wind farm at the immission points, he can assess whether or not the increase of the ambient noise level is lower than 3 dB at night-time. The review of numerous wind farm projects shows that the critical wind speed range is between 5 and 7 m/s (Figure 2).

9. Measurements at the immission point

In Germany, the sound pressure level at the immission point must not exceed the reference noise limit. Although the difference between the background and the resulting levels does not need to be determined, the uncertainty on the immission measurement is high. Repeated measurements at different periods of time could lead to differing conclusions. In order to ensure a long-term stable decision, an alternative method is preferred for the determination of the immission level. It is based on the measurement of the source and completed by a calculation of the propagation to the receptor location.

In France, the measurement at the immission point requires the measurement of the background noise as well as of the ambient noise. Since the difference between these two noise levels is often very small, the relative uncertainty is high. Furthermore, depending on the period of time, the measurement of the background noise is subject to large variations. As a consequence, the decision whether the level at the immission point is acceptable or not is subject to hesitations and hence unstable on the long term.

10. Wind turbine characteristics

The critical wind speed range is different for Germany and for France. As a consequence, the optimal wind turbine for a German project may be different from the optimal wind turbine for a French project. In Germany, the most relevant acoustic parameter is the maximum sound power level and manufacturers provide the capability to trade a lower sound power level for a limitation of the electrical power. Such a limitation may have almost no effect on the sound power level at reduced wind speeds.

Some designs are however tailored for a reduced sound power level within the critical wind speed range of French projects. Hence, the country-specific noise limits induce technological developments which lead to differences in the country-specific optimized wind turbines.

11. Tonal components

The level of noise from the wind turbines is an important criterion but it is not sufficient to explain the acceptance or rejection of some projects by the neighbours. Besides the level, the tonal character of the noise often causes the greatest annoyance. In order to reflect the increased annoyance caused by noise containing tonal components, a penalty can be added to the sound power level. Several methods for the evaluation of this penalty have been investigated by the Working Group on noise from Wind Turbines and reported in “The Assessment and Rating of Noise from Wind Turbines” [3].

In Germany, the *TA Lärm* considers a penalty for tonal components according to DIN 45681 [14]. This method has been initially developed for industrial applications but has been adapted to the assessment of wind turbine noise within the IEC 61400-11 standard [8] (Figure 3).

The French standard NF S 31-010 considers a tonality defined on the basis of the third-octave analysis named *tonalité marquée*. Such a criterion smears the information provided by the narrow-band components into one-third octave bands and fails to single out the real problems.

The French standard NF EN 61400-11, which is closely related to the IEC 61400-11, introduces nevertheless the notion of tonality on the basis of the narrow-band analysis. The discussion with French representatives showed however that this notion is not yet considered by the administrations during the permitting process.

The assessment of tonality relies on psychoacoustics and remains controversial but failing to take the tonal components into account leads to a biased evaluation of the situation. Trying to prevent the annoyance only by lowering the noise limits imposes unduly constraints on the wind farm development process.

12. Measurement methods

The wind energy community has developed measurement methods which lead to limited uncertainty and good reproducibility. This could only be reached through the adoption of special measures such as:

- secondary wind screens for the measurements with wind speeds up to 10 m/s [8]
- use of a large ground board in the vicinity of the wind turbine to reduce the wind-induced noise generated at the microphone, to improve the signal to noise ratio and to minimize the influence of different ground types [8]
- wind-speed measurement at hub height and on the basis of the electric power and of the power curve of the wind turbine [13].

Unfortunately, these methods are not compliant to the French standard NF S 31-010.

13. Uncertainties

The prediction of the acceptance level of a wind farm project by the neighbours is a difficult task. When the perception of a wind farm project is negative, the quality of the equipment, the wind turbine, is first suspected. Although this might have been justified in the past, most modern wind turbines have respectable acoustic characteristics. The measurement methods according to IEC 61400-11 lead to reproducible results with uncertainties in the range of +/- 1 dB. The propagation calculation performed during the acoustic study has usually an uncertainty in the range of +/- 3 dB. This is considered as state-of-the-art although many acousticians work at developing more accurate methods. As seen before, the measurement of the background noise in France is subject to large uncertainties due to seasonal as well as occupational variations. As a consequence of this unsteady reference level, the decision whether the contribution from the wind farm is acceptable or not is unstable on the long term.

In the end, the acceptance of the wind farm has to come from the neighbours. Depending on their sensitivity and subjectivity, they can have developed radical opinion on the wind farm. Even though negative opinions can be justified at a given period of time because of temporary poor operating conditions of the wind farm, it might get difficult to upset these negative opinions once the operating conditions have improved. Once people have focused on an acoustic issue they can sharpen their sensitivity so much that they remain sensitive beyond the correction of the initial acoustic problem.

The recommended strategy to improve the acceptance of wind farm projects is hence (Figure 4)

1. to prevent upsetting the sensitive neighbours,
2. to develop suitable and stable administrative criteria
3. to improve the propagation models
4. to improve the wind turbine acoustic qualities.

The measurement methods developed for wind energy such as the IEC 61400-11 have the goal of providing accurate results that can be verified by others. More demanding standards, such as those of MEASNET can lead to an even better accuracy [13].

The signal to noise ratio can be improved by mounting the microphone on a large board.

The wind-induced secondary noise sources must be characterized for a qualified analysis of the acoustic situation.

14. Discussion

Most of the information on the source provided by a measurement according to IEC 61400-11 is taken into account during the evaluation of a wind farm project in Germany, especially the tonality which has proven to be a very sensitive and selective issue [21].

The French standard NF S 31-010 on the other hand considers a tonality defined on the basis of the third-octave analysis named *tonalité marquée*. It usually oversees the spectral components which are more significant from a perceptual point of view and can only be resolved by a narrow-band analysis.

The IEC 61400-11 standards prescribes that the results of the measurements are shown for wind speeds between 6 and 10 m/s. This is convenient for several countries but unfortunately not for France where investigations at lower wind speeds are necessary to meet the administrative requirements. It is advisable here that France gets more involved in the standardization process so that its specific requirements are taken into consideration for the next release of the standard.

15. Recommendations to the developers and operators

In order to improve the acoustic acceptance of wind farm projects we recommend the following:

- Adapt the wind farm design rules in order to take the sensitivities of the country-specific regulatory framework under consideration. As an example, the typical controversial case of a wind farm on top of a hill with dwellings down-wind in the valley might be even more critical in France than in Germany because the *émergence* criterion might be more selective than a noise limit if the valley is considered to be French rather than German
- Assess the background noise with enough details. This usually requires long-term or repeated measurements
- Be conservative and adopt safety margins (at least 2 dB) to account for the uncertainties of the acoustic study
- Even though some issues are at first sight not relevant for the building permitting process, such as the narrow-band tonality in France, do pay attention to it because on the long term, the neighbours will be sensitive to this issue
- Avoid misunderstanding by addressing the relevant perceptive issues. Whereas administrations and experts might argue on acoustic indicators such as L_{Aeq}, L_{90} or L_{50}, opponents could be excessively reactive because of individual tones which are not reflected by these acoustic indicators
- Choose wind turbines whose acoustic characteristics are suitable for the project. Depending on the country of application, the focus might be at higher wind speeds, such as in Germany, or at medium wind speeds such as in France. Some manufacturers offer country-specific acoustic operational features
- If the wind turbine does produce unexpected noise after commissioning, be diligent and have these turbines fixed before opponents make an argument on the long term out of these initial problems
- Remember that almost no narrow-band tonality should be emitted by a state-of-the-art wind turbine

- Make use of all the available features of the wind farm management system in order to reduce the emission when necessary such as time- and weather-dependant power limitations
- Review the critical issues of the project during an acoustical due diligence before the construction of the wind farm. Many potential problems can be identified at the planning stage and solutions can then be found more easily than when the wind farm is already operating and neighbours are complaining.

16. Perspectives

An extension of the French NF S 31-010 standard for application in wind energy is under development. We hope that it will consider some of the remarks presented in this paper.

17. Acknowledgments

This paper draws up on a presentation given in January 2006 in Berlin within the framework of the German-French coordination agency for the development of wind energy [20].

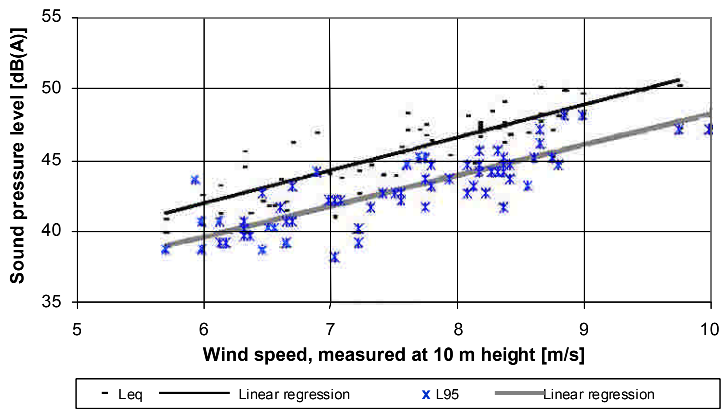

Figure 1: Example wind-induced noise level in relation to the wind speed in 10 m height.

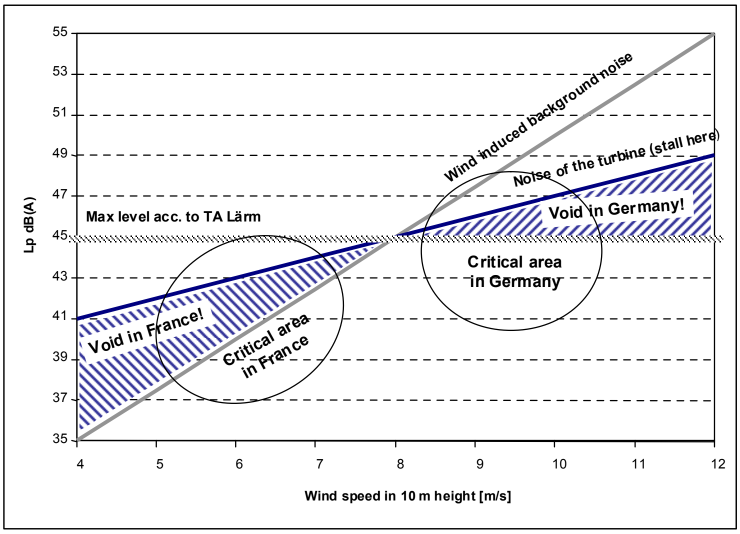

Figure 2: Wind turbine noise, wind-induced noise in relation to noise limits in Germany and France.

Erreur ! Des objets ne peuvent pas être créés à partir des codes de champs de mise en forme.

Figure 3: Illustration of classifying the spectral lines of a narrow band analysis.

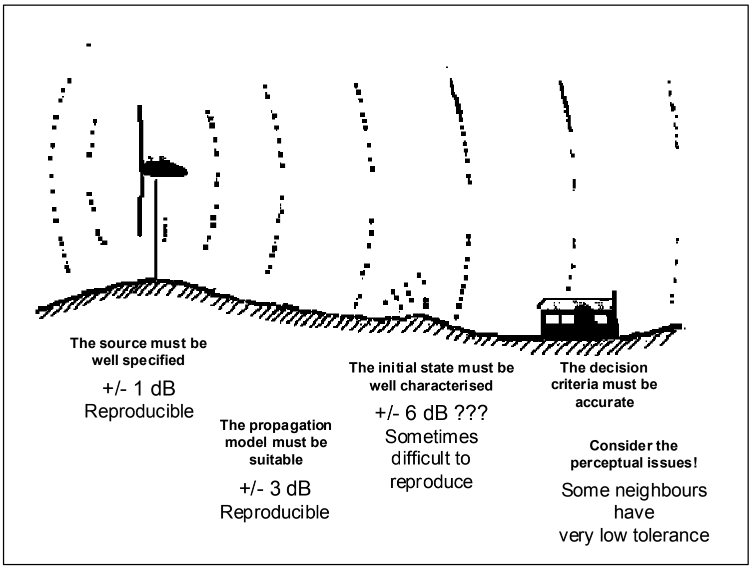

Figure 4: Typical uncertainties at the various phases of the acoustic study of a wind farm project.

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An Investigation of the potential for Noise and Vibration issues from Micro Wind Turbines for Domestic Use

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Abstract

The noise emissions from wind farms are well known, and are commonly cited as an objection to the construction of wind farms by neighbours at the planning stage. Despite this, the emergence of micro wind turbines has captured the imagination of the public.

This study carried out a thorough literature review of the potential noise and vibration issues that could surround the application of micro wind turbines in a residential/urban setting. This study also carried out an investigation of a micro wind turbine that was installed in an urban setting.

The principle conclusions of this study were:

i) There is an absence of any standards that may allow the prediction of the effects of micro wind turbines, i.e. standards that allow the determination of the sound power level;

ii) The vibration experienced at the contact point between the support structure of the micro wind turbine and the building exceeded $1 mms^{-1}$ (PPV in the vertical plane) under certain wind conditions;

iii) There is potential for the observed vibration to cause structure borne noise; and

iv) The airborne noise issues from the installed micro wind turbine was below background noise levels at the study site.

Introduction

Recent press attention within the UK has highlighted a relatively new innovation that involves the mounting of small scale wind turbines on residential or commercial buildings within urban and suburban areas. The development seems to have captured the public imagination and a leading DIY chain is stocking Micro Wind Turbines (MWT). [1] However, the noise and vibration issues from installing MWT's upon buildings are not understood in the same manner as their industrial-scale counterparts.

The UK government in signing the Kyoto Protocol agreed to reduce greenhouse gas emissions by 12.5% of the emissions of 1990 by 2010. [2] In order to help achieve this target the former Department of Trade and Industry (DTI) (now the Business, Enterprise and Regulatory Reform department (BERR)) have committed to increase the electricity generated by renewable sources in the UK from 4% in 2005 to 10% by 2010 with an aspirational target of 20% by 2020. In addition, pressures such as the increased cost of fossil fuels and concern surrounding the security of supplies of fossil fuels from other countries have increased the momentum surrounding generating electricity from renewable sources, i.e. biomass, solar electric (photovoltaic), solar water heating, tidal power and wind power.

In order to meet these targets it is accepted that immediate action is required. It has been claimed that the UK has approximately 40% of the total European wind resource and alternative technologies are not yet in a position to generate electricity more cost-effectively, hence wind power is considered the best option for the UK in the foreseeable future. [3]

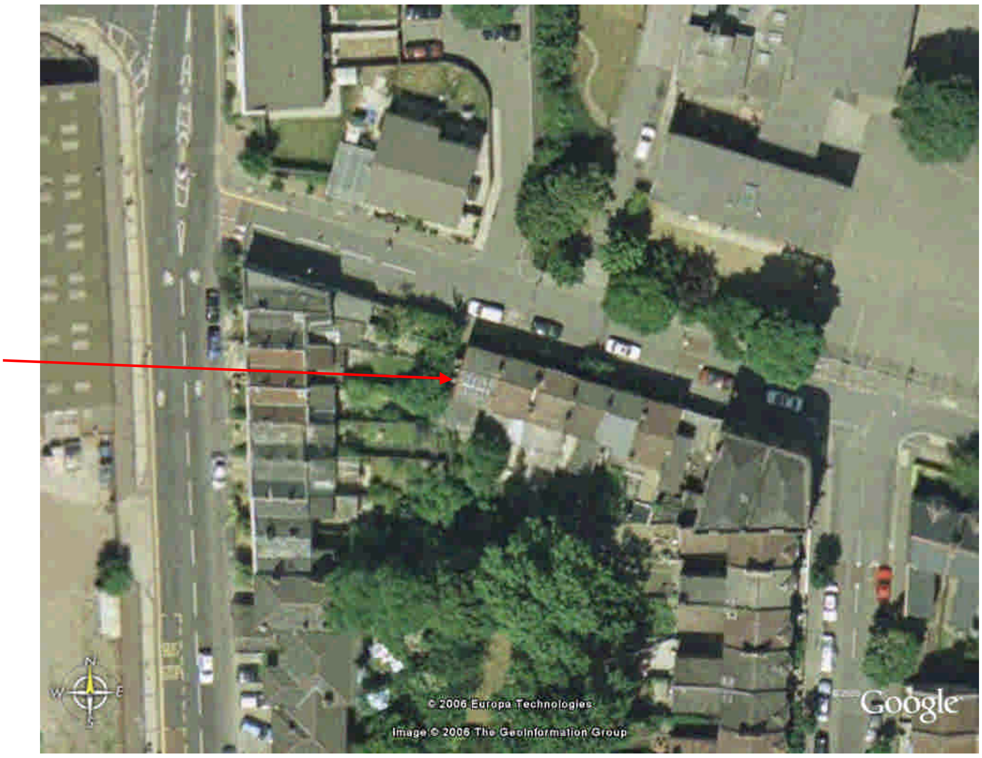
The DTI published a Microgeneration Strategy in 2006 which aimed to introduce small scale electricity and/or heat generation from low carbon sources at or close to the point of consumption. It has been claimed that, in the case of centralised electricity generation, between 30% and 50% of all the electricity generated is lost in transmission between the generator and the consumer. As a result, It could be claimed that for every Megawatt generated by microgeneration, two are not required to be generated by centralised power plants. [4]

The Energy Saving Trust (EST) have examined the role that microgeneration technologies can play in the UK and have suggested that, given favourable conditions, 30 – 40% of the energy needs of the UK could be met by microgeneration by 2050. In order to create these favourable conditions the government have offered grant schemes, and are examining the implications of removing administrative obstacles such as the requirement for Planning Permission for the installation of microgeneration technologies. [5]

The Site

The site that was chosen for study was located in an urban, inner city area in south London. An aerial photo of the area can be seen in Figure 1.

Figure 1: Arial photograph of the property.



The property was a two storey, cottage type property, which as can be seen from Figures 2 and 3 has its gable end faced by the rear gardens of the properties towards the left of the property.

Directly opposite the property was a low rise block of flats, while to the right of the property, directly opposite the remainder of the terrace was a primary school.

The wind turbine that was installed at the property was a five bladed, upwind horizontal axis micro wind turbine. It was mounted directly to the gable wall of the property by way of a wall bracket and pole. A photo of the turbine and the support structure can be seen in Figure 4.

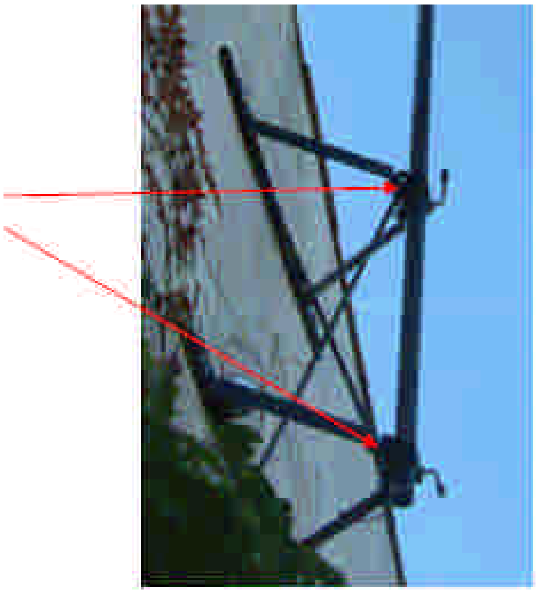
In response to complaints of noise from the owner of the property the manufacturers installed anti-vibration mounts to the support structure. Figure 5 shows the location of the mounts.

Figure 2: Photograph of the property.

Figure 3: Photograph of the property.

Figure 4: Photograph of the micro wind turbine and support structure.

Figure 5: Photograph of the support structure and location of the anti-vibration mounts.



The Methodology

During the design of the survey it was found that there was no data concerning the noise emitted from the turbine, a pattern that appeared consistent across the micro wind turbine industry. It was decided therefore that an assessment of the airborne noise immission at the nearest residential dwelling would be more appropriate.

To this end, an all weather microphone was installed at the boundary between the source and the nearest residential dwelling.

In addition, it was decided to monitor the vibration imparted into the structure of the building by the MWT and its support structure. The transducer was mounted at the point of contact between the support structure and the wall.

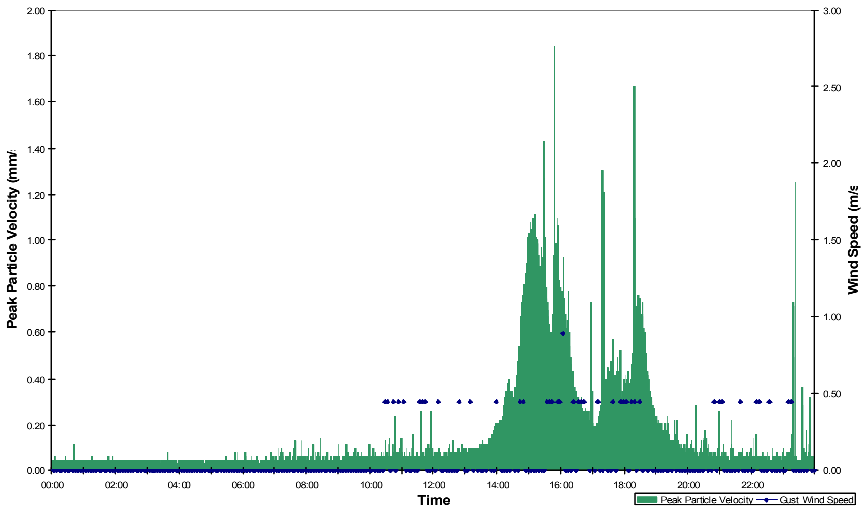
As the noise and vibration source was a wind turbine, it was recognised that there was a need to collect wind speed data in addition to the noise and vibration data. The wind speed data was collected from a nearby weather station.

The data sets were collected simultaneously over a seven week period.

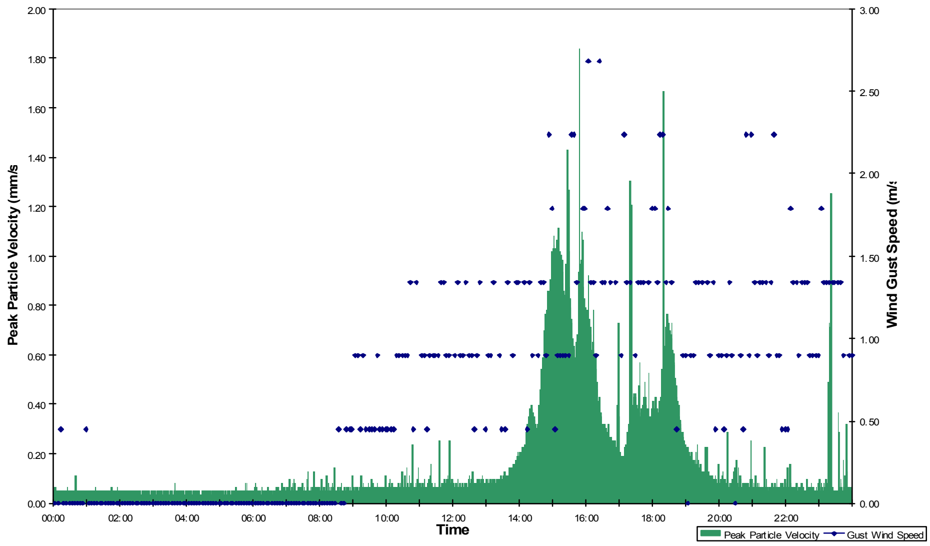
Results

It was found during the analysis of the data that wind speed was not the most appropriate issue to consider at this site. Graph 1 shows a comparison between the peak particle velocity (PPV) in the vertical direction against wind speed for a 24 hour period. Graph 2 shows a comparison of the PPV against gusting wind speed for the same period.

Graph 1: Comparison of Peak Particle Velocity against wind speed for the 26th August 2006.



Graph 2: Comparison of Peak Particle Velocity against gusting wind speed for the 26th August 2006.



As can be seen by the graphs, there is a much better correlation between gusting wind speed and PPV than between wind speed and PPV.

Having determined that only results that occurred when the gusting wind speed was high were of value an examination of the vibration experienced was carried out. Graph 3 shows the vibration profile experienced during gusting wind conditions.

As can by seen by the graph, PPV in the vertical direction was dominant. It can also be seen that the magnitude of the vibration was regularly over 0.5mms^{-1}, with occasional peaks over 1mms^{-1}.

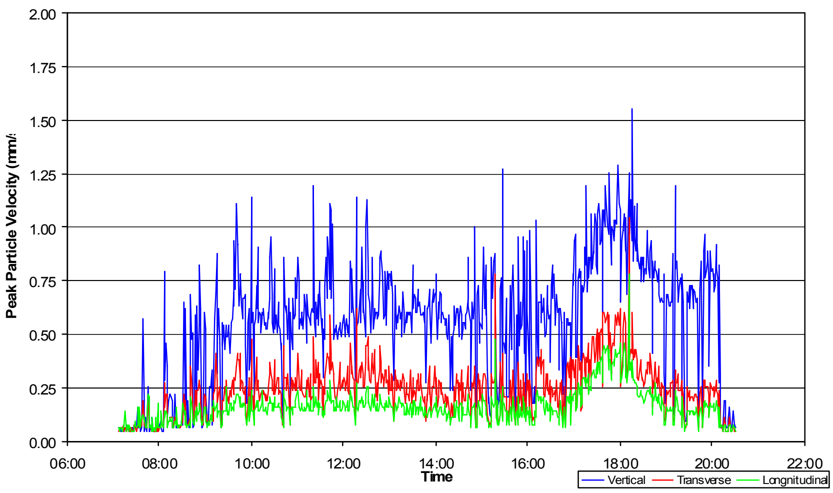
Having determined that there was sufficient need for further investigation a frequency analysis of individual events was carried out. Graph 4 shows a histogram of a typical vibration event. Graph 5 shows the Fast Fourier Transform analysis of the event.

As can be seen from Graph 5, the dominant frequency of the vibration event was in the 125 – 130 Hz range.

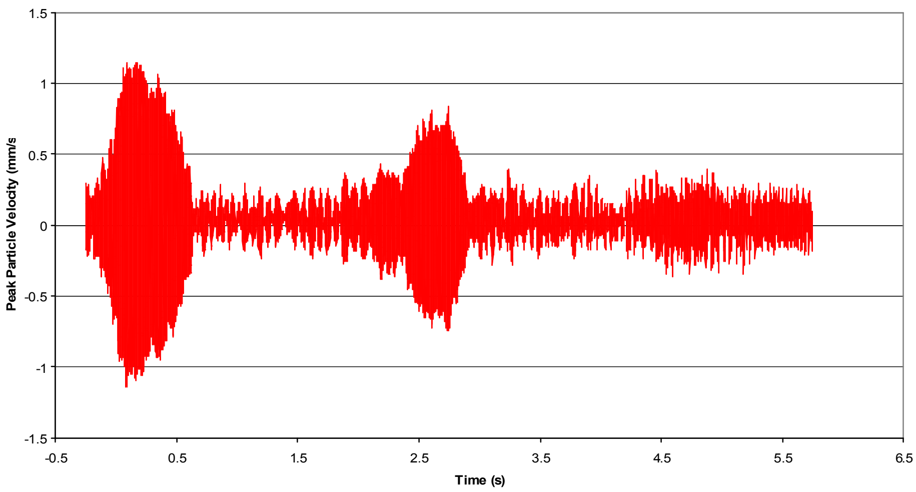
Comparison of a number of histograms of vibration events found that even though the dominant frequency were all in the 125 – 130 Hz range, the histograms were of a random nature, which would suggest that vibration caused by mechanical sources were not likely to be responsible.

In addition, when the it is remembered that the most PPV was experienced when the gusting wind conditions were high, it was deduced that the vibration experienced was due to the un-even wind loading, of the magnitude of approximately 70Kg, across the rotor of the turbine causing the support structure to resonate, which are transferred down the structure and ultimately into the building.

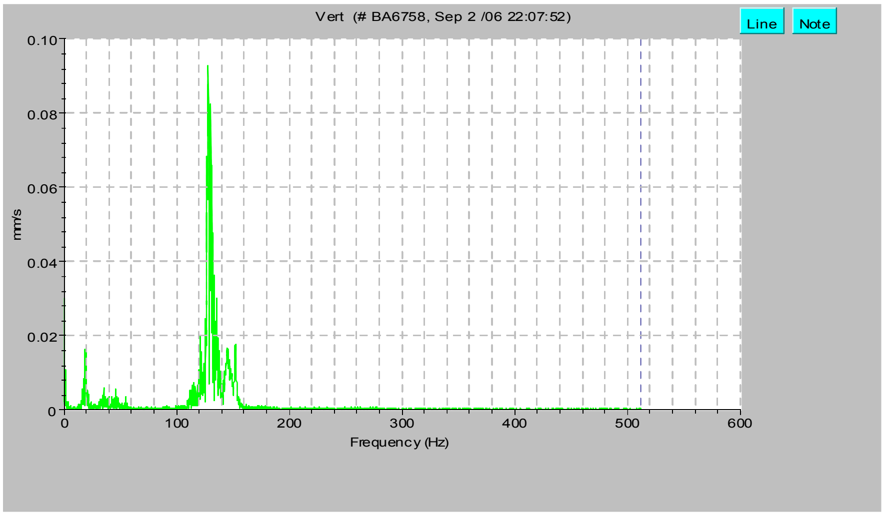
Graph 3: Peak Particle Velocity in Each Orthogonal Direction in Gusting Wind Conditions.



Graph 4: Histogram of Vibration Event in Vertical (z) Plane at 22:07:52 on 2nd September 2006



Graph 5: Fast Fourier Transform Analysis of Vibration Event in Vertical (z) Plane at 22:07:52 on 2nd September 2006



With regard to the airborne noise immission from the turbine, it was found during the analysis of the data that the background noise levels of the site were too high to allow the noise from the MWT to be detected at the site boundary of the nearest residential premises.

Conclusions

i) There is an absence of any standards that may allow the prediction of the effects of micro wind turbines, i.e. standards that allow the determination of the sound power level;

ii) The vibration experienced at the contact point between the support structure of the micro wind turbine and the building, despite the presence of manufacturer installed anti-vibration mounts, exceeded $1mms^{-1}$ (PPV in the vertical plane) under certain wind conditions;

iii) There is potential for the observed vibration to cause structure borne noise; and

iv) The airborne noise issues from the installed micro wind turbine was below background noise levels at the study site.

References

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2. Defra; (2004); Review of the UK Climate Change Programme Consultation Paper; TSO.

3. DTI; (2006a); Energy Review: Our Energy Challenge: Securing clean affordable energy for the long term: Consultation; TSO.

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5. EST; (2005); Potential for Microgeneration: Study and Analysis – Final Report; EST.

SECOND INTERNATIONAL MEETING

ON

Wind Turbine Noise
Lyon France September 20 – 21 2007

Assessment of Sound and Infrasound at the Pubnico Point Wind Farm, Nova Scotia

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1 INTRODUCTION

The Pubnico Point Wind Farm began operating seventeen Vestas 1.8 MW wind turbine generators in 2005. The closest residential neighbour to the wind farm had expressed concerns regarding the sound impacting his property, which is adjacent to the wind farm and about 330 metres north of the closest wind turbine generator. His concerns related to the audibility of the sound produced by the wind turbine generators, particularly when the wind is from the south, and suggested an increased impact during periods of fog. The resident was concerned about the potential for adverse health effects of infrasound due to the operation of the wind turbine generators. Howe Gastmeier Chapnik Limited (HGC Engineering) was retained by Natural Resources Canada to assess the environmental noise impact. This paper is based on the findings of that assessment, and the original report is available on line [1].

2 ASSESSMENT METHODOLOGY

The approach used in this assessment is to combine direct measurements of the impact of the wind turbine generators at the closest residence with analytical modelling. An automated sound level monitor was installed in the rear yard area of the closest residence, configured to continuously measure and record overall A-weighted sound levels. The automatically collected data recorded sound levels under a variety of weather conditions, including a period of calm, a period of light winds from the south, and a period of near gale-force winds. This provided a good representative sampling of atmospheric conditions, although the range was not exhaustive.

Attended measurements, including spectral sound level measurements in the form of both 1/3 octave band spectra and narrowband spectra were conducted. Measurements over the audible frequency range as well as at infrasonic frequencies were made. Measurements were conducted at the residence, and at a variety of other locations throughout the area near the wind farm, including a comparatively remote location to establish typical background sound levels, and within the wind farm itself to approximately determine the sound power level of a wind turbine generator under a specific wind speed.

3 ASSESSMENT CRITERIA

At the time of the assessment, there were no specific technical guidelines for assessing the acoustic impact of wind turbine generators in the province of Nova Scotia. Consequently Natural Resources Canada suggested that the noise guidelines of the Ontario Ministry of the Environment (MOE) form the basis of the assessment. The MOE guidelines describe a comprehensive approach to the measurement and assessment of industrial noise in general, and cover wind turbine generators specifically. MOE guideline NPC-232 *Sound Level Limits for Stationary Sources in Class 3 Areas (Rural),* provides guidelines for industrial noise impacting a sensitive land use in an acoustically rural location. An acoustically rural area such as Pubnico has sound levels generally dominated by natural sounds.

The MOE guidelines consider one-hour energy equivalent average sound levels (L_{EQ}), rather than instantaneous sound levels, in units of A-weighted decibels. Where background sound levels are low, exclusionary minimum criteria apply, with an exclusionary limit of 40 dBA specified for quiet nighttime periods, and 45 dBA specified for quiet daytime periods. It is important to note that the MOE guidelines do not require inaudibility. In fact, even if the sound levels from a source are less than the criteria, spectral and temporal characteristics of a sound often result in audibility.

Because wind turbines generate more sound as the wind speeds increase, and because increasing wind speeds tend to cause greater background sound levels, wind turbine generators have been identified by the MOE as a unique case. Supplementary guidance for the assessment of wind turbine generator noise is provided in publication *Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators* (hereafter, *Interpretation*). This publication, while based on NPC-232, provides the following criteria for the combined impact of all wind turbine generators in an area as a function of the wind speed at a reference height of 10 metres.

MOE Criteria for Wind Turbines.

Wind Speed (m/s)	4	5	6	7	8	9	10	11
Wind Turbine Noise Criteria, NPC-232 (dBA)	40	40	40	43	45	49	51	53

Interpretation specifies an analytical method of assessment; the manufacturers sound power data is used as input to a model which predicts the acoustic impact at a point of reception over a full range of wind speeds. The publication further specifies that the calculation methodology of ISO 9613-2, *Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation,* be used. ISO 9613-2 yields a receptor sound level under a single assumed propagation condition that does not reflect a realistic meteorological situation, but is generally favourable to the propagation of sound from a source to a receptor (essentially a moderate downwind condition in all directions). ISO 9613-2 does not describe a method for predicting sound levels under a specific meteorological condition, nor does it purport to define a sound level impact under a worst-case atmospheric condition.

Various papers and reports dealing with low frequency noise in general, and investigations of low frequency noise produced by wind turbine generators in particular have been published in recent years. Perception thresholds below which infrasound is generally not discerned have been suggested by various papers including Berglund and Hassmen [2] and Watanabe and Møller [3]. It is generally understood that imperceptible sound levels, including sound at infrasonic frequencies, do not cause health problems.

4 MEASUREMENT RESULTS AND DISCUSSION

Automatic Sound Level Measurements

The data gathered by the automatic sound level monitor is shown in Figure 1, together with related wind data and criteria. The figure contains five datasets. Sound level information is represented in Figure 1 in units of A-weighted decibels, with amplitude information provided on the left hand side vertical axis. Wind speed data is shown in units of m/s, with the amplitude shown on the right hand side vertical axis. Figure 1 has been divided into three time periods, as indicated at the top of the figure:

1st Period – During this interval, the winds were light, near the cut-in point of the wind turbine generators, and generally from the south, with high humidity and periods of fog. When calm, the sound levels dropped briefly below 30 dBA. Measured sound levels during the late evening periods increased to 53 dBA.

2nd Period – During this interval, the winds were somewhat higher for much of the period, and were for the most part from the west, north, or northwest. Lower humidity levels were also present through this period. Measured sound levels tracked the criterion of *Interpretation* quite closely. Several elevated sound levels correlate with activities on the residential property such as lawn mowing. Toward the end of Period 2, winds were briefly from the south, but the sound level did not increase as noted in Period 1, possibly since the humidity was low.

3rd Period – This interval initially saw winds largely from the west with low wind speeds, at which time measured sound levels were in excess of the criteria of *Interpretation* by a modest amount, and then saw winds rise to near gale force levels, with rain. The data during this period was highly influenced by the wind and rain and is of limited use.

The key points indicated by the data in the figure are discussed below.

1) Most of the time, sound levels at the residence are directly proportional to wind speed, suggesting that the approach of MOE publication *Interpretation* (i.e., that the assessment criteria should vary with wind speed) is appropriate.

2) At low wind speeds below the cut-in point of the wind turbine generators (5 m/s), background sound can fall significantly below 40 dBA.

3) During two distinct periods of low wind and high humidity, the measured sound levels exceed the criteria of *Interpretation* by a significant amount, peaking at an excess of 13 dB. The conditions occurring during these periods agree well with the observations of

the resident. There are a number of potential hypotheses related to wind shear and atmospheric variables which could account for these excesses, but further efforts would be required to identify the precise cause.

Subjective Audibility

At the closest residence, the sound of the wind turbine generators is principally discernable as a characteristic repetitive 'swoosh' sound. It is important to realize that while the amplitude of sound in the typically audible range is modulated at a low frequency rate, this does not indicate or imply that the sound has acoustic content in this low frequency range. Other than the 'swoosh', the sound of the turbines was not observed to be appreciably tonal or to have other identifying characteristics.

Even when the sound levels are at a relatively low magnitude, and in line with MOE criteria, the sound is audible at the closest residence. The measurements and observations indicate that the wind turbine generators are continually audible at the closest residence to varying degrees which depend on operational and atmospheric conditions.

Infrasound

To provide an idea of the magnitude of infrasound in the area, measurements of sound at infrasonic frequencies were conducted near to an operating wind turbine generator and adjacent to the closest residence. In both cases, the measured infrasonic sound levels were similar and approximately 20 dB below the pure tone threshold of perception.

Tones are easier for humans to identify than broadband sound, but no tones were observed. Because of the broadband nature of the measured infrasonic sound, a precise contribution of the measured spectra to the pure tone threshold curve can not be made. Additionally, the measured levels are conservative in that they may be overstated due to wind-induced turbulence at the microphone. However, ignoring these influences, it is clear that the infrasound measured in the area near the Pubnico Point Wind Farm is well below the threshold of perception.

5 ANALYTICAL RESULTS

The MOE standard *Interpretation* is an analytical, prediction-based standard rather than an assessment method based on receptor measurements. It is not completely appropriate to compare a measured impact at a specific moment in time to a criterion determined under the standard, as the standard indicates that calculations be made using the assumed meteorological conditions of ISO 9613-2 which are generally favourable to the propagation of sound from a source to a receptor, but does not consider specific environmental conditions or effects, and does not purport to define a sound level impact under a worst-case atmospheric condition. To provide a more appropriate assessment of the impact of the Pubnico Point Wind Farm, HGC Engineering modelled the resulting noise impact at the residential receptors as described below.

Interpretation specifies that the source sound data to be used should be provided by the equipment manufacturer, and should be obtained according to IEC 61400-11, *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*. However, due to confidentiality concerns, the manufacturer's data was not been used in the assessment.

Short-duration measurements were conducted on various sides of two wind turbine generators at a distance of 80 metres in order to estimate the sound power of the wind turbine generators under a wind speed of about 9 m/s. The data suggests that during these conditions, a sound power level of about 105 dBA re 10^{-12} W is produced by each operating wind turbine generator. While this sound power level is an estimate, in reference to typical power levels for modern wind turbines generators, such a level is what would be expected for a unit with an 80 metre rotor diameter [4].

This sound power level, with an associated measured octave band spectrum was used as input to a computer model using the Cadna/A acoustic modelling software system. Cadna/A uses the computational procedures of ISO 9613-2 to predict sound levels at receptor locations.

The results of the assessment, using the predictive mathematics of ISO 9613-2, suggest a sound level of 49 dBA would be expected at the closest residence based on a sound power level determined at a wind speed of about 9 m/s. Under *Implementation,* the guideline limit for a receptor in an acoustically rural environment at a wind speed of 9 m/s is 49 dBA, indicating compliance.

As noted above, ISO 9613-2 and accordingly *Interpretation,* does not necessarily consider propagation of sound under worst case environmental conditions. The effects of wind and atmospheric conditions was investigated using the methods of the CONCAWE [5] which allows for predictions under specific wind speeds or atmospheric conditions. The predictions indicate that the predicted 49 dBA level could be as high as 54 dBA at the closest residence when winds (including winds as light as 5 m/s) are from the south, or as low as 42 dBA with winds from the north. This is consistent with the monitored results, and demonstrates that even with an impact that is acceptable under *Interpretation*, there can be periods and conditions when the sound level impact is higher.

6 CONCLUSIONS

Much of the time, the measured sound level impact of the wind turbine generators is not significantly greater than the criteria of the Ontario Ministry of the Environment, specifically the criteria derived under *Interpretation*. However, under certain wind and atmospheric conditions when background sound would be expected to be low, the measured sound levels were found to exceed the criteria and expected background sound by up to 13 dB. In particular, sound levels were found to exceed criteria during periods when winds were light and from the south, with high humidity.

The sound of the operating wind turbine generators is continually audible at the most impacted points of reception, to varying degrees. No tones or other unusual attributes of the sound were noted or measured, other than the characteristic ‘swoosh’ of the moving blades.

Measurements made near the wind turbine generators, at the closest residence, and at a remote location indicate sound at infrasonic frequencies below typical thresholds of perception; infrasound is not an issue.

Acoustic modeling, undertaken to allow a more appropriate comparison of the acoustic impact of the wind turbine generators with the sound level criteria of *Interpretation,* indicate that the acoustic impact of the wind turbine generators complies with the criteria based on a sound power measured by HGC Engineering under a 9 m/s wind speed. Additional modelling indicates that there are environmental conditions when the sound level impact will be greater than the associated criterion level.

8 REFERENCES

1. http://www.noise-vibration-acoustics.com/2006/11/hgc_engineering.html

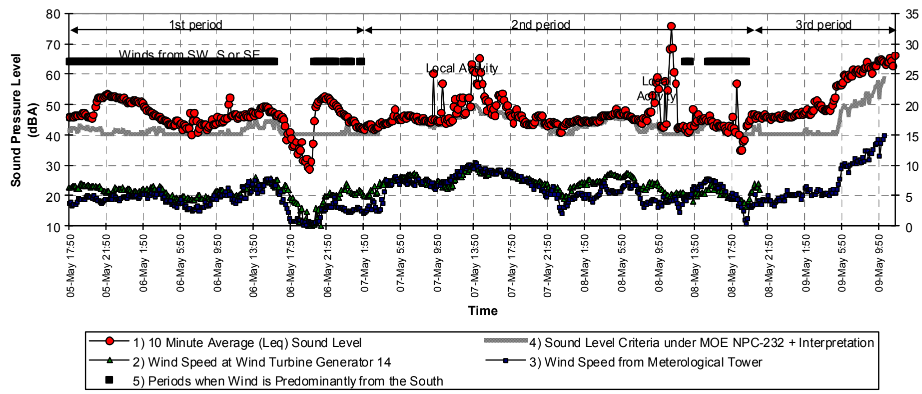
2. Berglund and Hassmén, "Sources and effects of low-frequency noise", Journal of the Acoustical Society of America, 1996.

3. Watanabe and Møller, "Low frequency hearing thresholds in pressure field and free field", Journal of Low Frequency Noise and Vibration, 1990b.

4. Hau, "Wind Turbines Fundamentals, Technologies, Application, Economics 2nd Edition", Springer-Verlag, 2006.

5. Haag, "The Propagation of Noise from Petrochemical Complexes to Neighbouring Communities", Conservation of Clean Air and Water – Europe (CONCAWE), 1981.

Figure 1. Sound Levels Measured in Rear Yard of Nearest Residence in Comparison to Wind Speeds at the Pubnico Point Wind Farm and MOE Criteria for Wind Turbines
Monitored May 5 to May 9, 2006 by HGC Engineering.



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Towards a Review of NZ Standard NZS6808:1998 Acoustics - Assessment & Measurement of Sound From Wind Turbine Generators

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Abstract

Since its publication in 1998, New Zealand Standard NZS6808:1998 has been widely adopted within Australia and New Zealand as a guideline for the measurement and assessment of wind farm noise.

This paper describes the aims of New Zealand Standard NZS6808:1998 and identifies a range of technical issues that have arisen supporting the possible improvement of this Standard via the formal Standards review process at some time in the near future.

An important input into the study was the views of New Zealand and Australian users of the Standard including industry groups and consent authorities as regulators of environmental noise. Salient technical matters have been identified requiring possible review or revision, while emerging issues have been identified that could be added into the scope of this Standard to provide the user with a more complete approach to wind farm noise assessment.

The information below represents an informed commentary and discussion on the adequacy of the current approach within NZS6808:1998, and puts forward broad recommendations for improvements in approach, if warranted. This paper provides a starting point for possible future discussions within the formal Standards New Zealand review process, to improve the methods used for the measurement and assessment of wind turbine noise in New Zealand and Australia.

Introduction

New Zealand's location within the roaring forty degree latitudes means the available wind energy resource is second to none. The wind energy industry in New Zealand has been rapidly expanding since the mid 1990's. Installed capacity of wind turbines has reached 171 MW in 2007, with another 158 MW under construction[2]. NZS 6808:1998 Acoustics – *The Assessment and Measurement of Sound From Wind*

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[1] Presenter.
[2] Reference: NZ Wind Energy Association. www.windenergy.org.nz. Site accessed July 2007.

Turbine Generators was developed during 1997 and published 1998 in response to an emerging need to assist planning authorities and regulators who were faced with handling applications to establish generation facilities which, at the time, was a relatively new type of activity in rural areas, and involved an unfamiliar noise source.

NZS6808:1998 was therefore developed to address a specific need. Approximately 10 years later in 2006 the New Zealand Wind Energy Association (NZWEA) and Energy Efficiency and Conservation Authority (EECA) jointly commissioned an investigation and a survey of stakeholder experience regarding the use and experience with NZS6808 (Hunt M, Halstead M, 2007). The study was undertaken by the authors, with this paper presenting the summary results of the study.

The review included a survey of 30 users and stakeholders. The Ministry of the Environment reviewed some aspects of the take-up of NZS6808:1998 within New Zealand planning procedures (MfE, 2006).The results suggest experience has been positive with NZS6808:1998 aiding both wind farm development and local authority planning procedures by providing a consistent and reliable method for the measurement and assessment of noise from these types of sources.

NZS6808:1998 achieves this by providing guidance on the limits of acceptability for sound received at residential and noise sensitive locations emitted from both single wind turbines and cumulatively from wind farms. The methods are mainly intended to be adopted when assessing potential noise effects of wind farms prior to their development at the planning application stage, however the scope also covers post installation sound level monitoring including the handling of potentially annoying types of WTG sounds.

NZS6808 recommends an assessment process based on background sound levels (L_{95}) measured at noise-sensitive receiving sites, under known wind conditions occurring on the wind farm site. Thus, the process requires extensive monitoring of L_{95} ambient sound levels under a range of typical wind conditions prior to establishing a wind farm. Wind speeds measured at the wind farm site are used to denote times when WTGs will be operating, with these wind conditions ensuring any variations of WTG sound output with wind speeds are taken into account when assessing WTG noise impact at receiving sites.

NZ6808:1998 recommends maximum wind noise limits at noise-sensitive receiving locations of 40 dBA or 5 dB above the background, whichever the greater.

Since NZS6808:1998 was published, the typical WTG being installed at wind farms in New Zealand has grown in terms of hub height and rotor diameter. Prior to 2007 the rated electrical output of the installed WTGs averaged 600kW. Of the 58 WTGs currently being installed in New Zealand in 2007, the rated electrical output averages 2 MW. The scale and significance of noise emissions as a result of increasing WTG size was considered relevant to the study as one of the aims of the study was to check the noise prediction methods and procedures recommended in 1998 remained appropriate for use with WTGs of greater dimensions now being installed in New Zealand.

This project involved a literature review and consideration of a wide range of wind turbine noise information sources that has developed both internationally and locally. Information from within New Zealand included court decisions and assessment reports following the use of NZS6808 within land use planning procedures for 13 of the 15 wind farms operating in New Zealand. This Standard has also been included within approximately five "District Plans" (local authority planning regulatory statements) in New Zealand (MfE, 2006). Reports were also reviewed pertaining to the use of NZS6808:1998 within some states of Australia (Huson, 2006).

Below, a range of technical acoustic issues are outlined which we identified within our study as warranting further investigation.

Technical Topic Areas For review

Technical topic areas identified in the study and discussed below are as follows:

1) Verify recommended approach to noise propagation modelling
2) Clarify and enhance noise measurement methodology
3) Add guidance on the assessment of potential low frequency + vibration
4) Address the recommended wind farm noise limits and their application
5) Update all references to related acoustic Standards
6) Update recommended methods for assessing special audible characteristics
7) Introduce a new section dealing with uncertainty
8) Introduce a new section on assessment of cumulative wind farm noise effects

Each issue is summarised as follows:

Noise Propagation Modelling

Noise propagation modelling is recommended within Section 4 of NZS6808:1998 to be carried out prior to the development of a wind farm in order to assess the potential noise impact. The predictions are recommended to be carried out using equation 1 as follows:

$$L_R = L_W - 10 \text{ Log } (2\pi R^2) - \Delta L_a \quad \text{.......... Equation 1}$$

Where:

L_R = The sound <u>pressure</u> level of noise received (in dBA) at distance R.

L_W = The sound <u>power</u> level of the noise source(s) (in dBA) as nominated within sound spectrum data provided by the WTG manufacturer (IEC 61400 - Part 11).

R = The distance between the source and the receiver in metres.

$\Delta L_a = \alpha_a R$

α_a = Attenuation of sound due to air absorption, in dBA/m for broadband sound which is typically 0.005 dBA (Ref. *ANSI S1.26 - 1995*).

The prediction method given in NZS6808 is a simple method of determining the sound pressure level at a given position relative to a wind farm. Its simplicity means that it can be implemented quickly, without specialist software, and it is a robust and transparent model. However it does not take into account ground absorption, barrier effects, or meteorological effects. Because these effects tend to reduce the propagated noise level, the model is considered to be conservative.

This method was checked by conducting trial predictions and comparing these predictions with field measurements of the sound emitted during the operation of existing 1.65 MW WTGs. Various noise model were also evaluated included the method set out within ISO9613 and Concawe[3].

The findings revealed in cases where the distances between turbines and receivers are significant undulating terrain, the ISO9613 model produces more accurate results. However, Equation 1 (above) modified to more closely reflect the ISO9613 model would more closely estimate the actual wind farm level, albeit at some loss of over-prediction which may have been considered a safety buffer within the prediction process

Given one of the main aims of NZS6808:1998 is to assist wind farm developers to design a wind farm which complies with noise limits, without requiring an excessively onerous safety margin due to prediction uncertainty, and the need to adopt a prediction method that is relatively easily understood by Councils, the approach to predicting WTG sound levels using equation 1 is supported, although some technical revision of the method appears warranted (amend to reflect relevant ISO methodologies).

Measurement of Ambient Conditions

NZS6808:1998 recommends measurement of ambient noise levels and wind speeds prior to the design and consenting of a wind farm provides two purposes:

1. To allow the effect of wind on “natural” sound levels to be quantified
2. To provide a baseline background level against which to compare the post-construction compliance measurements.

This topic covered data collection of both ambient sound levels and wind speed/direction. The specific issue of wind shear was investigated and the misalignment of wind speed information with actual wind conditions due to error in calculating wind speeds at various heights. The so-called “*van den Berg effect”* (van den Berg, 2005) was investigated, basically entailing a review of the methods by which measured wind speeds taken at one height are re-calculated to be applied at alternative heights, sometimes inadequately taking into account the wind shear occurring on site. Part of the issue has arisen historically due to the established reference wind speed measurement height of 10 metres (e.g. IEC61400 – Part 11). It was noted that so long as wind speeds collected at the wind farm site were taken at the hub height of the WTG proposed to be installed on-site, the miscalculation causing the van den Berg effect is entirely avoided.

Measurement data was also reviewed on applicability of some wind shear effects experienced in Europe and Australia compared to New Zealand sites. Research (eg.

[3] Concawe =Conservation of Clean Air & Water in Europe – a European oil industry sector group who have developed a noise prediction method commonly applied to industrial plants such as oil refineries.

Botha 2005) found New Zealand has many wind farms on exposed elevated ridge top sites with low wind shear or are located within coastal environments with highly stable wind regimes.

The recommendation for this topic was that if NZS6808:1998 was to be revised, the revision should avoid under-prediction of WTG sound levels by utilising wind speed data collected at the expected hub height of the proposed WTG.

Recommended Wind Farm Noise Limits

This section of the study reviewed the recommendations of NZS6808:1998 regarding guidance on the upper recommended noise levels received at noise-sensitive sites (such as dwellings).

It was noted that much of the research on which NZS6808:1998 was based is described in the ETSU-R-97 document "*The assessment and rating of noise from wind farms*". This document recommends noise from wind farms should be limited to 5 dBA above background noise for both day- and night-time. Unlike NZS6808 (which uses L_{95} to quantify the average background sound level) the ETSU document utilises the L_{90} descriptor, however these two units are very closely related.

As with NZS6808:1998, the ETSU document argues for the L_{90} descriptor as it allows reliable measurements to be made without corruption from relatively loud, transitory noise events from other sources in a windy environment. Thus the L_{95} or L_{90} unit are adopted for fully supportable technical reasons.

Regarding the numerical dBA guideline levels, ETSU recommends a fixed limit of 43 dBA for night time. This is based on a sleep disturbance criterion of 35 dBA within dwellings with open windows. In low noise environments the ETSU-97 report states daytime level of the L_{90} of the wind farm noise should be limited to an absolute level within the range of 35-40 dBA.

The rationale for the upper limit of 40 dBA recommended within NZS6808:1998 was examined in the light of available literature and experience with wind farm noise effects. The 40 dBA emerged as a reasonable option given the recommendations of the World Health Organisation (WHO 1999) and the dBA limits adopted within other countries to control WTG sound levels (Pederson & Halmstad, 2003). Whilst NZS6808:1998 allows for a more stringent limits to be applied (where warranted), the review found the currently recommend upper limit of 40 dBA was adequate to protect people from adverse noise effects, while offering a measure of consistency in approach with other NZ Standards.

The method of compliance testing was examined. The approach of NZS6808 is to compare noise levels of the background with the combined level of the background plus wind turbine immission. This relies upon measurements being made either prior to turbine construction or during "shut-down" periods. The WTG "on" and "off" appeared to offer potential for a compliance monitoring method that was simple and efficient to carry out. Measurements taken as part of the study revealed at least a 10 dB reduction in level between "turbine ON" and "turbine OFF" conditions can commonly be found near wind turbines, indicating that shutting turbines down effectively represents the pre-installation case.

Tests for Special Audible Characteristics

NZS6808:1998 refers to is referred to the application of a “penalty” when assessing sounds from WTGs that contain “special audible characteristics” to take into account the added annoyance likely to result from such sounds.

Although NZS6808:1998 allows for subjective evaluation to determine the presence of special audible characteristics, the Joint Nordic Method now in its second revision, described in the JNM II document (Pedersen, Soundergaard & Andersen, 1999) is identified as being a useful assessment method for detecting tonality. This method analyses the sound in narrow bands of sufficient frequency resolution that masking of tones can be considered within critical bands. Only by looking in detail at the tonal frequencies will it be possible to properly ascribe a numeric correct for properly assessing the subjective response to WTG sounds containing such tones. The JNM II method takes account of fluctuating tones which can sometimes be a factor.

Undertaking sample testing for tonality it was found both the Joint Nordic Method and the 1/3 Octave Band method for assessing tonality agreed with the subjective impression, however the study confirmed the appropriateness of the “Joint Nordic II” method was best for calculating an objective tonal penalty.

Analysis Of Ambient L_{95} & Wind Speed Data

The degree to which NZS6808:1998 controls noise impact is largely determined by the regression analysis of ambient sound levels (L_{95}) and wind speeds collected on the wind farm site.

Although NZS6808:1998 Clause 4.5.5 alerts the user it may be necessary analyse a number of separate regression curves (splits of data) depending on the number of “predominate” wind directions, and a separate analysis of the ambient sound level / wind speed relationship for daytime and night time conditions, one of the main findings of the study was the need for NZS6808 to give further guidance on the degree of data breakdown and degree of analysis required.

Although a review of the data collection method showed the r^2 correlation coefficient between L_{95} ambient sound levels and 10 minute wind speeds increases (and tends to stabilise) beyond around 2500 samples per major wind direction, no clear minimum sampling regime was able to be defined. This was due to the wide range of site conditions under which the NZS6808:1998 methodology is to be applied.

The review recommends an expansion of clause 4.5.5 including the reasons why detailed analysis of ambient L_{95} data / wind speed correlations are necessary, ie. to identify specific low ambient sound level conditions where the maximum wind farm recommended noise limits may be exceeded. The study also found it necessary for NZS6808:1998 to be adjusted to include guidance on minimum sampling within each predominant wind sector to ensure adequate sampling occurs.

Low frequency WTG Sound & Vibration

The study acknowledged the issues of low frequency WTG sound and vibration effects have been raised by concerned parties at planning hearings. The issue of vibration due to the operation of WTGs was investigated by review of available data and research. The Eskdalemuir study (Styles *et al*, 2005) provided compelling evidence that WTGs do generate vibrations in the ground at predictable frequencies (related to the speed at which the blades rotate and the normal modes of vibration of the towers), however this study was designed to measure effects of extremely low levels of vibration at one of the quietest sites in the world, utilising some of the most sensitive seismic equipment available.

The Eskdalemuir study produced results showing very low levels of vibration are emitted from operational WTGs, below thresholds of detection for humans and animals and well below levels which would cause any structural damage. Vibrations at this level (and in the frequency ranges found) were found to be caused by all kinds of sources such as traffic and background noise and are not confined to wind turbines.

The study found the issue of vibration could be better dealt with within any revised version of NZS6808:1998 by including concise statements confirming only low levels of WTG vibration that can be expected. It could be stated that compliance within acceptable vibration limits will always be assured for locations where compliance with specified limits on sound levels received at residential sites.

For low frequency sound and infra sound from WTG operation, the study again referenced available literature. Although some reports of measured low frequency sound from WTG operation are available these are commonly low frequency sounds of older, experimental machines[4] not representative of modern WTGs being installed in New Zealand. It is noted specialist reports (e.g. Jakobsen, 2004 and Leventhall 2001) have found

> "*From consideration of propagation and transmission of infrasound it is concluded that infrasound for upwind turbines can be neglected in the evaluation of environmental effects of wind turbines"* (Jakobsen 2004).

Overall, our study found research, measurements and investigations to date in New Zealand and internationally do not indicate low frequency WTG sound, infra sound or vibration effects are significant, however it is essential the Standard provide sufficient guidance in this area to ward of some perceptions about the significance of these issues. Thus, any revision of NZS6808:1998 should consider additional wording to allay fears of unusual or unexpected effects in this area.

Uncertainty

Uncertainty associated with measurement and prediction with wind farm sound levels is not currently covered by within NZS6808:1998. International acoustic standards are now dealing with this issue in some detail. The study divided uncertainty issues for NZS6808:1998 into two categories, measurement uncertainty

[4] eg. Hubbard and Shepard (1991).

and modelling uncertainty. Recommended guidance on this is to develop consistent reporting of uncertainty, preferably using meaningful estimates of standard error (or similar).

The study examined the range factors affecting field measurements of sound pressure levels. It concluded that uncertainty depends on many factors including the type of wind turbine sound, measurement periods, weather conditions, distance and propagation factors arising between the source and the measurement position..

For modelling (ie. prediction) uncertainty, the study found that this issue also involved complex factors. The recommendation to further examine the issue was made owing to the omission of consideration of this factor within the current wording of NZS6808:1998. The study has confirmed improvements in the Standard in this area would be not only be advisable, but almost a necessity. The study supported the use of reporting of implied measurement or modelling accuracy based on calculated standard error / standard deviation (e.g. ± 2 dBA 95% of the time), however such details are more properly the purview of any new NZS6808:1998 Standards committee, depending upon what level of accuracy is practical and achievable.

The study recommended that if a revision of NZS6808:1998 did occur, it should include new requirements for users of the Standard to include statements on both measurement uncertainty and uncertainty inherent within noise predictions.

Assessment of Cumulative Effects

The review found that the current wording of NZS6808 is not clear what is to be considered part of the "background noise" when assessing a wind farm proposal in a location which is already exposed to noise from a different wind farm. If sounds from an existing wind farm were to be considered part of the background sound environment, a case of "creeping noise level" could occur.

The study recommended any revised version of NZS6808:1998 consider making explicit statements on how the cumulative effects of wind farms should be dealt with. Without prejudging a possible future formal review of NZS6808:1998, the commonsense recommendation would require that existing WTG noise be subtracted from measured 'background' levels prior to calculating appropriate noise limits.

Specimen Noise Condition

The review found that users of the Standard would benefit from inclusion of sample wording of a generic noise conditions (i.e. specimen wording) as may be included within planning consents. While each wind farm application will differ in one or more respects between each other, users of NZS6808:1998 identified a need for generic wording of consent conditions dealing with WTG / wind farm noise to ensure consistency of approach.

Noise performance standards must be able to be enforceable in law and therefore need to comprise a number of basic elements which, in combination define the circumstances under which compliance with the noise performance standards can be verified. These elements are as follows:

1. The activity to be regulated and any exceptions,
2. Numerical noise limits,
3. Noise descriptor,
4. Location(s) at which noise limit is to be measured,
5. Times when noise limits apply,
6. Criteria for assessment of compliance with the limits.

Example conditions have been published for New Zealand wind farms (MfE 2006) while the ETSU document also provides some historical examples from the UK. Agreed wording for sample noise conditions would not appear to be too difficult to define by any incoming NZS6808:1998 Standards committee.

Conclusions

The review undertaken on behalf of NZWEA and EECA has delivered significant feedback on the current scope and application of NZS6808:1998 within wind farm applications in New Zealand and elsewhere.

The review has found that experience with NZS6808:1998 to date has generally been positive. It appears that while there is some discussion and concern regarding matters covered (or not covered) within the Standard, there do not appear to be fundamental flaws or major errors in the current wording of NZS6808:1998. To some extent it appears that experts and wind industry users have developed “best practice” beyond the minimum procedures set out in this 1998 Standard.

Any future formal Standards review of NZS6808:1998 is therefore more likely to be an update or enhancement as opposed to a complete re-write. Among the parties consulted in this review there appears to be some consensus to initiate a formal Standards review in the near future, possibly commencing in 2007.

On this basis, and until any future replacement Standard is published which includes the enhancements discussed above, it can be concluded that NZS6808:1998 offers a consistent, robust noise assessment methodology that should continue to be used with confidence to assist in the sustainable development of wind energy as an important source of renewable energy in New Zealand.

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Lyon France September 20 – 21 2007

Passive and Active Dynamic Vibration Absorbers for Gearbox Noise Reduction in Wind Turbines

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Abstract

In wind turbines the drive train, especially the gearbox, is a significant source of noise. Significant contributions come from the gear mesh and from resonances of the structure like the main frame or the torque arm. The structure-borne noise from these sources is transferred either to the rotor or to the tower and radiated to the environment. The contributions to the noise spectrum from these sources are single tones in the frequency range from about 100 Hz to about 600 Hz. Especially tones with high levels are annoying and must be reduced.
Several measures are possible to reduce these tones. One cost-effective and rapidly applicable method is to use passive vibration absorbers. The vibration absorbers for reduction of structure-borne noise developed by ESM are tuneable to nearly every frequency and mass required by the system. For special applications vibration dampers tuneable in all three co-ordinates are available.
Modern wind turbines are running with variable speed. Therefore, passive vibration absorbers which only work in a small frequency range come to their limit. For these challenging applications an active system based on piezo stack actuators shall be developed. This Active Vibration Absorber (AVA) works with two commercial piezo stack actuators in phase opposition.

Introduction – Single tone components in noise

Wind turbines have a rising share in energy supply and contribute to climate protection and saving of resources. With an ever increasing number of wind turbines also in densely populated areas the sound emissions are not be disregarded.

There are two main sound sources: the rotor blades and the drive train. Over the past years many researches dealt with the aerodynamic noise induced by the rotor blades [1]. The focus of this work lies on the sound generated by the drive train, especially by the gearbox inside.

A significant sound source is the tooth mesh of the gear wheels [2]. Most gearboxes consist of a planetary and a one or two-stage spur gear stage [2]. Typical tooth mesh frequencies are in the range of 100 Hz to 600 Hz (tones in the noise). The noise generated by the tooth mesh propagates through the roller bearings to the gearbox and through the impact noise insulation to the nacelle bedplate and the tower. Another transmission path is over the rotor shaft and the main bearing to the nacelle bedplate and from there to the tower. The large surface of the tower emits the noise to the environment. The rotor blades also emit gearbox noise in some cases. Sometimes the impact noise insulation is insufficient for these frequencies, since they mainly have to support the drive train and secure the position.

The resulting structure-borne noise is especially problematic, if it coincides with resonances of the whole system, i.e. the drive train and the nacelle.

The resonances amplify the tones from the tooth mesh. As a result large peaks at the tooth mesh frequencies, the so- called single tone components, are noticeable in the noise spectrum.

It is not possible to reliably avoid single tone components by a proper design and testing process, although wind turbines without tonality are state-of-the-art.

As single tone components cannot meet the required emission values, particularly in compliance with the regulations of pure tone penalty up to 6 dB [3], [4], the operation with reduced power is necessary. The profit of such wind turbines decreases.

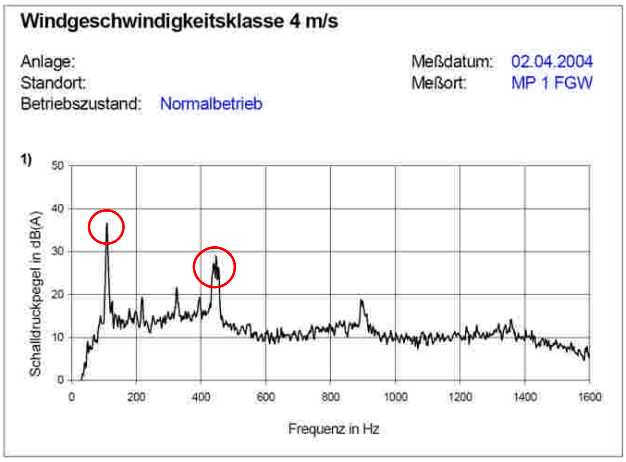


Figure 1: Single tone components in the sound pressure level

Figure 1 shows the noise pressure level of a wind turbine with two tones, one at 110 Hz and another at about 450 Hz. Pure tone penalties are required for this wind turbine: 6 dB for the 110 Hz frequency and 2 dB to 3 dB for the higher single tone component at 450 Hz.

Three different characteristics of single tone components are known:

1. The single tone component has a fixed frequency.
2. The single tone component varies with the rotational speed.
3. Different single tone components (with fixed frequencies or variable frequencies with rotational speed) exist.

Dynamic vibration absorbers introduced in this paper are an easy retrofit solution for the first case and the third case with fixed frequencies. Modern wind turbines are running with variable speed. In this case the passive vibration absorbers reach sometimes their limit due to a relative small frequency range which is limited by feasible damping. For these challenging applications an active vibration absorber based on piezo stack actuators shall be developed. A real time frequency tuning will be possible with an appropriate control algorithm.

Dynamic Vibration Absorber

Theory

A dynamic vibration absorber or a tuned mass damper is a vibrating counter mass which is able to reduce the vibration amplitude of a vibrating system clearly. A vibration absorber in the pure sense is an undamped spring-mass-system. This means no mechanical energy is transferred into heat. However, nearly for all technical applications a vibration absorber with high damping is used (see Figure 2 and Figure 3).

The spring is very often a metal-rubber-part with the stiffness c and the damping factor D which is in the range of D= 0.05 to 0.1. The mass m should be in the range of 5% to 10% of the mass of the main system. Due to limited available space and/or cost restrictions the mass of the absorber must sometimes be below 5%. Anyway, the parameters frequency, mass and damping factor must be tuned in an optimal way to achieve the maximum reduction of the vibration amplitude (Figure 3).

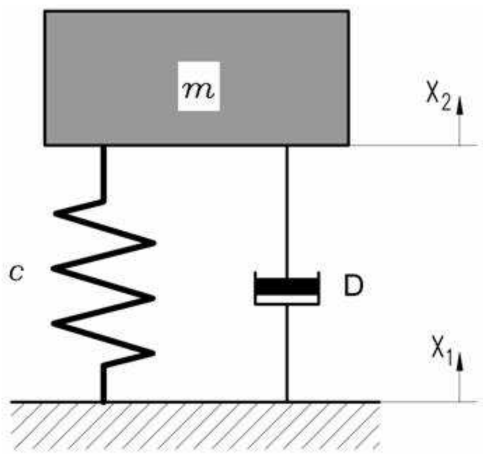


Figure 2: Tuned mass damper (schematic)

Dynamic vibration absorbers are used in a broad technical avenue like buildings, vehicles and other machines for reduction of low frequency vibrations and structure-borne noise. Vibration absorbers are not only available for transversal vibrations but also for torsional vibrations.

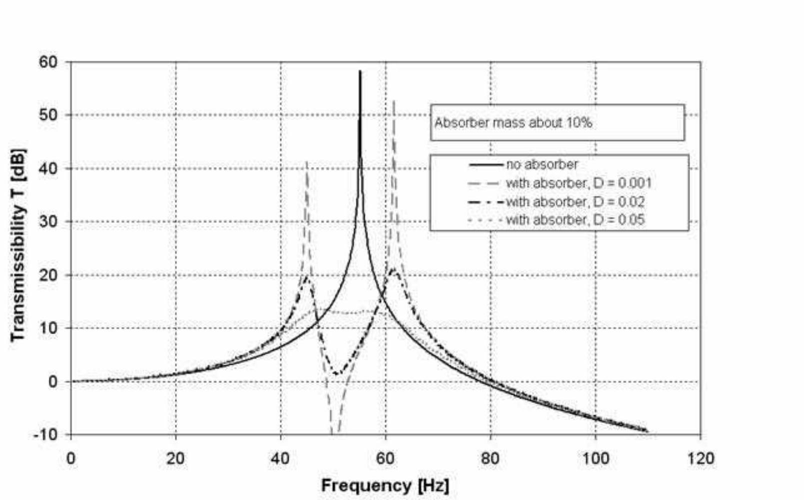


Figure 3: Transmissibility of a vibration system with dynamic absorber

Adjustable vibration absorbers

Tuned mass dampers are used in different designs for a lot of technical applications. In vehicles very often simple rubber-metal parts are used to reduce low frequency vibrations in the range around 10 Hz as well as for reducing tones in the interior noise spectrum. For these parts normally a metal part with about 0.5 kg up to about 15 kg is directly connected to a rubber part. The frequency of these components is fixed by the mass of the metal piece, the dimensions and the hardness of the compound of the rubber part.

For applications in wind turbines vibration absorbers have been developed which are easily adjustable. Therefore the stiffness of the vibration absorber may be changed by adjusting the pre-tension of the rubber part. For that just three bolts M16 must be tightened or loosened (Figure 4, only two of the adjusting bolts are shown). The mass may be changed in discrete steps of 15 kg from 30 kg up to about 500 kg. The absorber is mounted easily by just one central bolt. It can be used in the frequency range from approximately 50 Hz to approximately 600 Hz.

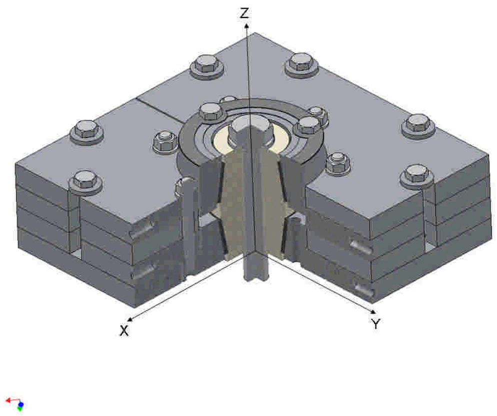


Figure 4: Adjustable vibration absorber, mass about 130 kg

Sometimes two or three vibration modes exist at the same position with different frequencies in different directions in space. In these cases it is extremely cost effective to use a tuned mass damper which can reduce vibrations in all three co-ordinates. Additionally, it is possible to save mass with such a component. Figure 5 shows a vibration absorber which is tuneable in three directions. The Z-direction may be tuned to any frequency. Concurrently the frequency in the X- and Y-direction can be tuned to the same frequency or any other different frequency. The data for frequency range and mass are the same as for the one-dimensional absorber.

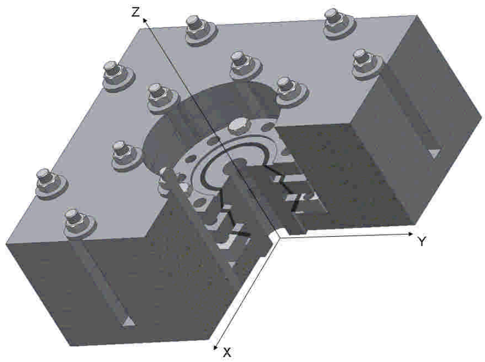


Figure 5: Three-dimensional vibration absorber

For rotating components an easy tuneable torsional vibration absorber is available. The frequency is in the range from about 50 Hz up to about 600 Hz continuously variable (Figure 6).

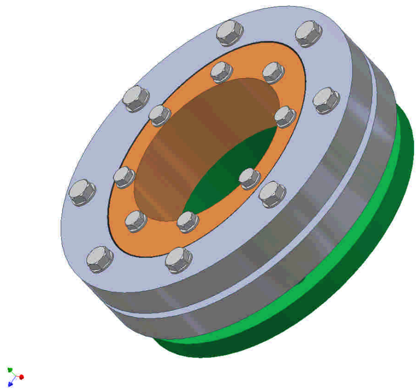


Figure 6: Torsional vibration absorber

Application and Results

As an example which clear impact tuned mass dampers can have on the emitted noise spectrum of a wind turbine the following application will be shown. A wind turbine in the 1.5 MW class had a tone with high level around 160 Hz in the emitted noise. Detailed vibration measurements in the whole turbine resulted in the knowledge that the main frame has a clear eigenmode at a frequency of 160 Hz. This resonance was excited by the gear mesh frequency of the intermediate state which was very close to 160 Hz. After the installation of two tuned mass dampers with a mass of approximately 150 kg on each side of the main frame the structure-borne noise at 160 Hz was reduced in the whole turbine (Figure 7). This reduction gave a clear improvement of the emitted noise spectrum and the acceptance measurement was passed without penalty.

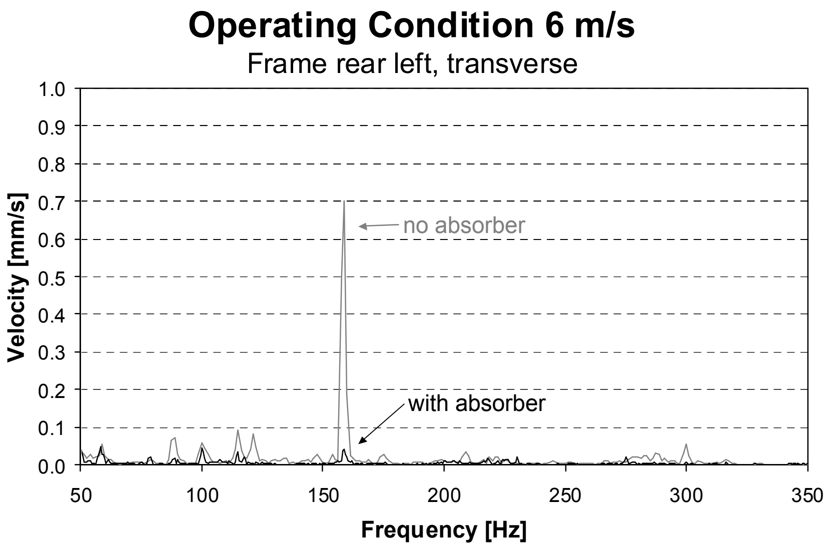


Figure 7: Structure-borne noise without and with dynamic vibration absorber

Piezo-based active vibration absorber

There is a need for an active solution, since passive dynamic vibration absorbers could not suppress single tone components successfully in all cases, in particular, if there are single tone components with a variable frequency as in wind turbines with variable speed.

An active vibration absorber is realized (Figure 8), if the counter mass is coupled with an actuator. With an appropriate control law additional damping, an increase of the effective absorber mass or a tuning of the natural frequency could be realized.

A specification for an active vibration absorber is derived from the measurements in the special case in the next section. Then the piezo-based active vibration absorber is introduced.

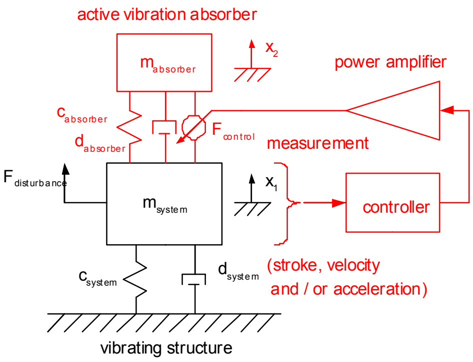


Figure 8: Active vibration absorber on a structure (schematic)

Measurements on a wind turbine

Noise and vibration measurements were performed on a wind turbine of the 2 MW class as reference to get a better specification for the active vibration absorber. The wind turbine emitted a single tone component around 130 Hz.

Acoustic noise measurements were taken in accordance to IEC 61400. These measurements are also part of the acceptance testing of wind turbines. The aim was the identification of operating conditions that lead to significant single tone components.

As the wind turbine works with variable speed, the frequency of the single tone component changes. The results are summarized in table 1. A pure tone penalty $K_T > 0$ dB is necessary for the given power range.

Operation Point	Electric Power [kW]	Tone- frequency [Hz]
Normal operation	300 ... 1200	120 ... 144

Table 1: Operating range of the wind turbine with significant acoustic emission of a single tone component [5]

The transmission path of the single tone components was determined by vibration measurements under operating conditions and also with an artificial excitation (Figure. 9).

The drive train is supported at three points in the examined wind turbine. The transmission of the single tone component over the rotor shaft and the main bearing was negligible. The main transmission path follows the gear supports, even though the gear supports are equipped with rubber bushings.

The required forces for compensation are calculated from mobility measurements at several points and the maximum velocities at these points under operation. Depending on the position forces up to 2 kN in the frequency of the single tone component are required [6].

Possible mounting points were determined by the measurement with artificial excitation. An electrodynamic shaker was mounted on the gear and driven by pink noise in frequency range of the single tone component. Then points with maximum velocity on the nacelle bedplate were located. These points are vibration antinodes and therefore good positions for a vibration absorber [7].

A mounting position on the gear supports is preferable. That minimizes the effort for measurements but needs the largest compensation forces.

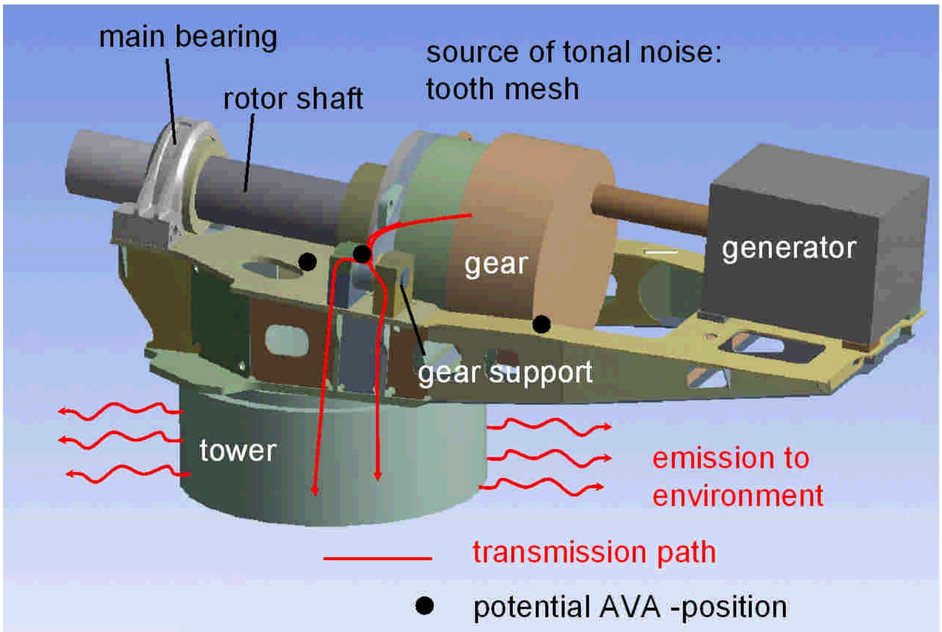


Figure 9: Transmission path of tonal noise at the reference wind turbine

Specification for an active system

One basic requirement for an active system to reduce the single tone components is the easy retrofit of affected wind turbines. Therefore, approaches to modify the construction of the plant were not taken into consideration [8]. The compensation of single tone components must be done close to their sources, i.e. near the gear. That guarantees usage of a small number of active systems. Two systems are especially suited to the symmetry of wind turbines. Approaches to improve the vibro-acoustic behavior of the radiating structure, i.e. the tower, require a high number of actuators [9]. In addition to that the metrological expense for the positioning and the installation of the actuators is respectable.

The active vibration absorber was developed to be compatible with a diverse set of plant constructions and their special manifestations of single tone components.

The active vibration absorber must meet the following requirements:

- Simple, cost-effective construction
- Modular assembly of the active vibration absorber mass for the basic frequency adjustment
- Frequency range from 100 Hz to 600 Hz
- Low measurement efforts for positioning and commissioning
- High damping.

High damping of the vibration absorber is necessary, since vibration absorbers lead to new resonance peaks below and above the resonant frequency. Other single tone components in the noise spectrum could be amplified if there is not enough damping realized with the system.

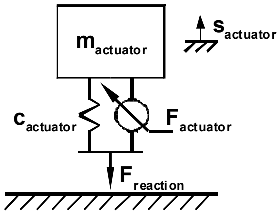
Operating points for actuators with additional mass

Active systems with additional mass basically operate in two different operating ranges. Without considering the dynamics of the actuator they behave like high passes with a distinct resonance between stop band and pass band (Figure 10). Adaptive and active absorbers work in resonance. If the system is tuned lower than the frequencies to be reduced, it works as an inertial mass actuator. In an inertial mass actuator the maximum force, passed into the structure, is directly defined by the maximum force of the actuator. If the system works in resonance, i.e. as an absorber, a comparatively small actuator is necessary.

The introduced system needs to function in both operating ranges in order to meet all requirements regarding frequency range and driving force.

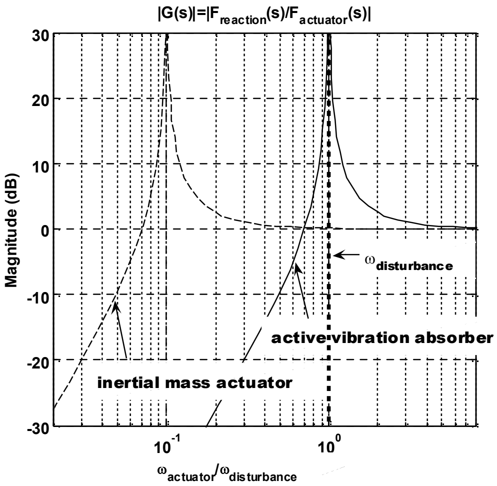
If the wind turbine possesses more then one single tone component the operation as inertial mass actuator is a better solution, since it works in wide band operation over its natural frequency.

The operation as active vibration absorber is an appropriate choice for one single tone component. Smaller actuators could be chosen.



a)

Figure 10: Operating points of an actuator with additional mass:
a) modeling,
b) normalized amplitude response



b)

Piezo stack actuators

Piezo stack actuators are electromechanical solid-state transducers, which use the inverse piezoelectric effect of polycrystalline ceramic materials like lead zirkonate titanate (PZT). These piezoceramics are capable of converting electric charges in mechanical quantities like forces and strokes. The actuators work with high voltages up to 1000 V and have a capacitive electrical behavior. They achieve strokes up to 0.1 percent of the actuators length. Maximum forces up to 100 kN can be realized. The achievable force mainly depends on the cross section of the actuator normal to the stroke direction that is driven by a certain voltage. A stack actuator is mostly characterized by a stroke-force-diagram (Figure 11). The maximum mechanical work of an actuator could be realized, if it counteracts against a stiffness (black dashed line in Figure 11) that is equal to its own stiffness. Piezo stack actuators are driven by special amplifiers for capacitive loads.

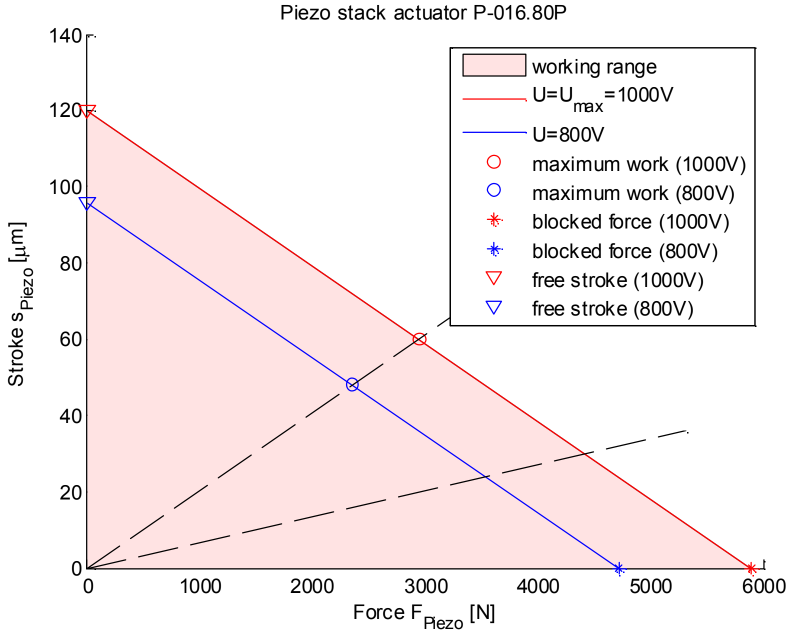


Figure 11: Stroke-force-diagram of a P-016.80P piezo stack actuator (based on [10])

Implementation

The active vibration absorber (Figure. 12) works with two anti-parallel controlled piezo stack actuators, in a so-called differential setup.

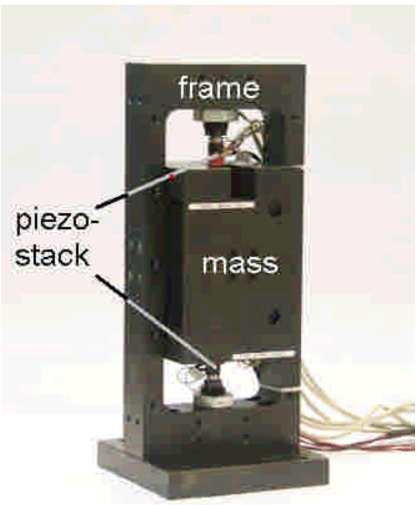


Figure 12: Implementation of the active vibration absorber

In a differential setup two actuators are located, attached and controlled in a way that their strokes have opposite directions (Figure. 13). The actuators are attached either to a single part located between both actuators or to two parts, which are placed at the opposite ends of the actuators. The reverse control voltage around half the operating voltage causes the movement of an adjacent component, here of the vibration mass. The differential setup is equivalent to a parallel arrangement of two actuators. Whereas, in contrast to the single actuator setup, the force could be generated in both motion directions with the same magnitude, the total stroke does not change [11].

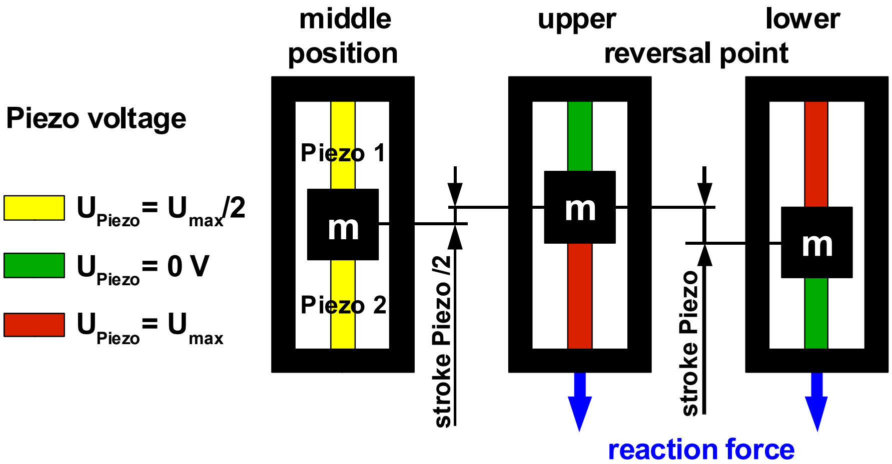


Figure 13: Differential setup of piezo stack actuators (principle)

The advantage of this concept is the better utilization of the working ranges of the actuators. At the same time the actuators are mechanically preloaded in a way that no pulling forces can affect the actuators.

In midway position both actuators are supplied with half the nominal voltage. This electrically generated additional mechanical preload is efficient in the displacement of the absorber mass, too. The mechanical preload of the actuator is nearly constant in the working range. In this way pulling forces on the actuators are avoided in dynamic operation.

The piezo stack actuators provide the stiffness of the vibration absorber. For the reference wind turbine a lower natural frequency is needed. The decrease of frequency is achieved by adding serial springs to the actuators.

Two commercial high voltage piezo stack actuators are used (Table 2, Figure 11).

The mass of the active vibration absorber is modular (Figure. 12). A mass of 19 kg or 29 kg could be realized with the actual setup. This corresponds to a natural frequency of 361 Hz and 293 Hz respectively. Other masses are possible.

The frame supports the piezo stack actuators and over leaf springs the absorber mass. The leaf springs guide the absorber mass and realize a high stiffness normal to the working direction.

It realizes the tension loop to provide the axial preload for the stack actuators in the differential setup.

Parameter	Value	Unit
Type	P-016.80P	PI Ceramic GmbH
Length	111	mm
Diameter	16	mm
Blocked force	5900	N
Free stroke	120	µm
Stiffness	49	N/µm
Capacitance	1	µF (approx.)
Operating voltage	1000	V

Table 2: Parameter of the piezo stack actuators ([10])

The frame is realized as stiff as possible. The finite stiffness leads to an asymmetry, which could be evaluated by so called design factors [11]. If the asymmetry is not negligible, the lower piezo actuator will be integrated with an additional serial spring.

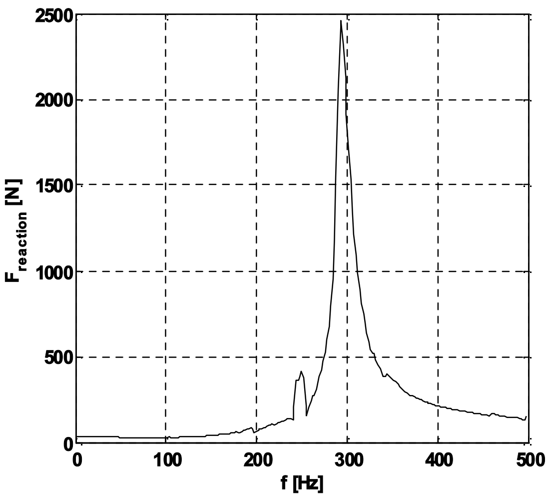


Figure 14: Measured reaction force for an chirp input voltage Û=40 V

Figure 14 shows the reaction force generated by a chirp driving voltage with an amplitude of 80 V, i.e. with 20 % of the nominal maximum voltage range.

Further work

A redesigned active vibration absorber with a stress-optimized design of the serial stiffness will be tested next time. The aim is a reduced natural frequency to meet the lower frequency bound of single tone components.

Different control algorithms will be evaluated on a test bench with the MATLAB xPC target. The direct velocity feedback [12] and delay compensation [13] are shortlisted. A microcontroller based hardware will be developed for the realization of the control algorithm.

A test of the active vibration absorber is planned for the reference wind turbine with noise and vibration measurements to prove the concept under real conditions.

Conclusions

In this paper, adjustable dynamic vibration absorbers are introduced that suppress gearbox induced tonal components radiated by wind turbines. An example shows the effective application of these easy retrofit absorbers.

In addition the development of an active vibration absorber is described. It is especially designed for applications, where passive systems reach their limits due to frequency variable single tones.

Acoustic noise and vibration measurements were done on a 2 MW wind turbine. A specification is suggested for an active system that can reduce single tones components.

A first realization of an active vibration absorber is realized on the basis of this specification. It works with two piezo stack actuators in a differential setup. The modular assembly allows an adjustment to the different forms of single tone components and to a wide frequency range.

Acknowledgements

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An Approach to RANS Based Prediction of Airfoil Trailing Edge Far-Field Noise

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Abstract

This paper describes a prediction scheme for the airfoil Turbulent Boundary Layer Trailing-Edge Interaction (TBL-TE) far-field noise to be applied for the combined aerodynamic and aeroacoustic airfoil design process. The model presented here follows the spectral solution of the Poisson equation for the surface pressure fluctuations underneath a turbulent boundary layer and evaluation of the noise emission from the trailing edge due to this fluctuating pressure by solving the diffraction problem. The final form of the model is expressed as an integral of the turbulence sources over the boundary layer height and another integral in the wave number direction. In previous investigations [15, 16, 18, 19], an efficient prediction method was developed and successfully applied to acoustic airfoil design. With that method the acoustic sources are calculated by means of the EDDYBL boundary layer code in combination to the XFOIL airfoil analysis method [6]. Presently, a RANS flow solver together with an appropriate turbulence model is coupled with the noise prediction scheme for the determination of source input parameters, and to improve the accuracy and consistency. The main advantage of the present RANS based approach is that a linearized viscous-inviscid coupling is avoided. Both approaches enable direct derivation of the required turbulence properties by means of different two equations and full Reynolds stress models. As a result the anisotropic behaviour of the turbulence noise source parameters can be analysed elaborately. Moreover, detailed investigations and a comparison study are carried out with the calculated noise spectra and source parameters (i.e. turbulent boundary layer parameters, vertical fluctuation velocity and integral length scale), and the experimental results obtained in the institute's Laminar Wind Tunnel (LWT). Encouraging results are obtained. The prediction scheme will be applied further in the design process of low noise airfoils.

1 INTRODUCTION

The problem of noise generation by low Mach number turbulent flows past the trailing edge of a rigid lifting surface (airfoil) is of interest to aerospace, automobile (wind-noise) and underwater acoustic communities. For this problem the trailing edge of the airfoil plays an important role in the propagation of noise to the far-field, and thus the problem is commonly referred to as the trailing-edge noise problem. This particular noise basically stems from an interaction of the turbulent eddies within the boundary layer and the associated pressure fluctuations with the trailing-edge of the lifting surface.

The turbulent boundary layer-trailing edge (TBL-TE) noise has been one of the main research areas of aeroacoustics for many years. Howe [12] gives an extensive review of various trailing edge noise theories and lists them in different categories. Most of the theories used in predicting trailing edge noise are based on Lighthills Acoustic Analogy, solution of an inhomogeneous wave equation for fluctuating pressure developed by Ffowcs Williams and Hall. Brooks et al. [2, 3] presented an extensive experimental airfoil self-noise data set and develop a semi-empirical airfoil self-noise prediction method, known as Brooks, Pope and Marcolini (BPM) method [3]. This semi-empirical self-noise prediction method (BPM) relates the noise emission to integral boundary-layer properties at the trailing edge.

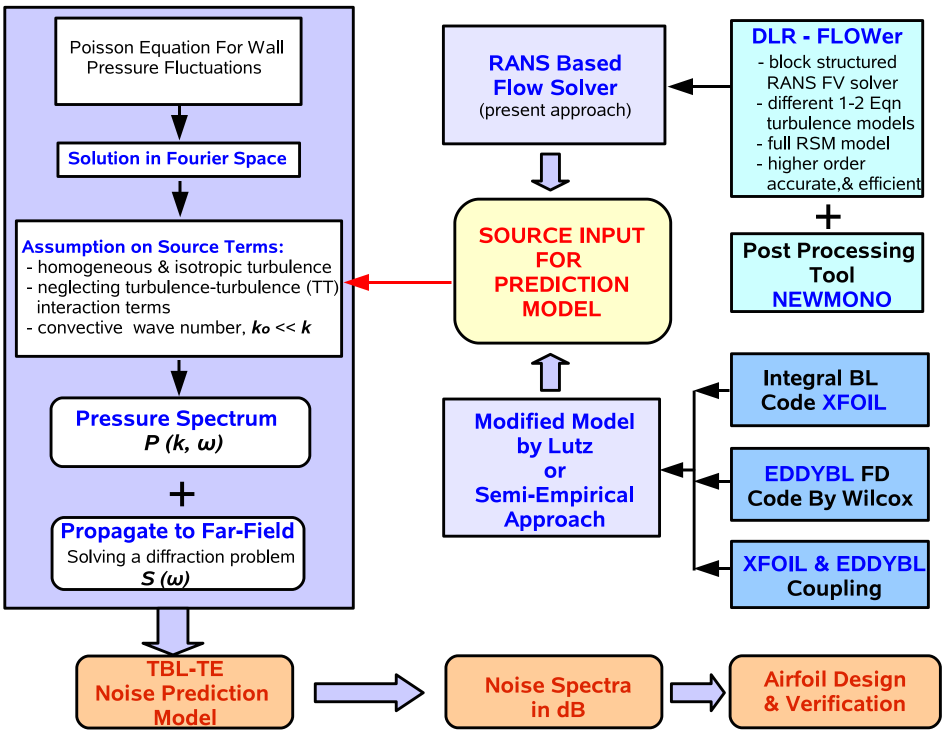

Figure 1: Flow Chart of the Noise Prediction Scheme

However, many of these TBL-TE noise prediction methods that used today are based on semi-empirical relations. A major deficiency of these models is they do not take the effect of the airfoil shape and the flow regime into account. Therefore, these models are not suitable in a design process of low noise airfoils.

In recent years, Computational Aeroacoustics (CAA) methods has been used to simulate acoustic scattering from trailing edges. These methods couple time-accurate flow field data obtained from RANS or Large Eddy Simulation solutions with acoustic equations to propagate the noise to the far-field. Singer et al. [25] performed computational simulations of turbulence crossing an airfoil trailing edge, where the radiated noise has been computed using a time-accurate RANS solver coupled to Lighthills Acoustic Analogy in the form presented by Ffowcs Williams and Hawkings. Other CAA studies on the simulation of trailing edge noise includes the work by Ewert [7, 23] and Wang [21]. The Computational Aeroacoustics methods can give accurate results, however they are very costly due to the computational expense associated with the very fine time and space resolution requirements.

The noise prediction method considered in the present study follows the spectral solution of the Poisson equation for the surface pressure fluctuations underneath a turbulent boundary layer following Blake [1], and the evaluation of the noise emission from the trailing edge due to this fluctuating pressure by solving the diffraction problem [4]. The final form of the prediction model is expressed as an integral of the turbulence sources over the boundary layer thickness and another integral in the wave number direction. The most important feature of the model is that it relates the structure of the turbulent boundary layer to the far-field sound. In principle this structure is determined by the distribution of mean velocity, turbulent kinetic energy, and integral length scale. These quantities may be determined either from a semi-empirical post-processing of data from an integral BL procedure, from more elaborate finite-difference boundary layer calculations, from a detailed RANS/LES simulation, or from measurements. In the course of an airfoil design process or a numerical optimisation RANS analyses are usually too time-consuming and the application of faster aerodynamic prediction methods as basis for the noise prediction is aspired. Thus, in previous investigations [15, 16, 18], an efficient method (to be denoted BL-TBLTE method later on) in combination with the XFOIL airfoil analysis code [6] and the Finite Difference code EDDYBL are implemented to derive the turbulent acoustics sources, and the prediction scheme is successfully applied in the frame work of the several EU project e.g. SIROCCO to design new, less-noisy airfoils for the outer blade region of three different wind turbines in the MW class. The main advantage of the BL-TBLTE noise prediction method is that it solves a complete Reynolds stress turbulence model, namely the Wilcox stress-ω, that accounts for anisotropy effects and provides the complete Reynolds stress tensor. Moreover, history effects are captured more accurately compared to isotropic turbulence models [15].

However, within the BL-TBLTE noise prediction method, anisotropy is considered for the fluctuation velocities only, but not for the approximation of turbulence integral length scales, which is approximated by a semi-empirical scaling law based on the experimental results. But previous investigation suggest that the determination of the turbulence integral length scale is the most crucial aspect in the processing of the turbulence noise source data and that its accurate determination has a decisive impact on the consistency of the noise prediction [15, 16, 18]. Therefore, the final objective of the present investigations is to avoid the semi-empirical scaling but to consider the anisotropy of the length scales on a sound theoretical basis.

The global objective of the present investigations is therefore to improve the accuracy in the determination of the turbulence properties considering anisotropy effects without loosing the efficiency of the prediction scheme. The current study includes an approach which uses steady, two-dimensional RANS simulations with a two-equation/full Reynolds stress turbulence model to calculate the noise source parameters used in the noise prediction model developed. In this paper the general procedure and the results obtained under the assumption of isotropic turbulence are presented. Future developments deal with the consideration of anisotropic effects in order to enhance the accuracy and consistency once more.

2 MEAN FLOW PREDICTION

A general outline of the noise prediction scheme is given in Figure (1). Time-mean flow fields and turbulent flow characteristics are obtained by solving the Reynolds Averaged Navier-Stokes (RANS) equations with a $k-\omega$ turbulence model by flow solver FLOWer [14], and used to predict the spectrum of wall pressure fluctuations at the trailing edge and its far-field noise spectra.

2.1 Governing Equations

For the mathematical description of turbulent flows the RANS equations in integral and conservation form are considered in FLOWer. But for the present description, the differential form of the incompressible equation of the fluid flow is considered, i.e.

$$\frac{\partial\left(\rho U_i\right)}{\partial x_i}=0, \tag{1}$$

$$\frac{\partial\left(\rho U_i\right)}{\partial t}+\rho U_j\frac{\partial U_i}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\sigma_{ij}-\rho\overline{u_i'u_j'}\right). \tag{2}$$

The vectors U_i and u_i' are mean and fluctuating velocity components at a position x_i, t is time, P is the mean pressure, ρ the density and $\sigma_{ij}=2\mu S_{ij}$ is the mean viscous stress tensor with molecular viscosity μ and mean strain-rate tensor S_{ij}. The quantity $\rho\overline{u_i'u_j'}$ is known as the Reynolds-stress tensor and we denote it by $\rho\tau_{ij}$, so that τ_{ij} is the specific Reynolds stress tensor given by $\tau_{ij}=-\overline{u_i'u_j'}$. The Reynolds stress is further formulated using a two-equation isotropic turbulence model, which in terms of $k-\omega$ in differential form reads,

Eddy Viscosity:

$$\mu_T=\rho k/\omega \tag{3}$$

Turbulent Kinetic Energy, k:

$$\rho\frac{\partial k}{\partial t}+\rho U_j\frac{\partial k}{\partial x_j}=\rho\tau_{ij}\frac{\partial U_i}{\partial x_j}-\beta^*\rho k\omega+\frac{\partial}{\partial x_j}\left[(\mu+\sigma^*\mu_T)\frac{\partial k}{\partial x_j}\right] \tag{4}$$

Specific Dissipation Rate, ω:

$$\rho\frac{\partial\omega}{\partial t}+\rho U_j\frac{\partial\omega}{\partial x_j}=\alpha\frac{\omega}{k}\rho\tau_{ij}\frac{\partial U_i}{\partial x_j}-\beta\rho\omega^2+\frac{\partial}{\partial x_j}\left[(\mu+\sigma\mu_T)\frac{\partial\omega}{\partial x_j}\right] \tag{5}$$

With Closure Coefficients

$$\alpha=\frac{5}{9},\ \beta=\frac{3}{40},\ \beta^*=C_\mu=\frac{9}{100},\ \sigma=\frac{1}{2},\ \sigma^*=\frac{1}{2}, \tag{6}$$

and Auxiliary Relations

$$\varepsilon=\beta^*\omega k \qquad \text{and} \qquad l=k^{1/2}/\omega \tag{7}$$

In general within two-equation turbulence model, the production term is modelled by using the Boussinesq assumption, where the constitutive relation must be appropriately extended [26] as

$$\tau_{ij}=2\nu_T\left(S_{ij}-\frac{1}{3}\frac{\partial U_k}{\partial x_k}\right)-\frac{2}{3}k\delta_{ij} \tag{8}$$

Diffusion due to velocity fluctuations is modelled by a gradient hypothesis, and finally viscous diffusion will be available from the exact equation of k. The diffusion due to pressure is usually negligible. The dissipation ε is derived from its own modelled transport equation assuming Taylor argument $\varepsilon\sim k^{3/2}/l$. Within the exact modelled $k-\omega$ model there exist five universal constants, most of these constants are evaluated based on the experimental results especially in log-region. The Boussinesq hypothesis expressed by equation (8) assumes that the turbulent diffusion is isotropic, so that primary shear stresses will be predicted well, but not secondary shear and normal stresses. As a result the Boussinesq hypothesis may not be suitable for many complex flows involving strong three-dimensional effects. Using the standard Boussinesq eddy viscosity hypothesis it is impossible to properly describe all turbulent flows with body force effects arising from a system rotation or streamline curvature and flow, which structures generated by the Reynolds stress anisotropy.

The $k-\omega$ model is significantly more accurate for two-dimensional boundary layer with both adverse and favourable pressure gradient. Therefore, for the present work computations are performed by the $k-\omega$ Shear-Stress Transport (SST) model of Menter and Wilcox.

2.2 CFD Flow Solver FLOWer

The FLOWer [14] flow solver solves the compressible, two or three dimensional Reynolds (Favre) averaged Navier-Stokes equations in integral form. A cell-centered based finite volume formulation on one block-structured grids (C-type mesh) was utilised for computations presented here. The convective fluxes of the main equations were discretized in space applying a second order central scheme with a blend of second and fourth order artificial damping terms, whereas diffusive fluxes were discretized purely central. The turbulence equations were discretized by a flux difference first order upwind scheme. Time integration to steady state for the main equations was accomplished by an explicit five stage Runge-Kutta scheme with local time stepping, where convergence was accelerated by a multigrid method on four grid levels with implicit residual smoothing. The source term dominated turbulence equations were integrated in time using a diagonal dominant alternating direction implicit (DDADI) scheme on the finest grid level at very high CFL numbers.

3 FORMULATION OF THE NOISE PREDICTION MODEL

The wall pressure fluctuations underneath a turbulent boundary layer can be described by a stochastic model based on the Poisson pressure equation. Kraichnan [13], followed by Panton and Linebarger [22], Blake [1], and Smolyakov, developed a spectral solution to the Poisson equation in the wave-number domain for pressure sources produced by the interaction of the turbulence with the mean shear. The model presented here follows the spectral approach, and is represented in terms of the wave-number frequency spectrum of the wall pressure fluctuations. From this general result, the point frequency spectrum and its far-field noise spectra can be derived. The final form of the model is expressed as an integral of the turbulent sources over the boundary layer height. The spectrum of the turbulent sources are modelled using the von Kármán velocity spectrum.

3.1 Poisson Equation for Fluctuating Pressure

The pressure fluctuations in an incompressible flow are governed by a Poisson equation which can be derived from the Navier-Stokes equations and Reynolds decomposition. By taking the divergence of the momentum equation, using the continuity equation to drop terms, performing a Reynolds decomposition into mean and unsteady terms, and then subtracting the time averaged equation, yields [15]

$$\nabla^2 p' = -\rho \left[\underbrace{2\frac{\partial U_i}{\partial x_j}\frac{\partial u_j'}{\partial x_i}}_{MT} + \underbrace{\frac{\partial^2}{\partial x_i \partial x_j}\left(u_i'u_j' - \overline{u_i'u_j'}\right)}_{TT} \right]. \tag{9}$$

The source terms on the right-hand side of Eq.(9) represent the mean shear-turbulence (MT) interaction (first term, which is linear or rapid) and the turbulence-turbulence (TT) interaction (second term, nonlinear or slow). Different authors [5] showed that the contribution of the TT interaction is an order of magnitude smaller than contribution of the MT interaction for wave numbers close to the convective wave number. Also, only the stream wise (x_1) component of the mean velocity is significant, and this dominated in the x_2 direction, so the mean-shear-turbulence term becomes

$$2\frac{\partial U_i}{\partial x_j}\frac{\partial u_j'}{\partial x_i} = 2\frac{dU_1}{dx_2}\frac{\partial u_2'}{\partial x_1}. \tag{10}$$

The form used in the present study for the Poisson equation for fluctuating pressure in a turbulent shear flow reads

$$\nabla^2 p' = -2\rho \frac{dU_1}{dx_2} \frac{\partial u_2'}{\partial x_1}. \tag{11}$$

For simplicity, the fluctuation terms are represented by u, p rather than prime on the following section.

3.2 Spectral Solution of the Wall Pressure Fluctuations (WPFs)

The solution to the Poisson Eq. (11) in wave number-frequency space according to Kraichnan [13] reads as follows,

$$\hat{p}_w(k_1, k_3, \omega) = 2\rho i k_1 \int_0^\infty \frac{e^{-kx_2}}{k} \frac{dU_1(x_2)}{dx_2} \cdot \hat{u}_2(x_2, \mathbf{k}, \omega) dx_2. \tag{12}$$

The wave number frequency spectrum that are homogenous in the $1, 3$ plane is quadratically related to the modulus of the $\hat{p}_w(\mathbf{k}, \omega)$ [1]

$$\mathbf{P}(k_1, k_3, \omega) \equiv \frac{\langle \hat{p}_w(k_1, k_3, \omega) \hat{p}_w(k_1', k_3', \omega') \rangle}{\delta(k_1 - k_1')(k_3 - k_3')\delta(\omega - \omega')}. \tag{13}$$

The δ functions indicate that the function need only be evaluated at $\mathbf{k} = \mathbf{k}'$ and $\omega = \omega'$. The wave number-frequency spectrum for the wall pressure in terms of Eq. (12) together with the MT source spectrum $\Phi_{22}(x_2, x_2', \mathbf{k}, \omega)$ and other approximations according to Blake [1] is given by

$$\begin{aligned}\mathbf{P}(k_1, k_3, \omega) = 4\rho^2 \left(\frac{k_1^2}{k_1^2 + k_3^2} \right) \int_0^\infty \Lambda_2(x_2) \left[\frac{dU_1(x_2)}{dx_2} \right]^2 \cdot \tilde{\phi}_{22}(x_2, k_1, k_3) \cdot \\ \phi_m (\omega - k_1 U_c) \cdot \left\langle u_2^2(x_2) \right\rangle \cdot e^{-2|\mathbf{k}|x_2} dx_2,\end{aligned} \tag{14}$$

where $\tilde{\phi}_{22}(x_2, k_1, k_3)$ is normalised wave number spectra of u_2, i.e.

$$\tilde{\phi}_{22}(x_2, k_1, k_3) = \frac{\Phi_{22}(x_2, k_1, k_3)}{\langle u_2^2(x_2) \rangle}, \tag{15}$$

Λ_2 represent a vertical integral length scale for the eddy field. And $\phi_m(\omega - k_1 U_c)$ is a moving axis spectrum. Note that RANS calculations yield $\langle u_2^2(x_2) \rangle$ and $\frac{dU_1(x_2)}{dx_2}$, but all the other terms are modelled.

The final form of the far-field pressure density spectra $S(\omega)$ can be expressed as. [15] ,

$$S(\omega) = \frac{L}{4\pi R^2} \int_{-\infty}^{\infty} \frac{\omega}{c_0 k_1} \mathbf{P}(k_1, \omega) dk_1, \tag{16}$$

where R is the distance to the observer from the trailing edge and L is the wetted length of trailing edge.

The determination of the total sound pressure level according to the present scheme involves three nested numerical integrations: The integration in wave number direction k_1, the integration in wall normal direction across the boundary layer and finally the integration vs. angular frequency ω. An evaluation of the integrals shows that especially the integration in k_1 direction requires special care since the integrand behaves quite different for different wall normal distances and considered frequencies. Furthermore, sharp peaks can show up. Therefore, a special adaptive numerical integration scheme was developed [19].

4 DETERMINATION OF THE NOISE SOURCE PARAMETERS

Returning to the Poisson Eq. (11), the source term for a turbulent shear flow is T^{MT}. Since the turbulent velocity u_2 is a stochastic variable, it can be characterised by a 3D wave number-frequency spectrum for each layer above the wall. Now it is important to model this spectrum $\Phi_{22}(\mathbf{k})$ and also the Reynolds stress tensor or the vertical velocity fluctuations $\langle u_2^2 \rangle$.

4.1 Turbulence Energy Spectra & Velocity Correlation

The first step towards the definition of the energy spectrum in turbulence literature is the velocity correlation tensor for two points separated by the space vector $\mathbf{r}$

$$B_{ij}(\mathbf{r},t) = \langle u_i(\mathbf{x},t) u_j(\mathbf{x}+\mathbf{r},t) \rangle \, . \tag{17}$$

The velocity cross-spectrum tensor and the two-point correlation functions form a Fourier transform pair, thus

$$\Phi_{ij}(\mathbf{k},t) = \frac{1}{(2\pi)^3} \iiint\limits_{-\infty}^{\infty} e^{-i\mathbf{k}\cdot\mathbf{r}} \cdot B_{ij}(\mathbf{r},t) d\mathbf{r}, \tag{18}$$

The integral of the turbulence energy spectrum $E(k,t)$ over all wave numbers yields the turbulence kinetic energy (per unit mass) [11],

$$\frac{1}{2} B_{ii}(0,t) = \frac{1}{2} \sum_{i=1}^{3} \langle u_i^2 \rangle = \frac{1}{2} \iiint\limits_{-\infty}^{\infty} \Phi_{ii}(\mathbf{k},t) d\mathbf{k} = \int\limits_{k=0}^{\infty} E(k) dk. \tag{19}$$

Empirical 3D Energy Spectral Model

One of the most important results of classical turbulence theory; is that the functional form of the energy spectrum $E(k)$ is reasonably independent of the class of flow (i.e., boundary layer, wake, jet, channel, etc.). There exist two well known empirical model for the 3D energy spectra, such are the Kolmogorov Spectrum and the von Kármán Spectrum. Kolmogorov spectrum is holds on the inertial subrange In functional form $E(k)$ becomes

$$E(k) = c \cdot \varepsilon^a \cdot k^b, \tag{20}$$

Using dimensional analysis it is found that the exponents must be $a = \frac{2}{3}$ and $b = -\frac{5}{3}$. Furthermore, experiments have shown that the Kolmogorov constant c ranges between 1.4 and 1.8, and slightly depends on the Reynolds number.

A model for $E(k)$ based on $k^{-\frac{5}{3}}$ high wave-number asymptote and a k^4 dependence for low wave numbers was proposed by von Kármán. The von Kármán 3D kinetic energy density spectrum $E(k)$ for isotropic turbulence reads,

$$E(k) = \frac{110\Gamma(\frac{5}{6})}{27\sqrt{\pi}\Gamma(\frac{1}{3})}\left(\frac{k_T}{k_e}\right) \cdot \frac{\left(\frac{k}{k_e}\right)^4}{\left[1 + (\frac{k}{k_e})^2\right]^{\frac{17}{6}}}. \tag{21}$$

Here $k = |\mathbf{k}|$, k_e represents the wave-number of the energy containing eddies which defines the maximum of the $E(k)$-spectrum, k_T is the turbulence kinetic energy and Γ is the Gamma function. For isotropic turbulence, all components of the velocity spectrum tensor Φ_{ij} can be obtained from the 3D energy spectrum $E(k)$ [11],

$$\Phi_{ij}(\mathbf{k}) = \frac{E(k)}{4\pi k^2}\left(\delta_{ij} - \frac{k_i k_j}{k^2}\right). \tag{22}$$

Again, assuming isotropic turbulence the energy density spectrum for the vertical velocity fluctuations in the $k_1 - k_3$ plane parallel to the surface reads as follows,

$$\Phi_{22}(k_1,\ k_3) = \frac{4}{9\ \pi} \cdot \frac{1}{k_e} \cdot \frac{(k_1/k_e)^2 + (k_3/k_e)^2}{\left[1 + (k_1/k_e)^2 + (k_3/k_e)^2\right]^{7/3}} \cdot \left\langle u_2^2 \right\rangle. \tag{23}$$

4.2 Vertical Integral Length Scale Λ_2

There exists much confusion in the literature about which scales are really appropriate to the description of the energy spectrum. Nonetheless, all agree in the need of a large scale for turbulence. The large scale we consider will be called physical integral length scale and is represented by Λ. It is defined from the integral of the correlation function. The length scale Λ_2 is related to the vertical extent of the turbulent eddies. More precisely, it is defined as the integral of the normalised spatial two-point correlation coefficient R_{22} of the vertical velocity fluctuations

$$\Lambda_2 = \int_0^\infty R_{22}(r_2)dr_2 = \int_0^\infty \frac{\langle u_2(x_2,t) \cdot u_2(x_2+r_2,t)\rangle}{\sqrt{\langle u_2^2(x_2,t)\rangle} \cdot \sqrt{\langle u_2^2(x_2+r_2,t)\rangle}}dr_2 \tag{24}$$

The length scale Λ_2, however, is not provided by any established turbulence model or boundary-layer procedure. To derive Λ_2 from known quantities, usually, a calculated turbulence length scale l or the mixing length l_{mix} is multiplied by an empirical scaling factor.

As Λ_2 measurements are hardly published a comparison of predicted and measured noise spectra may be used to derive the scaling factor. Such an approach is developed by Lutz [15], where the scaling factor is derived depending on the BL development of the respective flow. There exist different approaches to derive an expression for Λ_2 either based on k_e or l, but the order of magnitude of l and Λ should be same [11].

Hinze [11] proposed a relationship between k_e and the longitudinal integral length scale Λ_f for isotropic turbulence which can be written as

$$\Lambda_f \approx \frac{0.75}{k_e} \tag{25}$$

Λ_2 as Function of the Isotropic Turbulence Length Scale l

If a RANS computation is performed with a two-equation $k-\varepsilon$ turbulence model, then Λ_2 can be derived (from ref. [11]) by the scaling defined as

$$k_e = \frac{1.37}{l} \tag{26}$$

with the turbulence length scale given as

$$l = \frac{k_T^{3/2}}{\varepsilon} \tag{27}$$

Then comparison to Eqn. (25) yields,

$$\Lambda_2 = 0.75 \cdot \frac{l}{1.37} \approx 0.547 \cdot l \tag{28}$$

The same relation is also valid for a $k-\omega$ type two-equation turbulence model with length scale $l = \frac{\sqrt{k_T}}{C_\mu \omega}$. It is very important to note that this derivation implies that turbulence is isotropic and Λ_2 is nothing but the longitudinal integral length scale Λ_f derived by assuming $u^2 = \langle u_1^2 \rangle$.

5 COMPUTATIONAL RESULTS AND TEST CASES

In a next step the accuracy of the present noise prediction scheme was verified. For this purpose a set of different airfoils considered in the SIROCCO project and within previous investigations were examined in the LWT applying the new Coherent Particle Velocimetry (CPV) [9] method.

5.1 Laminar Wind Tunnel (LWT) at the IAG

The Laminar Wind Tunnel [27] of the Institute of Aerodynamics and Gas Dynamics (IAG) is of Eiffel type and has a closed test section of $0.73 \times 2.73 m^2$ and a maximum velocity of $90 m/s$. The unique features of the LWT are its very low turbulence level of Tu=0.02% (f=20-5000 Hz, 30 m/s) and that acoustic measurements can be performed exactly for the same test cases as the aerodynamics measurement. Its very low turbulence level makes it ideal for laminar boundary layer measurements and investigations of wind turbine or sailplane airfoils. The aerodynamic and aeroacoustics verification measurements in the present test cases were carried out in the LWT.

5.2 Outline of the Selected Experimental Test Cases

An airfoil for a wind tunnel model with variable shape was designed by Würz at IAG [17] in order to perform dedicated boundary-layer and aeroacoustic measurements. The shape variant (VTE_kav) chosen for the present comparisons shows a very strong, concave main pressure recovery on the suction side but almost no adverse pressure gradient on the lower side. Due to the steep pressure rise along the upper surface the airfoil features a rather thick BL and represents a hard test case for any prediction method. The aerodynamic measurements were executed with fixed transition by using turbulators on the pressure and suction side at 5% of the chord length. Moreover, aeroacoustic measurements were performed with an acoustic array and by the hot-wire based CPV [9] method.

The RANS computations are performed for a Reynolds Number $Re = 1.55 \cdot 10^6$, $Ma = 0.178$, and free-stream velocity of $U_\infty \simeq 60m/s$. As a first attempt all the RANS computations in present study are conducted by using isotropic two equation turbulence model, namely Menter (SST) and Wilcox ($k - \omega$), and corresponding turbulence properties such as vertical fluctuation velocity are computed from the relation $\langle u_2^2 \rangle = \frac{2}{3} k_T$. The vertical integral length scale is computed according to the relation of Section (4.2), which is also based on isotropic assumption. The chord length of the airfoil (VTE_kav) is chosen to $c = 0.8m$, and the observer distance $R = 1.0m$. The details about the CFD simulations are mentioned in Section (2.2) and a sample grid used in the computations can be seen in Figure (2) [Left]. Figure (2) [Right] shows a sample flow field as computed by FLOWer.

5.3 Discussion

Comparisons of the RANS data to the results of the XFOIL-EDDYBL turbulent boundary-layer procedure [15] as well as measurements are depicted in Figs. (3, 4). It is obvious [left most Fig. (3)] that the RANS results provide excellent results for the pressure distribution similar as the XFOIL-EDDYBL results [10]. The same is true for the skin friction distributions [second figure at Fig. (3)]. The distributions of the boundary-layer displacement and momentum thickness (third and fourth figure) also match well with the experimental results. The XFOIL-EDDYBL/BL-TBLTE results give almost identical distributions for the skin friction but show a slightly smaller level skin friction compared to the $k-\omega$ but a higher level than the SST RANS results. Similar but inverse behaviour is observed for the boundary layer displacement and momentum thickness. But it is confirmed that RANS reliable with SST turbulence model provided most efficient results compared to the others.

The calculated distributions of relevant Boundary Layer Parameters (BLPs) vs. wall normal distance were compared to experimental results obtained by means of a single hot-wire measurement. Several different arc length positions were considered, namely at $\frac{x}{c} = 0.55, 0.75, 0.95, 0.99, 0.995$. Figure (4) show exemplarily the distributions for the stream-wise mean velocity U_1, the turbulence kinetic energy k_T (normalized by free-stream velocity square) and the vertical turbulent fluctuations $\langle u_2^2 \rangle$ for the VTE_kav airfoil at $x/c = 0.995$. It should be mentioned that the experimental results for k_T were determined from measured values of $\langle u_2^2 \rangle$ applying the relation $k_T = 9/8 \langle u_2^2 \rangle$ as described in report [9]. It is clearly visible from the figures that the RANS simulations with $k - \omega$ case provide better results than the XFOIL-EDDYBL results for the parameters U_1, k_T and $\langle u_2^2 \rangle$, whereas SST case overpredict the experimental data. The deviation as appears in the Λ_2 distribution for the RANS cases compared to the measurement and XFOIL-EDDYBL prediction is significant, especially for SST case at the outer layer. The good approximation of XFOIL-EDDYBL prediction for this parameter is due to the scaling law as implemented in Reference [15]. It is clearly visible in Fig. (4), that at the near wall region (corresponding to inner layer) both cases ($k - \omega$ and SST) provide almost similar results but in the outer layer Λ_2 distribution for Wilcox $k - \omega$ case grows faster than SST. This result is physically relevant to the criteria of the SST model, because in his SST model, Menter retained the near wall advantages of the Wilcox $k - \omega$ model while eliminating its free-stream sensitivity at the boundary layer edge.

In a next step the accuracy of the noise spectra is verified. The predicted and measured noise spectra are compared in Fig. (5). It should be mentioned that the shift in the absolute noise level between the experiments and the predictions stems from different distance scaling laws that were used to map the noise spectrum to an effective standard observer position. It can be seen that the RANS based method using the SST/$k - \omega$ gives rather good results between the spectra as well as for the shapes of the spectra. The small deficiency after the position y where maximum of k_T appears [in Figure (4)], the RANS results does not have any strong effect on the peak of noise spectra. It is due to the fact that, the dominating noise source of TBL-TE noise is the near wall turbulence (inner layer) [20]. In this region RANS results with isotropic assumption matched reasonably well (underpredict approximately 1-4dB within frequency range 500Hz to 1kHz) with the measured data. This deviation may be attributed to the anisotropic behaviour of the turbulence length scales. It should be noted that the second peak at high frequency ($\sim$ 5-7kHz) is caused by Blunt-Trailing Edge (BTE) noise [8]. In the present prediction scheme BTE is not considered. The left most figures of Figs. (5) shows individual contribution of the total noise spectra from pressure and suction side. Clearly, the suction side contribution is higher than the pressure side contribution, which yields a peak in the spectrum in the low frequency domain.

Henceforth, in order to have an idea about the low noise airfoil design and optimisation process, a comparison study of the total noise spectra between a reference airfoil and two newly designed airfoils [15, 16, 24] are depicted in Fig. (6). It is important to mention that the results computed by XFOIL-EDDYBL are based on a Λ_2 scaling law as described in Reference [15]. It is evident that, RANS methods with isotropic fluctuation velocity and integral length scale provide reasonably good results than other approach. Therefore, independently it can be concluded that a RANS based method may provide more accurate and consistent results when anisotropy effect of turbulence can be modelled appropriately.

6 ACKNOWLEDGEMENTS

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Nomenclature

C_f	Skin friction coefficient
c_0	Speed of sound
$E(k)$	Kinetic energy density spectrum
k_1, k_2, k_3	Wave number in x_1, x_2 and x_3 coordinate direction
k_e	Wavenumber of the energy containing eddies
k_T	Turbulent kinetic energy
l	Isotropic Turbulence length scale
L	Wetted length of the trailing edge
p	Fluctuation pressure
$\hat{p}$	Fourier transform of p
R_{ij}, B_{ij}	Velocity spatial correlation tensor
R	Distance to the observer from source point
U_i, u_i	Mean and fluctuation velocity components
U_∞, U_c	Reference and convective velocity
x_i, x, y, z	Cartesian coordinates
ρ	Density
$\mathbf{k}$	Wavenumber vector
ω	Angular frequency
Φ_{ij}	Spectrum of velocity fluctuation
Φ_m	Moving axis spectrum
Λ_2	Vertical integral length scale
ε	Turbulent dissipation rate
δ	Boundary layer thickness
δ_1	Boundary layer displacement thickness
δ_2	Boundary layer momentum thickness

Figures

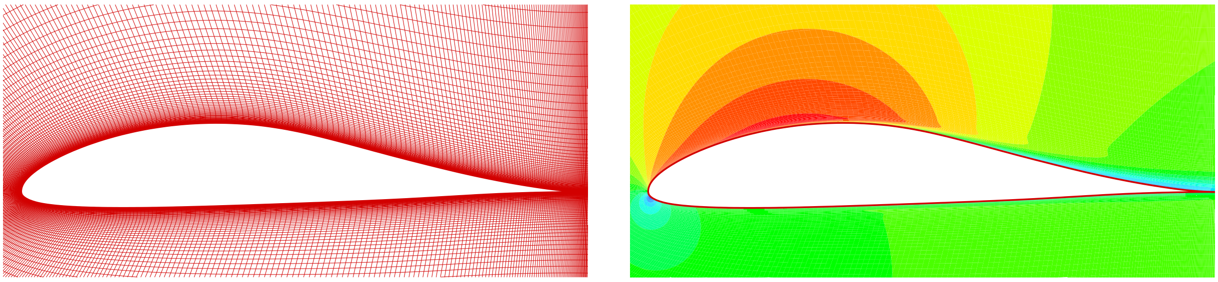

Figure 2: Computational Mesh (48×128) & Flow field $Re = 1.55 \times 10^6, c_l = 0.7$: VTE_kav

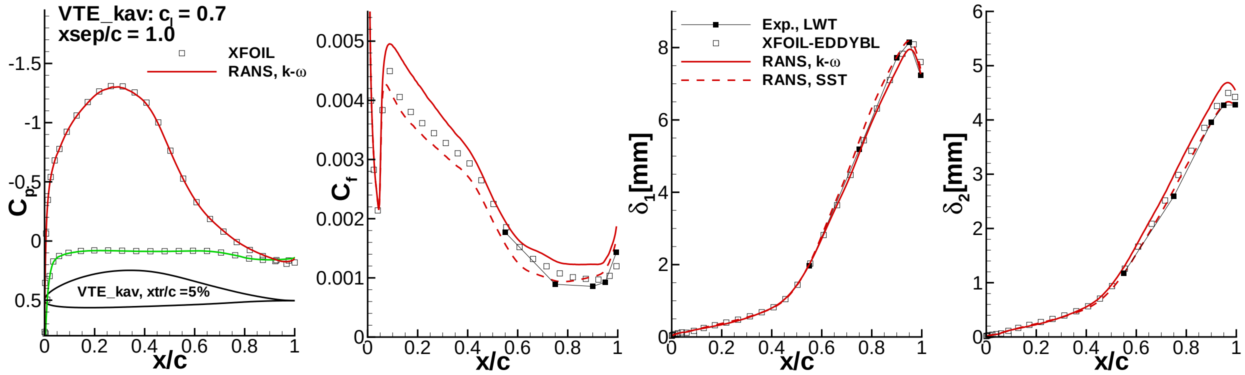

Figure 3: Measured and Predicted BLP $Re = 1.55 \times 10^6, c_l = 0.7$: VTE_kav

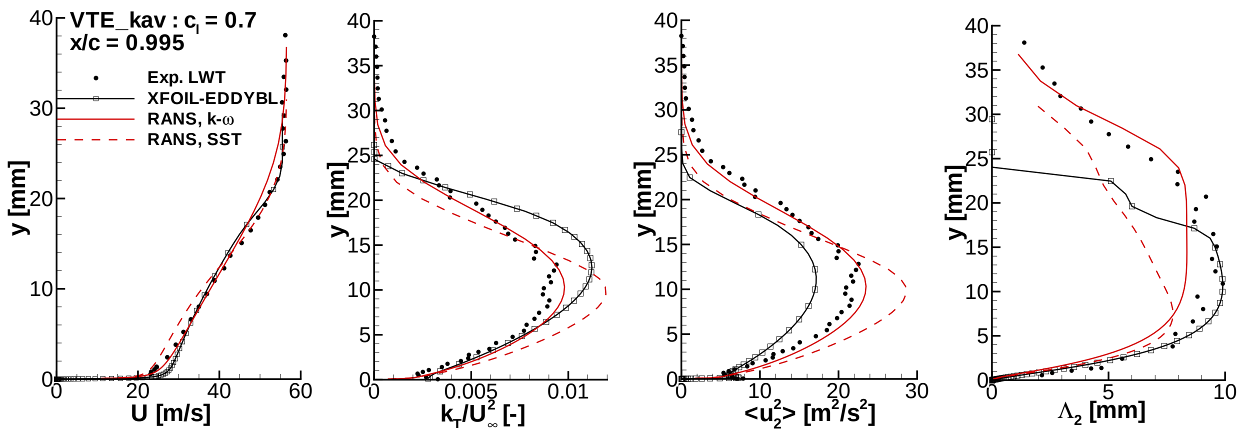

Figure 4: Measured and Predicted Turbulence Properties at $c_l = 0.7$: VTE_kav

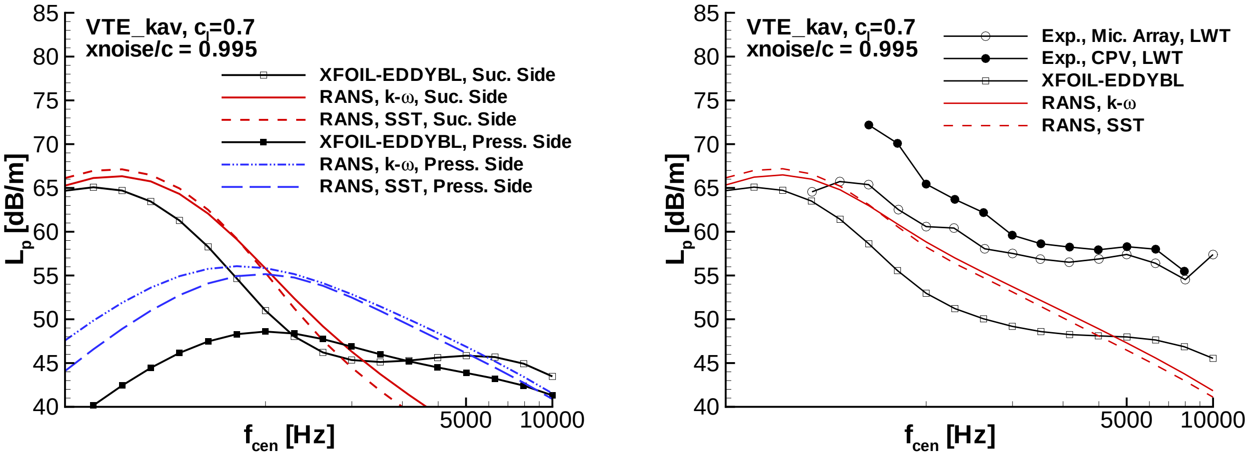

Figure 5: Measured and Predicted Noise Spectra at $c_l = 0.7$: VTE_kav

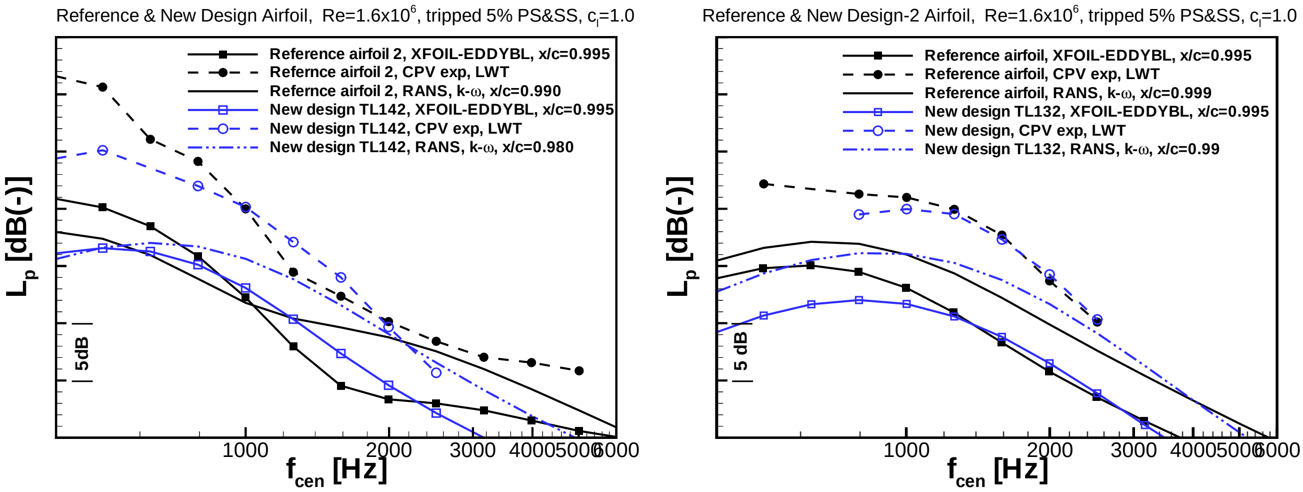

Figure 6: Comparison of Noise Spectra: Reference and New Design Airfoils

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A NEW MECHANISM IN VAWT

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Abstract.

*A kite always flies at height-- because wind is always availbale,though at a certain height.The question that remains is--"**Whether we can harness this ever-present wind efficiently or not.?**Presently,HAWT are in extensive use.We have proposed a reliable self-start mechanism for a 4-blade,improvised Darrieus wind turbine, a VAWT.The proposed design of the machine can generate sufficient initial drag to produce the necessary starting torque. From thereon It is primarily a lift-based machine which utilizes available wind efficiently being omni-directional and further enhances its performance by minimizing turbulence,as is the inherent nature of VAWTs.The 4-blade design helps it stay 'in' wind more and thus leads to better utilization of the highly unreliable power source.*

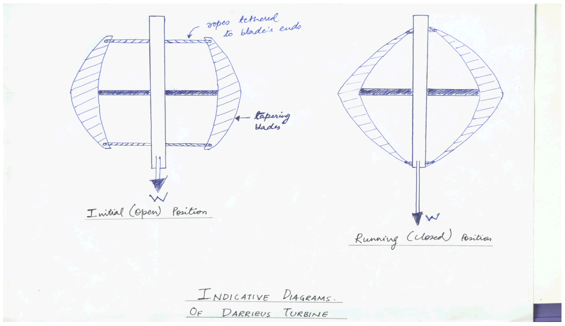
Self-start mechanism of Darrieus wind turbine

Introduction

Presently, the maximum percentage of wind turbines used the world over is comprised of HAWTs. And, except the Sandia National Laboratories, USA and a few places in Canada, the interest is all but dead in the VAWTs. Almost all the working wind-farms today exclusively use the HAWTs, such as the wind farms of Denmark, the Netherlands, USA and even western Ghat regions of India.

But, the main problem with the conventional turbines(horizontal axis) is that of "gust-loss"; unavoidable considering the bulky nature of rotor blades, despite optimization of its design. This is where Vertical Axis turbines score highly against their conventional counterparts, there's no gust-loss i.e. they don't 'miss' any wind, increasing the efficiency automatically. The chief reason for their remaining absent from the energy scene so far has been the lack of a reliable self-starting mechanism.

PROPOSITION. Here we propose a reliable self-start mechanism for Darrieus wind turbines.



This is a 4-blade version of the conventional 2 blade Darrieus turbine. The basic idea is that a giromill can start all by itself, but not a Darrieus turbine .so, the suggested model here is combining the features of these two VAWTs to construct one single, efficient and self-starting turbine.

The turbine starts from the ‘open’ position in which maximum wind drag acts on the turbine, thereby generating sufficient drag to make the turbine start rotating about the central axis. As soon as the turbine starts rotating, the central mass, attached through the central axial pole to all the four blades’ tips, starts falling/slipping down, thereby reducing the open position of the turbine to that of a “troposkein”, thus concentrating all the gyroscopic forces along the axis.

As the turbine starts to rotate, the tapered blades rotate about their own axis as well(not the central turbine axis)which reduces them to the ‘closed’ position, thereby, minimizing drag and making the turbine a primarily lift based machine. The airfoil based design maximizes the lift and increases the efficiency of the machine.

***Characteristics of VAWTs**.*

1. Darrieus turbine is basically lift based and thus it doesn't typically produce/need very high starting torque.
2. The number of blades that can be put up on the turbine is limited and the blades have to be properly designed so as to optimize the lift available as well as to reduce the drag.
3. Power is the product of torque

produced(directly proportional to the solidity of the turbine) and the rotor speed.. thus for a more efficient design ,rotor speed is kept high and solidity low. it reduces 'spiral' losses to a huge extent and deflection losses are already low in VAWTs.

4. Using 4 blades.(instead of the regular 2 or 3) will help the turbine stay more effectively in the wind thereby increasing the frequency of power produced as well as utilising the available wind far more effectively.
5. Since the speed of rotation of these VAWTs is almost the same as that of the available wind,it isn't a threat to the lives of birds, bats, etc. thereby removing the concerns of environmentalists.

6. this design is to be implemented in urban and semi-urban areas i.e not in stand-alone wind power plants and thus, this can be readily integrated in the existing utility supply set-up and, considering the low reliability factor, it can initially be used to power just 1 or 2 sectors of the utility...a city wise plan could be like.....

- In power starved but mushrooming suburbs, it could be exclusively used for recharging the batteries in homes, offices, etc.
- In metropolises, it could be used to handle street light, besides giving the extra power to neighbouring industrial units..
- In semi-urban areas, it could be used to work along with the utlity which isn't much reliable in our villages anyway.

7. The Darrieus turbine 'sees' wind even in a partially turned condition ,thereby generating sufficient lift for it to keep rotating, it stalls when the blades are parallel to the wind, enough lift is not generated, this problem is solved by using the 4 blade turbine, which'll always keep the turbine in a position to harness wind efficiently, though, it'll compromise a bit on solidity.

8. Ideally, these turbines can extract 40% of the energy available in theWind--easily comparable to the more popular HAWTs and, in some cases are even more effective too.

Why Darrieus Turbine?

Since the entire world's focussing on horizontal axis turbines(whether upwind or downwind)therefore a starting mechanism for a VAWT could be confused for something out of place and time. However the advantages of a VAWT against the conventional and more popular HAWTs are various and can be enumerated as--

1. It doesn't miss any wind i.e. it utilises the available wind in the most efficient manner as it doesn't have to face any "gust loss".they are omni-directional.

2. The design is mainly lift-based, instead of the usual drag-based machines...thus increasing the efficiency of the entire set-up by reducing the turbulence losses due to the retreating wind.

3. All gyroscopic forces act along the vertical axis of the turbine and thus there's no problem of "yawing" of the turbine. Plus, no problem of bending stress acting on the blades ,as wind turbines are already fatigue-critical machines thereby increasing the life of the entire turbine.

4. The construction of the machine allows for the generator and the the rest of the assembly to be mounted on the ground, a huge bonus for later repairs and maintenance, and a significant advantage over HAWTs.

5. The 'troposkein' shape of the turbine directs the centrifugal force through the blades' length to the point of attachment, thus creating tension in the blades, instead of bending. thus the blades can be kept light and strong and the set up need not be material-intensive.

6. Since this turbine is lift based therefore it has some inherent benefits like Betz limit used for wind turbines can be practically realized plus it's not material-intensive ,even on the power-plant scale..

7. VAWTs produce lesser noise than the conventional turbines as they operate at lower tip speed ratios.

8. These turbines cause far less electromagnetic interference than their horizontal axis counterparts.

Disadvantages of Darrieus Turbines—

1. The 4-blade design does compromise a bit on solidity but it helps the turbine stay 'in' the wind more and that further pushes up the efficiency of the turbine's power extraction from the wind considering the fact that it rotates almost on the same speed as that of the wind, so this disadvantage can be neglected as it results in a net increase in efficiency only.
2. The only major problem in this idea is regarding the blades' quality vis-à-vis it's strength, weight(or specific density), elasticity and fatigue resistance. Though fibre-glass can be used with some improvisation (very thick and hollow at centre and long, tapering ends, twisted on the tips but a right carbon fibre or carbon/glass hybrid composite can be expected to do the job alright.
3. The second major drawback doesn't lie in this turbine but it's highly variable and extremely unreliable power source—which is wind.
4. Instead of using a separate falling weight, the set-up at the bottom of the turbine viz. generator, coils etc. can all be encapsulated in a module and designed to do the job, but this will need a far different circuitry than the conventional ones used now-a-days.

Result. The proposed design of the turbine
Will be highly efficient in utlising the wind power and is an innovative new design of a VAWT which is expected to get self-started and produce green energy – quietly and harmlessly at that.

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Advanced Techniques for Continuous Vibration Monitoring of Wind Turbines

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Abstract

Environmental and technological characteristics of wind turbines, along with the importance of risks incurred in case of undetected failures to the drive train components, justify the use of continuous vibration monitoring, along with adequate diagnosis techniques for these machines.

Given the complexity of the drive train of a wind turbine and the variability of its operating conditions, the vibration analysis tools that are commonly used in industry are not suitable since they require perfectly stable and repetitive operating conditions.

01dB-Metravib offers a dedicated monitoring solution associated to innovating detection techniques based on time signals analysis. These techniques, which have successfully been tested in similar applications, are particularly adapted for rotating machines operating at very low speed.

Introduction

The wind energy market is growing fast in many countries in the world and tends to represent a significant part of the non fossil-fueled power generation.

With the increasing power and sophistication of modern wind turbines combined with the size of wind farms newly installed, the need for monitoring the key components of the drive train is becoming more and more obvious.

However, the wide and permanent changes of operating conditions (speed, torque) of these machines lead to extreme variations in the vibration data collected, which can dramatically reduce the ability of the system to detect failures at an early stage.

01dB-Metravib offers a complete innovating solution including a specifically designed hardware platform and embedded processing techniques based on impacts detection in the time domain signals for bearing wear and tooth cracking diagnoses.

This article describes the principles and main features of these up to date condition monitoring solutions.

Background

Most current vibration monitoring techniques used for rotating machinery usually rely on the analysis of frequency domain signals (spectra) obtained from the well known FFT algorithm. Obtaining meaningful data and consistent diagnoses from these analyses requires:

- The rotation speed and the load of the machine to be constant during the measurements periods which can be quite long - *a few seconds* - depending on hardware performances and processing involved;

- Operating conditions must be reproducible over time and identical for each measurement set.

The aforementioned conditions are never fulfilled for a wind turbine subject to permanent and very sudden changes in wind speed (gusts). Moreover, most current mid and high-power wind turbines now employ variable-speed drives associated to adjustable blade pitch to adapt continuously the rotating speed to the varying wind conditions.

Another specificity of wind turbines is the extremely low rotating frequency of the main shaft (< 0.3 Hz) which may induce very small amplitudes in the frequency domain even when a significant problem is present. Analysing time domain signals can gain invaluable insights in that case, and is more probably the only way to detect defects such as roller bearings defects or cracked teeth.

The rotation speed of the blades ranges from 0 to 20 RPM at rated power. Monitoring the main bearings and the speed-increasing gear(s) requires the acquisition of time blocks, the time span of which should include a few revolutions of the shaft (about 10 to 20 seconds), with a high enough sampling frequency (minimum 25.6 kHz) to detect impacting in the medium and high-frequency ranges (scaling, cracks, etc.).

Standard Guidelines (ISO 10816), spectral analysis, envelope analysis, cepstral analysis are the techniques most commonly used in industry but they are not satisfactory for wind turbines.

Fourier processing (FFT) does indeed only allows for the characterization of first-order periodic and stationary vibrations (unbalance, alignment, meshing, etc.), whereas most wear phenomena that need to be detected at an early stage are evidenced by cyclo-stationary (amplitude or phase modulation, etc.) and random and pulse (impacts, scaling, cracking) vibrations.

FFT processing do not allow for the correlation between the various vibration sources. On a spectrum or on an envelope spectrum, one cannot sort a modulation phenomenon - such as non-linearity due to tooth wear - from a shock phenomenon due to excessive bearing clearance.

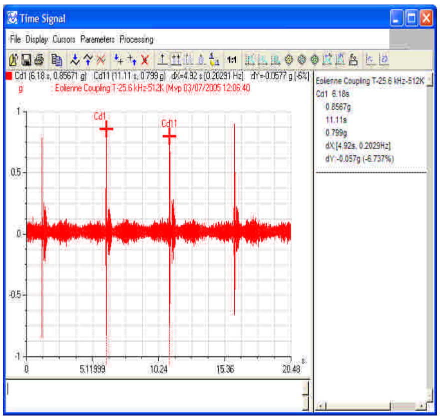

Figure 1: Vibration time domain showing a coupling defect

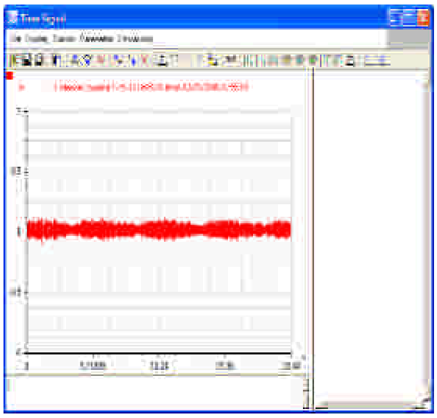

Figure 2: Vibration time domain without coupling defect

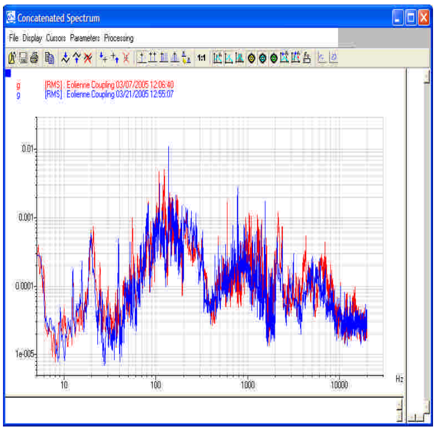

Figure 3: Frequency domain comparison, with and without defect

Figures 1 and 2 show time domain vibrations signatures collected on the bearing of a low-speed shaft (12 RPM) exhibiting – or not - a clear coupling defect. It is evidenced by a series of impacts at the shaft revolution speed period.

Figure 3 shows the limit of frequency analysis for the monitoring of low-speed machines like wind turbines. One can note that the impact phenomenon, which could be observed on the time waveform, is not clearly shown in the frequency domain.

Figure 4 shows an example of high vibration amplitudes changes on a 2 fixed speeds wind turbine (pole changeable generator) induced by the variations of operating conditions.

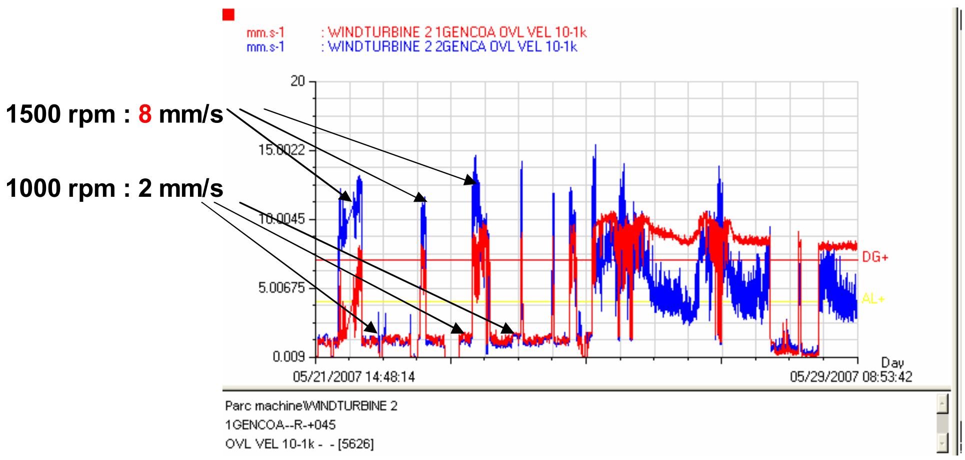

Figure 4: Evolution of vibration amplitudes under varying operating conditions on a 2 fixed speeds WT

The solution offered by 01dB-Metravib

There are two types of monitoring systems:

- The first mode is designed for machinery protection. It concerns with the structural elements of the wind turbine, such as the nacelle and the tower, as well as the blades, the aerodynamic behaviour of which must be monitored, along with the stress that they generate on carrier structures.

- The second monitoring mode, *which is concerned by this application note*, relies on the principles of **predictive maintenance**.

As far as diagnosis methods are concerned, this mode is very different and requires that the operating conditions of the wind turbines to be fully controlled.

Predictive maintenance of rotating elements

Our solution is based on the following operations:

1. **Synchronous time domain acquisition** when the required operating conditions are fulfilled: Wind speed, rotating speed, power, torque …

2. Checking that the operating conditions remain in a given range during signal acquisition.

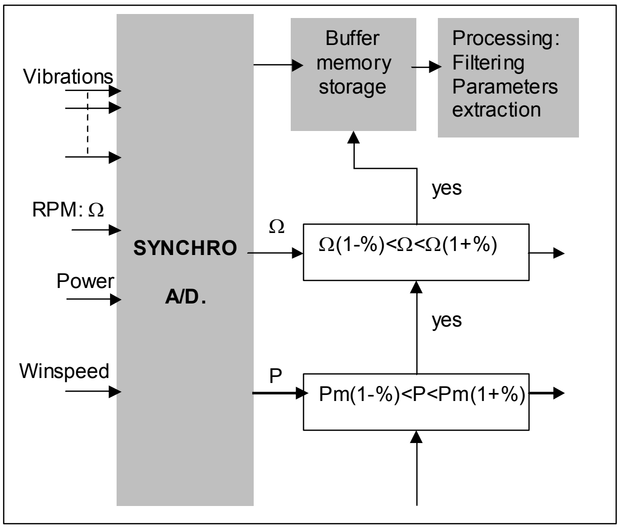

Figure 5: Acquisition principle

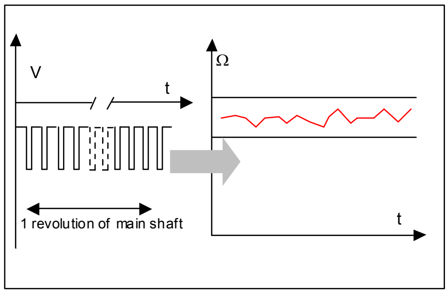

Figure 6: Tachometric signal conversion

The instantaneous rotating speed is derived from a tachometer on the high speed shaft of the equipment (generator), providing a large number of impulses per revolution of the main shaft. The acquired signal is then converted into a Ω_{RPM} = f(t) signal and compared to thresholds (Fig. 6).

Monitoring of bearings and gears: Impacts detection

The principle implemented for the vibration monitoring of bearings and the speed-increasing gear(s), which represent the number one cause of extended outages, rely mainly on a <u>specific algorithm for impacts detection</u> applied to time domain signals. These signals are acquired and low-pass filtered to remove “normal” vibrations due to shaft motions, meshing and non linearities: 1X, 2X, nX.

The **Kurtosis*** (statistical 4th-order centred moment) is calculated in a **sliding window** (Fig.7). associated with an impact counter (Fig.8). The window width, the counter triggering threshold and the maximum number of shocks are parameters that can be adjusted to allow for:

- The detection of periodic 1X impact on the low speed shaft due to excessive bearing clearances or teeth damage. The shock counter is incremented over a few revolutions, which allows ignoring possible disruptions and provides information on the shock repeatability.

- The detection of several shocks per revolution on the low speed shaft: Bearing defect. In this case, the window width is determined from the known defect frequencies of the bearing.

This method has already been used by 01dB-Metravib on similar machines: Radar drives, extruder’s speed-reducing gears, and presents the following advantages:

- Robustness with respect to small rotation speeds
- Low sensitivity to small changes in operating conditions
- Adaptable to all kinematic configurations: Low speed, high speed, etc.
- Intuitive for non-expert users.

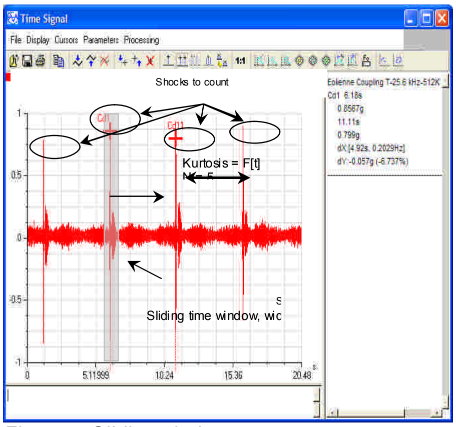

Figure 7: Sliding window

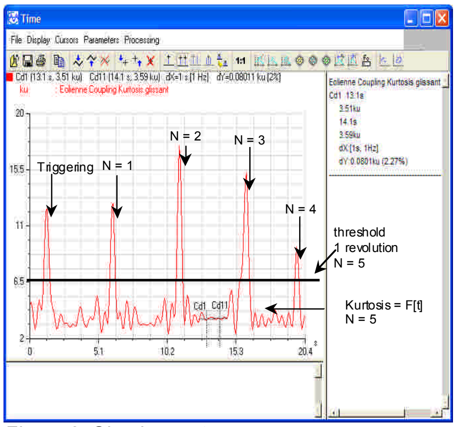

Figure 8: Shock counter

Monitoring the high-speed and the generator shafts

For those components, Fourier-based processing is suitable, provided that they are used within their "validity domain".

The small instant variations of the rotating speed are minimized by using proper triggering and spectra averaging. From the actual speed information, the following calculations or processing can then be extracted from acquired signals:

- Calculation of amplitude spectra and extraction of selective frequency components (1X, 2X,…, NX), on the roller bearings of the parallel-shaft speed-increasing gears and generator,
- Estimation of modulation induced lateral sidebands amplitudes around characteristic frequencies: Meshing, generator unbalance (Fig. 9),
- On the speed increasing gears, calculation of energy cepstra and extraction of fundamental components: 1X

Such processing, in addition to the impacts characterization algorithm allow early detection of the following mechanical failures:

- Generator rotor defects: Rotor bars cracks, dynamic eccentricity
- Coupling defects between the gearbox and the generator
- Generator unbalance, static eccentricity
- Tooth wear
- Mechanical looseness
- Structural resonances

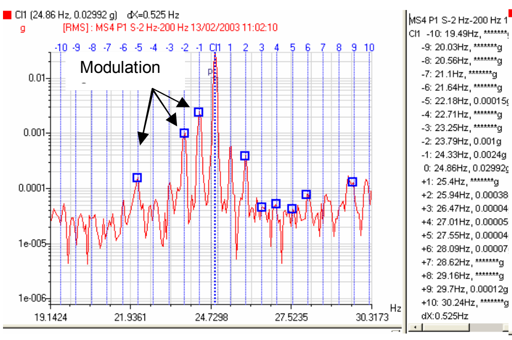

Figure 9: Modulations in the frequency

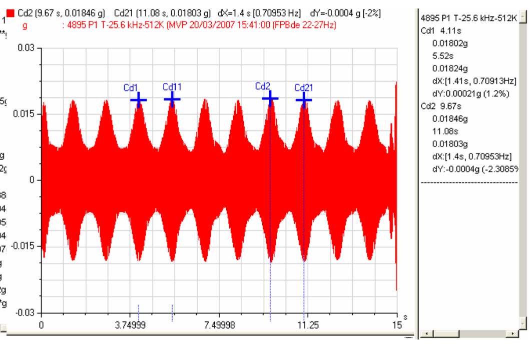

Figure 10: Modulations in the time domain

Required Instrumentation

Most modern windturbines drive trains consist of:

- One low-speed shaft supported by a rolling element bearing on the hub side
- One planetary first stage on the speed-increasing gearbox
- One or two additional parallel shaft stages
- A generator.

All drive train bearings are of the rolling element type. Figure 10 shows a typical wind turbine instrumentation scheme.

Our methodology uses low-cost industrial ICP accelerometers: 100mV/g, from 1 Hz to 12 kHz at 10%.

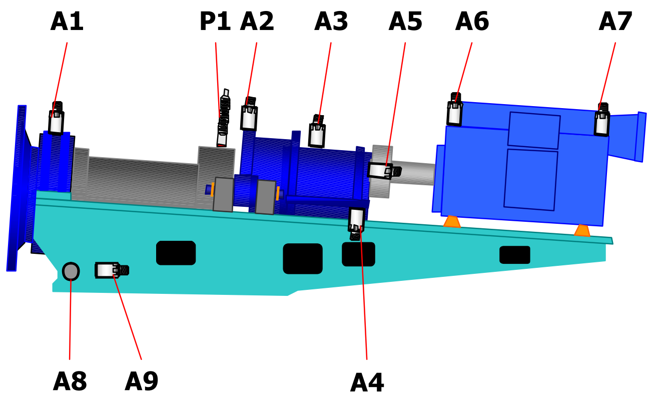

Figure 10: Typical arrangement a wind turbine drivetrain

Id	Sensor Location	Type
A1	Main Bearing	General purpose industrial accelerometer [2;12k] Hz
A2	Planetary gear stage	General purpose industrial accelerometer [2;12k] Hz
A3	Intermediate speed gears/bearings	General purpose industrial accelerometer [2;12k] Hz
A4	Intermediate speed gears/bearings	General purpose industrial accelerometer [2;12k] Hz
A5	*Int. & high speed gears/bearings (optional)*	*General purpose industrial accelerometer [2;12k] Hz*
A6	Generator inboard bearing (DE)	General purpose industrial accelerometer [2;12k] Hz
A7	Generator outboard bearing (NDE)	General purpose industrial accelerometer [2;12k] Hz
A8	*Nacelle transverse (optional)*	*Low frequency accelerometer [0.1;1k] Hz*
A9	*Nacelle axial (optional)*	*Low frequency accelerometer [0.1;1k] Hz*
P1	*Shaft displacement sensor (optional)*	*Eddy current probe (8 mV/µm)*

Id	Operating condition sensors	Type
K1	Generator speed	Non contact keyphasor (N pulse/rev)
K2	*Generator phase reference (optional)*	*Non contact keyphasor (1 pulse/rev)*
K3	*Rotor phase reference (optional)*	*Non contact keyphasor (1 pulse/rev)*
PWR	Active power (or load related signal)	Analog [0;10] DC voltage or [4-20] mA current
WS	Wind speed	Analog [0;10] DC voltage or [4-20] mA current

OneproD® System monitoring system

OneproD® MVX is an hardware acquisition system, which can be operated as a stand alone instrument to activate alarm relays or as a front-end connected to local or remote **OneproD® XPR** predictive maintenance platform.

Main features

- 16 ICP/voltage synchronous channels available for:
  - ✓ *7 high-frequency accelerometers*
  - ✓ *2 low-frequency accelerometers for monitoring the nacelle structure**
  - ✓ *1 LS shaft displacement sensor (optional)*
  - ✓ *1 generator tachometer (N pulses/rev.)*
  - ✓ *1 phase reference on generator shaft (optional)*
  - ✓ *1 phase reference on rotor shaft (optional)*
  - ✓ *2 operating conditions : Inst. power and wind speed*
  - ✓ *1 spare channel for additional measurements*

- Operating Condition based Data Acquisition: Acquisition will depend on :
  - ✓ *Speed of wind, rotating speed, power*
  - ✓ *Stability of rotating speed*

- Data processing:
  - ✓ *High-pass / Low-pass filtering*
  - ✓ *Calculation of statistical Kurtosis indicators*
  - ✓ *High resolution amplitude spectra*
  - ✓ *Envelope spectra*
  - ✓ *Frequency selective parameters from spectra: amplitudes, modulation ratios*
  - ✓ *Bearing defects*

- Sampling frequency: max. 51.2 kHz
- 4 logical inputs
- 4 logical output for alarms

Conclusions

Continuous wind turbine condition monitoring is getting more and more justified with the increasing size and complexity of the machines, since undetected failures may progress to serious damages leading to very high repairs costs, especially in the case of remote locations and offshore wind parks.

The monitoring systems and signals processing have to be specifically designed to take in account the permanently varying operating conditions and the specificities of the drive train: Multi-stage increasing-speed gears, very low speed of main shaft.

01dB-Metravib offers, with **OneproD® System** monitoring solutions, a cost effective response to the needs and objectives of the wind energy market.

Aerodynamic noise from micro wind turbines: Current situation and future perspectives

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Abstract

Micro wind turbines are set to play a role in the future mix of energy generation provided the concept of embedded power generation is fully supported by governing authorities. Apart from the obvious benefit of additional energy generation at or near the point of use, micro-wind power has an important role to play in terms of public education, which will promote the conservation of energy as well as an increased understanding and a better acceptance of wind power. Unfortunately, noise emissions from small wind turbines constitute one of the main obstacles to widespread use in populated zones, and a great deal of work is needed in this area if domestic wind power is to achieve a success comparable to that of domestic photovoltaic power generation or solar water heating. This paper presents a brief survey of the work published to date on the aerodynamic noise generated by horizontal axis micro-wind turbines. The noise generation mechanisms are reviewed in the context of small machines, thus identifying the most pressing issues in terms of noise generation. As an example, the effect of a proposed noise control device is assessed using a recently developed micro-wind turbine experimental research facility. This application is used to outline the scope for future work, and how this work can benefit the development of domestic wind turbines.

Nomenclature

SWT Small wind turbine
BPF Blade passage frequency [Hz]
Λ Characteristic turbulent eddy size [m]
C speed of sound [m/s]
M Mach number [-]
Re_c Reynolds number based on the blade chord [-]
R Rotor radius [m]
U_∞ wind speed [m/s]
TSR tip speed ratio [-]
U_{tip} estimated tip speed [m/s]

Context

Small wind energy converters represent a considerable potential market. This market is, to date, significantly under-exploited due to the lack of supportive policies, and the fact that the technology is yet to reach maturity.[1,2]. From a consumer perspective, the financial case for installing a machine is difficult to make because for a number of reasons. It is difficult and expensive to obtain a good statistical description of the wind potential at the required location and hence the potential return is unknown. Another hurdle for the consumer is perhaps the anticipation of difficult dealings with local authorities, which are keen to maintain a harmonious community. Local councils are reluctant to approve the installation of a system that may be perceived as unsightly by some members of the community, and a possible source of unwanted noise. The purpose of this paper is to summarise the noise generation mechanisms in the specific case of domestic wind turbines, assess the potential for mitigation for each source mechanism, and draw some conclusions regarding the way forward to improve acceptance from a noise perspective. This will then assist with the market penetration of small wind turbines.

The term "small wind" is generally applied to wind turbines of 100kW or less. The high-end of this range is clearly designed for small communities and wind farms, and the scope of this paper is limited to domestic horizontal axis wind turbines, typically 5kW or less, with a rotor diameter of less than 6m, with blade chord that is of the order of 0.2-0.3m. Most models in this category are of the variable speed type. The over-speed control mechanism is either stall with electric braking, or furling, either vertical or horizontal. Some models use blade flutter control but the associated noise levels are so large that they can not be regarded as representative in situations where noise is a design consideration. Gipe [3] provides a rather recent survey of the commercially available range of domestic wind turbines. The single most important criterion for wind turbine performance is the cost per kWh, which factors in the initial cost of the machine and its installation, servicing and life expectancy against the power production of the machine. However, the noise rating of a machine is equally, if not more important for its commercial success. Excessive noise emission will tip the delicate balance of public perception to the wrong side. The noise generation mechanisms documented on large wind turbines also affect domestic machines, although their relative importance is somewhat different.

Aerodynamic noise of wind turbines

There is a broad consensus on the identified wind turbine aerodynamic noise sources mechanisms, as reported by Hubbard and Shepherd [4], Lowson [5], or Wagner *et Al.* [6]. The latter in particular provide an interesting table summarising all known sources of aerodynamic noise, along with their relative importance in the case of large wind turbines. They also quantify the difficulty or otherwise in controlling or reducing each type of noise. When small wind turbines are considered, rotational speed and airfoil geometry are two major parameters that significantly alter these conclusions. At similar tip speed ratios, the rotational speed of a small wind turbine is a lot higher than that of a large machine. Conversely, a typical blade chord is typically an order of magnitude smaller on a SWT, which is then reflected on the Reynolds number of the flow past the airfoil. Another important consideration is that blade geometry is generally less complex on small rotors, which makes it more difficult to mitigate some sources that are identified as altogether avoidable in the case of large wind turbines. These differences are further detailed in this section for each aerodynamic noise mechanism, using the accepted nomenclature.

Deterministic noise

Steady thickness and steady loading noise are related to airfoil geometric and aerodynamic properties of the airfoil, respectively. The former is caused by the air displacement due to the blade rotation, and the latter results from the steady aerodynamic force on the moving blades. These tonal noises, with a fundamental frequency equal to the blade pass frequency (BPF), result from the motion of the blades relative to the observer. On large wind turbines, this noise is typically around 3-4 Hz, and has very little impact, at least for upwind designs. On small plants, however, the frequency of this noise can reach up to 50 Hz in moderate to fresh winds, well into the audible range, and cause significant annoyance. Due to its strong tonal nature, the masking effect of other natural noises is diminished, and this noise is likely to be perceived in dwellings nearby. Two identified mitigation measures are the reduction of the tip speed ratio and blade sweep as is routinely done on automotive fans. It could also be envisaged to use an uneven blade distribution, as is done on some helicopter tail rotors and automotive fans, to redistribute the acoustic energy over a larger number of less intense tones, but the cost of this solution, in terms of engineering as well as aesthetics, may well prove too expensive.

Inflow turbulence noise

Inflow turbulence noise results from the ingestion of atmospheric turbulence by the wind turbine rotor. Because of the wide range of turbulence length scale, this has a very broadband signature. The ratio between the characteristic turbulence length scale and blade chord also determines the source directivity and speed dependence of the radiated sound power [7]. If the eddy size is much larger than the blade chord, the noise produced by blade lift fluctuation is proportional to the sixth power of the tip speed and the directivity of the acoustically compact source is that of a dipole along the direction of the rotor axis. Conversely, if the eddy size is much smaller than the blade chord, the radiated noise is then assimilated to turbulence diffracted by a half plane, which is proportional to the fifth power of the tip speed. This mechanism also radiates noise in the plane of the rotor. The transition between the two behaviours occurs roughly when the ratio of turbulent eddy size to blade chord is comparable to the local Mach number $\Lambda/C{\sim}M$. This implies that, at a given tip speed ratio, the acoustically compact source behaviour occurs over a wider frequency range for smaller wind turbines. Wagner *et Al*. report that the inflow turbulence noise, although yet to be fully understood, is thought to be a source of broadband noise up to 1 kHz on large wind turbines. Blade profile, particularly at the leading edge, was found to have an influence on this noise. The problem of inflow turbulence noise is likely to be more pressing with small wind turbines, which are often located in conditions that are less favourable than large plants installations, near vegetation or buildings, and closer to the ground.

Airfoil self noise

Airfoil self noise [8] is generated by the flow around the blade profile itself. It consists of the following mechanisms.

Turbulent boundary layer-trailing edge (TBL-TE) noise results form the interaction of the turbulent boundary layer developed on the airfoil surface with its trailing edge. It is a similar sound generation mechanism as that of inflow turbulence noise in the non-acoustically compact case, because the characteristic eddy size is much smaller than the airfoil chord, and scales with the fifth power of the tip speed. The noise is of broadband nature, although the suction side contributes lower frequencies than the pressure side [9], as may be expected from the relative boundary layer thicknesses. Ensuring that the boundary layers remain thin and attached, and maintaining a high friction coefficient at the trailing edge helps minimise this source of noise [10]. Oerlemans *et Al* [11] demonstrated that adequate airfoil optimisation based on these parameters could lead to a trailing edge noise reduction of about 4dB compared to a rotor using the commonly used NACA-64418 profile without significant loss of efficiency, as measured on a two-bladed wind turbine in the large anechoic wind tunnel DNW-LLF. Trailing edge serration, as suggested by the theoretical work of Ffowcs-Williams and Hall [12], provided a further noise reduction of 2-3dB, even in the tripped case. Dassen *et Al*. [13] had previously confirmed experimentally with 2D airfoil wind tunnel tests the potential benefits of trailing edge serration, albeit significantly less than those predicted by the theory by Howe [14], but found that care had to be taken to keep the serrations aligned with the airfoil chord plane. Mitchell [15] reports contrasted results with the use of serrations.

Separation-stall noise occurs in situations where flow separation occurs at some station of the chord. This can be either a boundary layer separation near the trailing edge or further upstream in stall conditions. The areas of correlated unsteady loading on the blade can be modelled by acoustic dipoles, and the radiated noise has broad frequency content. This noise mechanism is an important one, since stall is often used as a regulation mechanism on all types of turbines. Furthermore, many small wind turbines use blades without twist or taper such as those obtained by pultrusion. In this case, parts of the blades operate in off-design conditions, with various degrees of flow separation depending on the distance from the hub. Finally, small wind turbines are often exposed to higher levels of turbulence due to their close proximity to the dwellings they serve, and this may result in significant variations in wind that may induce unsteady stall on some sections of the rotor.

Laminar boundary layer-Vortex shedding (LBL-VS) noise occurs at the low Reynolds numbers (Re_c<2 10^6) that are characteristic of small wind turbine airfoil flows, where there is a strong interaction between instabilities in the laminar boundary layer on the pressure side near the trailing edge and the flow at the trailing edge of the airfoil. Nash *et Al*. [16] proposed a revised model based on the massive amplification of Tollmien-Schlichting instability waves in the separating laminar shear layer on the pressure side near the trailing edge, which rolls-up in that region. LBL-VS is likely to be the dominant noise source in small wind turbines and the cause of great annoyance, unless proper tripping is applied. The cost of this technique in terms of performance is difficult to predict on small wind turbines, although Oerlemans *et Al*. [11] did not measure a loss of efficiency with boundary layer tripping on the experimental wind turbine tested in a wind tunnel.

Tip vortex formation noise results from the interaction of the tip vortex with the blade surface. This noise is difficult to quantify since other types of self noise are highest on the rest of the blade near the tip because of their 5th or 6th power dependence on of the local air speed. Wagner *et Al*. [6] report various attempts at designing low noise tip planforms that minimise the intensity of the tip vortex and its interaction with the blade edge. The ogee tip gave promising results, but the most successful outcome was obtained with blade tips with a bevelled trailing edge. Tip noise is believed to add 1-2 dB to the noise radiated by a large wind turbine.

Trailing edge bluntness vortex shedding noise occurs when the trailing edge radius is large compared to the displacement thickness of the boundary layer. This noise is easily adverted in large wind turbines simply by ensuring that the trailing edge is sharp enough. However, on small wind turbines, this requires razor sharp trailing edges, which are more onerous to manufacture, fragile, and delicate to handle. Bevelled trailing edges appear to reduce vortex shedding noise [7].

Furling noise can also be important in small wind turbines. These machines are frequently designed to yaw out of strong winds for over-speed protection, which is called furling. In the fully furled position, the rotor plane is nearly parallel to the wind. This situation leads to severe unsteady loading on the blades between the advancing and retreating sides, and the blade tip vortices remain in the vicinity of the rotor as they are convected downstream, which leads to blade-vortex interaction (BVI) noise, one of the two dominant noise mechanisms of helicopters, along with high speed impulsive (HSI) noise. A small wind turbine can potentially sound like a helicopter in the initial part of the furling phase, when the rotor RPM is still high and the yaw angle is of the order of 70 degrees, and a powerful thumping noise can be heard during that time.

Work recently published by Oerlemans *et Al.* [17] on a 58m diameter GAMESA G58 upwind wind turbine focused on the identification of sound sources with a purpose-designed microphone array mounted on the ground upstream of the rotor. They found that trailing edge noise from the outward part of the rotor was the dominant source of noise, and the source region location moved towards the tip as the frequency of observation increased, from 0.72 R at 315 Hz, to 0.90 R at 1600 Hz. They also found that artificially tripping the boundary layer significantly increased the trailing edge noise. No evidence of tip noise or trailing edge bluntness vortex shedding noise was found in these measurements. Finally, it should also be noted that the dominant noise sources perceived at the ground mounted array were located on the downward part of the rotor, due to the convective amplification effect and trailing edge noise directivity.
Concerted efforts in Europe [6,10] and in the USA [18] have produced useful predictive numerical tools to model the various types of noise source mechanisms described in this section. In light of the complexity of these tools, it is difficult to assess how this work can realistically be used by small wind turbine manufacturers without the direct involvement of the research institutions developing them. Prediction codes based on semi-empirical models, as developed by Moriarty and Migliore [19] for example, appear to be of practical use from the perspective of a small wind turbine manufacturer, as they appear to provide the correct trends and are simple compared to the full prediction codes. This is particularly useful considering that some of the noise mechanisms outlined above may affect small wind turbines more severely than large scale generators.

Aeroacoustic research on small wind turbines

Research publications on small wind turbine aerodynamic noise are scarce, possibly because of commercial reasons, and the cost of this research to manufacturers. In the USA, the NREL has offered technical support to the small wind industry in assessing their product and providing sound scientific information for their future design. Migliore *et Al*. [20] summarise the work carried out by NREL on eight small wind turbines, six of them of domestic scale. The scope of the paper is limited to measuring and comparing the apparent sound power level of the selected models at 8m/s following the relevant Standard [21], and no source identification was attempted, although a change of blades on a Bergey Excel resulted in a 10-15 dB noise reduction compared to the original blade set. This demonstrates the scope of improvement that can be obtained from targeted research. An example of such research work was published by Oerlemans and Migliore [22], who measured in the NLR small anechoic wind tunnel the noise emitted by six airfoils suitable for small wind turbine applications. Airfoil self noise and inflow turbulence noise were investigated. They observed dominant tones associated with LBL-VS noise, which could be controlled by adequate tripping of the boundary layer. The radiated sound power level as derived from the microphone array measurements is also reported with all profiles tripped. The authors also found that inflow turbulence noise increased with decreasing leading edge radius of curvature. This work led Southwest Windpower to choose the S822 profile for their "Storm[i]" prototype [23]. It should also be noted that the company benefited from extensive technical support from NREL, under a government-sponsored scheme. As recognised by Industry [1], there is currently little research work in the field of small wind turbines, and this does certainly show in the very low number of publications on the topic of noise.

Establishment of a test site for small wind turbines

Micro-wind turbine aeroacoustics is poorly documented in the literature. This may be due to the cost of investigative noise measurements, which most small wind turbine manufacturers cannot afford without the financial support of a third party. In the few cases where wind turbine noise was measured, the testing facility was mainly designed for large plants and measurements on smaller machines are often affected by excessive background noise. It therefore became apparent that it would be beneficial for the design of domestic wind turbines to have a specific testing facility with good winds and low ambient noise. Such a facility, which is presented in this section, was developed at a site on the Fleurieu Peninsula approximately 60 km south of Adelaide, South Australia. The primary purpose being research, development and diagnostics of small wind turbines rather than certification, the microphone are not ground-mounted at a distance, but mounted on masts around the turbine in locations that are representative of observation angles in a typical domestic application. The site is located on a ridge extending from East to West, on the North shore of an artificial lake, as illustrated in Figure 1. This shows an aerial view of the site, with 10 m contour lines and basic wind data logged for two weeks in late June 2007. The results show strong South-Easterly winds favoured by the presence of the lake and the topography, which acts as a concentrator. North-Westerly winds are not as strong as

[i] The turbine was subsequently commercialised under the name "Skystream 3.2 Residential power appliance"

could be guessed from the contour lines, due to the presence of significant vegetation North of the site. Although this may be seen as a problem, it is actually a useful feature since it is important to estimate the performance domestic wind turbines in such a situation, which is representative of a populated environment. The ambient noise is quite low and most of the background noise is generated by wildlife and cattle. A small 2.2 m diameter 200W Yueniao FD200W wind turbine was mounted on a 11.5 m mast instrumented with a NRG Maximum#40 Anemometer and a NRG #200P Wind Direction Vane, approximately 2.5 m below the nacelle. This location is a compromise between the required measurement height and the need to avoid excessive interference from the rotor. It should also be noted that North-Easterly winds are not accurately measured because the sensors are then in the wake of the mast. This explains the low measurement of North Easterly winds, which are infrequent. It is possible to fully characterise the wind turbine, as illustrated by the power curve shown in Figure 2. The wind turbine was slightly modified, a new hub was designed and slip rings were installed. The original controller was replaced by a programmable prototype based on an Atmel Mega8 processor [24].

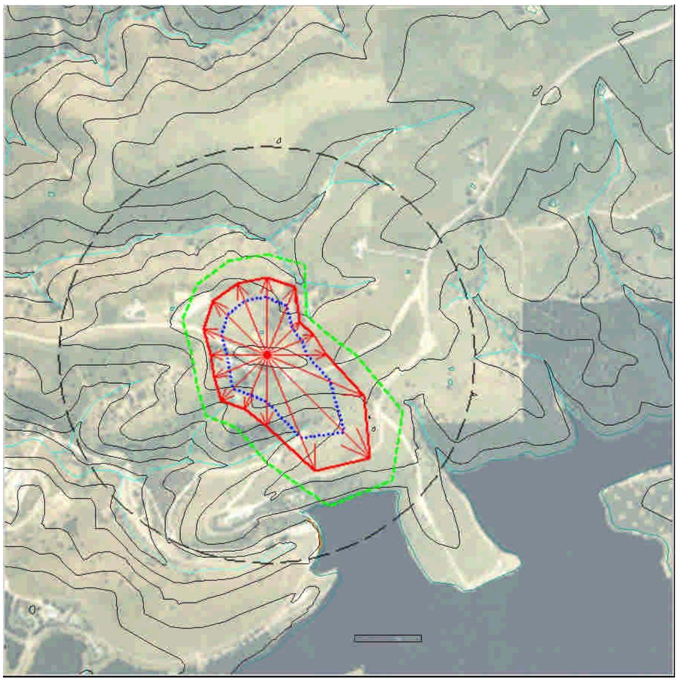

Figure 1 Aerial view of the test site location with topography and wind data. The interval between contour lines is 10 m, altitude at site: 303m. This picture covers an area of approximately 4 km^2. Over imposed are the wind speed percentiles as measured between 17/06/07 and 01/07/07: ▪▪▪: 25%; —: 50%; - - -: 75%. The dashed outer circle represents 10 m/s.

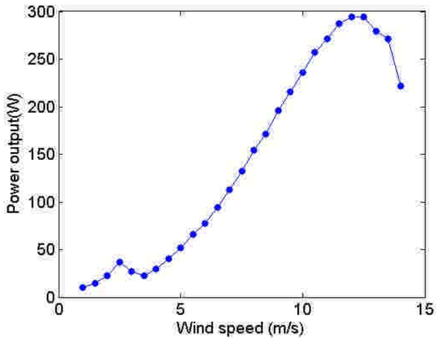

Figure 2 Power curve measured with a 4Ω resistive load and no controller.

The rotor is made of three 1 m long pultruded fibreglass blades of unknown profile, with a chord of 0.1m, without twist or taper. The initial configuration was judged subjectively noisy although no noise measurements were made at the time. After a protective coat of paint was applied and the blade surface became smoother, strong tonal noise became apparent. This could be associated with laminar boundary layer instability noise since a smoother blade surface worsened the problem. However, the trailing edge of the blades have a 3 mm thick rounded edge, which is quite blunt compared to the boundary layer thickness estimated from flat plate theory. The peak in measured noise power spectral density, shown in Figure 3, is consistent with the hypothesis of vortex shedding noise emanating from the outer quarter of the blades and a Strouhal number of 0.2. Furthermore, strong boundary layer tripping has been applied, which reduces the correlation length of the velocity fluctuations [25] at the trailing edge, which explains why a hump remains apparent at the frequency where the peak was observed with the smooth blades.

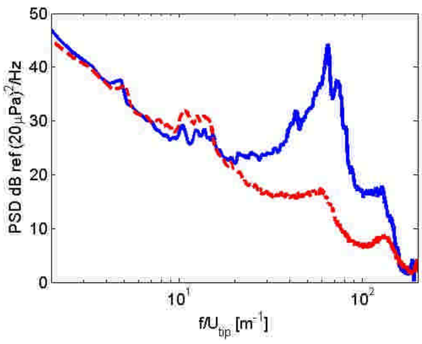

Figure 3 Noise power spectral density measured at two reference microphones before (——) and after (---) tripping was applied to the suction side. U_∞=8m/s, TSR=0.67.

Tripping the boundary layer on the suction side reduced the tone by more than 20 dB, and the sound pressure level measured at the reference microphones decreased by 13 dB(A). Figure 4 and Figure 5 indicate that the overall noise agreed quite well with the 5th power of the estimated tip speed, in the smooth and tripped configurations respectively.

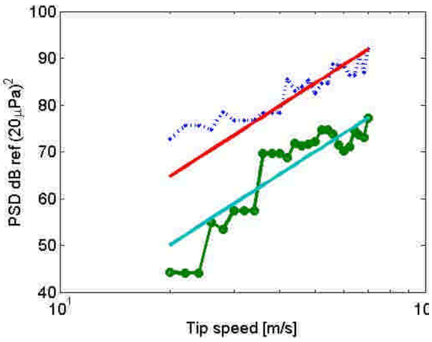

Figure 4 Smooth blades: Measured overall sound pressure levels as a function of estimated tip speed. ···■···: linear; —•—: A-weighted. Straight lines indicate the 5th power of the tip speed.

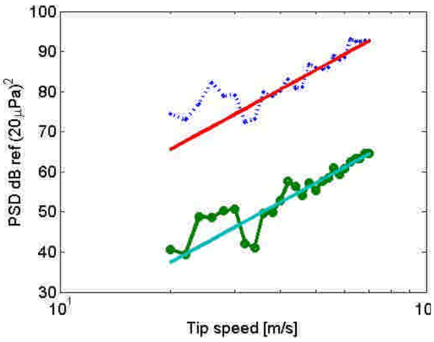

Figure 5 Tripping applied to the suction side: Measured overall sound pressure levels as a function of estimated tip speed. ···■···: linear; —•—: A-weighted. Straight lines indicate the 5th power of the tip speed.

Although tripping was an extremely efficient way of removing the strong tonal characteristics of this test wind turbine, it proved slightly excessive and reduced the operating tip speed ratio by more than 10%, which is not acceptable in terms of performance. Furthermore, the tonal noise frequency appears to be proportional to the tip speed, which is indicative of bluntness noise rather than laminar boundary layer instability tones, for which the frequency is approximately proportional to $U_{\mathrm{tip}}^{3/2}$ [7]. A sensitivity study of the trip thickness would help refining the exact level of tripping that is necessary to break up coherence in the blunt trailing edge vortex wake.

Conclusion

Noise mitigation measures clearly have a significant impact of the complexity and manufacturing cost of a wind turbine. For example, a set of pultruded blades are less expensive to manufacture than blades with twist, taper, and even sweep. However, a large portion of the blades will operate in suboptimal conditions, which is likely to generate more aerodynamic noise than blades with taper and twist.

Tip speed ratio is by far the single most important parameter determining noise emissions. Unfortunately, a reduction of the nominal tip speed ratio in small wind turbines is accompanied by an increase of complexity and cost associated with the introduction of a gearbox or a high torque, low RPM generator, and an increase of rotor solidity to maintain aerodynamic efficiency.

Although it may be extremely difficult to eliminate some of the noise generating phenomena, design choices can certainly be made to minimise them, provided sufficient information is available to the designer. With the help of existing literature and a dedicated testing facility such as the one briefly presented in this paper, it is possible to quickly identify and control the noise mechanisms that would otherwise ruin the commercial potential of an efficient machine. This would provide ways to develop domestic wind turbines in a reduced time frame, improve competitiveness in terms of noise emissions, and enhance penetration of a market that is broadly recognised as largely under-developed.

Acknowledgements

Philip G. Schmidt designed and built the controller and other electronic components as required. He also wrote the initial version of the controller software. His availability and tireless support are gratefully acknowledged.

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Auralization and Assessments of Annoyance from Wind Turbines

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Abstract
Noise from wind turbines is of great concern for the neighbours. Both the sound level and other characteristics of the wind turbine noise are of significance for the annoyance. By applying a model for sound propagation, it is possible to auralize the sound from the wind turbine at the neighbouring residents. This approach potentially gives a more realistic presentation of the actual wind turbine noise as input to the decision-making process. In the present work, five different wind turbines were recorded and auralized at two distances using the Nord2000 propagation model. 20 subjects rated the processed recordings on overall annoyance both with and without additional natural background noise. Relevant sound attributes like loudness, pace, tonality and swishing sound were also rated by the subjects and compared with physical metrics. As a result, a metric for swishing sound is proposed. Finally, a model based on the results from this study on annoyance of sound from wind turbines is presented.

Introduction
The development of wind turbines moves towards maximizing the produced power by increasing size. In general larger often means louder and that gives rise to concern for people living near places for new wind turbine projects. Therefore focus also is kept on minimizing the emitted sound to make wind turbines more acceptable for the people living near them. A measure for the emitted sound is the A-weighted sound pressure level. This quantity is also referred to in legal requirements. However, this value is not the only parameter of relevance for the annoyance. Also other sound characteristics, the context and personal variables play a role. The annoyance should be the key parameter when deciding where to build any new wind turbine park. Earlier studies have addressed this issue and identified perceptive attributes of the wind turbine sound that contributes to the overall annoyance. But how does outdoor sound propagation and natural background noise influence on these quantities?

In the present study five different wind turbines were auralized at the distances of closest allowed residence according to Danish legislation (6 hub heights) and twice that distance. Perceptive attributes were evaluated for the auralized sounds by a group of 20 selected subjects and the evaluations were attempted linked to physical metrics. The effect on annoyance when adding recorded natural background noise was also addressed.

This project was part of a larger investigation financed by the Danish Ministry of Science, Technology and Innovation on noise annoyance of different outdoor sound sources [11].

Stimuli

Recordings of Wind Turbines

Five different wind turbines ranging in power from 225 kW to 2 MW were recorded at wind speeds around 5 m/s and at distances of 1.5 and 3 hub heights (HH) according to the procedures described in DS/EN 61400-11. Specifications on the recorded wind turbines are found in Figure 1.

Wind turbine	**1**	**2**	**3**	**4**	**5**
Power	600 kW	1 MW	2 MW	225 kW	850 kW
Hub height (HH)	35 m	45 m	60 m	30 m	54 m
Rotor diameter	39 m	71 m	80 m	27 m	52 m

Figure 1 - Specifications on the five recorded wind turbines. The recordings were made at distances of 1.5 and 3 hub heights from the wind turbines.

The wind turbines were placed in the western part of Denmark and away from major roads and other disturbing sound sources. Some of the turbines were placed in groups of 2-5 but during the recordings, the nearest wind turbine was shut down, so only one turbine was recorded at a time. The recording system consisted of a Brüel & Kjær Head and Torso Simulator (HATS) type 4100 and a laptop based recording software which stored the sound files on a hard disk. The recording height (at the ears of the HATS) was 1.7 m above ground. To eliminate wind noise in the microphones, the HATS was equipped with a special designed Rycote fur wind cap.

The recordings of the wind turbines did not contain significant natural background noise from wind in trees or bushes. However, since the influence of background noise on the overall annoyance was a parameter for the listening test, recordings of natural background noise was made in the early autumn in a soundscape close to trees and bushes representative for a typical Danish garden in the countryside. No traffic noise or other unnatural sounds were present in recording and birds singing were also avoided.

Auralization

It was decided to auralize the wind turbines at a fictive distance of 6 and 12 HH. The reason for choosing these distances was that according to Danish legislation wind turbines have to be more than 6 HH away from the nearest residence. The Nordic sound propagation model called Nord2000 was employed for the spectral manipulation of the recorded sounds [5]. The model accounts for wind speed, -direction, -gradient, temperature, relative humidity, and terrain properties and calculates the attenuation in 1/3-octave bands. Nord2000 is implemented in an easy to use software version called SPL2000 developed by Birger Plovsing, DELTA. This software was used for calculation of the sound propagation attenuation. By defining the source and receiver position besides parameters for ground and air absorption, sound pressure levels in 1/3-octave bands at the receiver point can be exported to a spreadsheet file for further use implementation in sound editing tools like Adobe Audition.

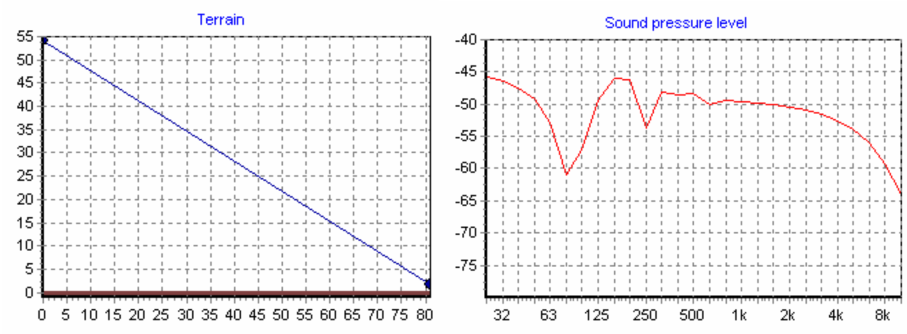

Figure 2 - Example of calculation made with SPL2000 for the sound propagation from a 55 m tall (HH) wind turbine measured at a receiver point 82 m away and at 1.7 m height above ground.

Stimuli for Listening Tests

The sound samples for the listening tests were constructed from 3 elements: a) wind turbine recordings, b) auralizations at 6 and 12 HH, and c) wind generated vegetation noise, see Figure 3. The HATS recordings made at 1.5 HH were auralized to a distance of 6 HH and the recordings at 3 HH were auralized to 12 HH. The recordings were as a first step band pass filtered to 20 Hz - 20 kHz (to avoid low frequency components to “occupy” part of the dynamic range). Next step was to apply the 1/3-octave band attenuations calculated with SPL2000. The values were found as the sound pressure attenuation difference $\Delta L_{p(Hr1-Hr2)}$ between the propagation path from the hub centre of the wind turbine to receiver positions at 1.5 HH and at 6 HH (and also at 3 HH and 12 HH). The third and final step of the signal processing was necessary because the inevitable wind generated noise in the microphone on the recordings sounded very unnatural after the spectral shaping in step 2. It was important to eliminate the low frequency rumble leftovers to keep focus on the wind turbine sound in the listening test. Therefore a high pass filter was applied to filter out frequency content below 150 Hz (for the 6 HH auralization) and 200 Hz (for the 12 HH auralization). The main components of the wind turbine noise are above these frequencies.

The recording of natural background noise from vegetation was band pass filtered (50 Hz-20 kHz) and adjusted -6 dB in level to avoid complete masking of some of the wind turbines.

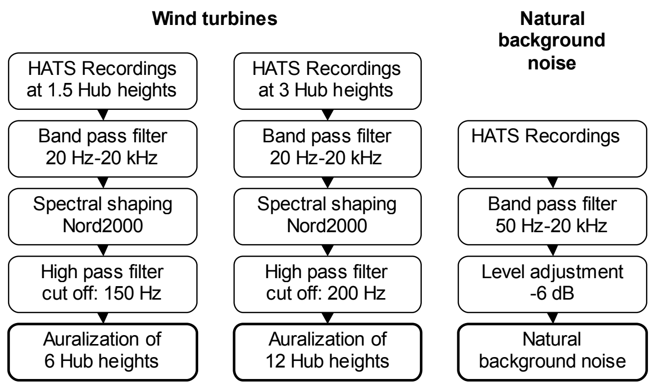

Figure 3 - Illustration of the performed editing path of the HATS recordings.

Three groups of stimuli were prepared for the listening tests. The first and second group of stimuli was intended for assessments of annoyance according to the questions in ISO 15666 [3] and therefore relatively long 90-second excerpts of the auralized sounds were selected. The first group of stimuli contained only the 'clean' wind turbine sound at the auralized distances. The second group used the same stimuli as group one, but had a 90-second excerpts of the natural background noise mixed together with it.

The third group of stimuli was intended for assessments of perceptive attributes and hence 20 second excerpts of the stimuli in group one were selected for this listening test. The reason for shortening the stimuli was that the method used for these assessments was based on comparison of stimuli rather than absolute ratings which meant that the listeners most likely would listen to short parts of the sound stimuli due to our short acoustic memory. The total A-weighted sound pressure levels of the final stimuli for the listening test are given in Table 1.

Wind turbine	**Distance**	**L_{Aeq} [dB re 20 µPa]**	**L_{Aeq} [dB re 20 µPa]**
		Wind turbine alone	With background noise
1	6 HH	39.5	43.8
	12 HH	33.4	41.8
2	6 HH	35.8	42.4
	12 HH	30.0	41.5
3	6 HH	39.3	43.6
	12 HH	34.2	42.1
4	6 HH	31.8	41.7
	12 HH	29.1	41.4
5	6 HH	41.3	44.5
	12 HH	35.3	42.3

Table 1 - Equivalent A-weighted sound pressure levels of the stimuli used in the listening tests.

Listening Experiments

The listening test was divided in two parts. In the first part assessments of annoyance of the sound from the wind turbines according to the questions in ISO

15666 using an 11-point category scale (0-10) with verbal labels were made. The second part of the test addressed the characteristics of the sound from the wind turbines using a method that combined semantic differential and paired comparison methods.

Test Subjects

20 Danish naive test subjects participated in the test. All test subjects reported normal hearing for their age but no audiograms were measured. The subjects were 24 to 63 years old, with an average of 46.6 years.

Subjects qualified for participation if they either lived in the country side or declared that they had a wish to live in the countryside. This screening criterion was included in order to get a representative group of people with a preference for more quiet surroundings.

Scenario

For the assessments of annoyance the scenario that the subject was instructed to imagine was: sitting at home in their own garden in the countryside drinking a cup of coffee or tea and maybe reading the newspaper or a book.

To help visualize the context for the subjects a picture of a wind turbine was projected on a large screen in front of them in the standardized listening room. The pictures supported the presented stimuli by bringing the wind turbine closer (enlarging) for the stimuli at 6 HH than the ones at 12 HH. The visual angle of the turbines at the screen was approximately as they would be when seen at these distances.

Attributes

For the assessments of perceptive attributes in the second part of the listening test, a list of four attributes was defined. The attributes were: Loudness, Swishing sound, Tonality and Pace. Besides these a repeated question for the annoyance under these circumstances was included.

For each attribute, a written definition was provided for the subjects to minimize the effect of divergent concepts of the attributes. Also an acoustical example on Swishing sound and Tonality was presented for the subjects before the test to ensure their understanding of these terms.

Answering Scales

Different scales were used for the two listening tests. The answering scale used for the assessments of annoyance according to ISO 15666 was an 11-point category scale with five verbal labels added for clearer definition of the scale across subjects. The scale is shown in Figure 4.

Not at all		Slightly			Moderately		Very			Extremely
0	1	2	3	4	5	6	7	8	9	10

Figure 4 - Rating scale used for assessments of annoyance according to ISO 15666.

Danish translations of the words on the scale shown were used [6]. Ratings on the different perceptual attributes were given on continuous scales on a computer screen via a mouse. The screen layout is shown in Figure 5.

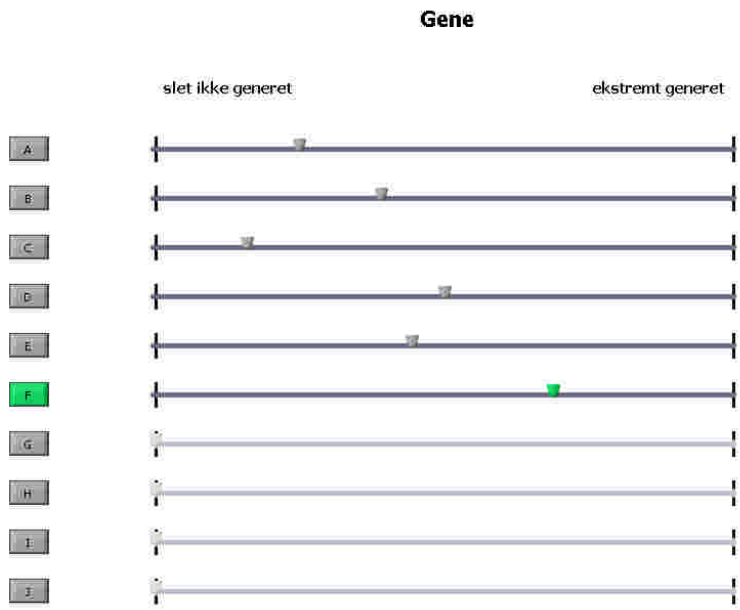

Figure 5 - Screen layout for presentation and assessment of the stimuli.

The slider's positions were read by the software on a continuous scale from 0 to 15. The 15 units correspond to the length of the scale in centimetres when displayed on the screen.

Test Procedure

The listening tests were conducted in an EBU 3276 standard listening room at DELTA. The stimuli were presented via headphones. A photo of the setup is shown in Figure 6.

Figure 6 - The setup in the listening room at DELTA.

The sound pressure levels of the system were calibrated each day by measuring the acoustical output of the headphones placed on a HATS. Groups of up to four subjects performed the listening test simultaneously.

For the assessments of annoyance according to the question and scales of ISO 15666 all subjects in the group were presented with the same stimulus via headphones and they were instructed to wait until the completion of each stimulus before placing their individual final mark on the printed rating scale. The rating was given on the basis of the following question: 'If you imagine this is the sound in your garden, how disturbed or annoyed would you feel of the sound from the wind turbine?' The subjects were not allowed to talk to each other during the listening test. The stimuli for the ISO 15666 assessments were divided into two groups: at 6 HH and at 12 HH distance. Each of the stimuli groups was subdivided into groups with and without natural background noise. A stimulus with only the sound of natural background noise was added to each of the groups containing stimuli with natural background noise. The stimuli were randomized within groups and for group presentation order across subject groups to eliminate order effects.

In the second part of the listening test concerning assessments of perceptive attributes, the subjects were conducting the test individually. For each attribute, the subject could shuffle between all 10 stimuli and make ratings at own will until they felt confident about the assessments. The order of the attributes was fixed for the first two attributes to be 'Annoyance' and 'Loudness'. The remaining attributes were randomized between subjects. The answers from the test subject were automatically stored.

On completion of the listening tests, each subject completed a 9-item noise sensitivity questionnaire developed by Karin Zimmer and Wolfgang Ellermeier translated into Danish (to be found in [11] in English and Danish).

The total time of the listening tests was about 1 hour 30 min including break.

Instrumental Analysis

In the search for objective psychoacoustic metrics to describe relevant perceptive attributes of the sound from the wind turbines, all stimuli used in the listening test were analyzed using Brüel & Kjær PULSE Sound Quality software. Calculations on loudness, sharpness, roughness and fluctuation strength were made. To measure tonality in the stimuli the noise analysis software “noiseLAB” developed by DELTA was used [7]. In noiseLAB tonality is measured according to the international standard ISO 1996-2 Annex C.

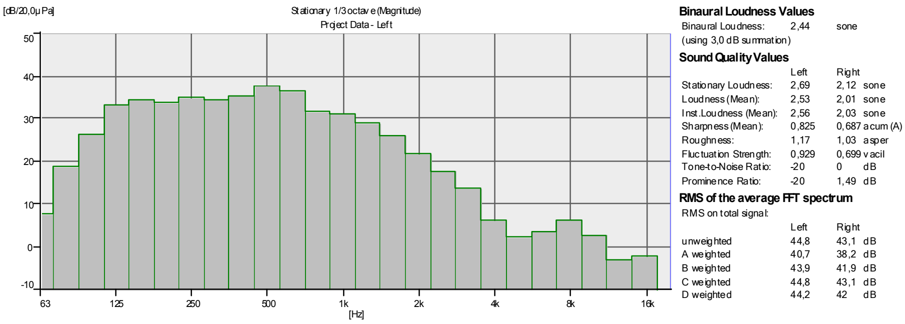

Figure 7 - Output from Brüel & Kjær PULSE Sound Quality software for 1/3-octave average spectrum with sound quality metrics.

Physical Metric on Swishing sound

The perhaps most dominant characteristic in the emitted sound from large wind turbines is the swishing sound caused by the wings rotating in the air. This component is described in most studies on annoyance of wind turbines as being a significant contributor to the overall annoyance. An attempt was made to create a metric describing the swishing sound.

First step of the process was to find the frequency band where the swishing sound was most dominant for the auralized distances of 6 HH and 12 HH. A first suggestion for a pass band was made by applying different band pass filters to the stimuli and listen to the outcome. The target of a metric would be a measure for the amplitude and frequency modulation in the specified frequency band. The psychoacoustic metric called fluctuation strength already exists and measures both types of modulations in sounds [2]. Therefore by applying the fluctuation strength for the specified frequency band a first version of a psychoacoustic metric on swishing sound was formulated.

In Bruël & Kjær PULSE Sound Quality software the fluctuation strength was measured for the 350 Hz – 700 Hz band pass filtered stimuli. Different cutoff frequencies and band widths were tested to verify that the largest value on fluctuation strength was found at exactly the identified pass band. (In an earlier study [4] for smaller turbines the same effect was found to be most prominent in the 1 kHz range, but the 350-700 Hz range seems to be the optimum for large modern wind turbines).

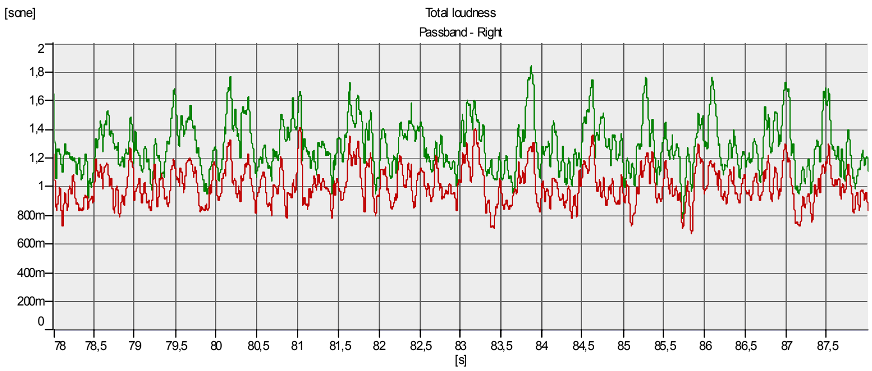

Figure 8 - Stationary Loudness vs. time in the pass band 350 Hz – 700 Hz for a selected sequence of 10 seconds to illustrate the metric on swishing sound. (Green: left ear, Red: right ear channel).

Results

The results from the ISO 15666 scales annoyance ratings on the 90-second stimuli with and without natural background noise (BN) are given below:

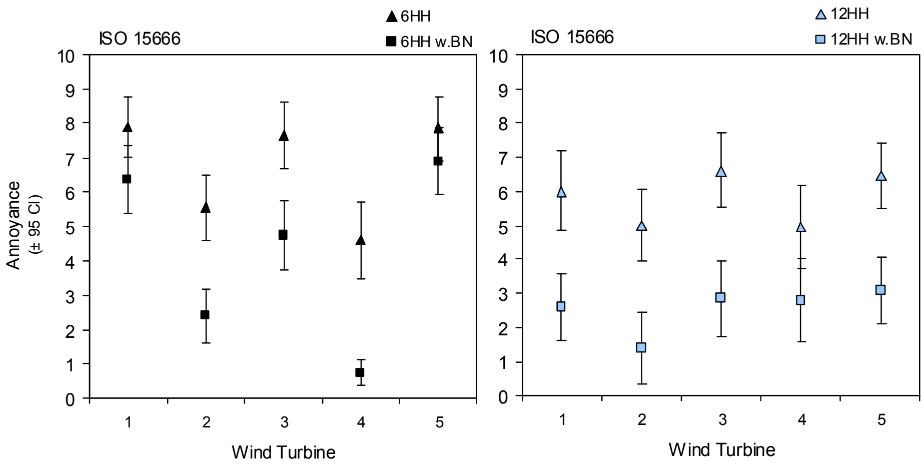

Figure 9 - Assessments of annoyance according to the scales of ISO 15666 on 90-second stimuli at auralized distances of 6 HH and 12 HH from the wind turbines with and without natural background noise.

The influence of natural background noise on the annoyance of sound from the wind turbines is significant. The annoyance decreases from 6 HH to 12 HH except for wind turbine 4. However, this can be explained by the presence of a clearly audible tone placed in a frequency band of which the sound propagation induces less attenuation at 12 HH than for 6 HH.

The results from the assessments of perceptive attributes for 20-second stimuli of wind turbines at auralized distances of 6 HH and 12 HH are presented as a function of the corresponding calculated physical metric.

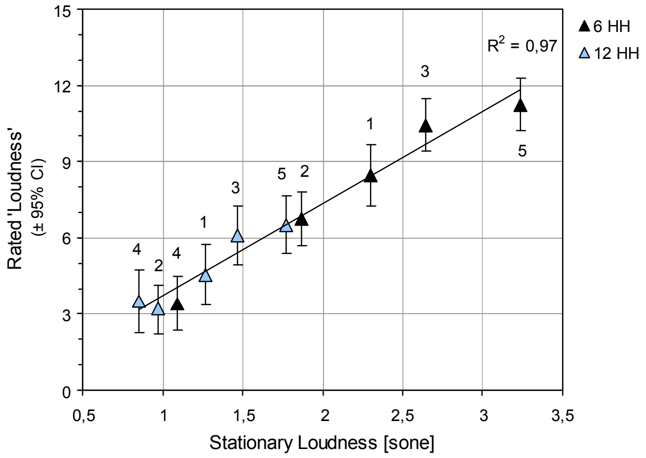

Figure 10 - Rated 'Loudness' versus calculated Stationary loudness.

There was a high correlation ($R^2 = 0.97$) between the perceptive rated 'Loudness' and the metic for stationary loudness of the stimuli. The correlation between rated loudness and A-weighted sound pressure levels of the stimuli was $R^2 = 0.94$.

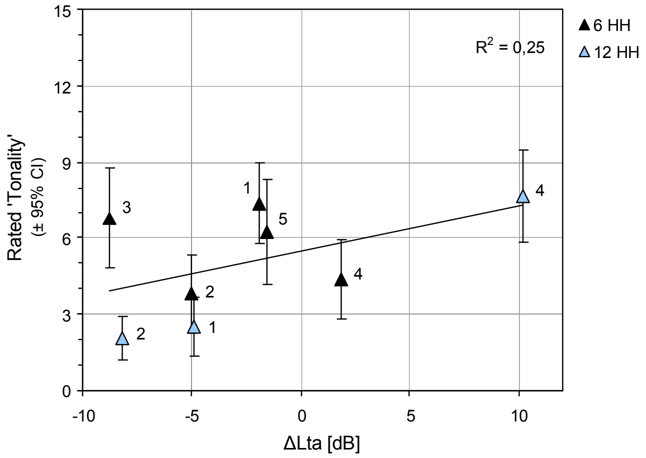

Figure 11 - Rated 'Tonality' versus calculated prominence of tones ΔL_{ta} according to ISO 1996-2.

Perceptive rated tonality did in this case not correlate very well ($R^2 = 0,25$) with the metric for the prominence of tones. The combination of stimuli with tone levels below the average masking threshold ($\Delta L_{ta} = 0$ dB) and the use of only slightly trained naive listeners may explain this. According to [8] naive listeners should be used for affective judgements (e.g. annoyance) while trained listeners or experts should be used for perceptive assessments.

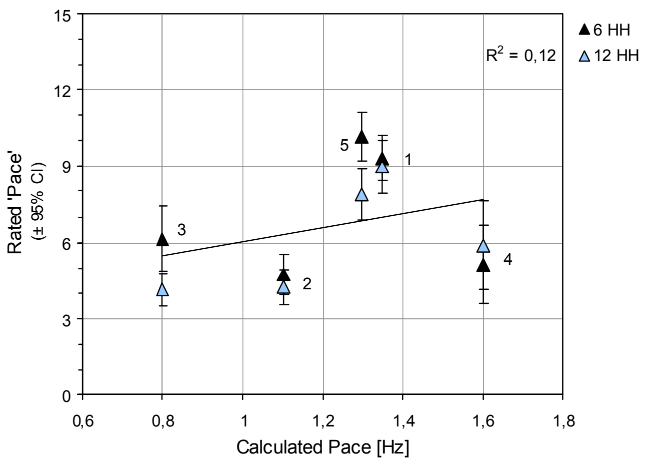

Figure 12 - Rated 'Pace' versus calculated 'Pace'.

It was surprisingly hard for the subjects to rate the pace of the wind turbines, even though the subjects were allowed to shuffle between all 10 stimuli before giving their final rating.

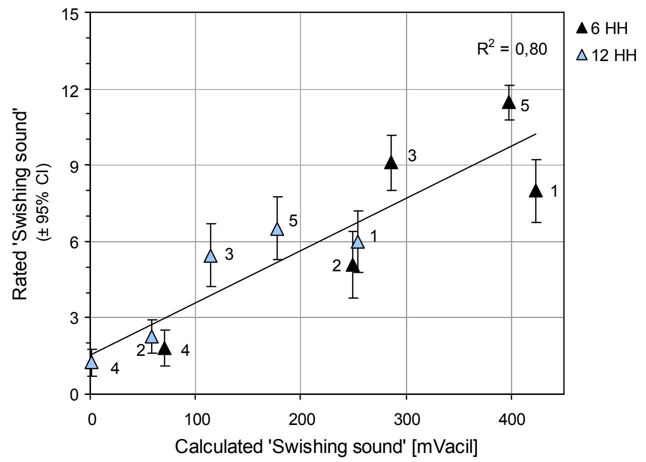

Figure 13 - Rated 'Swishing sound' versus calculated 'Swishing sound'.

The metric on swishing sound correlated well (R^2 = 0.80) with the perceptive ratings on 'Swishing sound'.

Results from the noise sensitivity test showed no correlation with age (R^2 = 0.04) or with the mean annoyance rating (R^2 = 0.01). The mean noise sensitivity of the subjects was 64 on a 0-100 scale, which is categorized as medium noise sensitive (33-66).

The results from the annoyance assessments of the 90-second stimuli can be described as a logistic function which is derived from logistic regression analysis [11]. Results from two international field studies are also modelled in [11] and shown in Figure 14.

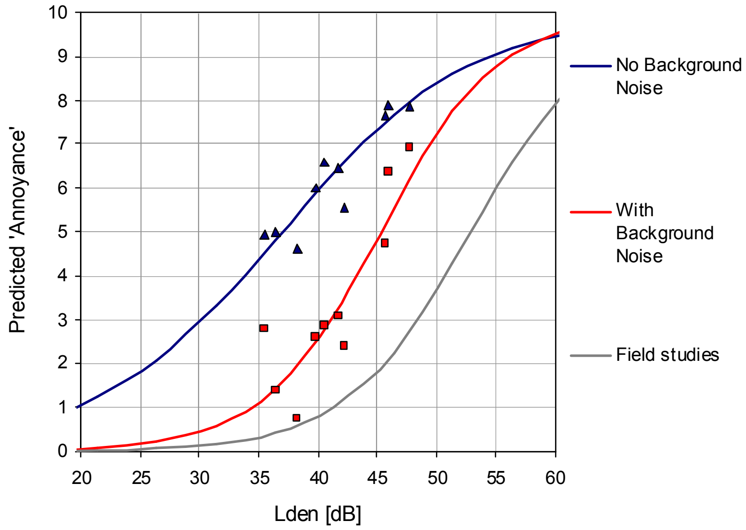

Figure 14 - Prediction model on annoyance for the 90-second wind turbines sounds with and without natural background noise. A common model for results from two field studies is also shown.

The prediction model is based on the day-evening-night level (L_{den}) of the wind turbines. The common curve for the two field studies is calculated in [11] from results in [9] and [10].

The effect of natural background noise is clear. By adding natural background noise, the wind turbine sound is masked at low levels and becomes less annoying. Other results, not presented in this paper, show that the model for annoyance can be improved by including the metrics for prominent tones and for the swishing noise.

By comparing the results from this laboratory study with the results from the two field studies, it is clear that many factors influence the result. The primary difference between the field studies and this laboratory study is the context. Even though great effort was made to create a relevant context in the listening room, it is not possible to make people feel at home. Another difference is that the subjects in this study were asked specifically about how annoyed they would be of the wind turbine sound if they were sitting in their garden in the countryside. In the field studies the questions were on a more overall level (“at home”). The use of different scales in the field studies and this laboratory study may also be a factor even though the scales have been normalised to the same range.

Conclusion

In the presented study wind turbines were recorded and auralized at distances relevant for the environmental aspects in the Danish legislation for protection of the people living next to them. Auralization was based on the sound propagation model Nord2000. The effect of natural background noise on the annoyance of sound from wind turbines was also investigated. Listening experiments were conducted using subjects who were representative for the group of people living in the countryside near wind turbines.

Natural background noise had a significant effect on the rated annoyance. By adding natural background noise to the wind turbine sounds, the rated annoyance decreased. This does not come as a surprise since the masking effect from wind generated noise in the vegetation is well known. One could then consider whether background noise should be a parameter in the Danish legislation when setting noise limits and assessing annoyance in the environment around new wind farms?

Perceptive attributes relevant for the annoyance of sound from wind turbines were also rated in the listening experiment and the results were linked to calculated physical metrics. The two primary attributes related to annoyance in wind turbine sounds are tonal components and the swishing sound from the rotating blades. The rated tonality of the stimuli did not correlate too well with the metric for prominence of tones ΔL_{ta} in this experiment. A metric for calculating swishing sound was developed and it correlated well with the ratings on ‘Swishing sound’ in the stimuli.

Finally, noise sensitivity measured on the participating subjects did not correlate with the mean annoyance score.

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A proposal for evaluating the potential health effects of wind turbine noise for projects under the Canadian Environmental Assessment Act

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Abstract

The *Canadian Environmental Assessment Act* (CEAA) requires certain projects with federal government triggers to undergo an environmental assessment (EA) before receiving federal government approval. The intent is to ensure that actions are taken to promote sustainable development and to ensure that projects do not cause significant adverse environmental effects. Environmental effects may include health effects from project related noise. To help the responsible authorities for an EA make this determination, they may request specialist information and knowledge from Health Canada or other specialists, as prescribed under CEAA. For wind turbine projects, Health Canada has provided advice based on the evaluated project-related changes in high annoyance, per ISO 1996-1 and U.S. Federal Transit Administration (FTA) noise impact criteria. In the U.S document, a 6.5% increase in high annoyance can be considered a severe noise impact. Extension of the U.S. FTA document to wind turbine noise in quiet rural settings implied that a severe noise impact for wind turbines could correspond to sound levels as low as 45 dBA. This takes into account the finding that in quiet rural areas there may be a greater expectation for and value placed on "peace and quiet" equivalent to up to 10 dB. A constant sound level less than 45dBA measured outdoors also corresponds to the WHO threshold level for sleep disturbance when windows are partially opened. Furthermore, if sound levels at the receptor are kept below 45dBA, the ANSI S12.2 rattle criterion will not be exceeded in the 63 Hz octave band. Turbine noise has been evaluated at the wind speed that produces the highest noise from the turbine, and background noise has been evaluated in calm winds. This allows for sheltering

by obstructions or wind speed gradients related to stable atmospheric conditions. Wind turbine construction noise has been assessed in terms of whether widespread complaints may be expected from its normalized day-night sound level, based on the EPA “Levels” document.

Introduction

The *Canadian Environmental Assessment Act* (CEAA) requires certain projects with federal government triggers to undergo an environmental assessment (EA) before receiving federal government approval. The intent is to ensure that actions are taken to promote sustainable development and to ensure that projects do not cause significant adverse environmental effects. Environmental effects may include health effects from project related noise. To help the responsible authorities for an EA make this determination, they may request specialist information and knowledge from Health Canada or other specialists, as prescribed under CEAA [1;2]. Noise has been an issue in a number of projects of major social, economic and military importance and wind turbine projects have become more common in the recent past.

As of 2006, Canada became one of 13 countries to exceed 1000 megawatts of wind capacity [3]. This was owing in large part to a doubling of wind energy capacity in 2006 in Canada to 1459MW and it has been projected that Canada will increase this capacity to at least 10,000MW by 2015. The increase in projects falling under CEAA can be explained by the fact that the development of wind energy in Canada is partially related to financial support through Federal government programs such as the now completed Wind Power Production Incentive (WPPI) program and the current EcoEnergy for Renewable Power program. EcoEnergy for renewable power is coordinated by Natural Resources Canada with a Federal commitment of $1.48 billion to increase Canada’s supply of clean electricity from renewable sources such as wind, biomass, low-impact hydro, geothermal, solar photovoltaic and ocean energy. The EcoEnergy initiative is intended to increase the production of energy to 14.3 terrawatt hours from renewable energy sources [4].

As a starting point for the potential development of Health Canada guidelines, this paper provides proposals for criteria for evaluating the potential health effects of wind turbine noise for environmental assessments. The reasoning behind the proposals is summarized.

Proposed Criteria for predicted sound levels

On the assumption that the wind turbines produce constant noise, it is proposed that a 45 dBA Leq for the sound level not be exceeded at the most exposed façade of a noise sensitive receptor during wind turbine operation in quiet rural settings[1]. In the rare cases where turbines have been erected in more urbanized areas, higher levels are proposed for the criterion value of the assumed continuous sound level (i.e. from 55 to 69 dBA Leq). In these latter cases, the proposed criterion value is the wind turbine sound level that leads to a 6.5% increase in the percentage highly annoyed.

The Leq value is the predicted sound level determined for the highest wind turbine sound power level found as a function of wind speed, evaluated as if all noise sensitive receptors are sited under favourable, propagation conditions.

The proposed sound level criteria are based on project-related changes in high annoyance, evaluated in terms of changes in the percentage highly annoyed (%HA) from the noise environment without the wind turbine(s) to the noise environment with the wind turbines, as per ISO 1996-1 [6]. The second factor determining the proposed criterion value, is the U.S. Federal Transit Administration's (FTA) [7] consideration that a 6.5% increase in the %HA corresponds to a severe noise impact. Furthermore, if sound levels at the receptor are kept below 45dBA, the ANSI S12.2 [8] rattle criterion will not be exceeded in the 63 Hz[2] octave band. A 45 dBA Leq for constant noise is also consistent with the World Health Organization's (WHO) recommendation that the equivalent sound level indoors should not exceed 30 dBA for continuous background noise for a good night's sleep[9]. With windows partially opened, this

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[1] The characterization of an area as a "quiet rural" is ultimately left up to the project proponent to determine through community consultation. However, until the proponent makes this determination, Health Canada assumes an area to be a quiet rural area when the background sound levels are below 45dBA during the day and 35dBA during the night. In such areas, population density is typically less than 8 dwellings per square kilometre [5].

[2] In ANSI S12.2 [8] recommendations are given for the 16, 32 and 63 Hz octave bands, but 63 Hz is the lowest measured band in the normative section of IEC 61400-11.

translates into an outdoor continuous sound level of 45 dBA. A 40-45 dBA limit is also similar to the most stringent values used for industrial noise sources in quiet areas in some of the provinces in Canada (e.g. Alberta, Quebec, Ontario and Manitoba -- a more detailed discussion of Provincial guidelines is given below).

Dose response for annoyance

Preferably, the proposed criteria would be based on a dose response relationship that was specific to wind turbines. Independently verified dose response relationships are available for transportation sources [10], but there has only been a small number of published dose response relationships available that are specific to wind turbines [11;12].

One study of older wind turbines from Sweden [12] suggested that the percentage "very annoyed" by wind turbine noise was around 8% at a predicted value of 36 dBA Leq, rising steeply to around 36% as a predicted sound level of 40 dBA was approached. However, these authors did not reproduce this observation in a follow up to this study [11] where there was no statistically significant relationship between wind turbine sound level and the percentage of surveyed respondents who indicated that they were either rather or very annoyed by wind turbine noise.

Adjustments compared to other industrial sources

Quiet areas

The lack of a specific dose response relationship for wind turbines and health effects requires that effects be evaluated by applying the relationships for other sources. It is common to apply adjustments to other sources, but it is not immediately obvious what, if any, should be applied to wind turbines.

In quiet rural areas where wind turbines are typically sited, it is proposed that a 10 dB adjustment be applied to project noise compared to industrial sources in urbanized settings. This is a precautionary adjustment based on the statement in ISO1996-1:2003 [6] indicating that research has shown that there is a greater expectation for and value placed on "peace and quiet" in quiet rural settings, which may be equivalent to up to 10 dB.

Tonal noise

It is not common for modern wind turbine designs to be associated with tonal noise, however, it needs to be verified whether the project gives rise to tonal sound. This sound level information should be available if the manufacturer's specifications conform to the requirements of International Electrotechnical Commission (IEC) standard IEC 61400-11 (2002) on Wind turbine generator systems - Part 11: Acoustic noise measurement techniques [13]. In accordance with the ISO 1996-1 standard, audible tonal sound is adjusted by +5dB in the determination of noise annoyance. To the extent that tonal noise is present, the proposed criterion level of 45 dBA will need to be reduced.

Low frequencies

Even though research shows that annoyance is greater when low frequency noise is present [6;14], modern turbine designs are not normally associated with audible levels of low frequency or infrasound [15]. Natural levels of wind induced noise make wind turbine noise below the 50 Hz 1/3rd octave band difficult to measure and this information is not required by standard IEC 61400-11 [13]; although it is considered optional information. Therefore, the proposed criterion sound levels are based on a comparison of sound levels from the project in the 63 Hz octave band[3] to the ANSI S12.2 [8] rattle criterion to indicate the effect that these low frequency sounds may have on the noticeability of noise-induced vibrations in light-weight ceilings and duct work and rattling in light fixtures, doors and windows. In the 63 Hz octave band, moderately noticeable vibrations are associated with a sound level of 70 dBZ, or 43 dBA (conservatively assuming that all the sound energy is in the 63 Hz octave band)

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[3] In ANSI S12.2 [8] recommendations are given for the 16, 32 and 63 Hz octave bands, but the 50 Hz 1/3rd octave band is the lowest measured band in the normative section of IEC 61400-11.

[16]. Above 43 dBA, rattles due to low frequency noise may become a possibility for wind turbine noise impacts. If this level is exceeded, then a comparison should be made to 80 dBZ for the 63 Hz band. At 80dBZ, clearly noticeable vibrations may occur and they could be ongoing [8]. Therefore, it is reasonable to conclude that there could be an increase in annoyance from these vibrations.

Other Potential Sound Level Adjustments

Other sound level adjustments that would help predict community reaction/annoyance towards wind turbines were also considered in the development of the proposed criterion. These other adjustments have not been applied due to lack of supporting data. In ISO1996-1 source specific adjustments are applied to aircraft and electric rail, which reflect human response to these, but no similar adjustments have been proposed for wind turbines.

Wind turbines create a characteristic “swooshing” sound [13]. In the province of Ontario, in land use guidelines [17;18] a +5 dB adjustment is specified for a project that contains a cyclic variation in sound level. This adjustment is applied when the project noise has an audible “beating” or other amplitude modulations, but not applied to wind turbines, nor has it been used in other jurisdictions. For these reasons, this adjustment was not applied to the proposed wind turbine criterion.

Although it has not been adopted in the proposed criterion, another plausible adjustment for consideration stemmed from an analysis of the similarities between some aspects of aircraft noise and wind turbine noise under certain conditions. When large turbines are built close to homes (e.g. less than 5 times the turbine hub height), the source may be more similar to an overhead source than a typical ground-level industrial source. When turbines are located close to homes, the noise can enter through the roof of the house, which has comparatively less sound insulation than the walls. Noise barriers have little effect, and unlike ground based sources, there is no acoustic shadow due to wind direction and temperature gradients. ISO1996-1 2003 suggests a +3 to +6 dB adjustment on aircraft noise. It has been hypothesized that one of the reasons for the demonstrated adjustment for aircraft noise is the fact that it is an overhead source, suggesting that the potential for a +3 to +6 dB adjustment for wind turbine noise may need to be investigated if large turbines are built close to homes where they may begin to take on the characteristics of an overhead source. More research would be needed to assess this potential adjustment. Also, at this time, it does not appear to be an issue in Canada because most large turbines are installed at set-back distances further than about 5 times the turbine hub height; however, no guidelines exist on how far a turbine should be from a noise sensitive receptor.

Justification for use of the predicted worst case

The proposed criterion sound level is the predicted sound level determined for a worst case condition for the highest wind turbine sound power level found as a function of wind speed, evaluated as if all noise sensitive receptors are sited under favourable, propagation conditions.

Frequently the wind speed at the receptors is assumed equal to the wind speed associated with the noise levels obtained using the IEC standard [13]. However, this can create a risk of unexpected annoyance from intruding wind turbine noise because the wind speed at the noise sensitive receptor may be significantly different than that at the turbine hub due to sheltering by obstructions or wind speed gradients related to stable atmospheric conditions.

The United Kingdom's Department of Trade and Industry [19] has suggested that, in some cases, receivers can be sheltered from the wind so that there is no masking of the turbine noise by ground level wind noise. In Canada, wind turbines are often sited on hilltops. On level ground sheltered areas due to treed wind breaks are common to avoid winter whiteout and snow drifting. These stands of trees can attenuate wind noise heard on the ground, yet may do little to attenuate wind turbine noise (i.e. turbine noise becomes more noticeable at the receptor).

Also, under conditions of atmospheric stability, (i.e., clear nights) wind speed at receptors may be significantly lower than wind speed at the turbine hub. Van den Berg [20] has shown that the wind speed at night is up to 2.6 times higher at the turbine hub than on the ground (at 10m). Based on atmospheric stability data from the Netherlands [21], worst case conditions might be expected on clear nights when wind speed on the ground may be less than 5 m/s and speed at the turbine hub can exceed 10 m/s. Therefore the wind turbine noise can be well above the background sound level due to the wind at receptors since some turbine noise levels peak at wind speeds between 9 to 12 m/s [22].

The noise level criteria proposed here should not be considered as strictly applied limits. It is possible that the noise from the wind turbine could be masked by wind noise. This situation can be identified by historical data for wind speed as a function of height and documented wind noise at the noise sensitive receptor.

Prediction

In Canada, predicted noise levels are usually based on ISO 9613-2 1996, which has a standard uncertainty of +/- 3 dB [23]. As a result, it is proposed that a cautious approach in environmental assessments would be to prepare possible mitigation measures if uncertainties in predicted noise levels suggest that the proposed criterion levels may be measurably exceeded in operation.

Provincial guidelines

As noted above, the proposed criteria are not to be interpreted as strictly applied limits. First and foremost, in order to take into account regional variations in noise sensitivity to industrial installations, applicable provincial or territorial legislation, guidelines and policies need to be met. In the provinces and territories, wind turbines are evaluated under the category of stationary or industrial noise sources. For Zone I land use (i.e., isolated single family detached or semi-detached dwellings, schools, hospitals or other teaching, health or convalescent institutions) Quebec’s night time limit is Leq 40 dBA. This limit increases to 45dBA for Zone II land use (i.e. multi-family dwellings, mobile home parks, institutions or camping grounds) [24].

Ontario and Alberta are the only provinces with guidance specific to wind turbines [24-26], and this limit increases with increasing wind speed. In quiet areas when wind speeds at 10 m height is below 6 m/s the noise limit is 40 dBA and at 11 m/s the noise limit rises to 53 dBA. For industrial sources in quiet areas in Ontario the regulated noise limit is 40 dBA at the property line of the nearest noise sensitive receptor [17]. In a rural area, application of Alberta's Energy Utilities Board Directive 038 [26] would yield a criterion with a night time Leq of 40 dBA for wind speeds between 6-9 m/s. Of note, in Alberta, existing noise due to wind turbines and other energy projects are not considered background noise but are considered to contribute to the noise produced by the new project.

Audibility

An increase in community reaction can occur if an intruding noise which was supposed to be inaudible or barely perceptible is readily heard by the community. Therefore, it is also proposed that environmental assessments avoid statements that suggest wind turbines are inaudible, or that changes of up to 5 dB are either not, or barely noticeable. Health Canada's knowledge of some community complaints and follow ups regarding wind farms suggests that it is difficult to predict whether wind turbine noise will be identifiable (i.e., audible/noticeable). The EPA "Levels" document [27] states that when the "normalized day-night sound level of an identifiable intruding noise is approximately 5 dB less than the day-night sound level" the community is expected to have "no reaction although noise is generally noticeable." In the "Levels" document, sporadic complaints would be expected for a 3dB increase in environmental noise level due to an identifiable intruding noise.

Construction noise

In Canada construction noise limits are typically governed by municipal noise by-laws. One exception is the province of Quebec, where, for isolated single family dwellings the daytime limit is 45 dBA and the night time limit is 40 dBA [24]. Due to typically large setback distances from residences, wind turbine construction noise is not usually an issue at noise sensitive receptors. However, it is proposed that, if potential health effects from construction noise are to be assessed, then, for each representative noise sensitive receptor, the environmental assessment should provide the expected duration of construction (years, months or weeks or days) and an estimate of noise levels, or sound limits that will be met as well as any plans to monitor or mitigate construction noise or complaints arising from construction noise.

It is also proposed that short term construction noise be evaluated using the US EPA “Levels” document method of assessing qualitative complaint reactions [27]. If the resulting levels are predicted to result in widespread complaints or a stronger community reaction (according to [27]), noise mitigation is proposed. Health Canada has used the Alberta Energy Utilities Guide 38 [5] for guidance as to whether construction noise should be considered temporary. If it lasts for less than 60 days at a receptor, then it can be considered temporary[4] [26].

Based on an interpretation of the US EPA “Levels” document, for receptors in quiet rural areas, it is proposed that an Ldn of 57 dBA can be used as a typical criterion value. This measured value is based on a normalized value of 62dBA. The corrections needed to determine the measured value from the normalized value can be obtained by assuming (i) a quiet rural community (-10dB), (ii) the community is aware that the operation causing noise is very necessary and will not continue indefinitely (+10dB), and (iii) pure tone or impulsive character is present in the construction noise (-5dB).

[4] EUB Directive 038 Noise Control states that “Drilling and servicing rigs fall into the temporary facility category even if they are expected to be at a location more than 60 days. Temporary activities generally do not require an NIA. The licensee is responsible for noise control.” p.13

Conclusions

To provide protection from high annoyance and sleep disturbance, the health effects, standards literature and published data on wind turbines provide support for a proposed criterion value of 45 dBA for wind turbine noise at residences, where the value refers to the Leq predicted for the maximum sound power level found as a function of wind speed. Complaint reactions and their follow ups for wind turbines and other noise sources indicate that it is advisable for environmental assessments to not refer to inaudibility or lack of noticeability of wind turbines. The criteria proposed in this paper appear to be a useful starting point for comparison to applicable provincial guidelines and the potential development of Health Canada guidelines for provision of advice on wind turbine noise to Natural Resources Canada under CEAA.

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Perceived loudness of wind turbine noise in the presence of ambient sound

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Abstract

Human responses to wind turbine noise are difficult to predict. Many non-acoustical factors influence the likelihood of annoyance. Even acoustical factors, such as $L_{A,eq}$, are often not sufficient to fully describe the range of responses, especially at lower levels. Similar difficulties are encountered in applications as diverse as personal computers, environmental sound emitted from industrial sources, and sound transmitted through partitions. In each case, it has been found that the auditory masking effect of the local ambient environment plays a significant role. It turns out that the "quietest" environment may not be a silent one, but rather one in which the local ambient sound is perceived by the subject as neutral and/or appropriate in quality and which masks intrusive sounds of lesser perceived quality. In the case of wind turbines, annoyance is most often reported out of doors, where the local ambient is affected to a highly variable degree by vehicular traffic and by wind conditions. In the ideal result, the intruding sound is fully masked and becomes inaudible. Zwicker developed a method of "partially masked loudness" to estimate the residual loudness of a sound in the presence of ambient sound. The method will be applied to wind turbine noises juxtaposed against natural ambient sounds. This method will have its primary usefulness at greater distances from the turbine where levels approach ambient and where, because a larger area is swept out, a larger pool of potentially annoyed subjects may reside.

Introduction

Environmental noise challenges are similar to product sound quality challenges in that every sound carries a message. If the message is not explicit, one will be assigned by the listener. When that sound emanates from "elsewhere", such as a wind turbine or industrial plant, the message may differ from that typical for the local environment. At that point, individuals may find that they dislike the message and thus experience annoyance.

Numerous product sound quality studies have shown that loudness is a key contributor to annoyance. Zwicker [1] showed that unbiased annoyance tracks N_{10} (the loudness exceeded 10% of the time) raised to a power somewhere between 1.3 and 1.8. If the loudness of a sound is reduced through noise control efforts, the annoyance it creates will also be reduced. However, loudness (and annoyance) can also be reduced through the presence of a benign masker.

Psychoacoustic masking is the process by which one sound is obscured by another. A complete discussion of the psychophysical mechanisms of masking is beyond the scope of this paper (see Zwicker and Fastl [2]). The degree of masking is determined by both the relative levels of the two sounds and the relation of their spectral shapes. When the intrusive and ambient sounds vary with time, the degree of masking can also vary with time.

Studies of human response to wind turbine noise [3][4] show moderate correlation to the computed time-averaged A-weighted sound pressure level $L_{A,eq}$ of the turbine noise. Unpredictable responses occur however and seem to become more numerous at lower sound levels. Outright reversals, in which lower sound levels are rated more annoying, are not uncommon. It is likely that a great deal of this variation is due to individual personalities and experiences. However, this paper explores the influence that differing local ambient sounds can have on the perceived loudness, and hence the annoyance, of wind turbine noise.

Partial masking method

Zwicker [5] developed a method for estimating the residual loudness of a stationary sound in the presence of a masking sound. The specific loudness distributions [6] for the intrusive sound and masker are compared. If the masker is significantly louder at a particular frequency, the residual loudness is zero: the intrusive sound at that frequency is not perceived. If however the intrusive sound is significantly louder than the masker, the loudness of the intrusive sound is unaffected. In between, a transition zone exists wherein the intrusive sound is perceived but at a reduced loudness.

The partially masked specific loudness distribution N'_P is calculated from the specific loudness distribution of the intrusive sound N'_I and the masker N'_M as:

$$\begin{aligned} N'_P &= 0 && \text{for } N'_I \le 0.8N'_M \\ N'_P &= \left(\frac{5N'_I - 4N'_M}{3}\right) && \text{for } 0.8N'_M \le N'_I \le 2.0N'_M \\ N'_P &= N'_I && \text{for } N'_I \ge 2.0N'_M \end{aligned} \tag{1}$$

and

$$N_P = \sum N'_P \Delta z \tag{2}$$

where N_P is the partially masked loudness of the sound, and z is the critical band rate in bark.

In order for a sound to be masked to the point of imperceptibility ($N_P = 0$), the specific loudness of the masker must be at least 25% (~ 4dB) greater than the intrusive sound in all critical bands. Partial masking occurs all the way up to the point where the specific loudness of the intrusive sound is double that of the masker (~10-12 dB greater).

The most effective masker is therefore a sound with the same spectral shape as the intrusive sound: in would need to be only 4 dB greater to achieve complete masking. Masking becomes less effective as the masking spectral shape diverges from that of the intrusive noise. The degree of masking benefit is therefore not solely a matter of A-weighted level difference or any other single number rating.

This method has been used successfully to optimize the perceived performance of partitions [7][8][9], leading in the limit to the illusion of "soundproof" partitions.

Application to wind turbine noise

A high quality recording of a wind turbine was obtained [10]. The level of the sound was normalized to 40 dBA to simulate what might be received at a distant location. The turbine noise was dominated by a 625 Hz tone, a low-frequency swishing sound associated with blade pass, and a high-frequency complex related to individual blade passes and Doppler-shifted blade-tip whistling.

Two examples of local ambient environments were recorded, one at 41 dBA and one at 49 dBA, and for the purposes of this paper represent two different locations exposed to the same turbine noise. The former was recorded in the lee of a building, farther away from trees, under reduced wind conditions. The latter was recorded in close proximity to some large, leafy trees during moderate wind conditions (~ 3 m/s) and included insect noises and birdsong. One-third octave band spectra L_{eq} are illustrated in Figure 1.

The time-averaged one-third-octave band spectrum of the turbine is slightly above the 41 dBA environmental spectrum level from about 200 Hz to 1600 Hz. With respect to the 49 dBA environment however, only the 625 Hz tone lies above the masker.

Specific loudness plots for each sound were derived using ISO 532B (see Figure 2). The turbine and the 41 dBA ambient sound have approximately the same loudness (3.5 sone). But because of the difference in the specific loudness distributions the 625 Hz tone is essentially unmasked, and many other components although masked are still perceptible. The residual perceived loudness of the turbine noise is approximately half of its unmasked value (1.8 sone). In the 49 dBA environment, only the 625 Hz tone is faintly perceptible, reducing the turbine noise to approximately 1/10 of its unmasked loudness.

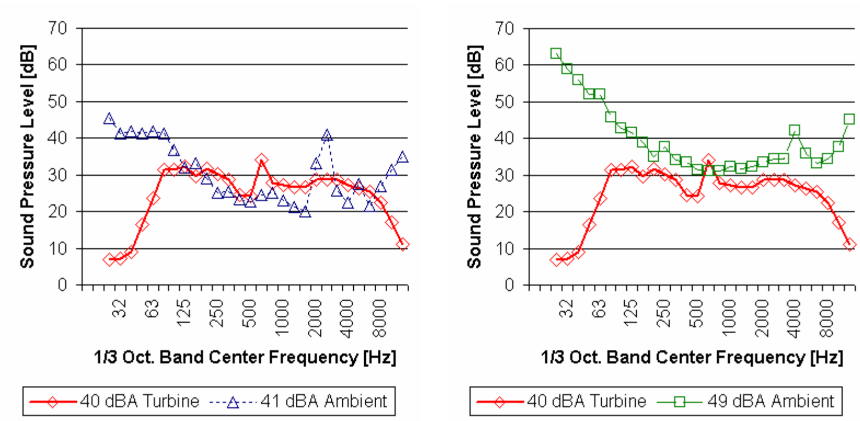

Figure 1: 1/3-octave band spectra of turbine and environmental ambient sounds

Were the 49 dBA environmental spectrum strengthened by several dB in the 630 Hz band, the turbine noise could apparently be rendered imperceptible. It might be easier to add noise of a neutral character (trees, water feature, etc.) at this location instead of reducing the level of the turbine. Conversely, it should be clear that the loss or reduction of environmental sound (e.g., loss of nearby trees) could render the turbine suddenly audible. The author has personally witnessed a case where a newly installed highway noise barrier unmasked a tone from a nearby industrial facility, precipitating significant dissatisfaction in the community.

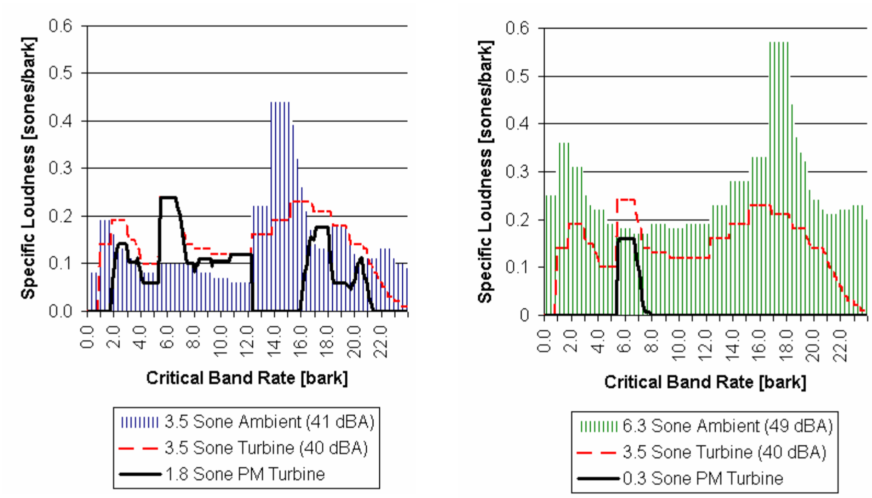

Figure 2: Specific loudness and partially masked specific loudness

Time variation

Short-term time variations can be a significant factor for environmental noise. The presence of wind gusts or turbulence modulates the spectrum of the wind turbine as well as the local wind-driven ambient. Additional sources of environmental noise such as automobile traffic have their own dynamics which are independent of wind conditions. The most obvious time variation associated with wind turbine noise is the “swish” of the blades. And so, just as A-weighted levels provide inadequate detail in the frequency domain from which to assess masking, time averaged sound levels may also provide inadequate detail in a dynamic environment.

Time-varying loudness can be computed according to a method by Widmann and Fastl [11]. The fine structure of the time-varying audibility can then be assessed by applying the partially masked loudness method to time-varying specific loudness distributions. Temporal masking factors [2] are then applied to simulate the “inertia” of human hearing. This method has not yet been standardized.

The loudness and residual loudness of the various components as perceived in the two ambient environments are illustrated in Figure 3 (note the differing vertical scales). The results in terms of N_{10} and N_{50} are summarized below in Table 1.

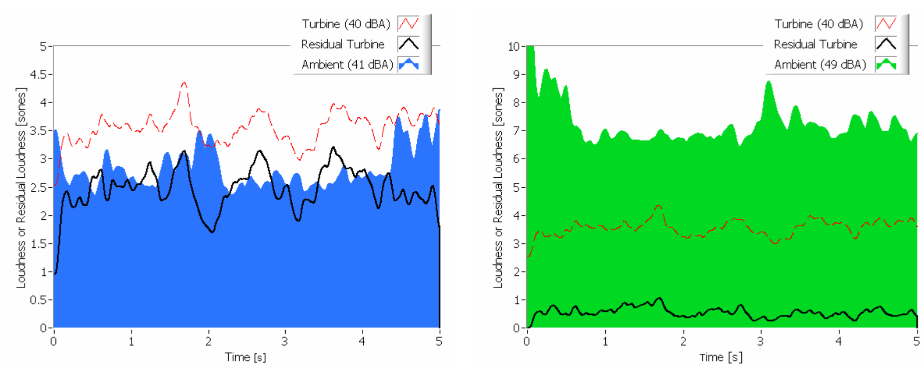

Figure 3: Time-varying residual loudness

Table 1: Statistics of time-varying loudness [sone]

	Turbine	41 dBA masker	Residual Turbine	49 dBA masker	Residual Turbine
N_{10}	3.9	3.4	2.9	8.3	0.8
N_{50}	3.6	2.8	2.5	7.3	0.5

The perceived reduction in average loudness is not as dramatic as was estimated from the stationary L_{eq} spectra because of the nonlinearity of the masking process. The perceived reduction in N_{10}, which drives annoyance, is less than that for N_{50} because it is controlled by the high loudness excursions where masking is weaker.

Conclusions

Variations in local ambient sound conditions may be responsible for reducing correlation in dose-response relationships because the turbine noise may be masked differently at different locations. Zwicker's partially masked loudness method provides an effective tool for assessing these effects through comparison of the wind turbine noise and ambient sound spectra. This method has been adapted to account for the significant time variations of both the noise and masker and yields a residual N_{10}, which in turn is known to correlate with unbiased annoyance. It may therefore be found that dose-response relationships correlate better with the residual N_{10} rather than with $L_{A,eq}$.

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PREDICTION OF WIND TURBINE NOISE AND COMPARISON TO EXPERIMENT

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Abstract
This paper describes the application of a semi-empirical prediction method for trailing edge noise to calculate the noise from two modern large wind turbines. The prediction code only needs the blade geometry and the turbine operating conditions as input. The availability of detailed acoustic array measurements on the same turbines enabled a thorough validation of the simulations. Generally a very good agreement was observed between experimental and simulated results, not only in terms of source spectra and overall sound levels, but also in terms of the noise source distribution in the rotor plane as a function of frequency and observer position. The deviation between predicted and measured overall sound levels (as a function of rotor power) was smaller than 1-2 dB for both turbines, which is smaller than the scatter in the experimental data. All in all, the present study provides a firm validation of the prediction method, which therefore is a valuable tool for the design of quiet wind turbines and for the planning of wind farms.

1 Introduction
Wind turbine noise is still one of the major hindrances for the widespread use of wind energy. The availability of fast and accurate wind turbine noise prediction methods is important for the design of quiet wind turbines and for the planning of wind farms. The present paper describes the application of a semi-empirical prediction method for trailing edge noise to calculate the noise from two modern large wind turbines. The availability of detailed acoustic array measurements on the same turbines provides a unique possibility to assess the predictions not only in terms of source spectra and overall sound levels, but also in terms of the noise source distribution in the rotor plane as a function of frequency and observer position.

The experimental results used in this study were obtained in the European SIROCCO project[1], which aims at a reduction of wind turbine noise by designing new blades with low trailing edge noise emissions. The project focused on two wind turbines: an 850 kW GAMESA turbine and a 2.3 MW GE turbine, with rotor diameters of 58 m and 94 m respectively. Acoustic field measurements were performed on both baseline turbines, to characterize the noise sources and to verify whether trailing edge noise from the blades was dominant. A large horizontal microphone array, positioned roughly one rotor diameter upwind from the turbine, was used to measure the distribution of the noise sources in the rotor plane and on the individual blades. A detailed description of the GAMESA measurements is given in Ref.2.

The simulations in this study are based on the trailing edge noise prediction code developed by Brooks, Pope, and Marcolini[i3] ('BPM' code), which is incorporated in the wind turbine noise prediction code SILANT[4]. Based on boundary layer displacement thicknesses calculated with an airfoil design code, SILANT provides the radial noise source distribution on the blades. This radial source distribution is then extended with the effects of trailing edge noise directivity and convective (or Doppler) amplification, as a function of rotor azimuth and as perceived by an observer at a given position (in this case the position of the microphone array). Finally, in order to allow direct comparison to the measured array results, the calculated rotor noise source distribution is input to an array simulation code, to yield the simulated acoustic source maps.

The organization of this paper is as follows. First, Section 2 outlines the results of the acoustic field measurements on both turbines. Next, Section 3 describes the structure of the wind turbine noise prediction method. The experimental and simulated results are then compared in Section 4. Finally, the conclusions of this study are summarized in Section 5.

2 Field measurements

The acoustic measurements on both turbines were carried out using the same elliptically shaped array of 148 microphones, mounted on a horizontal wooden platform of about 16x18 m^2. The platform was positioned roughly one rotor diameter upwind from the turbine, resulting in a 'view angle' of about 45° (Figure 1). The 'misalignment angle' α is the angle between the rotor axis (depending on wind direction) and the line from turbine to array. Whereas the blades of the GE turbine were untreated, for the GAMESA rotor one blade was cleaned, one blade was tripped, and one blade was left untreated, in order to assess the effect of blade roughness due to e.g. dirt or insects. More details about the test set-up and data-acquisition and -processing procedures are given in Ref.2.

Figure 2 shows pictures of the test set-up in Spain (GAMESA) and The Netherlands (GE), with typical noise source distributions in the rotor plane (averaged over many revolutions). Note that these source maps correspond to the upwind measurement position on the ground, and that the colour scale is relative to the maximum level for each measurement. For both turbines it can be seen that, for an observer on the ground, most of the noise is produced by the outer part of the blades (but not the very tip), during their downward movement. As described in Ref.2, this source pattern, which causes the typical swishing noise during the passage of the blades, can be explained by trailing edge noise directivity and convective amplification. The GAMESA turbine also shows a minor noise source at the nacelle.

Interestingly, for some frequencies both turbines also showed small noise production when the blades pass the tower (see Figure 3 and Figure 5). The nature of this minor 'tower source' is hard to assess on the basis of the present data, but it could originate from (1) reflection of blade noise on the tower, (2) impingement of blade tip vortices on the tower, and/or (3) the upstream influence of the tower on the flow field around the blade.

3 Prediction method

Since the experiments indicated that trailing edge noise is the dominant noise source for both wind turbines, a prediction code was developed which calculates the trailing edge noise from the blades. The calculation can be divided in four steps:

1. The prediction code only needs the blade geometry and the turbine operating conditions (RPM, wind speed, and blade pitch angle) as input. First, the blade is divided into a number of radial segments (21 for the present cases). Next, the local Reynolds number and angle of attack are obtained from an aerodynamic wind turbine model, based on the blade element momentum theory. Then, the RFOIL airfoil design and analysis code[5] is used to calculate for each segment the trailing edge boundary layer displacement thicknesses on the pressure and suction side. RFOIL is an extension of XFOIL[6] and takes into account rotational effects.

2. The boundary layer thicknesses and Reynolds numbers are used as input for the BPM model[3], which is a 2D semi-empirical prediction code for trailing edge noise. This yields the blade noise spectra for the different radial segments of the blade.

3. Next, the effects of trailing edge noise directivity and convective amplification[2] (including the Doppler frequency shift) are applied to these radial source strengths (as a function of rotor azimuth), to obtain the effective noise source distribution in the rotor plane, as perceived by an observer at a specified position. For the present simulations the observer position was taken to be the position of the microphone array in the field tests.

4. Finally, the rotor noise source distribution is used as input for an array simulation with the same geometry and processing method as in the field tests[2]. In this way, simulated acoustic source maps are obtained, which can be directly compared to the measured maps. The rotor noise spectrum is then determined by applying a power integration method[7] to the simulated or measured source maps.

4 Comparison between simulation and experiment

In this section the simulations will be compared to the experimental results. This assessment will be made in terms of the noise source distribution in the rotor plane (Section 4.1), the rotor noise spectra (Section 4.2), and the overall noise levels as a function of rotor power (Section 4.3).

4.1 Noise source distribution in rotor plane

The measured and simulated source maps for both turbines are shown in Figure 3 to Figure 6. Note that these source maps correspond to the upwind measurement position on the ground. The range of the colour scale is always 12 dB, and the maximum is adjusted for each individual frequency band. The experimental source maps were averaged over all measurements, which were carried out for misalignment angles α (see Figure 1) around 0° and wind speeds (normalized to 10 m height) between 6 and 10 m/s. The simulations were done for a misalignment angle of 0° and a wind speed close to the average experimental wind speed.

In general a very good qualitative agreement is observed between experiments and simulations. As in the experiments, the simulated source maps show dominant noise radiation from the outer part of the blades, during their downward movement. Similar to the experiments, the source maximum shifts to a higher radius for increasing frequency, which can be attributed to the thinner trailing edge boundary layer at higher radius. In some cases even the minor side-lobes (e.g. around "11 o'clock" for 400-500 Hz in the GE results), which are an artefact of the array method, are reproduced in the simulations. Obviously, the minor experimental noise sources, at the nacelle and the tower, are not reproduced in the simulation, because these are not simulated in the trailing edge noise prediction model.

For the GAMESA turbine, the simulated source radius seems to be slightly higher than in the experiments. This may be due to the fact that the measured rotor had one tripped, one clean, and one untreated blade, while the simulations are done for clean blades. Tripping results in a thicker trailing edge boundary layer, so that the trailing edge noise at a given radius shifts to lower frequencies.

Whereas the previous results were obtained for misalignment angles around 0°, for the GE turbine measurements were also done for large misalignment angles. The measured and simulated source maps for these angles are shown in Figure 7. It can be seen that the location of the source region shifts upward or downward when the right- or left-hand side of the rotor plane is turned towards the array respectively. This can be qualitatively explained by the change in the component of the blade velocity in the direction of the array, which results in a change in convective amplification. At the high misalignment angles the array resolution reduces due to the oblique view angle. Again a good qualitative agreement between simulation and experiment is found, indicating that the changes in source pattern are well captured by the trailing edge noise prediction method. In the remainder of this paper all results will be for a misalignment angle of 0°.

4.2 Rotor noise spectra

As explained in Section 3, the source maps were quantified using a power integration method. Before comparing the simulated to the measured rotor noise spectra, first some intermediate results from the simulations are discussed. As an example, Figure 8 shows three rotor noise spectra from the GE simulations (the GAMESA results were similar): the 'BPM' spectrum (output of simulation step 2), the rotor spectrum after including directivity and convective effects (output of step 3), and the integrated rotor spectrum from the array simulation (output of step 4). Note that the sound levels PWL are *apparent* Sound Power Levels, because the measurements were only done for the upwind array position on the ground, rather than on a sphere around the turbine. By comparing the first two lines, it can be seen that directivity and convection result in a small shift of the spectrum to higher frequencies, because the blades are moving towards the observer on the ground when they produce most of their noise. Interestingly, the noise *level* is hardly affected: although directivity and convection yield a large asymmetry in the noise source distribution, the effect is rather small when averaged over all rotor azimuths.

By comparing the second and third line, it can be seen that the power integration method results in an underestimation of the actual rotor noise level. The difference is small at low frequencies, but increases to almost 5 dB at the highest frequency. This deviation is probably due to assumptions and simplifications in the power integration method, which are not completely true for the simulated source maps[8]. As a result, the power integration method underestimates the actual overall rotor source level by about 1 dB for the present simulation. Note that this effect occurs both for the simulated and the measured integrated rotor noise spectra.

The measured and simulated integrated rotor noise spectra for the GAMESA turbine are shown in Figure 9. These spectra correspond to the source maps presented in Figure 5 and Figure 6. As mentioned before, the experimental results were averaged over all measurements, and the simulations were done for a wind speed close to the average experimental wind speed. Since the GAMESA rotor had one tripped, one clean, and one untreated blade, while the simulations were done for a clean rotor, the experimental GAMESA spectrum was corrected on the basis of the individual blade noise spectra[2], to obtain the spectrum of a 'clean' rotor. For the measured source maps the hub region was excluded from the integration. Figure 9 shows a good agreement between the measured and simulated spectra, in terms of levels and spectral shapes. For the GE turbine, the simulated spectrum (Figure 8) showed the same level of agreement with the experimental spectrum. This good agreement between measured and predicted spectra for both turbines indicates that the prediction method captures the physics well.

4.3 Overall noise levels as a function of rotor power

In the previous section it was shown that the average experimental spectra for both turbines corresponded well to the simulations for the average experimental wind speed. Next, it was investigated if the simulations also accurately predict the dependence of the turbine noise on wind speed. Simulations were done for a range of wind speeds and the overall sound level was determined as the sum of the calculated rotor source distribution (output of simulation step 3). The experimental sound level was determined from the integrated rotor spectrum for all measurements, to which 2 dB was added for both turbines to account for the underestimation by the power integration method (see previous section) and coherence loss effects[9]: a comparison between overall integrated rotor levels and measured levels at the single array microphones (for the GE turbine) indeed showed an offset of 2 dB. In addition, on the basis of the individual blade noise spectra[2] 1.5 dB was subtracted from the overall levels of the GAMESA turbine, to account for the fact that the rotor had a tripped and untreated blade, while the simulations are for a clean rotor. In order to avoid disturbing effects from uncertainties in the measured nacelle wind speed, the sound levels were plotted as a function of the rotor power.

Figure 10 to Figure 12 show that for both turbines a good agreement is obtained between the predicted and measured overall levels. The dependence on rotor power is also well reproduced. For both turbines the difference between measurement and prediction is smaller than 1-2 dB, which is smaller than the scatter in the experimental data.

5 Conclusions

This paper describes the application of a semi-empirical prediction method for trailing edge noise to calculate the noise from two modern large wind turbines. The availability of detailed acoustic array measurements on the same turbines enabled a validation not only in terms of source spectra and overall sound levels, but also in terms of the noise source distribution in the rotor plane as a function of frequency and observer position.

The prediction code only needs the blade geometry and the turbine operating conditions as input. Based on boundary layer thicknesses calculated with an airfoil design code, a trailing edge noise prediction code provides the radial noise source distribution on the blades. After application of directivity and convective effects, the rotor noise source distribution is input to an array simulation code, to allow direct comparison to the measured source maps.

In general a very good agreement was observed between experiments and simulations. As in the measurements, the simulated source maps show dominant noise radiation from the outer part of the blades, during their downward movement. This source pattern, which causes the typical swishing noise during the passage of the blades, can be explained by trailing edge noise directivity and convective amplification. The source maximum shifts to a higher radius for increasing frequency, which can be attributed to the thinner trailing edge boundary layer. For high misalignment angles between array and turbine, the simulations show the same shift in source pattern as in the experiments. For both rotors a good agreement between the measured and simulated spectra was observed, in terms of levels and spectral shapes, which indicates that the prediction method captures the physics well. Moreover, the dependence of noise levels on rotor power was well reproduced: the deviation between predicted and measured overall sound levels was smaller than 1-2 dB for both turbines, which is smaller than the scatter in the experimental data.

All in all, the present study provides a firm validation of the prediction method, which therefore is a valuable tool for the design of quiet wind turbines and for the planning of wind farms. In a next step, it is planned to extend the prediction code to the calculation of noise footprints around a wind turbine as a function of rotor azimuth. This will allow an assessment of the locations where the highest noise levels are perceived, and where the noise level variations during one revolution (swishing) are largest.

Acknowledgments

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Figures

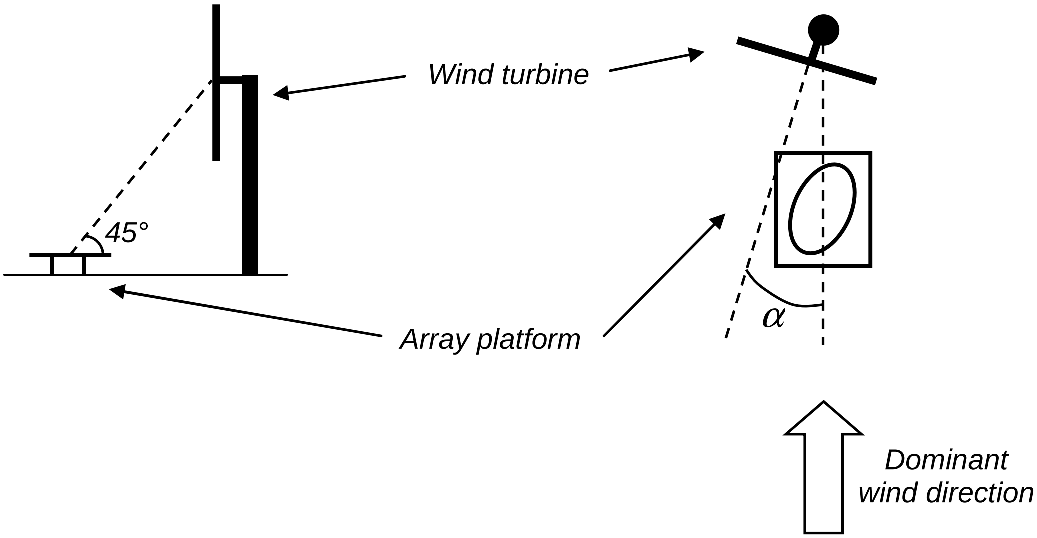

Figure 1: Side view (left) and top view (right) of test set-up.

Figure 2: GE 2.3 MW turbine (left) and GAMESA 850 kW turbine (right) with typical noise source distribution in the rotor plane.

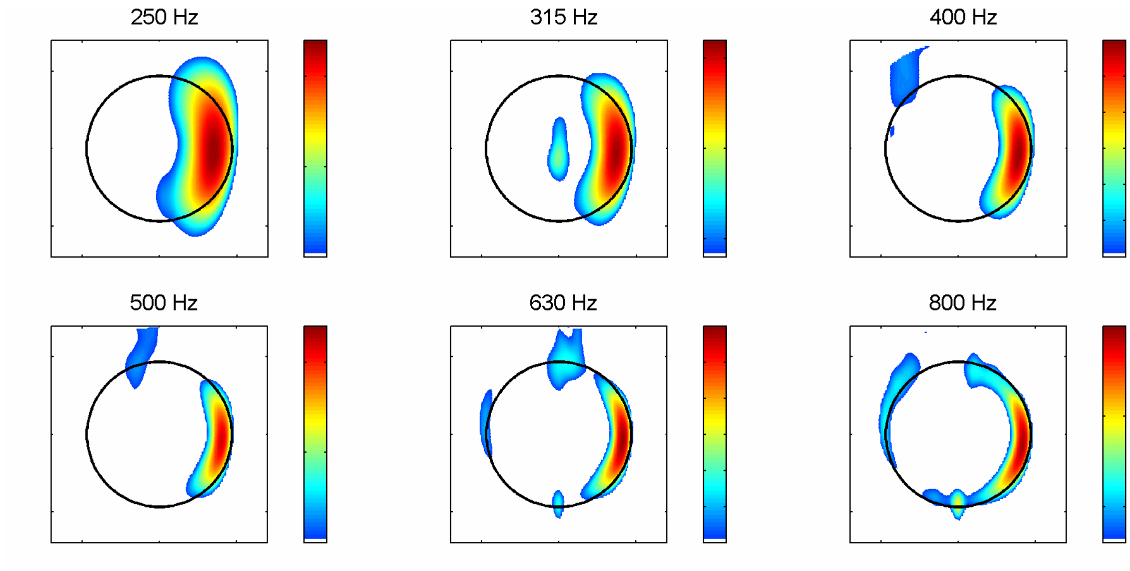

Figure 3: Measured source maps for the 2.3 MW GE turbine (the black circle indicates the 94 m rotor diameter). *The method and plots generated are all relative data corresponding to only one configuration upstream of the rotor and detected hot spots within the dynamic range of the acoustic beamforming testing.*

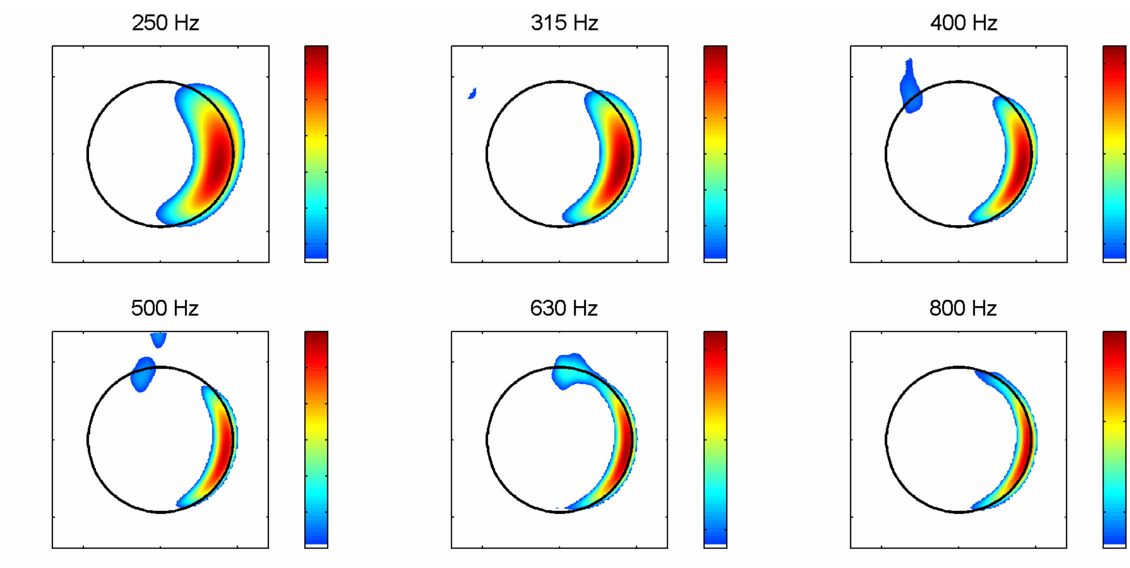

Figure 4: Simulated source maps for the 2.3 MW GE turbine (the black circle indicates the 94 m rotor diameter). *The method and plots generated are all relative data corresponding to only one configuration upstream of the rotor and detected hot spots within the dynamic range of the acoustic beamforming testing.*

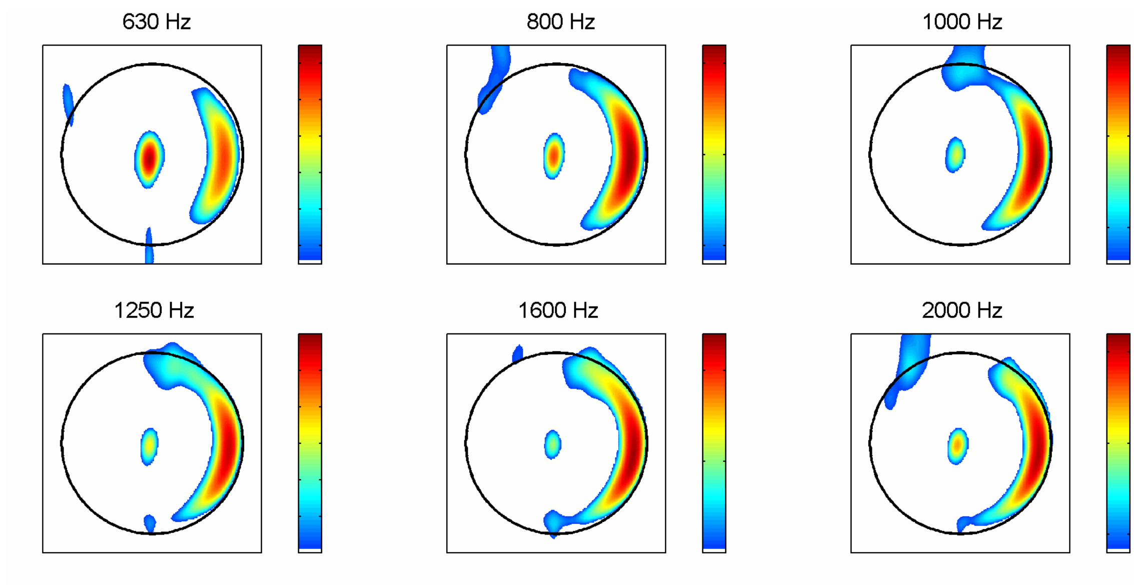

Figure 5: Measured source maps for the 850 kW GAMESA turbine (the black circle indicates the 58 m rotor diameter).

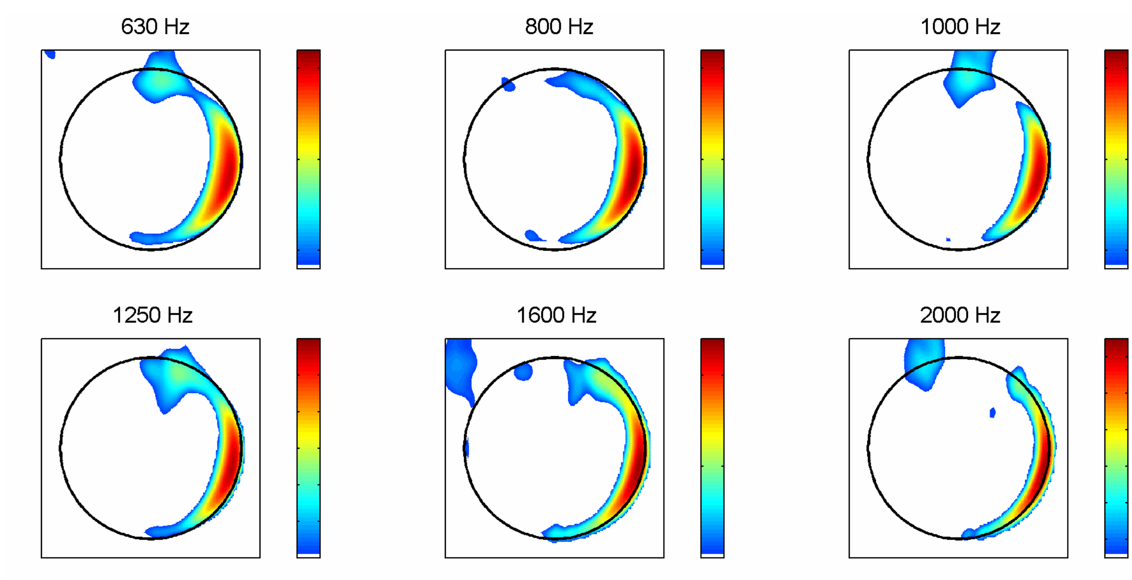

Figure 6: Simulated source maps for the 850 kW GAMESA turbine (the black circle indicates the 58 m rotor diameter).

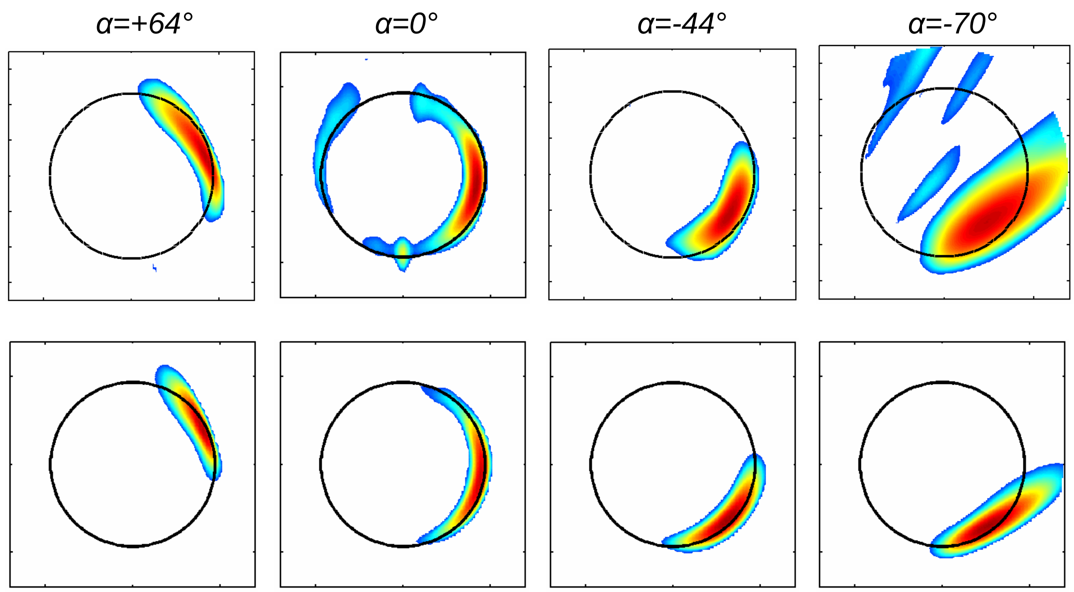

Figure 7: Measured (upper row) and simulated (lower row) source maps for GE turbine at different misalignment angles (800 Hz).

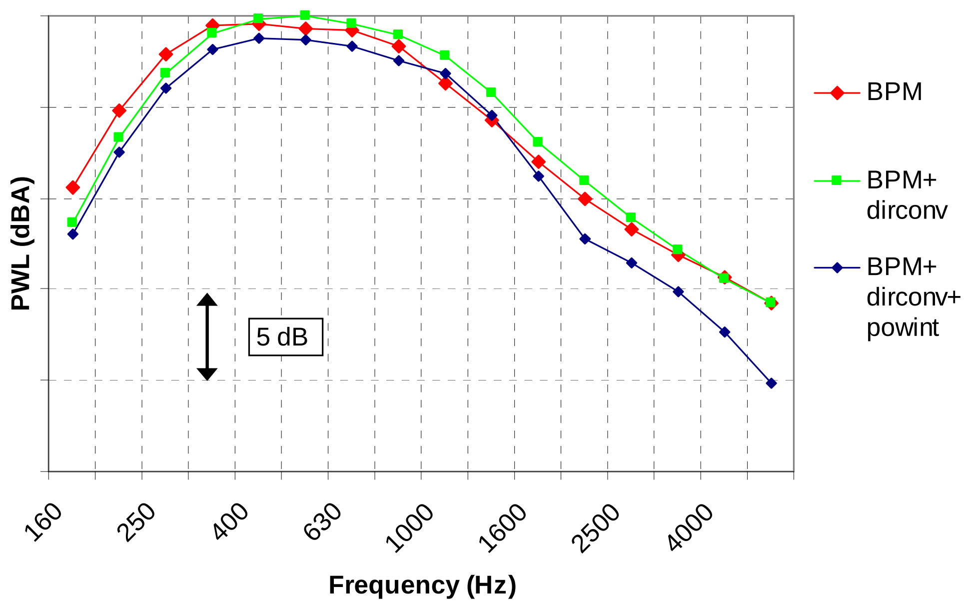

Figure 8: Intermediate rotor noise spectra from the simulation of the GE turbine.

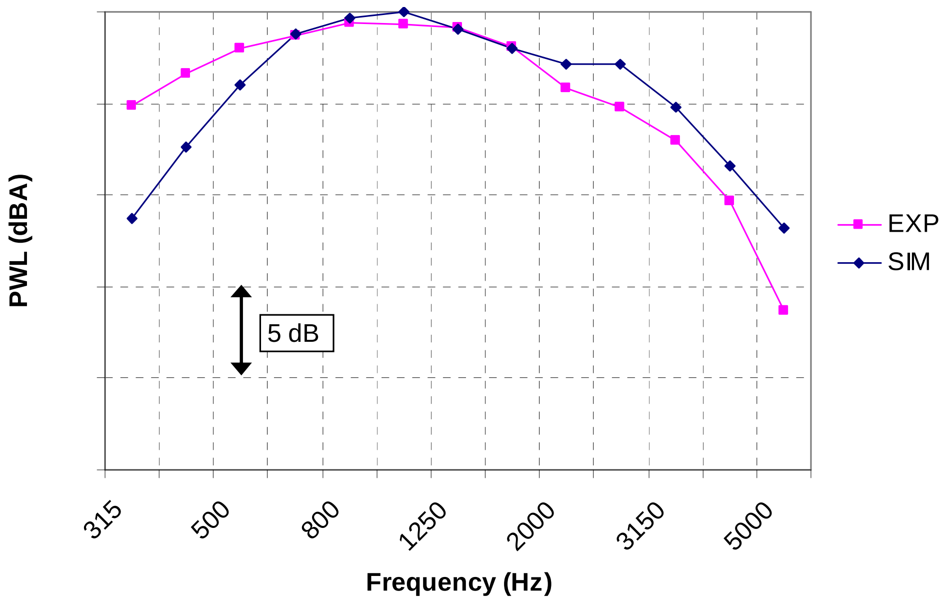

Figure 9: Measured and simulated GAMESA rotor noise spectra.

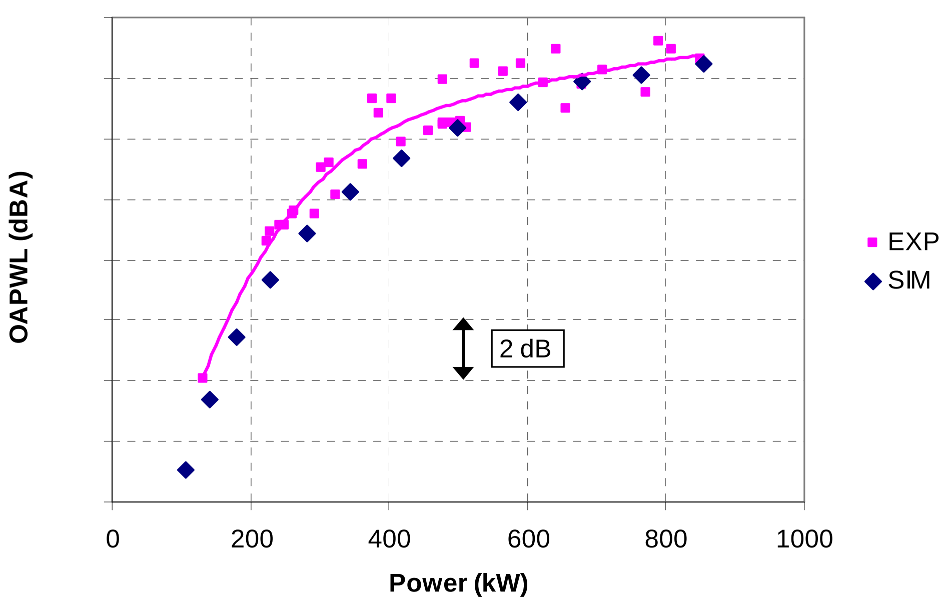

Figure 10: Measured and simulated overall rotor noise levels as a function of power for GAMESA turbine.

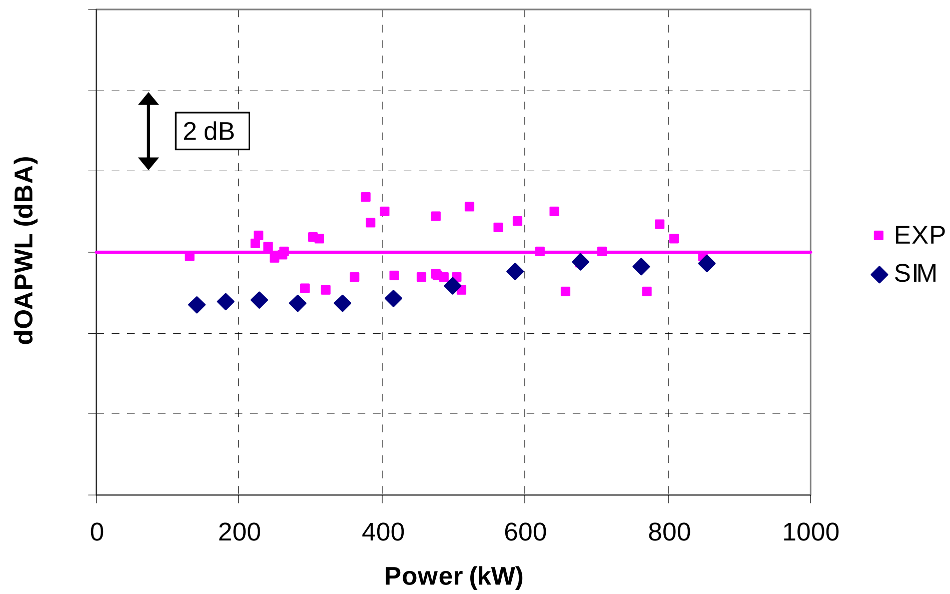

Figure 11: Deviation between measured and predicted overall noise level as a function of power for GAMESA turbine. The levels are normalized using a curve fit through the experimental data (see Figure 10).

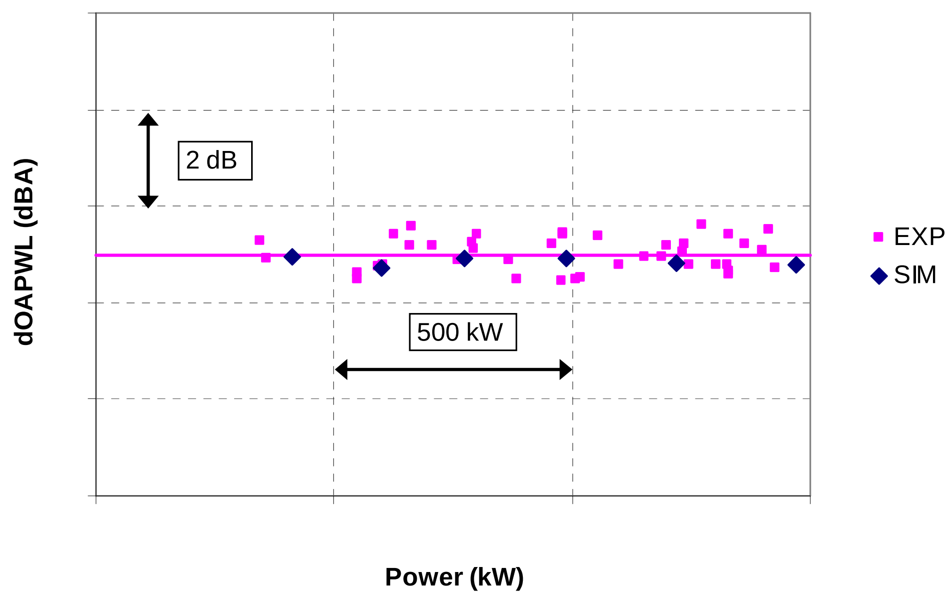

Figure 12: Deviation between measured and predicted overall noise level as a function of power for GE turbine. The levels are normalized using a curve fit through the experimental data.

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Uncloaking the Nature of Wind Turbines
– Using the Science of Meteorology

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Abstract
One fact everyone agrees about wind turbines – you either love them or you hate them. The larger proportion of the general population who live far from them think wind turbines are great – while the smaller proportion representing people with homes near where wind turbines have been erected have concerns, particularly about noise. On a popular vote basis, as seen by elected officials, the choice is clear, but on a justice basis, who looks out for the impacted few?

Applying the tenet that widely expressed concerns usually have some basis in truth, this paper applies the unemotional standard of science to determine that truth. A clue was given in the dissertation of Dr. G.P. van den Berg [1], *"The sounds of high winds – the effect of atmospheric stability on wind turbine sound and microphone noise"* published in 2006. Dr. van den Berg identified that as the atmospheric profile changes from unstable in the sunlit hours to stable after sunset it could have a significant impact on the noise perceived by residents around wind farms. He was unable to fully compare wind velocities at 10 metres and hub height to correlate with his noise measurements as the turbine hub height data was not readily available.

The province of Ontario, in Canada installed its first large scale commercial wind farms rated at 40, 68, 99, and 189 MW capacity in 2006 (See Figure 1) [Figures are given in greater detail at the end of the paper]. The Ontario wind farm hourly electrical output is available to the public on the internet [2], and from this and the power curve of the installed wind turbines the hub wind speed can be accurately estimated. Simultaneously, the Environment Canada meteorological services weather office makes available on the internet hourly wind speed at 10 metres for weather stations near the wind farms [3]. These two pieces of information provide the raw data that was unavailable to Dr. van den Berg in his work to correlate the wind velocities at different elevations to noise.

This report correlates weather and electrical output data for two wind farms for a full year. One is the 39.6 MW Kingsbridge Wind Farm, consisting of 22 Vestas V80 1.8 MW turbines, north of Goderich Ontario, located near the shore of Lake Huron, where the weather station is within sight of the turbines (See Figure 2). The second

is the 67.5 MW Amaranth Wind Farm, consisting of 45 GE 1.5 MW sle turbines, located well inland of the great lakes, north west of Shelburne Ontario. The results for both wind farms show a strong day to night pattern, as well as a seasonal nature that explains a significant part of the noise problem that people near turbines face.

The results of this paper show that the understanding expressed by the Ontario Ministry of the Environment (based on the IEC 61400-11 standard [4]) does not protect the public from excessive annoyance. Since many national or provincial standards seem to be based on IEC 61400-11, it is hoped that the data presented, and the methodology shown will enable anyone to calculate the effect from readily available information. This should be of interest to the developers of standards. This paper recommends that the sound level for wind turbines be calculated for the highest predictable value of wind shear that is expected when turbine output is high to prevent future problems faced by residents near wind farms.

Introduction

The research that generated this report arose from a simple question, which received an elusive answer. While reviewing the expected environmental impacts for the proposed 199.65 MW Enbridge Ontario Wind Project, which was to become the largest single wind project in Canada, a reference to a copy of the paper by Dr. Frits van den Berg [5], *"Effect of the wind profile at night on wind turbine sound"* was found. The simple question was asked of the wind farm proponent if this phenomenon, of a change in wind profile at night, could be a factor to be considered when siting wind turbines near homes?

The response received, instead of being simple, was obscure. "The van den Berg paper … is in specific reference to UK approaches" the response assured. Also, "the technical source data … was obtained using the procedures of international standard IEC 61400-11" and "the analysis was done using state-of-the-art, 3-D, acoustical modelling software based on another standard for analysing outdoor sound propagation, ISO 9613-2 [6]."

Further, the response reassured that "a range of wind speeds has been used and compared against the Ministry of the Environment's (MOE) requirements … the modelling techniques … have been used for several years … with no problems arising." There is a lesson here, if a simple question is not answered, but the response liberally drops code names and assurances of "no problems ever", suspicions are raised.

A curious nature, heightened by reports from people living near recently commissioned wind farms where noise problems were being experienced, as well as a tiny concern of what might be hidden by the smoke screen in the answer received, resulted in this study that led to some very clear conclusions. There is a problem in the way we are siting wind farms, and it explains why the public around the world living near wind farms are facing concerns. Application of scientific principles shows conclusively that noise problems can be predictably forecast, problems that can and should be averted. Wind turbines must not hide under the cloak of being an environmental panacea, if their development destroys the local environment for people living near where the turbines are installed. The goal of this paper is to bring the facts into the light of the truth. To love our neighbours, we must not hurt them, and it is only by standing on the truth that either science or faith can be fulfilled.

Ontario Wind Farms - Main locations installed in 2006 *Figure 1*	**Goderich Airport and Weather Station** – Kingsbridge Wind Farm in background *Figure 2*
	

Sources of the Problem

Noise limitations on Ontario wind farms fall under the Ministry of the Environment *"Sound Level Limits for Stationary Sources in Class 3 Areas (Rural)"*, Publication NPC-232 [7], or the *"Sound Level Limits for Stationary Sources in Class 1 & 2 Areas (Urban)",* Publication NPC-205 [8]. These guidelines require the assessment of a "predictable worst case" considered to be a planned and predictable mode of operation. If background sound levels are low, the allowable One Hour Equivalent Sound Level (L_{eq}) in evening and overnight hours at a rural point of reception is 40 dBA, and at an urban point of reception is 45 dBA. The Ministry of the Environment document *"Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators"* [9] expects that background sound levels will increase with average wind speed, and allows an increase in the wind turbine noise criterion for either the rural case (NPC-232) or the urban case (NPC-205) as shown in Table 1.

Table 1 – Allowed Wind Turbine Noise per Ontario MOE "Interpretation for … Wind Turbine Generators" document

Wind Speed (m/s) at 10 m	4	5	6	7	8	9	10	11
Wind Turbine Noise Criterion NPC-232 (dBA)	40	40	40	43	45	49	51	53
Wind Turbine Noise Criterion NPC-205 (dBA)	45	45	45	45	45	49	51	53

This table implicitly assumes a constant relationship between wind speed at the hub of a wind turbine and wind speed at the level of the receptor. Assuming a constant relationship between wind speeds at different levels will be shown to be a problem. A separately issued Frequently Asked Questions document identifies that all sound level data, including wind turbine manufacturer's specifications and the MOE limits at

point of reception, should correspond to wind speeds measured at 10 metre height above grade.
The Ontario *"Interpretation for … Wind Turbine Generators"* document refers to the IEC Standard 61400-11. This standard shows a logarithmic relationship between wind speeds measured at the rotor centre height and a reference height of 10 metres based on the site roughness length.

The fact that standard IEC 61400-11 converts wind speeds at height to a reference condition by the same logarithmic wind profile relationship for all hours of the day using site roughness may be fine if comparing noise measurements for two different turbines, but it is of little use to predict noise levels achieved at a receptor, and is not consistent with the understanding of wind shear as known by meteorologists and aviators. These professionals understand that variations in wind speed in a vertical direction (wind shear) changes at night, and it is not accurate to describe it as being a consistent logarithmic relationship based on surface roughness at all hours of the day. This can have a significant noise impact on people living near wind farms.

A good introduction for non-meteorologists is found in the Environment Canada – Meteorology Self Instructions course available on the internet [10]. The module on "Pressure and Wind" for "Lower Level Winds" shows that diurnal changes in surface wind speed and direction occur as a result of daytime heating of the surface.

Over land on a hot day, the winds tend to conform to the winds at the 1000 metre level. In making this change from its usual speed and direction, the surface wind will tend to "veer" (wind direction changes to be aligned to the isobars) and increase in speed. During the night, the surface cooling reduces the eddying motion of the air in the lower levels. The surface wind now, instead of conforming to the 1000 metre level, tends to assume it's normal direction and speed, and it "backs" (wind direction changes to be from higher to lower pressure isobar) and decreases in speed.

Pilots and Air Traffic Service Personnel learn the same principles from their training material, such as from the NAV-CANADA Aviation Weather Hazards document [11]. It describes the stability and diurnal variation of the wind. Going on it describes the development of inversions after sunset that permit creation of a low-level nocturnal jet, mainly in the summer on clear nights. The winds just below the top of the inversion will begin to increase just after sunset, reach its maximum speed a couple of hours after midnight, then dissipate in the morning.

When wind turbine manufacturers determine the sound power level referenced to wind speeds measured 10 metres above grade, they must also assume some relationship between the wind speed at the hub height and the wind speed at the reference height. Compounding the problem is that manufacturers do not assume a consistent relationship even for different turbines from the same manufacturer. An example of this is shown in Table 2, which shows the sound levels for 4 cases.

Shear values were calculated in Table 2 by equating the wind speed at height (V(Z)) in the logarithmic profile and the power law profile equations:

$$V(Z) = V(Zr) \bullet (\ln(Z/Zo) / \ln(Zr/Zo)) \qquad \text{(Logarithmic Profile)}$$

$$V(Z) = V(Zr) \bullet (Z / Zr)^{\alpha} \qquad \text{(Power Law Profile)}$$

$$\therefore \; V(Zr) \bullet (\ln(Z/Zo) / \ln(Zr/Zo)) = V(Zr) \bullet (Z / Zr)^{\alpha}$$

Reducing, and solving: $\alpha = (\ln(\ln(Z/Zo) / \ln(Zr/Zo))) / (\ln(Z/Zr))$

Here: $Zr = 10$ m, Zo = roughness length, $Z = 80$ m, α = wind shear from 10 to 80m

Table 2 – Sound Levels for Wind Turbines per Manufacturer's Documentation

		Vestas V82 IEC Class II	**GE 1.5 sle IEC Class II**	**Vestas V80 IEC Class II**	**Vestas V82 IEC Class II**
Source of Information		Vestas [12] Spec Sheet 4000258-02	GE Energy[13] Technical Description	Vestas [14] Spec Sheet 944411.R3	Valcoustics [15] Noise Assessment
Basis of Rating		Shear of 0.13	Surface Roughness (Z_{oref}) = 0.03m	Danish Roughness Class 2	Provided by manufacturer (Vestas) for site
Roughness Length (m)		0.01 m	0.03 m	0.1 m	0.3 m
Shear 10 to 80m		0.13	0.15	0.18	0.22
Stated Sound Levels for wind speeds at 10 m (Z_r)	3 m/s	101.1 dBA	< 96 dBA		
	4 m/s	101.4 dBA	<96 dBA	99.5 dBA	101.6 dBA
	5 m/s	101.6 dBA	99.1 dBA		101.8 dBA
	6 m/s	101.8 dBA	103.0 dBA	101.3 dBA	102.4 dBA
	7 m/s	102.2 dBA	<104 dBA		104 dBA
	8 m/s	103.2 dBA	<104 dBA	102.8 dBA	106.9 dBA
	9 m/s		<104 dBA		108.9 dBA
	10 m/s		<104 dBA	103.9 dBA	109.9 dBA
	11 m/s		<104 dBA		108.7 dBA
	12 m/s		<104 dBA		107.5 dBA

Table 2 shows it is difficult to compare the turbines to determine the quietest, or the noisiest. A clearer understanding is found by showing the sound output based on the wind velocities at 80 metres in Table 3 (following) derived by converting the wind speeds at 10 m in Table 2 to wind speeds at 80 metres using the power law:

$$V_{80} = V_{10}\,(80\text{m}/10\text{m})^{\alpha}$$

Table 3 – Sound Level for Turbines as a Function of Wind Velocity at 80 Metres

80 metre Velocity (m/s)	**V80 Sound Level (dBA)**	**V82 Sound Level (dBA)**	**GE 1.5 sle Sound Level (dBA)**
6.0	99.5	101.6	97.2
8.0	100.7	101.8	102.5
10.0	102.0	102.8	104.0
12.0	103.0	106.5	104.0
14.0	103.7	108.6	104.0
16.0	103.8	109.7	104.0

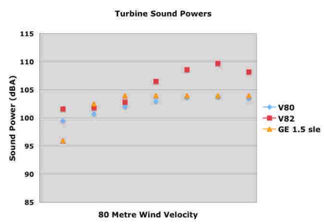


Table 3 recognizes that the sound level for a wind turbine is dependant on the wind speed passing the blades, and not the wind velocity at the 10 metre level. The results can be surprising. When information is presented in a common basis, it shows that some turbines may be considerably noisier than others as the hub height wind speed increases, even though electrical output may be less. Claims of "operating sound levels … among the lowest on the market, regardless of wind speed” may not always be what they seem.

Calculating Wind Shear Variation From Day to Night

The electrical output of all Ontario electricity generators of greater than 10 MW is available on the internet on an hourly basis on a web site maintained by the Ontario – Independent Electrical System Operator (IESO).

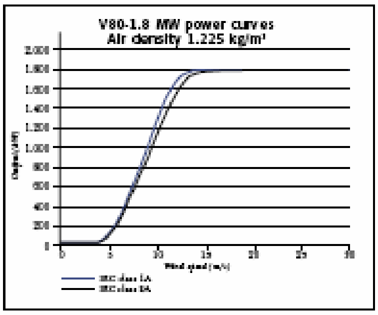
The Environment Canada Meteorological Services of Canada provides an hourly record of historical weather data for 761 stations. The closest weather station to the Kingsbridge wind farm is the automated station at the Goderich Airport (which meets World Meteorological Organization (WMO) standards). The distance from the weather station to the turbines ranging from about 4 km to about 19 km.

IESO data for the hourly Kingsbridge wind farm electrical output was converted to wind speed at the turbine hub by a simple algorithm of linear steps to approximate the power curve of the Vestas V80 turbine shown in Figure 3..

Vestas V80 Turbine Power Curve

Figure 3

[16]

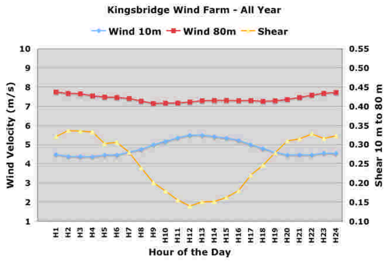
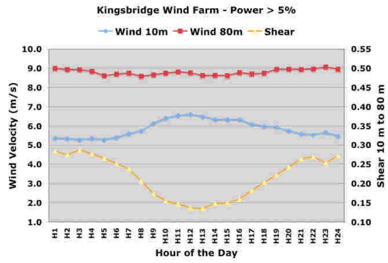


For a zero electrical output, the wind speed at 80 m was set to 4 m/s, the starting wind speed for the V80 turbine. For electrical outputs from 0 to 200 kW, the wind speed was increased in a linear manner to 5.5 m/s. For electrical outputs from 200 to 1600 kW, the wind speed was increased linearly from 5.5 m/s to 12.5 m/s, and for electrical outputs from 1600 to 1800 kW, the wind speed was increased in a linear fashion up to 15 m/s (full power for these turbines).

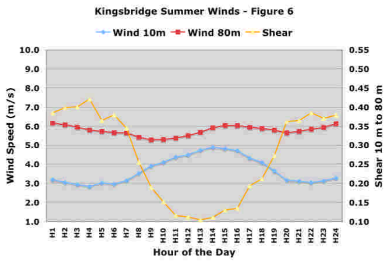
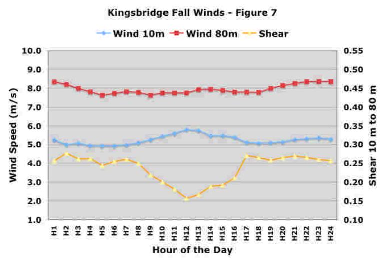
Although it is known that in the purest definition, to calculate a wind shear the wind speeds need to be measured on the same vertical tower, a calculated shear value was determined following a pattern developed by Dr. James Young in preparing a set of shear(α) values for the Kingsbridge wind farm [17] using the wind speed at 10 metres measured by the Goderich Airport Weather Station and the wind speed at 80 metres derived from the turbine electrical output. The shear for each hour of the year was calculated using the power law equation $V_{80} = V_{10}\ (80m/10m)^{\alpha}$

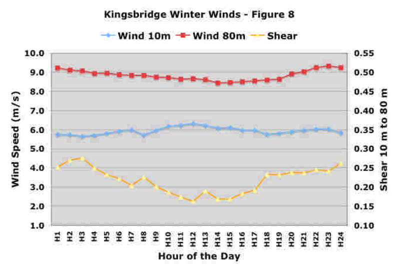
The minimum wind speed at 10 metres used was 2 km/hr, the starting value for the anemometer. If any turbine in the array is out of service, this reduces the total array output, but as the total array output is averaged over all turbines, the individual output is thus lower than if it was averaged over a reduced number of turbines.

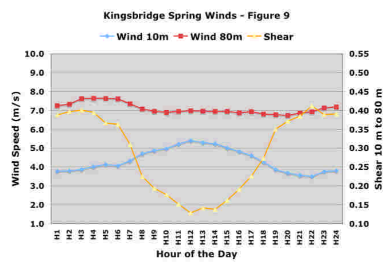
Wind shear (α) could not be calculated with zero values of wind speeds for either the 80 metre winds or the 10 metre winds. (Natural logarithms of zero do not compute). To determine how much impact using minimum startup values of wind speeds for the weather station anemometer and the wind turbine values might have (might overstate wind shear for low wind speeds as the turbine requires much more wind for startup than the anemometer) all data representing less than 5% electrical output was eliminated and the annual curve was redrawn. This artificially increased the average wind speeds, as it removed about 30% of the low speed data. Calculated wind shear at night was about twice the shear in the daytime in both cases. At night the wind speed at 10 metres falls and the wind speed at 80 metres rises.

Kingsbridge Wind Farm – All Data *Figure 4*	**Kingsbridge Wind Farm – Power >5%** *Figure 5*
	

The seasonal curves (including the low speed data) show large changes between day and night shear occurs in the spring and summer, with differences in the order of a factor of 3. Winter wind velocities are higher, but the difference between day and night time shear is less.

Kingsbridge Wind Farm - Seasonal Variation in Wind Speed and Shear *Figures 6,7,8 and 9*	
	

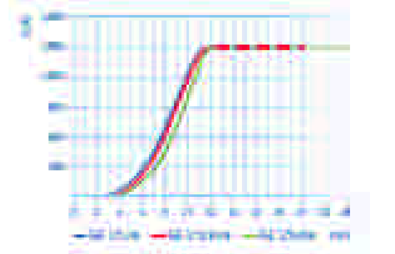




In a similar manner, the shear values were calculated for the Amaranth Wind Farm. In this case, the representative Environment Canada weather stations are the Mount Forest automated weather station located about 40 km west of the centre of the site, and the Egbert automated weather station located about 43 km north east of the centre of the site. Again, both meet World Meteorological Organization standards. In order to calculate the shear in a conservative manner, the larger of the 10 metre wind speeds from either Mount Forest or Egbert was used along with the 80 metre wind speed derived from the IESO hourly electrical output and the turbine power curve.

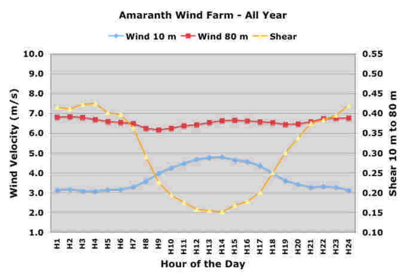
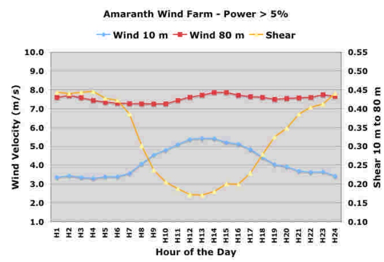
GE Energy 1.5 sle Turbine Power Curve

Figure 10 [18]



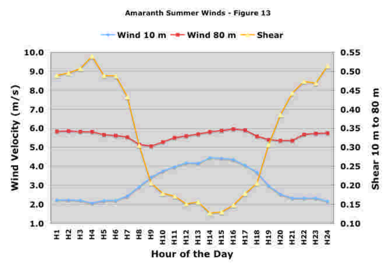
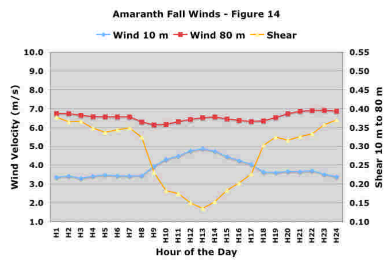
The turbine power curve was approximated in a linear manner. For zero electrical output, the wind speed at 80 metres was set to 3.5 m/s, the starting wind speed for the GE 1.5 sle turbine. For electrical outputs from 0 to 300 kW, the wind speed was linearly increased to 6.5 m/s. For electrical outputs from 300 to 1200 kW, the wind speed was increased linearly to 10.5 m/s, and for electrical outputs from 1200 to 1500 kW, the wind speed was ramped from 10.5 m/s to 12 m/s, the full power wind speed, as shown in figure 10.

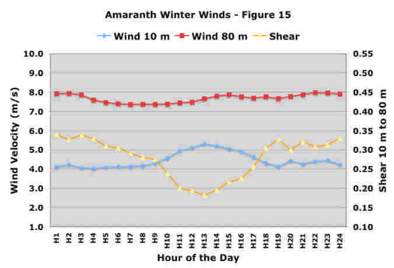
Again, to ensure that the effect of setting the anemometer minimum speed to 2 km/h and the hub height minimum velocity to the turbine start up velocity of 3.5 m/s (12.6 m/s) does not exaggerate the calculated shear values, the difference is shown in Figures 11 and 12 below between the shear values drawn using all data, and the shear values drawn using only powers greater than 5% to avoid the low wind speed values. In this case, plotting greater than 5% output removes about 25% of the low wind speed data. Although it results in increased values calculated for the 10 metre and 80 metre wind speeds, the change in shear displayed the same pattern.

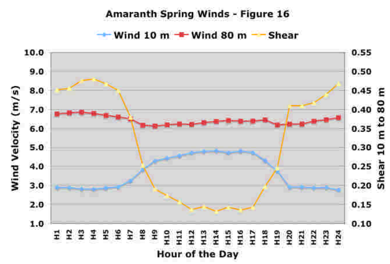
Amaranth Wind Farm – All Data *Figure 11*	**Amaranth Wind Farm – Power >5%** *Figure 12*
	

The seasonal results for the Amaranth case shown in Figures 13, 14, 15 and 16 show again that the calculated shear differences from day to night are greatest in the spring and summer with each showing a difference greater by a factor of 3 from day to night time shear. As for the Kingsbridge case, the difference was less in the fall and winter, while the wind velocities were greater in those seasons. The Amaranth case does not show the 80 metre wind speeds to be as high as for the Kingsbridge case largely due to the fact that for the Amaranth case the maximum computed wind speed was 12 m/s as at that point the GE sle 1.5 turbine reach maximum output, while for the Kingsbridge case the maximum was 15 m/s as that was the point at which the wind speed increase resulted in no further increase in electrical output on the V80 turbine.

Amaranth Wind Farm - Seasonal Variation in Wind Speed and Shear
Figures 13,14,15 and 16





Changes in calculated wind shear from day to night observed at both the Kingsbridge Wind Farm and the Amaranth Wind Farm are consistent with the observations recorded in the work published by the United States National Renewable Energy Laboratories. The paper *"Evaluation of Wind Shear Patterns at Midwest Wind Energy Facilities"* [19] by Kelley and Smith published in 2002 identified a very similar diurnal wind shear pattern at 5 different facilities in the United States. A similar pattern was again recorded by Schwartz and Elliott in their 2005 paper *"Towards a Wind Energy Climatology at Advanced Turbine Hub-Heights"* [20]. Additionally, the variation in wind speed profile between day and night was recorded again in the *"Toora Wind Farm – Review of the Environmental Noise Monitoring Program"* [21] prepared by Graeme E. Harding & Associates published in Australia in 2005.

The results shown in this paper and from previous studies make it clear that the pattern reported by Dr. van den Berg, of changes in wind shear from day to night need to be accounted for when calculating the sound levels of wind farms.

Impacts of Wind Shear Changes

The effect of changing the shear value is shown in Table 4. Here the velocity at 80 metres is compared to the velocity at 10 metres as the shear changes, calculating the effect using the power law.

Table 4 – The Effect of Changing Shear on Wind Speeds

Velocity (m/s) At 80 metres	Velocity (m/s) at 10 metres					
	Shear 0.15	Shear 0.20	Shear 0.26	Shear 0.33	Shear 0.38	Shear 0.44
4.0	2.9	2.7	2.3	2.0	1.8	1.6
5.0	3.7	2.2	2.9	2.5	2.8	2.0
6.0	4.4	4.0	3.5	3.0	2.7	2.4
8.0	5.9	5.3	4.7	4.0	3.6	3.2
10.0	7.3	6.7	5.8	5.0	4.5	4.0
12.0	8.8	8.0	7.0	6.0	5.4	4.8
14.0	10.2	9.3	8.2	7.0	6.4	5.6

The impact of increasing wind shear can be plainly seen if one considers the effect on a Vestas V82 turbine as shear increases. Take first for example a shear of 0.15.

At this point, wind velocity of 2.9 m/s at the 10 metre elevation is needed for a wind velocity of 4.0 m/s at 80 metres, the V82 turbine start up speed. A 4.0 m/s wind speed at 10 metres would result in a wind speed of about 5.5 m/s at 80 metres, with a noise output of 101.5 dBA. An increase in wind turbine sound output would start to be permitted by the Ontario *"Interpretation for … Wind Turbine Generators"* document at a wind velocity of 6 m/s at 10 metres, at which point the velocity at the 80 metre level would be just over 8 m/s. At this wind speed the V82 turbine is at about 46% of its rated output, producing a sound power of 101.8 dBA. However, if the shear increases to 0.44, then a hub height velocity of 4.0 m/s for start up is achieved at a velocity of 1.6 m/s at the 10 metre height. At this shear value, a 4.0 m/s wind speed at 10 metres will result in 10 m/s at 80 metres, and a sound power of 102.8 dBA. By the time the wind velocity at 10 metres reaches 6.0 m/s to allow any increase in sound power by the Ontario *"Interpretation for … Wind Turbine Generators"* document, the turbine sound level would have increased by more than 7 decibels to over 109 dBA.

The correlated electrical output and weather station data of the one year period collected for both the Kingsbridge Wind Farm and the Amaranth Wind Farm was reviewed. The assumptions proposed to the Ontario Ministry of the Environment for the siting of Vestas V82 turbines at another site were applied to this correlated data. They would be used to determine the separation distances from turbines to residences by calculating the turbine sound power based on a fixed value of wind shear. The assumptions allow an increase in turbine sound power as the 10 metre wind speed increases above 6 m/s. Had these turbines and assumptions been applied given the wind speeds found from the data at the 10 metre reference level and the 80 metre turbine hub level at he Kingsbridge site, it would have resulted in sound in excess of the Ontario allowed values on 158 days of the year, totalling 599 hours. At the Amaranth site, the sound would have been in excess of the Ontario allowed values on 173 days of the year, totalling 1036 hours.

It is clear that if the allowable distance to separate wind turbines from "sensitive receptors" (e.g. residences) is done by using a single figure of average wind shear, as is done in Ontario, then there will predictably be forecast cases of noise in excess of the limits, and there will be chronic annoyance.

Conclusions

The paper shows that calculation of wind turbine sound power levels based on a constant wind shear between the turbine hub height and the reference level 10 metres above the grade results in predictable and preventable noise annoyance for people living nearby. To prevent noise excesses from wind turbines being a continuous irritant, calculation of the sound power levels for a wind turbine must consider the fact that wind shear changes from day to night, and from season to season. As a result turbine power increases at night, while ambient sound produced by winds at the level of the receptor falls. The perceived increase in difference between the turbine sound and the ambient sound, as well as the turbine sound increases, will result in increased annoyance at night.

The sound power level used to determine separation distances from residences to turbines must be calculated for the highest predictable value of wind shear in effect at times of high power output when closest to the sound level limits. In the Ontario case where the limit varies with wind speeds at the 10 metre level, the most critical time is just before the allowed sound level is permitted to start to increase above the base level as this is when the limit is closest to the actual sound level at receptors.

Wind turbine proponents must recognise that evidence does not support the widely made – but inaccurate - claim that as turbine output goes up ambient noise caused by ground level winds prevents annoyance. Evidence shows the truth is - as night falls – the ground level winds fall, and the ambient noise becomes less, while the noise from the turbine increases.

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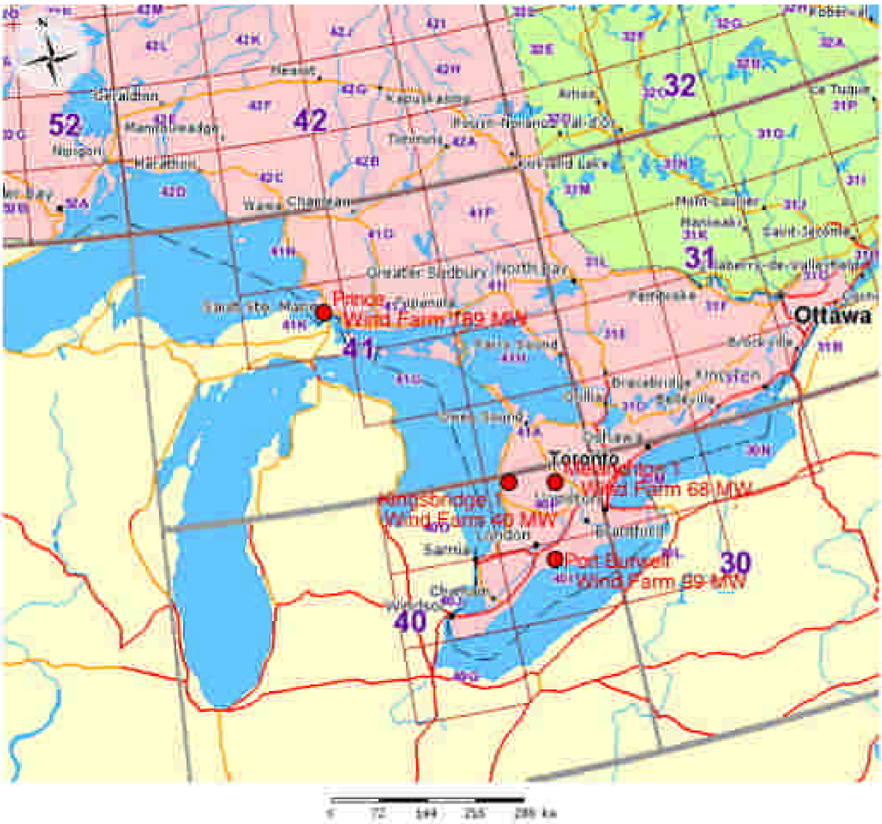
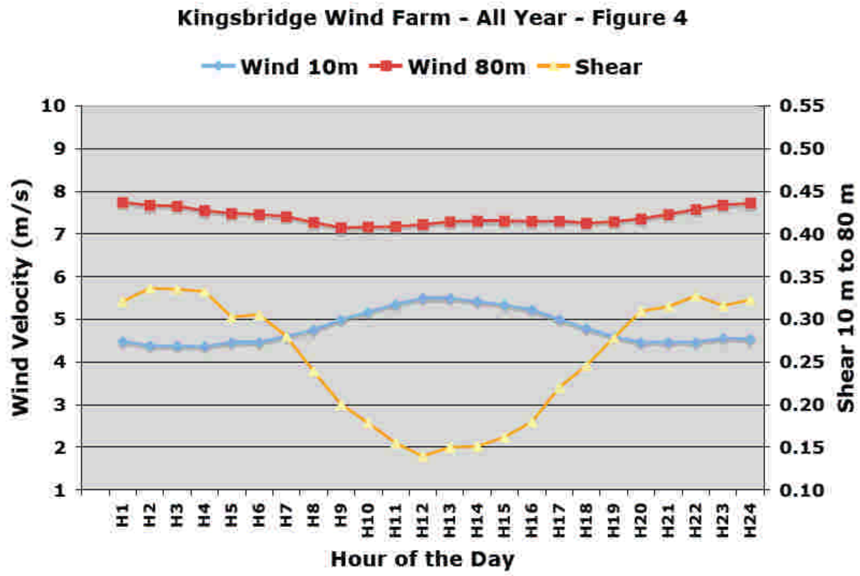
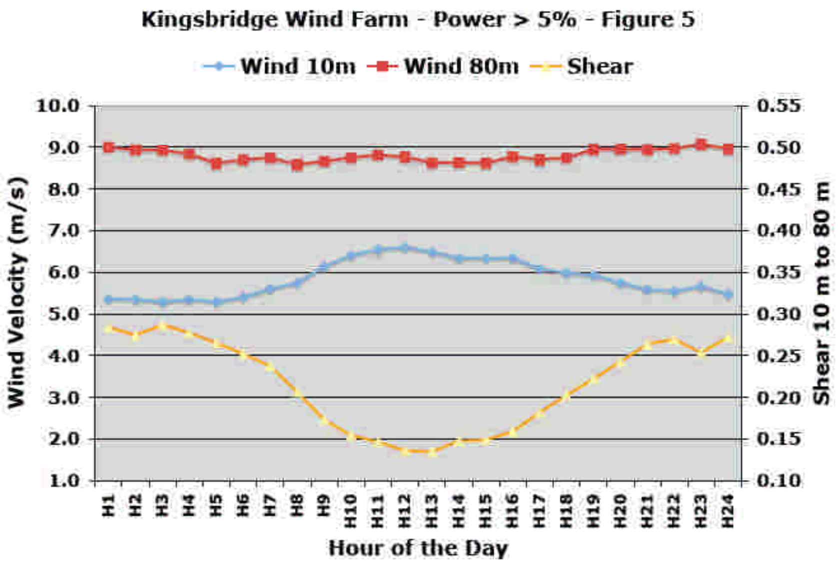
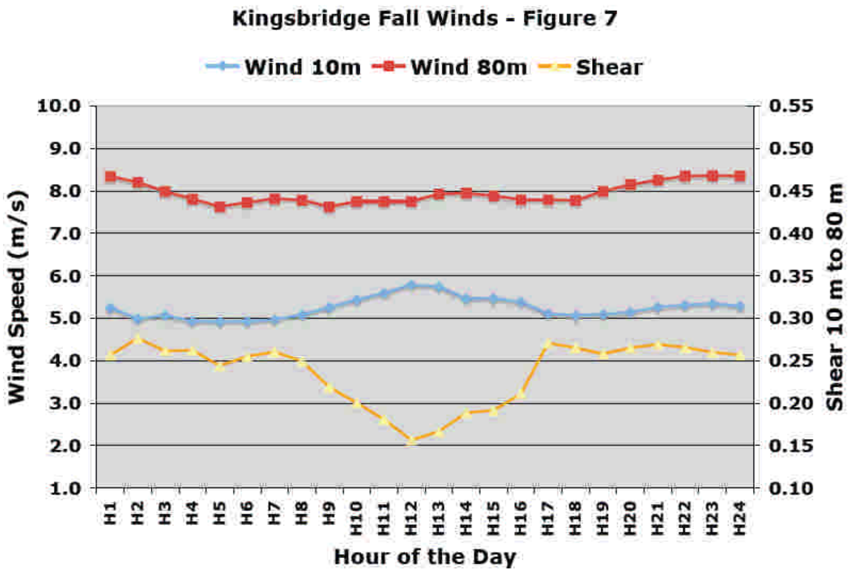
Figure 1

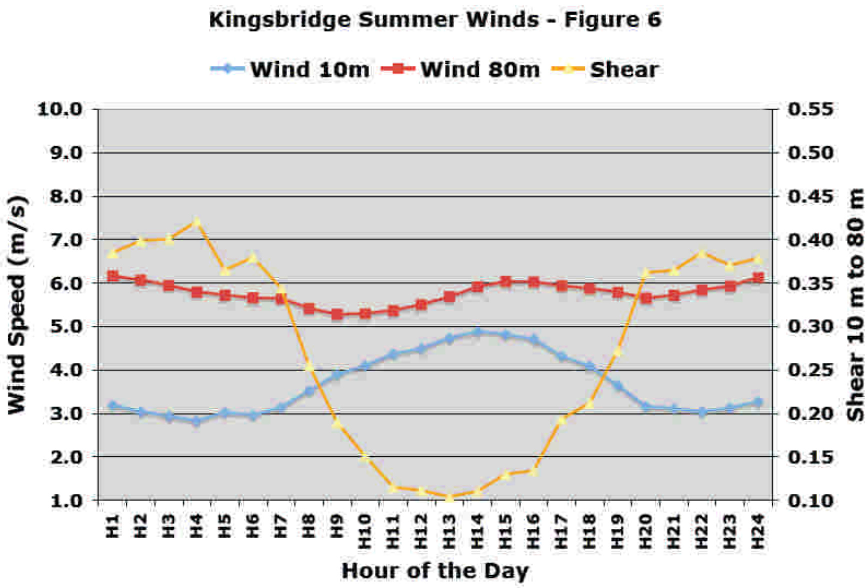
Ontario Wind Farms

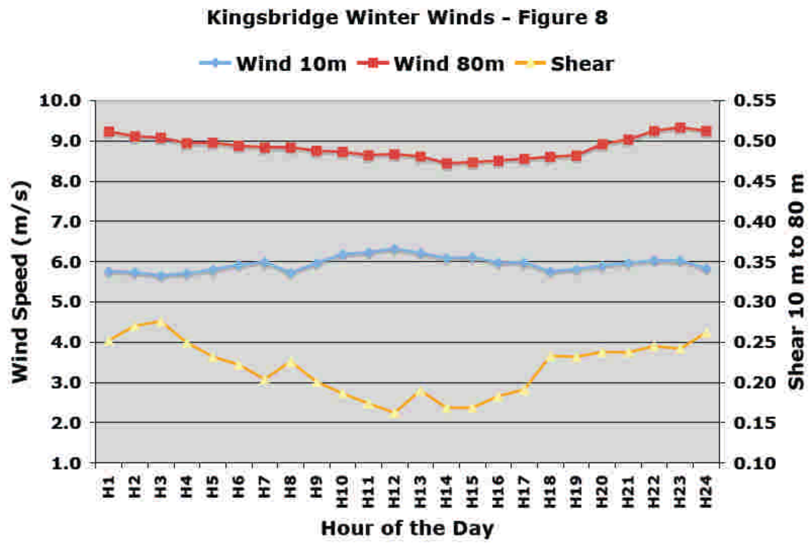



Kingsbridge Wind Farm - All Year - Figure 4
Wind 10m
Wind 80m
Shear
Wind Velocity (m/s)
Shear 10 m to 80 m
Hour of the Day
10
9
8
7
6
5
4
3
2
1
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
H1 H2 H3 H4 H5 H6 H7 H8 H9 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24


Kingsbridge Wind Farm - Power > 5% - Figure 5
Wind 10m
Wind 80m
Shear
Wind Velocity (m/s)
Shear 10 m to 80 m
Hour of the Day
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
H1 H2 H3 H4 H5 H6 H7 H8 H9 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24


Kingsbridge Fall Winds - Figure 7
Wind 10m
Wind 80m
Shear
Wind Speed (m/s)
Shear 10 m to 80 m
Hour of the Day
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
H1 H2 H3 H4 H5 H6 H7 H8 H9 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24


Kingsbridge Summer Winds - Figure 6
Wind 10m
Wind 80m
Shear
Wind Speed (m/s)
Shear 10 m to 80 m
Hour of the Day
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
H1 H2 H3 H4 H5 H6 H7 H8 H9 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24


Kingsbridge Winter Winds - Figure 8
Wind 10m
Wind 80m
Shear
Wind Speed (m/s)
Shear 10 m to 80 m
Hour of the Day
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
H1 H2 H3 H4 H5 H6 H7 H8 H9 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24

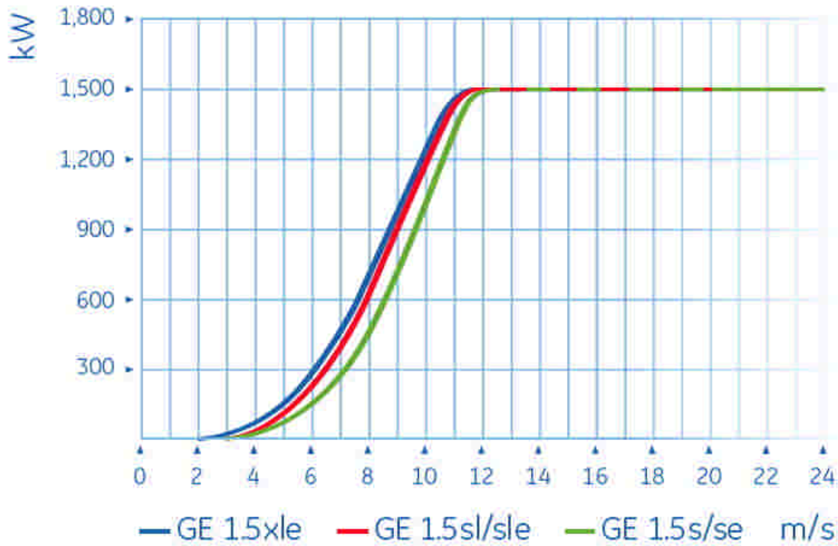
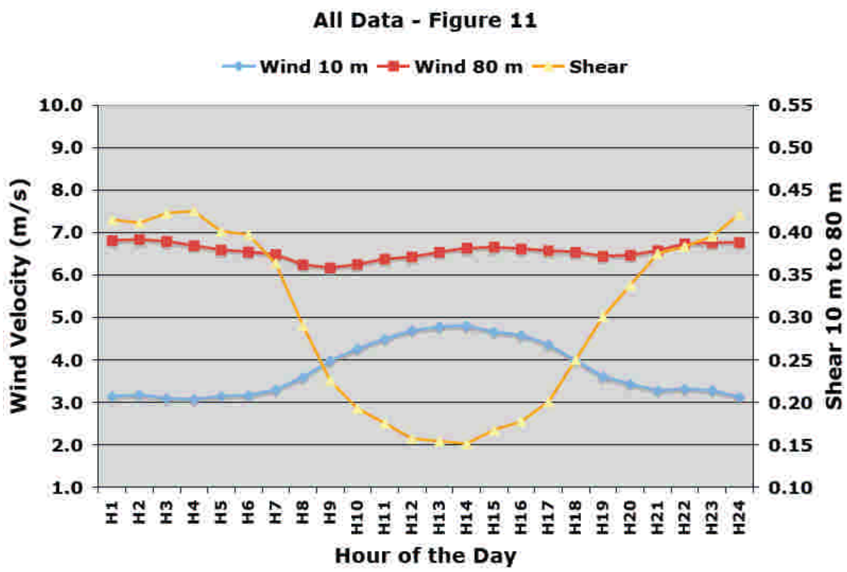
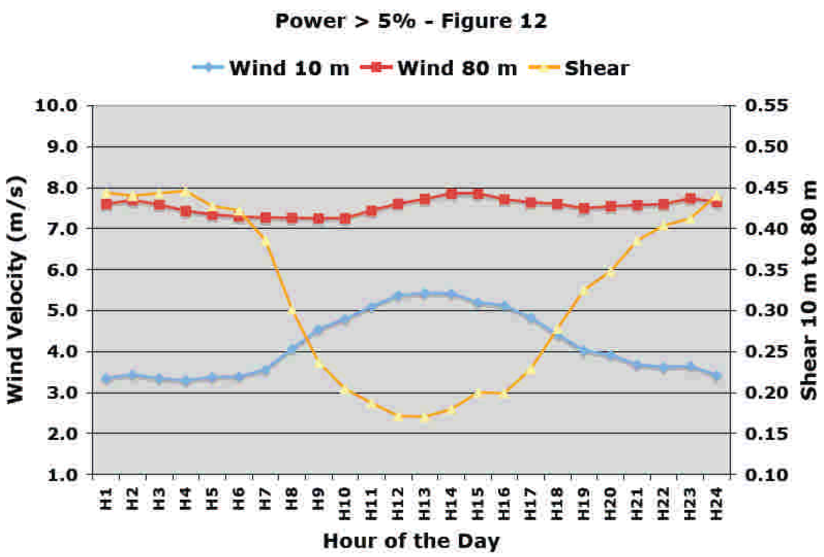

kW
1,800
1,500
1,200
900
600
300
0 2 4 6 8 10 12 14 16 18 20 22 24
GE 1.5xle
GE 1.5sl/sle
GE 1.5s/se
m/s

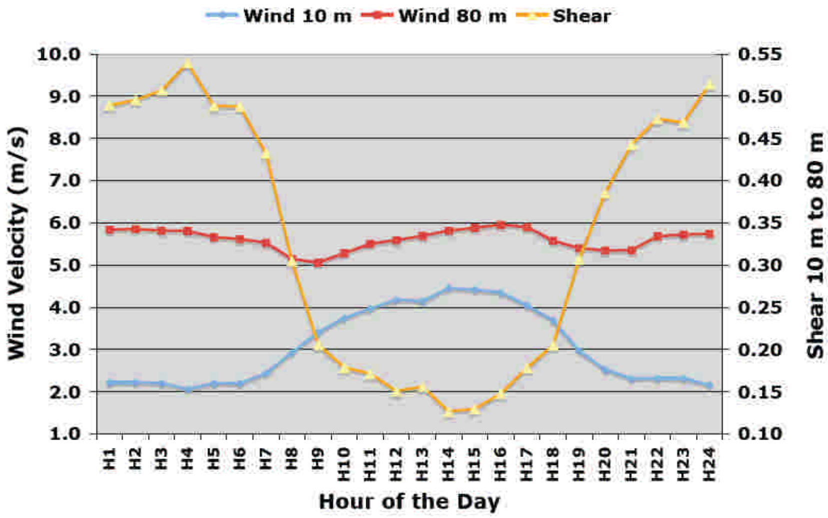
Figure 10


All Data - Figure 11
Wind 10 m
Wind 80 m
Shear
Wind Velocity (m/s)
Shear 10 m to 80 m
Hour of the Day
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
H1 H2 H3 H4 H5 H6 H7 H8 H9 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24

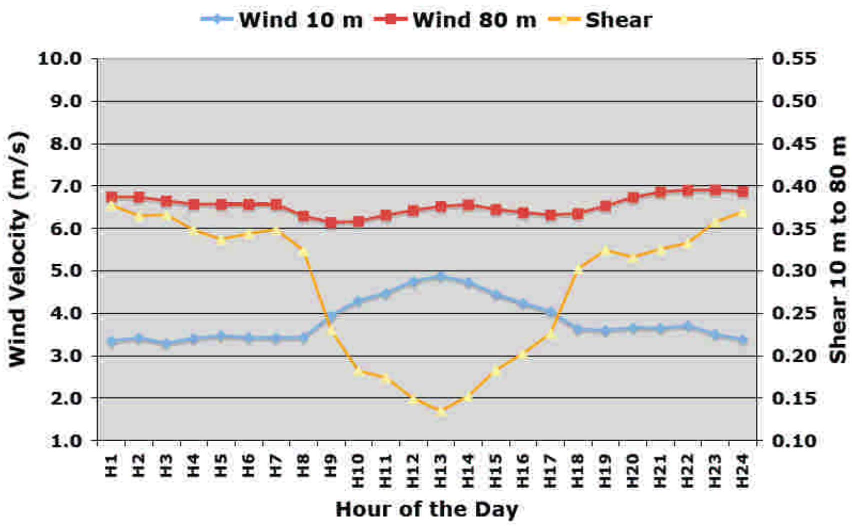

Wind 10m
Wind 80m
Shear

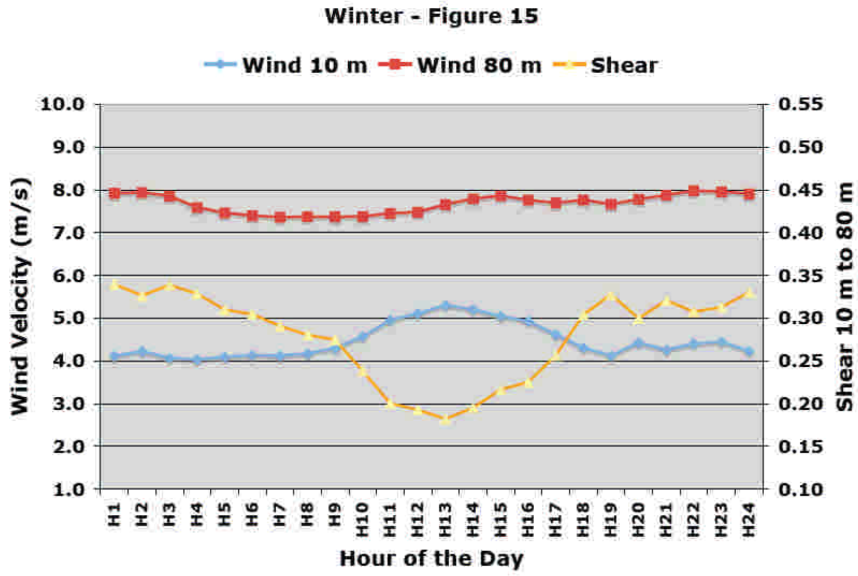

Power > 5% - Figure 12
Wind 10 m
Wind 80 m
Shear
Wind Velocity (m/s)
Shear 10 m to 80 m
Hour of the Day
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
H1 H2 H3 H4 H5 H6 H7 H8 H9 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24

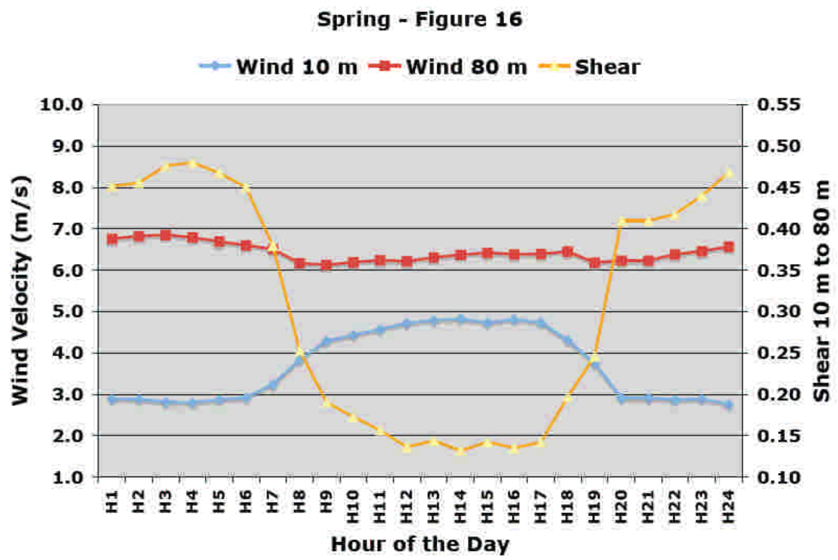
Summer - Figure 13



Fall - Figure 14




Winter - Figure 15
Wind 10 m
Wind 80 m
Shear
Wind Velocity (m/s)
Shear 10 m to 80 m
Hour of the Day
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
H1 H2 H3 H4 H5 H6 H7 H8 H9 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24


Spring - Figure 16
Wind 10 m
Wind 80 m
Shear
Wind Velocity (m/s)
Shear 10 m to 80 m
Hour of the Day
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
H1 H2 H3 H4 H5 H6 H7 H8 H9 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24

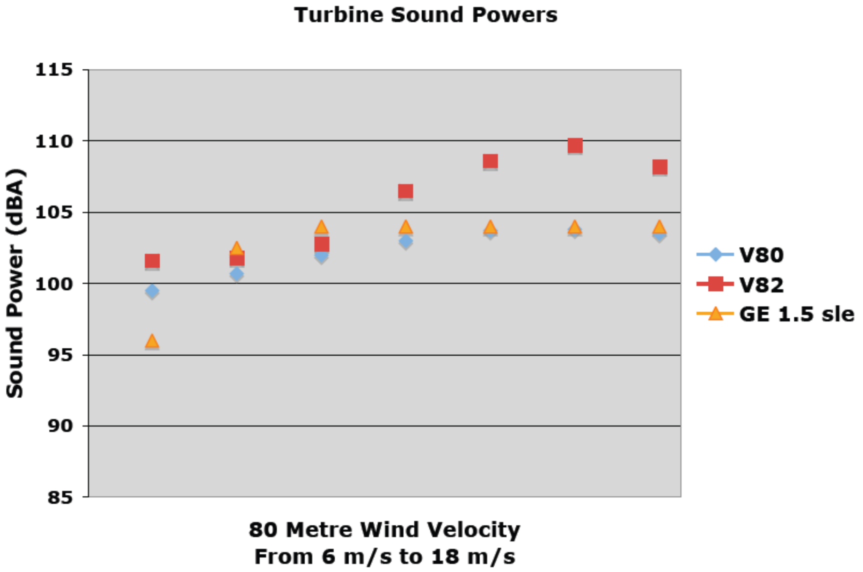


Figure in Table 3

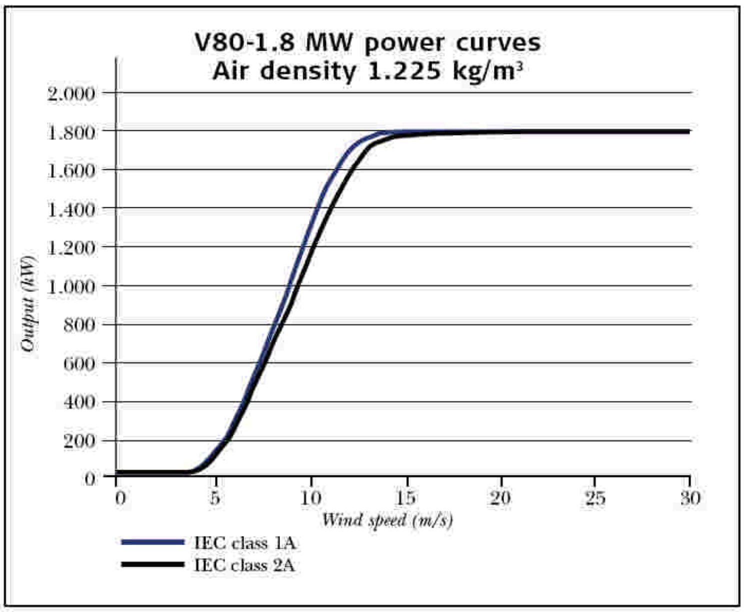


Figure 3

Second International Meeting
on
Wind Turbine Noise
Lyon France September 20 – 21 2007

WIND FARM perception – A study on acoustic and visual impact of wind turbines on residents in the Netherlands

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Abstract
A growing concern for the impact of wind farms on residents in the Netherlands has led to resistance against further development of onshore wind power. The concern is partly based on scattered reports of annoyance with wind turbine noise among people living near operating wind farms. Previous studies have shown that wind turbine noise could be annoying at sound pressure levels lower than those known to be annoying for other community noise sources, such as road traffic. This could be due to the special characteristics of wind turbine noise (amplitude modulations) that make the sound easily perceptible. It could furthermore be due to atmospheric situations influencing large modern wind turbines more than older ones, leading to higher sound exposure than accounted for in the planning process. A Swedish study found the prevalence of annoyance in relation to A-weighted sound pressure levels to be higher in rural areas than in suburban areas. In addition to differences in background sound, people's expectation of their living environment varied. The prevalence of annoyance from wind turbine noise in the Netherlands could consequently not be derived without additional knowledge. The objectives for the study WINDFARMperception were to assess the prevalence of annoyance from noise and visual exposure in relation to sound immission levels outside the dwellings of people living in the vicinity of wind farms in the Netherlands, to identify factors interacting with annoyance and to explore possible health effects. Three types of study areas were selected: rural with no main roads, rural with a busy road, and built up areas. The study areas comprised at least two wind turbines larger than 500 kW at a mutual distance of 500 m or less. The study sample (n = 1,948) was randomly selected among people living at different immission sound levels (preliminary calculated) within 2.5 km of a wind farm. Responses to environmental stressors in the living environment, including wind turbines and road traffic, were

assessed in a postal questionnaire sent out in April 2007. The questionnaire also comprised questions measuring self-reported health and well-being (GHQ-12). Measures for aural and visual exposure from the nearest wind farm were calculated for each respondent. Preliminary results will be presented at the conference.

Background

The total installed capacity of wind power in the Netherlands was at the end of 2006 1,560 MW, of which 356 MW was installed during 2006 [European Wind Energy Association 2007], i.e., an increase with more than 20%. This rapid increase is by NWEA (Nederlandse Wind Energic Associatie) foreseen to continue. Even though NWEA predicts a shift towards offshore developments in the future, the erecting of wind turbines onshore will continue; the installed capacity onshore will, according to their scenario, be twice as large in 2012 as today [Cleijne et al. 2007]. However, a growing concern for the impact of wind farms on residents in the Netherlands has led to resistance against further development of onshore wind power. The concern is partly based on scattered reports of annoyance with wind turbine noise among people living near operating wind farms. The Dutch non-governmental organization NKPW (Nationaal Kritisch Platform Windenergie) has called attention to the need for more scientific knowledge of how people who live close to wind farms are affected by the turbines. Such knowledge is essential at the prospect of further wind farm developments.

Previous Swedish studies exploring the response to wind turbine noise have found a dose-response relationship between A-weighted sound pressure level and noise annoyance [Pedersen and Persson Waye 2004; 2007]. The dose was in these studies calculated as free-field values of A-weighted sound pressure levels outdoors at downwind conditions 8 m/s at 10 m height. Response was assessed as self reported noise annoyance. Wind turbine noise was in these Swedish studies found to cause annoyance at sound pressure levels lower than those known to be annoying for other community noise sources, such as road traffic. This could be due to several factors, not yet fully explored. Some suggestions are given below.

The special characteristics of wind turbine noise (amplitude modulations) make the sound easily perceptible. The amplitude modulation is an effect of differences in wind velocity at different heights of the area swept by the rotor blades and an effect of the wind being slowed down by the tower, increasing and decreasing the wind-induced sound power levels with the pace of the rotation [Van den Berg 2006]. Amplitude modulations in a sound are easily detected by the human ear, but best at the modulation frequency 2–4 Hz [Zwicker and Feldtkeller 1967; Landström et al. 1996]. A modern wind turbine with variable rotational speed typically has a modulation frequency of 0.5 Hz at the wind speed 4 m/s and 1.0 Hz at 20 m/s, which is within the span where modulations can easily be detected. In one experimental study the threshold for detection of a sound with a modulation frequency of 1 Hz was found to be 1–2 dB below a masking noise [Arlinger and Gustafsson 1988]. The masking noise had its energy within the same frequency band as the modulated sound, thus providing optimal possibilities for masking.

Amplitude-modulated sound has also been found to be more annoying than sound without modulations. In an experimental study it was found that a 30 Hz tone, amplitude-modulated with a modulation frequency of 2.5 Hz, generally caused higher annoyance, symptoms and change in mood. However, the difference compared with a non-modulated tone at 30 Hz was only statistically significant for subjective reports of drowsiness [Persson et al. 1993]. In another study, subjects given the possibility to change the modulation frequency avoided the start value of 2 Hz and chose either higher or lower modulation frequencies [Bengtsson et al. 2004]. Furthermore, combining equivalent SPLs and a weighting function that gave a penalty for amplitude modulations of 0.5–4 Hz successfully predicted annoyance in an experimental setup [Bradley 1994]. Experimental studies exploring response to wind turbine noise have shown consistent findings. In a study where 25 subjects were exposed to five different wind turbine sounds with an A-weighted equivalent sound pressure level of 40 dB, differences between the noises regarding annoyance were found [Persson Waye and Öhrström 2002]. The most annoying noises were predominantly described as “swishing”, “lapping” and “whistling”. These could all be seen as being related to the aerodynamic sound and as descriptions of a time-varying (modulated) sound.

The observed frequency of annoyance at low sound pressure levels in the Swedish studies could furthermore be due to atmospheric situations influencing large modern wind turbines more than older ones, leading to higher sound exposure than accounted for in the planning process – and also not accounted for in the calculations of sound immission levels in the Swedish studies. It is often assumed that there is a fixed relation between the wind velocity at hub height and at a reference height of 10 meter [van den Berg 2006]. However, when the atmosphere is stable, a situation occurring at night, the differences between wind velocities at different heights could be substantially larger than assumed. This leads to higher sound immission levels than expected, but also to increased amplitude modulation (from approximately 2 dB in daytime to 5 dB at night). These findings indicate that the observed frequency of annoyance with wind turbine noise at relatively low sound pressure levels could be due to insufficient exposure assessments. Several measurements of exposure should therefore be tried as dose in future dose-response studies of wind turbine noise.

Factors related to the physical environment moderates the response to wind turbine noise. Wind turbines are often placed in rural or semi-rural environments. Most studies on response to community noise (road traffic, railways and airports) have been carried out in urban areas and hence the prevalence of noise annoyance in rural areas for these noise sources is not known. Living in a clearly rural area in comparison with a suburban area increases the risk of annoyance with wind turbine noise [Pedersen and Persson Waye 2007]. This could to a part be explained by differences in background sound. Background sound in a rural area presumable has a lower equivalent sound pressure level than that of a suburban area, but also mainly comprises natural sounds. Sound from a technical device such as a wind turbine may therefore be appraised as incongruent with the background sound and hence cause annoyance. People’s expectations of their living environment also vary. People who looked upon their living environment as a place suitable for economical growth and technical development were in an interview study indifferent of the wind turbine noise [Pedersen et al. 2004]. Expecting the home and its surroundings to be a suitable place for resting and gaining strength could conversely lead to an appraisal of the sound as threatening personal values. The sound was described as an intrusion into privacy that changed the image of a good home. If this is a universal reaction or a mere cultural phenomena is not known; expectations of the living environment presumable differ between countries.

The prevalence of annoyance from wind turbine noise in the Netherlands could consequently not be derived without additional knowledge. The objectives for the study WINDFARMperception were to assess the prevalence of annoyance from noise and visual exposure in relation to sound immission levels outside the dwellings of people living in the vicinity of wind farms in the Netherlands, to identify factors interacting with annoyance and to explore possible health effects.

Method

Three types of study areas were selected: rural with no main roads, rural with a busy road, and built up areas. The study areas comprised at least two wind turbines larger than 500 kW at a mutual distance of 500 m or less. The study population comprised all households within 2.5 km from the turbines. The study population was divided into sub-groups of 5-dB imission sound levels (preliminary calculated) from the wind turbines in the area. In subgroups comprising 50 or less households all households were assigned to the study sample. In subgroups of more than 50 households the study sample was randomly selected. The total study sample comprised 1,948 households (Table 1).

Subjective responses were obtained through a questionnaire masked to give the impression of investigating general living conditions in the countryside. The questionnaire comprised questions on response to several sources of possible disturbance in the living area, including wind turbines and road traffic. The questions were to a part the same as in a previous survey in Sweden [Pedersen and Persson Waye 2007], but the questionnaire was modified to suit conditions in the Netherlands. Response to wind turbine noise was assessed by a 5-point verbal rating scale (VRS), where 1 = “do not notice”; 2 = “notice but not annoyed”; 3 = “slightly annoyed”; 4 = “fairly annoyed”; and 5 = “very annoyed”, and also by an 11-point scale rating from 0 = “I am not at all annoyed” to 10 = “I am extremely annoyed”. Attitude towards the noise source were measured both as the general opinion on wind turbines and the impact of wind turbines on the landscape scenery. The questionnaire also comprised questions measuring the respondent's judgement of the current living environment, noise sensitivity, self-reported health symptoms and socio-economic status. Psychological distress was assessed by the General Health Questionnaire GHQ-12 [Sanderman and Stewart 1990].

The questionnaires were sent out in April 2007. One person of age 18 or older, having his or her birthday coming up next among those in the household, was asked to answer the questionnaire. The questionnaires were satisfactory returned by 717 respondents (response rate: 37%). The response rate was approximately the same regardless of noise immission levels (preeliminary calculated) or area characteristics (Table 1).

Table 1. Study population, study sample and response in relation to sound levels and area characteristics.

	Built up area				Rural area with busy road				Rural area			
	Study population	Study sample	Response	Response rate	Study population	Study sample	Response	Response rate	Study population	Study sample	Response	Response rate
25-30	6268	153	56	37%	5255	142	56	39%	5371	178	70	39%
30-35	1785	161	60	37%	2478	160	44	28%	2561	173	51	29%
35-40	404	155	68	44%	1242	163	63	39%	792	184	71	39%
40-45	91	36	12	33%	177	127	51	40%	206	119	49	41%
>45	10	5	1	20%	123	82	29	35%	150	110	36	33%
Total	**8558**	**510**	**197**	**39%**	**9275**	**674**	**243**	**36%**	**9080**	**764**	**277**	**36%**

Results

Preliminary results will be presented at the conference.

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SIROCCO: SILENT ROTORS BY ACOUSTIC OPTIMISATION

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Abstract
In this paper the results from the European 5th Framework project 'SIROCCO' are described. The project started in January 2003 and will end in August 2007. This project is coordinated by the Energy Research Centre of the Netherlands (ECN) with the following participants: National Aerospace Laboratory (NLR, the Netherlands), the University of Stuttgart (USTUTT) from Germany and Gamesa Eólica from Spain. GE Wind Energy joined the project in May 2005. The main aim of the SIROCCO project is to reduce wind-turbine aerodynamic noise significantly while maintaining the aerodynamic performance. This is achieved by designing new acoustically and aerodynamically optimised airfoils for the outer part of the blade. The project focussed primarily on reducing trailing edge noise, which was broadly believed to be the dominant noise mechanism of modern wind turbines.

1. Introduction
Wind turbine noise is still one of the major obstacles for the widespread use of wind energy in Europe. For this reason the European 5th Framework project SIROCCO is performed with the aim to obtain a significant noise reduction on full-scale wind turbines, without negative effects on the aerodynamic performance. The project's

main focus is on the reduction of trailing edge noise, which, before the project started, was broadly believed to be the dominant noise mechanism of modern wind turbines. For that purpose silent airfoils are designed which replace the existing airfoils at the outer part of a baseline blade. Only the outer part of the blade needs to be considered, because this part is exposed to the maximum flow velocities and consequently produces the highest aero-acoustic noise levels.

The SIROCCO project started in January 2003 with 6 participants: the Energy Research Centre of the Netherlands (ECN), the National Aerospace Laboratory (NLR) and Composite Technology Centre (CTC) from the Netherlands, the University of Stuttgart (USTUTT) and NOI Rotortechnik from Germany and Gamesa Eólica from Spain. Since then the project consortium has undergone some changes: In 2004 NOI and CTC withdrew and in 2005 GE Wind Energy joined the project. The project is scheduled to end in August 2007.

The activities in the SIROCCO project were carried out on two reference turbines: A three bladed Gamesa 850 kW turbine (D=58 m) which is located near Zaragoza (Spain) and a three bladed 2.3 MW turbine (D=94 m) from GE Wind Energy, which is located on ECN's Wind Turbine Test Site Wieringermeer, EWTW (the Netherlands), see the figures 1 and 2. Having results from two different turbines is believed to give much more general insights on the validity of the applied methods.

The project's first phase was to characterise the noise sources on the existing wind turbines with acoustic field measurements. Thereto a new acoustic array measurement technique, developed in the former DATA project [1] has been extended and utilised to localise and quantify noise sources on the rotating blades. The aim of this task was to verify that trailing edge noise is indeed the dominant noise source for the baseline turbine so that it is worthwhile to continue the project and spend further effort on the reduction of this noise mechanism. These activities were mainly carried out by NLR, where as a spin-off activity, ECN compared the measurements with calculations.
Within the second phase, a combined aero-acoustic design methodology that was developed in DATA has been extended and improved to design low-noise airfoils for the outer part of the rotor blade taking into account the constraints imposed by the manufacturers.
This activity was mainly carried out by the University of Stuttgart with support from the manufacturers.
Subsequently, in a third phase the acoustic and aerodynamic performance of the new airfoils were tested in a two-dimensional wind tunnel environment. This activity was mainly carried out by the University of Stuttgart in their Laminar Wind Tunnel. Part of the acoustic measurements were performed by NLR in the AWB anechoic wind tunnel from DLR.
After the airfoils have been designed and their behaviour was validated in the 2D wind tunnel environment, the fourth phase was executed in which the airfoils were implemented into full-scale rotor blades by Gamesa and GE. These blades were then mounted on the wind turbines and ECN and NLR carried out extensive field measurements of noise, power and loads at different operational conditions to assess the performance of these airfoils under 3D, rotating and atmospheric conditions.

The present paper can be considered as an update of [2] and [3] in which the 'Gamesa-results' from the first three phases of the project are described. It repeats the main results from these former papers, but in addition the results on the GE turbine and the results from the final phase are reported.

2. Acoustic field measurements (baseline measurements)

The results from the baseline acoustic measurements on the GAMESA turbine are described in [4]. The aim of these baseline measurements was to assess whether trailing edge noise is the dominant noise source indeed.
The acoustic measurements were done using an acoustic array (with typically 150 microphones). The array signals were processed to obtain the noise source distribution in the rotor plane. The measurement time for each data point was 30 s. Synchronously with the acoustic measurements, several turbine parameters and meteorological conditions were stored. Then the 'best' data points (i.e. data points with small variations in wind speed, yaw angle, small misalignment between array position and wind direction, etc.) were selected for further processing.

In a later stage, similar measurements have been done at the GE 2.3 MW. The main conclusions for the results obtained on the Gamesa turbine and the GE turbine turn out to be the same, see the figures 1 and 2 which show the test set-up and a typical acoustic 'source plot' for both turbines. Note that the position of the rotor as projected into the figures is arbitrary in view of the fact that the acoustic sources are averaged over 30 s:

- The figures show that the blade noise (i.e. the aerodynamic noise) is dominant where mechanical noise coming from the nacelle plays a minor role.
- It furthermore shows that practically all the noise is produced by the outer part of the blades, although, opposite to the expectations, it is not the very tip of the blade which dominates, but roughly speaking the part of the blade which is between 75 and 95% span.
- Most of the noise is produced when the blades are moving downwards. This effect was observed for all measurements and all frequencies, and it is very similar to results obtained earlier on the model scale wind turbine in the DATA project, where it was attributed to a combination of convective amplification and directivity of trailing edge noise. It should be noted however that for a different observer location, the pattern may be different.

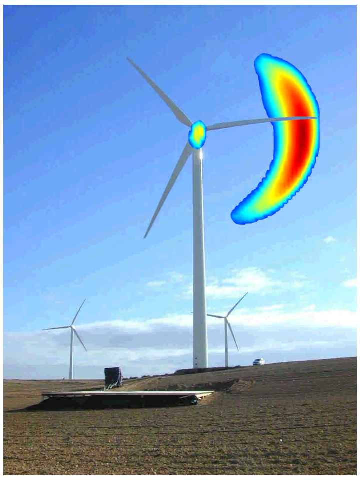

Figure 1: Picture of test set-up for acoustic measurements on the GAMESA baseline turbine. The distribution of noise sources (30 s averaged) in the rotor plane is projected onto the picture. The rotor rotates clockwise.

Figure 2: Picture of test set-up for acoustic measurements on the GE baseline turbine. The distribution of noise sources (30 s averaged) in the rotor plane is projected onto the picture. The rotor rotates clockwise.

Using a power integration method, the acoustic source plots were translated to absolute sound levels. The results indicated that the noise produced by the blades is proportional to the 5th power of the wind speed at the blades, which is an indication that the responsible mechanism is trailing edge noise. Another aerodynamic noise source, i.e. inflow-turbulence noise, typically shows a U^6 speed dependence.

In a next processing step, an alternative method was used (ROSI – ROtating Source Identifier) which allowed locating the noise sources on the *rotating* blades, so that the noise from the three blades can be distinguished, see figure 3. Figure 3 shows the results on the Gamesa blades, where 1 blade is cleaned, 1 blade is untreated and the third blade is tripped. It is found that the tripped blade is much noisier. This observation is again an indication that trailing edge noise is the dominant mechanism (if inflow-turbulence noise were dominant, then tripping would have no effect on the noise levels).

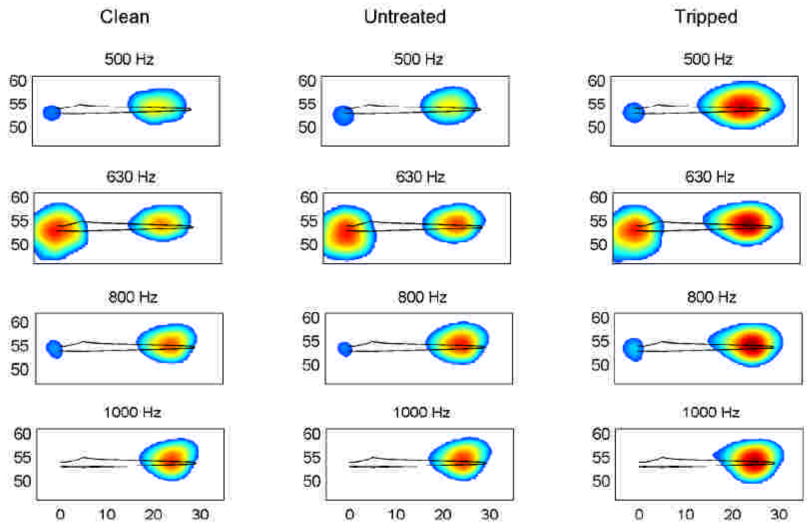

Figure 3: Typical acoustic source plots showing the noise sources on three different G58 blades

Hence, even although the resolution of the source localization method does not seem to be sufficient to determine directly whether the noise comes from the leading- or trailing edge of the blades, the above-mentioned observations indicate convincingly that trailing edge noise is the dominant source mechanism. This is further confirmed by calculations which are presented in the next chapter.

3. Validation of aero-acoustic wind turbine code SILANT with acoustic array measurements

As a spin-off to the investigations described in the previous chapter, the NLR-measurements have been used to validate the aero-acoustic wind turbine code SILANT. This code was developed in 1996 by a Dutch consortium that consisted of Stork Product Engineering (SPE), the Dutch Aerospace Laboratory (NLR) and TNO. For a detailed description of the code reference is made to [7]. The SILANT code calculates the sound power level of the wind turbine blades and sums it to the overall wind turbine sound power level. The input for the code consists mainly of geometrical and aerodynamic data, operational conditions and external conditions.

Basically SILANT calculates the noise level as follows:

- The wind turbine blades are divided in a number of segments (usually 10 to 20);

- For every blade segment two noise sources are calculated:
    - Trailing edge noise: According to the model of Brooks, Pope and Marcolini [8].
    - Inflow noise: According to the model of Amiet and Lowson [9]

  The noise sources are ('acoustically') summed over the segments in order to obtain the total blade and turbine sound power level.

The above-mentioned models from Amiet and Lowson and the model from Brooks, Pope and Marcolini require the following data for each blade segment:
- Reynolds number;
- Pressure and suction side boundary layer displacement thicknesses.

The displacement thicknesses come from a database, which was created a-priori and delivered along with the SILANT program. These displacement thicknesses were calculated with the RFOIL airfoil design and analysis code [11] for a number of angles of attacks, Reynolds numbers and airfoils. RFOIL is developed by ECN, NLR and DUT. It is an extension of XFOIL [10], taking into account rotational effects. The Reynolds number and angle of attack for each blade segment are obtained from an aerodynamic wind turbine model, based on the blade element momentum theory.

The comparison between the SILANT results and the G58 measurements is already presented in [2] and [3]. At a later stage some refinements were made to the SILANT code and the results from the updated code are presented in the figures 4 and 5. They show the SILANT calculated and measured overall sound power level as function of the electrical power (The G58 calculated power is aerodynamic power). It is noted that no results can be presented for above rated conditions due to the fact that the noise-power curve becomes multi-valued at constant rated power.

Generally speaking a very good agreement is found. A slight overprediction is found in the G58 calculations, but it must be noted that the measured overall sound power level as detected from an array of microphones will be too low in the order of 2 dB(A). This is due to the fact that the noise levels as measured by the array of microphones will not be fully coherent over the array area [21]. The measured values for the GE turbine have been corrected for this effect.

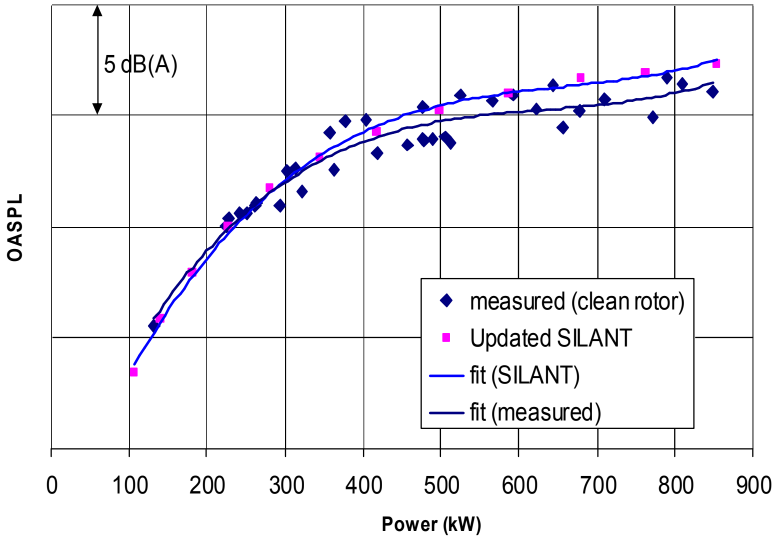

Figure 4: G58 turbine: Calculated and measured noise production as function of power for a rotor with 3 clean blades

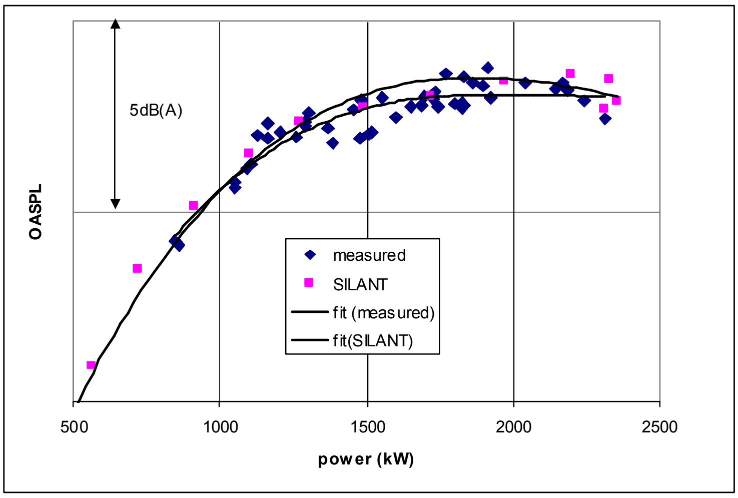

Figure 5: GE turbine: Calculated and measured noise production as function of power (untreated rotor)

Furthermore SILANT has been used to compare the inflow noise to the trailing edge noise. For both turbines the trailing edge noise exceeds the inflow noise with at least 8 dB(A) for all wind speeds. This is a further indication that trailing edge noise is dominant.

A more detailed comparison of the calculated and measured noise predictions is described in [21]. In this paper the source strengthes as calculated by SILANT at different radial segments of the wind turbine blade are input to the same acoustic array processing code as in the experiments, which then enables a direct comparison to the measured results.

4. Aero-acoustic design methodology

The main aim of the SIROCCO project is to design low-noise blades. Thereto the airfoils at the noisiest outer part of the blade are replaced by acoustically optimised airfoils with the same aerodynamic performance.

The low noise airfoils were designed with a combined (2D) aerodynamic/aero-acoustic model, which was implemented into a numerical optimisation tool, see also [5], [20].

The basic philosophy in the design of low noise airfoils relies on the idea to modify the boundary layer state at the trailing edge. This is mainly accomplished by adjusting the main pressure recovery at the rear part of the airfoil. For this purpose an aero-acoustic design methodology, which is capable of modelling the boundary layer around an airfoil and the resulting noise levels was required. As described in [5] it was originally attempted to design airfoils using the noise prediction scheme developed by TNO-TPD in the EU project DRAW [12]. This TNO-TPD model is based on the theory proposed by Chandiramani [13] and Blake [14]. It essentially calculates the spectrum of the trailing edge noise from several boundary layer properties, one of which is the mean velocity profile u(y) at the trailing edge. This profile is approximated from an integral boundary layer procedure based on integral parameters like displacement thickness, momentum thickness or skin friction, where the boundary layer profiles were assumed to behave according to the Coles law of the wall profile in combination with the law of the wake.
The integral boundary layer parameters were calculated by the airfoil design and analysis code XFOIL [10].
Apart from the mean boundary layer profile u(y), the TNO-TPD model requires a number of turbulence quantities across the boundary layer at the trailing edge, which are calculated from a mixing length approach. Furthermore the integral length scale Λ_2 of the vertical velocity fluctuations in the boundary layer is required, which was found by multiplication of a specific turbulence length scale with an empirical constant.

It was found that such methodology is not suitable for designing low noise airfoils. This is mainly due to the assumption of the boundary layer being in equilibrium, where the low noise airfoils, due the adjustment of the main pressure recovery at the rear part of the airfoils, have flow regions with a significant acceleration/deceleration. Such flow regions violate the equilibrium boundary layer approach, which forms the basis for the Coles velocity profile, the mixing length approach, and the assumption of a constant scaling factor to calculate the Λ_2 from a given turbulence length scale.

The fact that the equilibrium approach is not valid, was among others proven by an extensive experimental program in the Laminar Wind Tunnel from the University of Stuttgart where boundary layer measurements on an airfoil with a variable trailing edge (and consequent pressure recovery) were carried out, see section 5.

Hence it was necessary to take into account the history and anisotropy effects in the boundary layer. Therefore the aero-acoustic design method was changed. Although the acoustic part remained essentially the same, the boundary layer was represented with the finite-difference EDDYBL procedure in combination with a stress-ω turbulence model [15]. In this way the boundary layer and the turbulence equations are solved on a computational grid with discretisation in streamwise and wall normal direction. The stress-ω turbulence model provides a direct estimate of the turbulent properties at the grid points, in which the anisotropy and history effects of the boundary layer are automatically taken into account. The stress-ω turbulence model also calculates a turbulence length scale, which is then used to derive the Λ_2 scale. The relation between the 'stress-ω turbulence length scale' and the Λ_2 is determined semi-empirically from the experimental database with measurements on the airfoil with variable trailing edge (section 5). Opposite to the previously used scaling factors it takes into account the boundary layer development. In this way the scaling factor has become variable instead of constant.

The combined aero-acoustic models have been implemented into the numerical optimisation environment POEM [5]. This made it possible to generate airfoil shapes with a minimal noise production in an automatic way. The resulting design methodology produced airfoils which were indeed quieter, as demonstrated in the wind tunnel measurements (see section 5.1 and 5.2). It must be noted that the inclusion of the constraints imposed by the manufacturer played an important role. This holds among others for aerodynamic and geometric requirements. One can think of constraints on $c_{l,max}$, α_0, c_l/c_d, stall characteristics, parts of the airfoil geometry which should remain unchanged etc. It is noted that for the GE airfoil, a challenge arose due to an additional constraint on c_{lmax} compared to the baseline airfoil. To meet this constraint, it was necessary to introduce a sharp suction peak that consequently produces an increase in noise above the design c_l. As a result, if the airfoil operates above the intended design point, a reduction in the noise gain is to be expected.

It should be emphasized that these constraints are a result of the fact that the present project aims to modify existing blades. It is only the outer part of the blade that will be equipped with new airfoils and in order to fit the outer and inner part, constraints should be imposed on the aerodynamic behaviour of the new airfoils. If low noise blades were designed from 'scratch', many constraints could be released, which, by definition, yields better performance.

5. 2D wind tunnel measurements

In the previous section, it was already pointed out that 2D wind tunnel measurements have been carried out which supported and validated the theoretical design efforts. Several types of wind tunnel measurements have been performed. Roughly speaking they can be distinguished into the following categories:

1. Measurements on an airfoil with a variable trailing edge (VTE). The upper airfoil shape has been made variable between x/c = 0.4 and x/c =1.0, leading to different pressure recoveries at the rear part of the suction side. These measurements aimed to understand the effect of different pressure recoveries on the trailing edge boundary layer properties. They proved, among others, that the equilibrium approach was not valid for low noise airfoils and it led to the selection of appropriate turbulence models for the noise models (see section 4);
2. Measurements of aerodynamic polars c_l, c_d (α) etc. on the reference airfoils and the optimised airfoils. These measurements aimed to verify the aerodynamic performance of the optimised airfoils in comparison with the performance of the reference airfoil;
3. Acoustic measurements on the reference airfoils and the optimised airfoils. These measurements aimed to verify the acoustic behaviour of the optimised airfoils in comparison with the behaviour of the reference airfoils.

Most of these measurements were done in the Laminar Wind Tunnel (LWT) of the Institute of Aerodynamics and Gas Dynamics, University of Stuttgart. The exception lies in the acoustic measurements on the G58 airfoils, which were also done in DLR's Aeroacoustic Wind Tunnel AWB, which is located in Braunschweig. The AWB measurements were performed under supervision of NLR. The acoustic measurements on the GE airfoils were only carried out by USTUTT in their LWT using the new Coherent Particle Velocimetry Method (CPV) technique, which is described in [16, 17, 18].

This method is comparable to the COP method by Hutcheson and Brooks [19], but instead of microphones special hot wire sensors are used to measure the particle velocity of the sound wave. Due to the high directional sensitivity of the hot wires it is possible to improve significantly the SNR with respect to parasitic background noise. The use of cross-correlation technique for the signal processing further suppresses uncorrelated noise sources. Numerical simulation of the sensitivity of the whole experimental set-up with respect to the sound radiated by a line source located at the trailing edge finally leads to quantitative sound pressure levels at a selected observer position. Within the framework of SIROCCO the CPV method was applied for TE-noise measurements on cambered airfoil sections for the first time. Detailed comparisons with array measurements performed in the AWB on the same wind tunnel models showed a very good quantitative agreement. Therefore the GE airfoils could be validated aerodynamically and acoustically in a single test campaign in the LWT.

Beside a significant speed up of the validation procedure, the drawback of open jet effects [6] present in the AWB are completely avoided and the consistency of the data increased.

5.1 Aerodynamic verification in wind tunnel

As mentioned in section 4, the acoustically optimised airfoils have been generated with an optimiser using a number of constraints, which were imposed by the manufacturers. The constraints mainly result from the fact that the new airfoils should be implemented on the outer part of an existing blade, where the inner part of the blade remains the same. This limits the 'design freedom' considerably and generally speaking the optimised airfoils were only allowed to differ slightly from the reference airfoils in terms of α_0, c_{dmin}, $c_{l,max}$, c_l/c_d and airfoil thicknesses.
In order to check whether the theoretical constraints are met, the aerodynamic performance of the airfoils has been measured in the LWT. The measurements were done at a Reynolds number of 1.6 x 10^6 (Gamesa) or 3x10^6 (GE) with natural and fixed transition (x_{tr}/c=0.05). More detailed information on these measurements is given in [6] but the most important conclusion is that the aerodynamic constraints are met indeed. This is illustrated in the figures 6 and 7 which show the measured aerodynamic performance for the reference airfoils (denoted as GAM or GE) and the optimised airfoil (denoted as TL132 or TL151).

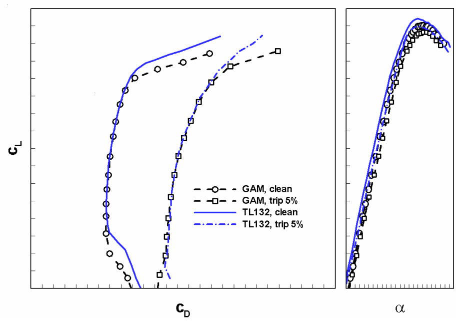

Figure 6: Measured aerodynamic performance for reference (GAM) airfoil and optimised airfoil (TL132).

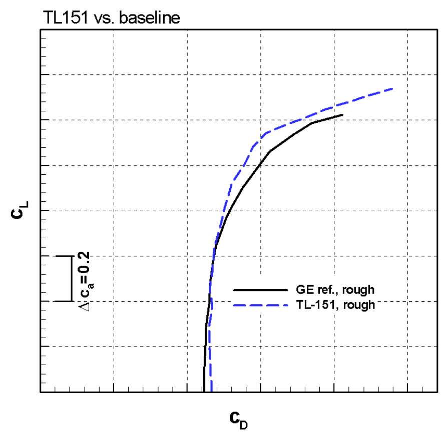

Figure 7: Measured aerodynamic performance for reference (GE) airfoil and optimised airfoil (TL151).

5.2 Acoustic verification of optimised airfoils in wind tunnel

In order to validate the noise reduction, which was expected from the combined aerodynamic/aero-acoustic design method, wind tunnel measurements were performed of the noise production of the optimised airfoils and the reference airfoils. The acoustic measurements on the G58 airfoils were carried out in both the AWB tunnel of DLR and the LWT tunnel [6], where the acoustic measurements on the GE airfoils were only carried out in the LWT tunnel. The measurements on the G58 airfoils were mostly done at a Reynolds number of 1.6×10^6 with natural and fixed transition ($x_{tr}/c=0.05$) and the measurements on the GE airfoils were done at a Reynolds number of 3×10^6 ($x_{tr}/c=0.05$)
For the G58 airfoils, generally speaking a noise reduction is found between 1.0 and 1.5 dB(A), see figure 8. This figure shows the total sound pressure levels of the two airfoils (the reference airfoil, GAM and the optimised airfoil TL132) for tripped conditions (for clean conditions a slightly larger reduction is found) for both the AWB and the LWT wind tunnel. It is noted that the noise reduction is mainly obtained at the lower frequencies (say f < 1500 Hz), where the higher frequencies show a noise increase.
Figure 6 shows the expected noise reduction for the GE airfoils. The noise reduction turns out to be in the order of 2-3 dB(A). This noise reduction too, is mainly reached at the low frequencies.

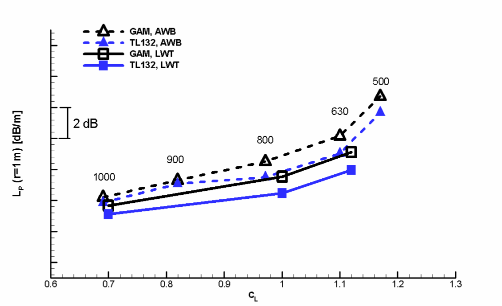

Figure 8: Total sound pressure level for reference (GAM) and optimised (TL132) airfoil as function of c_l); tripped conditions

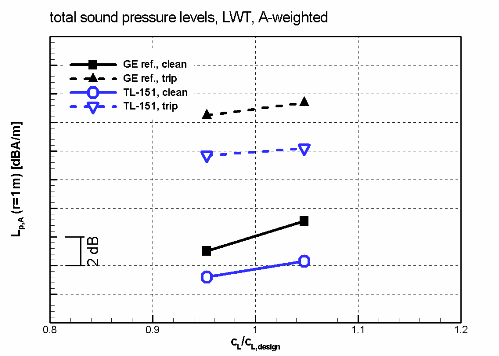

Figure 9: Total sound pressure level for reference (GE) and optimised (TL151) airfoil as function of c_l

6. Field measurements

As described in the previous chapter, the 2D wind tunnel measurements on the newly designed airfoils, led to a noise reduction at the same aerodynamic performance. In order to assess the possible noise reduction from these airfoils in the 3D environment, i.e. on a full scale rotating blade, the industrial partners (Gamesa and GE) incorporated the new airfoils in the outer part of the blade. The optimised blade (denoted as SIR blade in the sequel of this paper) then replaced one of the baseline blades. This results in a 'hybrid' rotor with one SIR blade and two baseline blades. The question whether or not a noise reduction is achieved is answered with acoustic array measurements from NLR. This measurement technique (see section 2) makes it possible to distinguish the noise production of the separate blades. Hence the use of a hybrid rotor enables a direct comparison of the noise production on the different blades at (almost) similar conditions, and as such the achieved noise reduction from the acoustic airfoils can be assessed in a direct way.

The remaining question, i.e. the question whether the aerodynamic performance of the SIR blade is similar to the performance of the baseline blades is more difficult to answer. Thereto ECN measured the blade root bending moments on the GE turbine. The use of a hybrid rotor then makes it possible to compare directly the loading of the separate blades at almost similar conditions. It must be realised however that these blades loads are not a 'pure' aerodynamic quantity since they are also affected by the structural dynamic behaviour of the blade. Therefore additional information (for the G58 turbine: The only information) is searched from a comparison of the measured rotor performance on the baseline rotor and the Sirocco rotor. It should be realized that such procedure is far from ideal when trying to assess a possible difference in aerodynamic performance from the acoustic airfoils. This is partly due to the fact that the overall performance is not very sensitive to the aerodynamics of the silent airfoil: Only one blade on the Sirocco turbine will be affected by a difference from the silent airfoils and the other two blades (which also contribute to the overall power) are unaffected. An additional problem lies in the fact that a relatively small difference needs to be assessed from results, which are measured at different periods of time in the free atmosphere. Such comparison is obviously complicated due to the expected small differences and by the stochastic nature of the wind conditions.

6.1 Field measurements on G58 turbine

The measurement program on the G58 turbine can roughly be characterised as follows:

- Between October 2005 and April 2006 long term power performance measurements were carried out on the baseline turbine.
- Subsequently in April 2006 dedicated acoustic measurements were carried out in different phases, see table 1. In this table, the SIR blade denotes the optimised blade and the G58_1 and G58_2 blades denote the original Gamesa blades. It can be seen that three states have been measured where all three blades are treated differently. Among others blades have been cleaned and/or tripped. Furthermore two types of brushes have been applied at the trailing edge of the blade. These brushes are acoustic devices which are expected to reduce the noise level. The purpose of state 1 was to assess the acoustic performance of the SIR blade for clean conditions, and to get an indication of the aerodynamic state of the untreated blade. The purpose of state 2 was to assess the acoustic performance of the SIR blade for tripped conditions, and to determine the acoustic effect of brush 1. The purpose of state 3 was to test the effect of brush 2, and to obtain a comparison between the two nominally identical tripped G58 blades, as a reference for the brush 1 effect in State 2.
    - All blade treatments, except the cleaning of the G58_1 blade (which was done when the rotor was on the ground), were carried out by climbers.
    - The state of the three blades was inspected prior to the acoustic measurements, when the rotor was on the ground, directly before the acoustic measurements. Unfortunately, due to the handcraft manufacturing techniques employed in order to keep the price of the blade within the budget, the surface quality of the new SIROCCO blade was found to be rougher than those of the two G58 blades, manufactured using industrial processes and techniques. Moreover, in contrast to the G58 blades the SIROCCO blade was equipped with an anti-erosion band on the leading edge of the blade, which effectively acts as a trip. Due to these observations it was decided to adjust the turbulator positions to the anti-erosion band on the SIR blade in order to make a fair comparison. Finally the actual SIR blade contour was found to deviate from the prescribed TL-132 airfoil, as a result of the positive manufacturing technique used.
    - The 'trip*' entry for the G58_2 blade, see table 1, indicates that at some point during state 2 this blade started to whistle (most of the time). After removal of the brush for state 3 the whistle was still present, so it was probably caused by a partially loose trip.

	SIR blade	G58_1 blade	G58_2 blade
State 1	clean	clean	untreated
State 2	trip	trip	trip* + brush 1
State 3	trip + brush 2	trip	trip*

Table 1: Acoustic measurements on the Gamesa rotor: Different states

- After carrying out the acoustic measurements, the trips and brushes were removed and the performance on the untreated rotor could be measured during May and June 2006. The measurements within this period were then used to compare it with the performance of the baseline turbine.

Figure 10 shows the averaged dedopplerized blade noise spectra for the three different states. The overall noise production (compared to the level of blade 1) is summarized in table 2 for the different states.

The power performance of the (untreated) hybrid rotor has been compared with the performance of the untreated baseline rotor as function of the free stream wind speed. The free stream wind speed was measured with a meteorological mast, which is placed 1.6 D North of the turbine. Measurements are selected with the meteorological mast at an undisturbed position. It was found that the scatter of the power performance can be significantly reduced by plotting the power versus the nacelle anemometer wind speed, but this did not change the mean power curve. On the other hand the measurement uncertainty from the nacelle anemometer is significantly higher and this was believed to be even more true if a different rotor (i.e. the Sirocco rotor) is mounted upstream of the nacelle anemometer.

The most important conclusions are:

- The power production of the hybrid rotor is slightly reduced. The differences can be expressed in terms of an artificial annual energy production (AEP) which only considers the below rated conditions (at above rated conditions the power of the hybrid and baseline rotor will anyhow be similar). For an annual mean wind speed of 8 m/s, the reduction in AEP turns out to be in the order of 1.4%, which is below the measurement uncertainty, but which can also be attributed to the erosion trip on the Sirocco blade. Furthermore it should be mentioned that the Sirocco airfoils have a slightly different α_0 (See figure 6). This was compensated by pitching the Sirocco blade over this difference, by which the production of the inner part of the Sirocco blade is slightly reduced. As such the power reduction cannot be attributed to a poorer aerodynamic performance of the airfoils itself.
- For the clean condition, the noise of the SIROCCO blade is 0.6 dB(A) higher. The increase can be attributed to the anti-erosion band on the leading edge of the SIROCCO blade. Since this band was not present on the G58 blades and effectively acts as a trip, no fair comparison is possible for the clean condition. Interestingly, the untreated G58 blade turns out to be quieter over the whole frequency range than the clean G58 blade. This suggests that the untreated

blade was aerodynamically clean and that small deviations from the nominal blade contour can have a significant effect on the noise.

- For the tripped condition, the SIROCCO blade is 0.6 dB quieter (table 2). This is mainly due to a noise reduction at higher frequencies (figure 10.b). Actually this result is opposite to the acoustic wind tunnel tests on the new airfoil which showed a low-frequency noise reduction (section 5.2). It may be explained by the deviations from the prescribed blade surface geometry for the SIROCCO blade.
- Table 2 shows a 0.5dB noise reduction from the first type of brush. This is mainly reached at low frequencies (say < 1000 Hz), see figure 10.b. The second brush, table 2, gave a noise increase of 2 dB.

	Sirocco blade	G58_2 blade	G58_1 blade
State 1	0.6	-1.4	0
State 2	-0.6	-0.1	0
State 3	1.4	0.4	0

Table 2: Gamesa: Differences in overall sound power levels (relative to blade 1 level)

6.2 Field measurements on GE turbine

The measurement program on the GE turbine can roughly be described in the following way:

- In November 2005, the power performance measurements on the baseline turbine were carried out, simultaneously to the acoustic measurements which are described in section 2.
- In March/April 2007, the acoustic measurements were performed in two phases, see table 3. (In this table the SIR blade denotes the optimised Sirocco blade and the GE_1 and GE_2 blades denote the original GE blades). The state 1 measurements were carried out between March 29 and April 5, 2007. In state 1 the acoustic performance of the Sirocco blade is assessed at tripped conditions (and cleaned blades). Furthermore one of the baseline blade was equipped with trailing edge serrations (an acoustic device which aims to reduce the noise level). As such the purpose of state 1 was to assess the acoustic performance of the SIR blade for tripped conditions, and to get an indication of the noise reduction from the serrations. Thereafter, in state 2, the trips were removed but the serrations remained. So the purpose of state 2 was to assess the acoustic performance of the SIR blade and the serrations for untreated conditions. The acoustic measurements in state 2 were performed until April 20, 2007. The performance and load measurements on the state 2 rotor continued until May 14th, 2007.

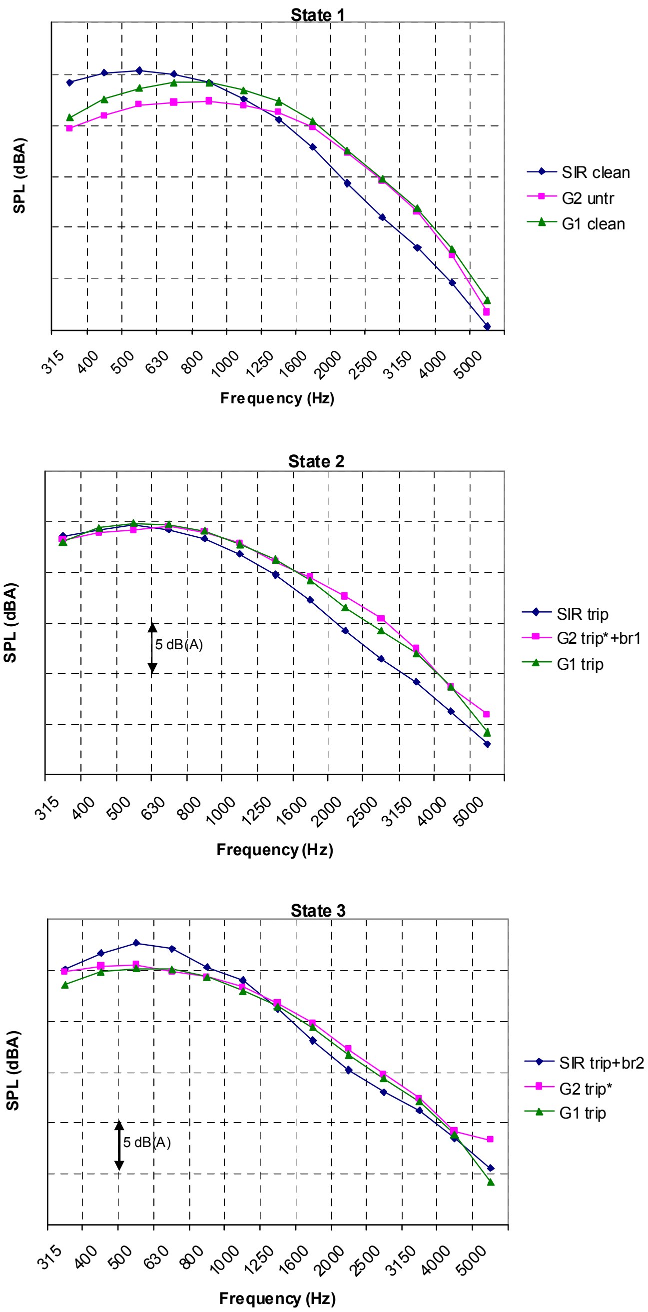

Figure 10: Gamesa: SPL of the three blades on the hybrid G58 rotor at the different states

- The first blade treatments needed for state 1 (i.e. the mounting of the serrations and the cleaning of the blade) were done when the rotor was on the ground. The removal of the trips was carried out by climbers.
- The state of the three blades was inspected prior to the acoustic measurements, when the rotor was on the ground. Generally speaking the blade quality turned out to be very acceptable although some deviations occurred in the shape of the pressure side of both reference blades at one radial position.
- Due to persisting low wind speeds from the wrong direction, the pre-defined criteria for the acoustic measurements (see section 2) could only be met for state 2, which was considered to be most important state. For state 1, measurements were only obtained for the lowest three wind speed bins, with the array facing the back side of the rotor. Such 'back side' measurements were also done in state 2, but they will not be reported in this paper. As such the present paper only discusses the clean results with the array upstream of the turbine.

The power performance of the (untreated) hybrid rotor is compared with the production of the untreated baseline rotor as function of the free stream wind speed. The free stream wind speed is measured with a meteorological mast placed 2.36 D from the turbine where wind directions are selected with the met-mast beside the turbine.
The figures 11 and 12 show the mutual comparison of the out-of-plane and in-plane moments on the different blades (averaged values per data point), where the latter shows the contribution of the blade to the rotor shaft torque (note that the sum of these three blade moments resulted in the rotor shaft torque indeed). In table 4 the differences in overall sound power levels are presented.

	SIR blade	**GE_1 blade**	**GE_2 blade**
State 1	clean with trip	clean with trip	clean with trip + serrations
State 2	untreated	untreated	serrations

Table 3: Acoustic measurements on the GE rotor: Different states

The most important conclusions are as follows:

- The power production of the hybrid rotor turns out to be slightly higher than the production of the baseline turbine. The differences can again be expressed in terms of an artificial annual energy production (AEP) which only takes into account the below rated conditions. For an annual mean wind speed of 8 m/s the increase in Annual Energy Production is in the order of 2.8%. The figures 11 and 12 show the moments of the Sirocco blade to be similar to the moments on the blade with serrations, but at a level which is slightly higher than the loads on the baseline blade. The differences in blade loads may be caused by a slightly higher performance of the modified blades. It must be mentioned however that, in particular for the mean in-plane loads, the measurement uncertainty is large and the differences are within the measurement uncertainty. As such it can be concluded that the aerodynamic performance of the Sirocco blade is similar or slightly better than the performance of the baseline blades.

- Table 4 shows the Sirocco blade to be slightly more quiet. The reduction increases with wind speed but the average reduction is in the order of 0.5 dB(A). It appeared that the gain is reached at low frequencies, where the higher frequencies yield a noise increase. It is noted that the acoustic wind tunnel measurements of the airfoils also indicated a reduction at low frequencies and an increase at high frequencies.
- The serrations yield a clear noise reduction. It appeared that the gain is reached at low frequencies where the noise at the high frequencies is increased. The overall noise reduction from the serrations turns out to 3.2 dB.

	SIR blade	GE_2 blade (+ serration)	GE_1 blade
State 2	-0.5	-3.2	0

Table 4: GE: Differences in overall sound power levels (relative to blade 1 level)

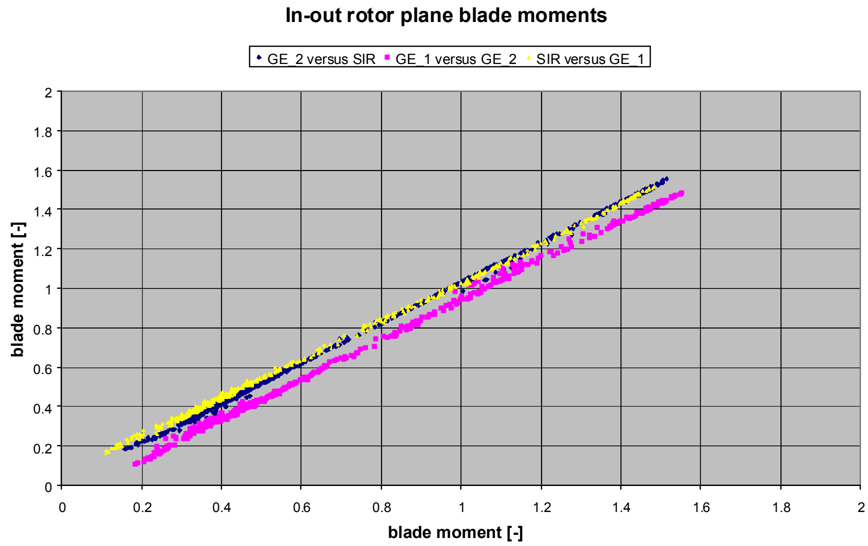

Figure 11: GE: Mutual comparison of out of plane moments of the three blades

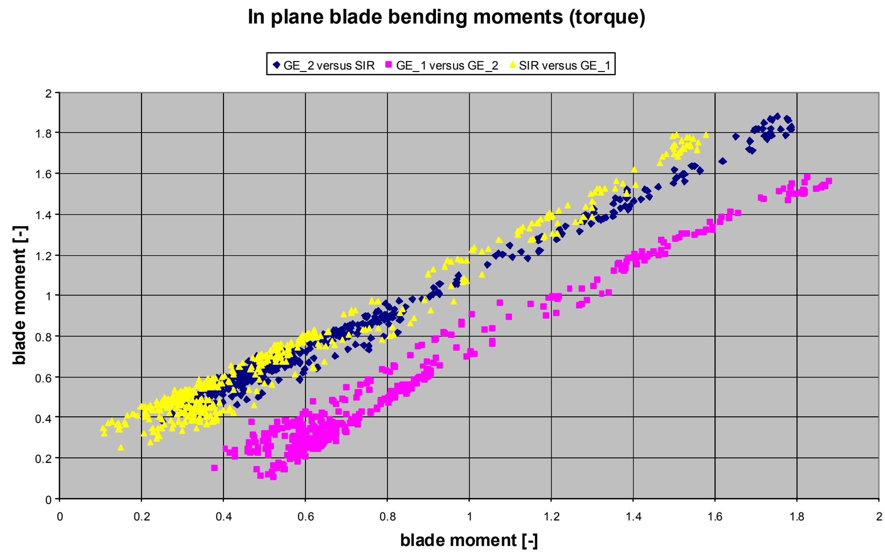

Figure 12: GE: Mutual comparison of in plane moments of the three blades

Conclusions and recommendations

- The acoustic array method showed, for the first time ever, the detailed aero-acoustic behaviour of a wind turbine blade. Many important new insights were found:
    - Trailing edge noise turns out to be the dominant noise source;
    - For an observer standing in front of a turbine, most of the noise is produced at the downward movement of the blade;
    - For the turbines under consideration, most of the noise is produced at the outboard part of the blade, but generally not at the very tip.
- Low noise airfoils were designed for the outer part of two existing wind turbines with a combined (2D) aerodynamic/aero-acoustic model. Thereto an existing design method for acoustic airfoils has been improved and extended. The most important improvement was the more detailed calculation of the turbulence properties taking boundary-layer history and anisotropy effects into account.
- The behaviour of the acoustic airfoils has been verified by means of 2D wind tunnel measurements. The noise reductions at the prescribed design lift range appeared to be 1-1.5 dB(A) and 2-3 dB(A) respectively, where the aerodynamic performance remained the same or it was even improved. A very good quantitative agreement between prediction and measurement was observed.

- Field measurements showed the noise reduction from these airfoils to be in the order of 0.5 dB(A) where the aerodynamic performance remains the same.
- It is not fully understood yet why the noise reduction in the field is lower than the noise reduction in the wind tunnel. Apart from blade quality, it is possible that instationary inflow conditions in the field lead to lift fluctuations well beyond the prescribed design lift range. This will further be investigated in order to include the off design behaviour into the airfoil design methodology.
- The present project showed that it is possible to design airfoils which fully maintain their aerodynamic behaviour but which at the same time can meet additional acoustic criteria. As such it is recommended to add, if relevant, these acoustic criteria in the future designs of airfoils.
- Acoustic devices have been added to the trailing edge of a wind turbine blade. It was shown that these devices can lead to an additional noise reduction
- A very good agreement was found between the wind turbine noise prediction code SILANT and acoustic measurements

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Acknowledgement

Financial support for this research was given in part by the European Commission's Fifth Framework Programme. Project Reference: ENK5-CT-2002-00702 Sirocco: SIlent ROtors by Acoustic Optimisation. ECN and NLR received additional funding from SenterNovem under project number 400003700

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WIND TURBINE NOISE 2007
SECOND INTERNATIONAL CONFERENCE
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CALCULATE NOISE OF WIND-FARMS

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ABSTRACT
During the conference Wind Turbine Noise 2005 in Berlin, we described [1] a model which had been developed and used for noise mapping adapted for wind-farms. This model takes into account the influence of the meteorological characteristics upon the sound propagation. Moreover It differs from the conventional models of specular reflection in that it is based on the assumption that the sound waves are diffused when reflecting back from it**.** The meteorological characteristics are defined by temperature and wind speed changes at height. This model assumes that these changes are homogeneous on the area which is investigated. This current paper describes the evolution of the model with the view to taking into account the non-homogeneity of the changes of wind and temperature on the area.

INTRODUCTION
In France, the noise impact of wind turbines is measured by what is called the "sound emergence". This measured value must not be exceeded. Noise impact studies have to make predictions in order to ensure that this limit is not exceeded and if necessary indicate to wind farm developers how their projects can be modified to satisfy this requirement. These modifications often consist in decreasing the number of wind turbines in operation if the weather conditions would cause the legal limits to be exceeded. Therefore these conditions have to be identified as closely as possible.
Weather conditions have an impact on sound propagation and are one of the parameters which influence this "sound emergence". The noise level may vary considerably upwind and downwind of a noise source. The models used for the impact assessment should take into account the weather conditions which are least propagators of noise emissions so that the operation of the wind turbines can be adjusted to suit these conditions. Thus, models which are defined for airborne noise emissions only (such as ISO 96-13) are not sufficient to cover these particular site characteristics. Moreover, in France, wind turbines are often installed on hilly terrain. The models must therefore take into account the influence of topography on sound propagation.
The model presented at WTN05 had been developed and applied to operational forecasting for with wind farms (short calculation, time, noise map plotting, etc.). We present here the modifications of the model and the new comparisons between the calculations and the measurements.

THE REFRACTION INFLUENCE

In the context of a wind turbine impact study, we seek to calculate the noise levels far from the sources. Any changes in the characteristics of the atmosphere will have an influence on the result. Two phenomena are to be taken into account:

- The change of sound velocity with altitude leading to the refraction of the sound waves
- The absorption of sound by the atmosphere

This latter point is included in our model, as proposed by standard ISO 96-13 Part1. Thus we will not expand on it further here and will examine the refraction phenomenon.

The variation in the temperature and the wind speed with altitude induces a celerity change with altitude which leads to refraction of the sound waves propagated in the atmosphere. This well-known phenomenon leads to curvature of the sound waves. There are complex models for solving the parabolic approximation of the Helmoltz equation which translates acoustic wave propagation (FFP, PE, GF-PE, Split-step Padé, LE and Lagrangien Model) exist. They are expensive in calculation time and cannot be easily adapted to operational applications such as ours. This is part of the geometrical acoustic approximation. In our case, it consists in determining[1] the trajectory of the "ray" of sound. This results from the integration of the classic following equation:

$$\frac{dz}{dx} = \frac{c(z)\,\cos i(z)}{c(z)\,\sin i(z) + U(z)} \qquad \text{(Eq.1)}$$

where, c(z) is sound's celerity and U(z) wind's speed, at the height z.

The trajectory is curved and the curvature is oriented towards the ground or towards the sky. In the latter case, from a certain distance there would no longer be any acoustic energy coming from the source (shadow zone).

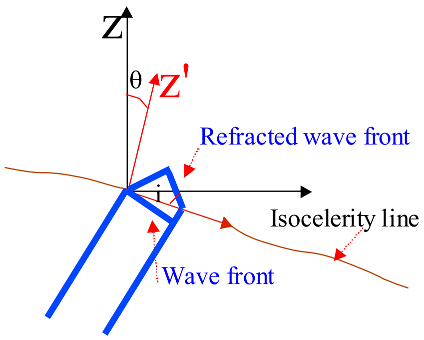

Figure 1 - Refraction

[1] And use of this trajectory in the model presented in reference [1]

However, experience has shown the existence of energy in this zone. Several factors explain this acoustic irrigation of the shadow zone (presence of turbulence in the atmosphere which diffuses the sound energy, diffraction of sound waves by the ground, etc.)
At present, our model takes into account this shadow zone irrigation phenomenon by the diffraction of the sound wave on the ground and by diffusion of the sound energy striking the ground.

It is to be noted that, in cases of complex topographies and meteorological environments, the equation for the trajectory (figure 1) becomes:

$$\frac{dz}{dx} = \frac{U(z)\sin(\theta + \alpha) + c(z)\cos i(z)}{U(z)\cos(\theta + \alpha) + c(z)\sin i(z)} \qquad \text{(Eq.2)}$$

With

- θ is the angle of the isocelerity line to the horizontal
- α is the angle of inclination of the wind speed to the horizontal

The model presented at WTN05 consists of analytic resolution of eq.1 for each configuration “noise source / receptor”. For this resolution we evaluate the celerity for each point (source/ receptor) and we assume that the evaluation of the celerity is linear between the two. This hypothesis allows the analytic resolution and gives one equation for the sound wave trajectory.
This model underestimate the high curvature of the trajectory near the ground. This high curvature is given by the “logarithmic” evolution of the celerity in according with the height, near the ground. This underestimation gives one sound level's estimation a little higher than wished in the “shadow zone”.
To mitigate this disadvantage, we have adapted a numerical resolution of the equation 2 (based on a upwind scheme).The trajectory of sound waves take, like this, in account the variation of celerity's gradient and is more realistic.
This resolution's method allows us to take into account of the spatial variation of the celerity's evolution with height. So, we are currently working at integrating a model of temperature's evolution and wind's speed's evolution that is better adapted at broken relief than our current model.

COMPARISON OF THE CALCULATED RESULTS WITH MEASURED RESULTS

The modification of the method of resolution didn't have any impact on the results presented previously [1], so we present here only results obtained for a new site.
An impact study type of approach has been used to measure the noise level. The purpose of this approach is not to detail its thoroughness. These results are meant to be representative of the noise level generated by the wind turbines alone (i.e. corrected for background noise).

The new site is a rural site with bush vegetation.
There are seven wind turbines on this site (70 m hub height). As with site 2 & 3 [1], they are on a crest and the relief is broken. The level difference between the

highest wind turbine and the lowest point of reception is approximately 260m. The measurement points (1 to 4) are between 1000 and 1500m away from the wind turbines. The measurements compared with the computated results correspond to nighttime operation with a north-west wind at an average wind speed of 8m/s, 10 m above the ground. The mean temperature during this period is 17°C. The image below schematises the wind turbines (red points) and the measurement points (green points):

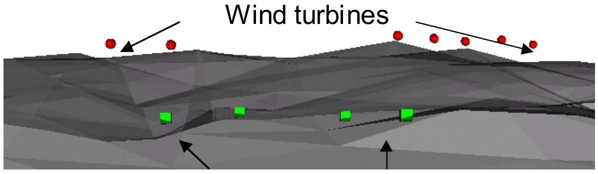

Fig. 2. Site 4

This site is interesting in that it is critical with regard to the combined influence of the topography and refraction. The wind turbine line is not directly visible from these points. However, the noise generated by the wind turbines is audible, and impacts on the noise level in dB(A).
The following table shows the computed results obtained compared with the measured results.

Table 1. Computed results for site 4

Points	Level dB(A) Measu.	Our calcul	Calc. ISO 96-13	Calc. without refr.
1	34	32	--or 12(1)	13.5
2	34	32.5	--or 13(1)	14.5
3	26	28	--or 12.5(1)	14
4	32	34	--or 12.5(1)	14

(1) if ground considering like a screen

The last column shows the results of calculations without taking into account the influence of refraction: the masked effect caused by topography is clearly visible.

CONCLUSION

The model that we have presented in this paper can be used to assess the noise impact of wind turbine farms by accurate calculations which match the accuracy of measurements and take into account the main factors that influence sound propagation over long distances. These factors are atmospheric absorption, refraction, diffusion and diffraction on the ground, and topography.
This model is sufficiently operational to allow dimensioning of scenarii in the context of wind turbine impact studies, and to plot useful sound maps for

communication to residents living close to wind turbine farms. Moreover, it is better suited to the calculation of wind farm impact than the one proposed by standard ISO 9613-2.
His recent modification allows us to take into account the inhomogeneity of meteorological data on the site.

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NOISE PREDICTION OF A NEW 34 MW WIND FARM

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Abstract

Is under environmental impact assessment study a new wind farm of 34 MW. The analysis needs also an acoustic evaluation of noise impact in the neighbour. Italian laws do not have a specific legislation for wind turbine noise. The study is carried out using common environmental Italian laws. The results show that there isn't an acoustic impact in the frequency range contemplated by Italian laws.
The aim of this work is to show national law situation and to define a guideline for noise assessment impact for wind farm in according with Italian rules, making in evidence problems and limits of actual acoustic regulamentation.

Introduction

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The site

Marche region has published a document (PEAR) about environmental and energetic guidelines for viability of energetic project, environmental and landscape bonds.
The document in chapter 6, gives specific guidelines for wind farm installation and impose environmental and energetic limits.
In particular PEAR imposes specific technical topics about:

- Annual mean speed
- Annual energetic production
- Annual operating hours
- Anemometric measurements duration
- Maximum number of generators and maximum power installed in the same site

PEAR for wind farms also predicts a preventive environmental impact assessment that includes:

- Electromagnetic impact
- Visual impact
- Noise impact
- On vegetable and on animals (birds in particular) impact
- Safety

The site has been chosen after a 5 years evaluation about anemometric condition. In the following fig. 1 there are the anemometric data of medium annual situation of the Region, measured at 25 meters on ground level.

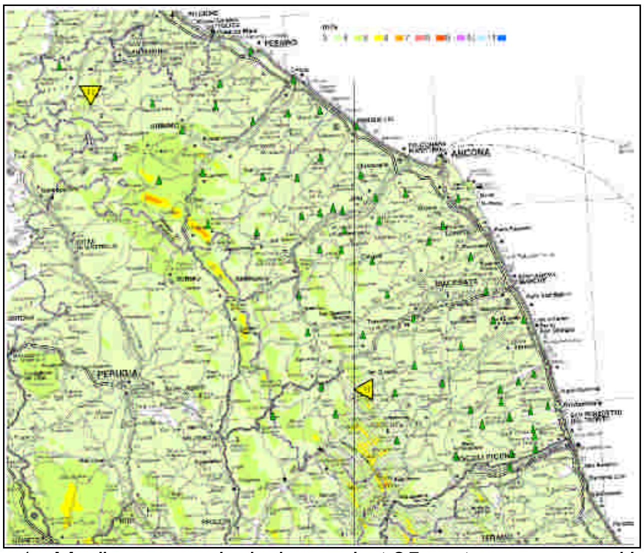

Fig. 1 - Medium annual wind speed at 25 meters on ground level

There are several sites of regional interest. In ten different sites medium annual wind speed is over 10 m/s^2 , as is shown in Fig. 1 in yellow areas. The main project has been located in the site with best characteristics and minimal environmental impact.

The site is located in Marche region, in the centre of Italy (Fig. 2), in a mountain zone, including three different towns, for a global extended area of 8000 m^2. The wind farm area is from 800 to 1200 meters on sea level in order to have mean wind speed upper than 6 m/s.

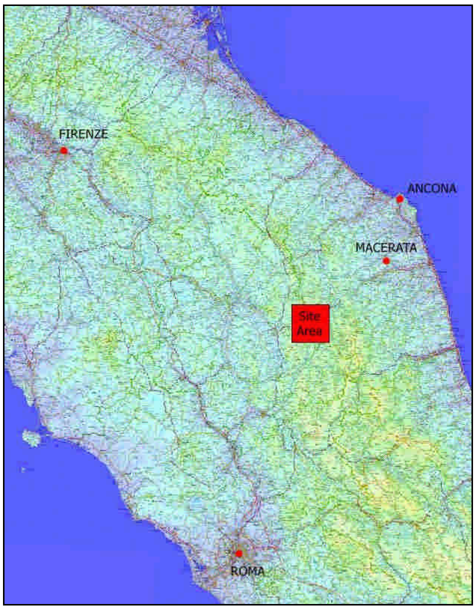

Fig. 2 – Site location area

Italian laws for wind turbine noise

In Italy there isn't a specific legislation for wind turbine noise. The reference legislation is the environmental regulation. The only way to study the noise impact of this kind of sources is considering a wind farm such as an industrial site. In according to Italian acoustic laws was necessary a noise impact study for the new site. The limits for noise level at receiver are specified in the follow table, classified by type of receiver areas. In Italy receiver areas are divided in six different groups named "class". For example the class I identifies green areas with reduced human presence, class VI identifies industrial areas.

In the case-study the wind turbines are located in a I class and houses are in III class, in accord with acoustic regional classification parameters, considering that there are not only residential areas, but little group of buildings with houses, markets, offices, etc.

Acoustic Class	***Noise level at receiver [dB(A)]***	
	Day Period (6,00 - 22,00)	***Night Period (6,00 - 22,00)***
I ***Green areas***	50	40
II ***Only-residential areas***	55	45
III ***Mix-areas***	60	50

In accord with Italian standards acoustic impact assessment has to be separated in two parts. The forecasting part is before wind turbines installation and it is named "*ante operam*" evaluation. When wind farm will be installed there will be a second part of the study of noise impact that will regards the "*post operam*" noise evaluation. In this work are defined guidelines for an "*ante operam*" and "*post operam*" acoustic assessment, but at the moment the site noise assessment considered has concluded only the first part (document are under authority analysis).

The first part ("*ante operam*") is carried out in three different phases:

1. Evaluation of actual acoustic situation
2. Prediction of future situation
3. Comparison with acoustic standard limits

The second part, when wind generators are installed, is separated in three phases:

1. Measurement of noise levels at receivers (in control point defined in precedent part)
2. Comparison with "*ante operam*" predicted levels
3. Comparison with acoustic standard limits

Phase I "Ante Operam"

In the first phase is important to fix on the position of control points. Control points are chooses near particular receiver, such as residential areas, school, hospital, etc.

In control points are measured acoustic level in the actual situation. In fig. 3 control points are signed up in aereo-photografic map, in tab. 1 there are noise level in control points defined in the map.

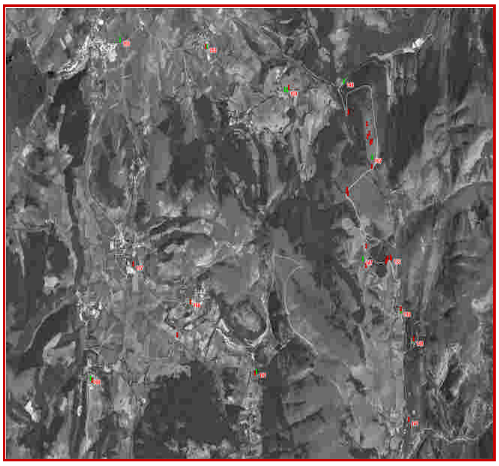

Fig. 3 – Control points

Control Point	*L_{eq} [dBA]*
P1	*34,1*
P2	*36,7*
P3	*39,8*
P4	*36,6*
P5	*31,1*
P6	*42,3*
P7	*45,7*
P8	*39,1*
P9	*47,9*
P10	*39,9*
P11	*37,1*
P12	*39,0*
P13	*39,7*
P14	*23,7*

Tab. 1 – L_{eq}(A) in control points

In this phase are also studied visual impact, electromagnetic impact, etc. In following picture is represented an example of photo rendering from a point of view located near a residential area.

Fig. 4 – Photo rendering

Phase II "Ante Operam"

The noise prediction is carried out using two different propagation models: the model based on ISO 9613-2 (as Italian law imposes) and the Danish model for wind turbine noise ("Description Of Noise Propagation Model Specified By Danish Statutory Order On Noise From Windmills - Nr. 304, 14 May 1991" produced by The Danish Ministry Of The Environment National Agency For Environmental Protection). Input data can be calculated from aero-acoustic mathematic models or can be obtained from measurement session accordingly with 61400 part 11.

The first solution seems to be not applicable to new 2 MW generators because the modern mathematical models from literature are over 10 years old. Input data used had been carried out from scientific literature about wind turbine noise measurement. It was not possible to apply 61400-11 directly in an existing wind farm because there is not 2 MW-generators wind farm sited in the centre of Italy area. In the following graphic are shown noise power level of a new 2 MW wind turbine, a Vestas V80.

Frequency [Hz]	***L_w [dBA]***
31,5	*71,1*
63	*82,3*
125	*90,7*
250	*95,2*
500	*96,2*
1000	*93,0*
2000	*91,7*
4000	*84,5*
8000	*73,8*

Tab. 2 – power noise level of V80

Using mathematical model have been developed two different propagation simulations. The two simulation give same results, as is shown in the following pictures.

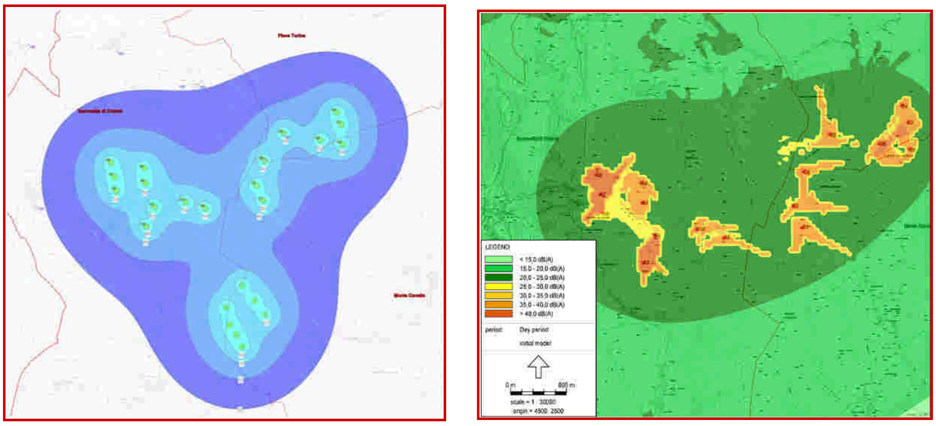

Fig. 5 – noise propagation models

Phase III "Ante Operam"

Mathematical models give results from 20 Hz to 20 KHz frequency. Total levels from wind turbines are in every control points under 40 dBA. As defined before, residential areas are in III Class: for noise level at receiver the day limit is 60 dBA and the night limit is 50 dBA. The levels at receivers are given from the actual noise levels in addition with noise levels from wind generators. Total levels obtained from the logarithmic sum have to be compared with national regulation's limits.

Conclusions

The noise level at the receivers are respected in all situations analysed. For the frequency range of interest (20 Hz – 20 KHz).

The two prediction models used give similar results. It means that ISO 9613 can be used for wind farm noise impact assessment in according to Italian laws.

Recent studies make in evidence that a lot of problem of annoyances for population are in the low frequency range. In the area in witch the new wind farm will be installed there are few resident people. The major part of houses are used for holidays. Low frequency noise is the noise in the frequency range from 1 Hz to 200 Hz. In this range there are several problems for sleep annoyance, stress, task performance, etc. Some problems are correlated to vibration in buildings. Infrasound (frequency under 20 Hz) propagation causes vibration for light structures in buildings as windows or wood element. This kind of material and structures are very frequently used in local constructions. In particular windows are frequently of old fabrication. This aspect is very important for noise annoyance problems but is not considered in Italian analysis of environmental assessment for wind farm.

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Low Frequency Noise from Large Wind Turbines

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Abstract

Noise is one of the determining factors when planning new sites for wind farms or single wind turbines. Especially low frequency noise and infrasound have been brought up during later years. Lack of knowledge have made it difficult for planners and authorities to include this in the planning and decision process

In the Danish project "Low Frequency Noise from Large Wind Turbines" financed by the Danish Energy Authority, Dong Energy, Vattenfall, Elsam, E.ON, Vestas Wind Systems and Siemens Wind Power a series of investigations is planned to clarify the situation on low frequency noise from modern wind turbines.

The projectpartners are: DELTA (Project leader), Risø, Dong Energy and Acoustics at the University of Aalborg.

The project has as its major goals to:

1) Decide whether or not there is a substantial amount of low frequency noise/infrasound (or other characteristics that might be mistaken as such) in the noise from modern wind turbines, including designing a suitable out door measurement method.
2) Select a method for calculation of/estimating the low frequency noise level/infrasound level inside residences and the relation between the indoor and outdoor level of the low frequency noise/infrasound
3) Determine a method for assessing the level of the natural background noise at low frequencies.
4) Make an assessment of the annoyance and the dose response relationship of low frequency noise/infrasound from wind turbines

Several investigations are included in the project but in this presentation only investigations involving measurements and prediction methods will be presented.

These parts of the project aim to give tools for objective assessment of noise at low frequencies through:

- Sound Power measurements techniques and noise data
- Noise propagation models
- Noise insulation measurement techniques and data
- Evaluation on the development of noise at low frequencies from small to large wind turbines

The investigations are centered around the RISØ test site for large wind turbines at Høvsøre in Denmark, where prototype wind turbines are tested and where there have been complaints on low frequency noise.

Introduction

As it is not possible to make measurements on all wind turbines (especially future wind turbines) the most important part of the project is to supply methods or guidelines on how to predict the low frequency noise at the neighbours similarly to the predictions made already in the standard frequency range (50 Hz to 10 kHz).

The four steps of prediction of the low frequency noise at the neighbours are illustrated in Figure 1. Contrary to noise in the standard frequency range low frequency noise is often most audible inside a house as the house acts as a low-pass filter.

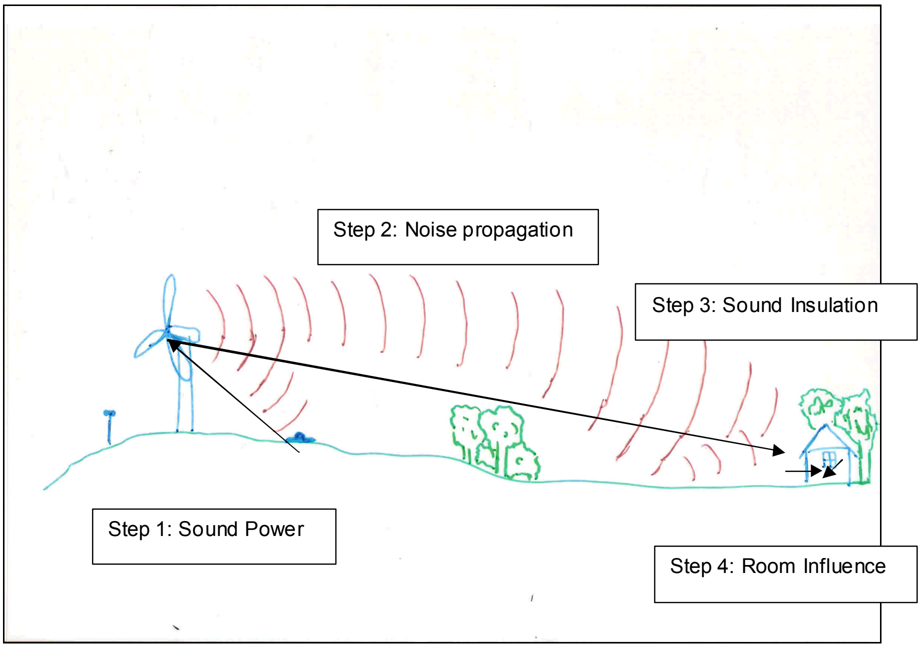

Figure 1. The for steps of noise prediction

Existing standards and methods are used and developed further in order to maintain consistency in the predicted noise levels as there is an overlap in the frequency ranges.

Sound Power Measurement method

IEC 61400-11 [1] is the most used standard for measuring the emitted sound power level from wind turbines. Measurements according to [1] give the sound power level in the frequency range from 50 Hz to 10 kHz thus covering most of the low frequency range. In annex A it is recommended to use the standard down to 20 Hz in case of significant low frequency noise. In this project it is necessary to make measurements to at least 10 Hz and preferably even lower.

The measurement method described in [1] is shown in Figure 2.

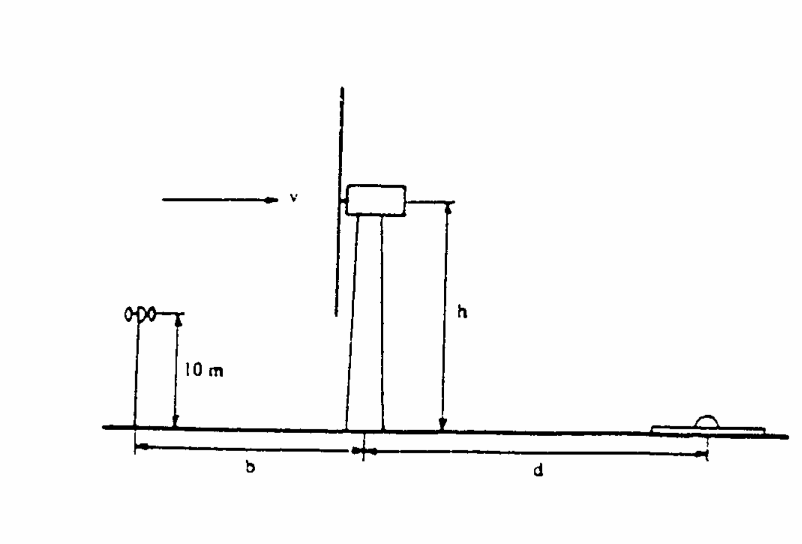

Figure 2 Measurement setup.

The microphone is mounted on a board on the ground mounted with a half standard wind screen. The wind speed is measured through the produced power and a calibrated power curve. An anemometer is placed in front of the wind turbine making it possible to measure the wind speed when the wind turbine is stopped and the background noise is measured.

The measurement position on a ground board serves 2 purposes:

- It keeps the microphone out of the wind and reduces the wind noise in the equipment
- It reduces the ground reflections to a simple + 6 dB correction at all frequencies due to pressure doubling. More details on reflections in the ground board can be found in [6] and [7]

The measurement method is developed in the 1980's and is partly based on references [2] and [3] and the ideas are taken from the Nordic Large Source method [4] and [5]. The general idea behind the methods is to measure in the far field avoiding local phenomena in the noise radiation. This makes it possible to model the source as a point source or if needed due to screening, as a set of incoherent point sources. No assumptions are made on the frequency range in developing the standard and there are therefore no problems in extending the frequency range further down.

As the ground board simplifies the ground reflection, the main problem is wind creating low frequency pressure variations at the microphone position. Usually a 20 Hz high pass filter and a half standard wind screen is sufficient to deal with this.

It is important that the wind shield is fitted carefully to avoid wind between the wind screen and the board. This becomes even more important if the high pass filter is not applied. From experience it is possible to make measurements without extra protection against the wind even at wind speeds of 10 – 15 m/s at 10 m height. However even at moderate wind speeds gusts can result in overload of the measurement system.

In [1] there is a general description of a secondary wind screen that can be applied.

> *The secondary windscreen may be used when it is necessary to obtain an adequate signal-to-noise ratio at low frequencies in high winds. For example, it could consist of a wire frame of approximate hemispherical shape, at least 450 mm in diameter, which is covered with a 13 mm to 25 mm layer of open cell foam with a porosity of 4 to 8 pores per 10 mm.*
>
> *This secondary hemispherical windscreen shall be placed symmetrically over the smaller primary windscreen.*
>
> *If the secondary windscreen is used, the influence of the secondary windscreen on the frequency response must be documented and corrected for.*

From [8] DELTA has experience with different types of wind screens. An almost spherical wire frame with a cover of Rycote Windjammer cloth was used for noise measurements from wind farms at heights around 1.6 m above terrain with good results. The frequency range investigated was from 20 Hz to 10 kHz. The wind screen is shown in Figure 3

Figure 3 Immission measurements with a secondary windscreen

A similar hemispherical wind screen has been made and tested in the field and no low frequency disturbances have been found. No high pass filtration was used during measurements meaning that data from about 4 Hz is available. So far measurements up to average wind speeds over 1 minute of 16 - 18 m/s have been made. The wind screen is shown in Figure 4 and Figure 5. The wire frame is heavy enough to keep it in position and no extra fixation is necessary.

Figure 4 Test Wind screen with Rycote Windjammer cloth

Figure 5 Wind screen used in the project with a Reinhardt windshield

The general recommendation is to use a secondary wind screen when measuring at low frequencies and/or at high wind speeds. Different types can be used as long as the insertion loss is measured and corrected for. As the wire frame can influence the noise field in narrow bands it is suggested to keep the minimum dimension of 450 mm diameter. It might be necessary to demand that the difference in insertion loss between neighbouring 1/3-octavebands should not be larger than e.g. 2 dB to prevent distortion of the resulting narrow band spectra.

Noise Propagation models

Most calculations of noise from wind turbines are made according to empirical models like

- ISO 9613-2: Attenuation of sound during propagation outdoors – Part 2: General method of calculation [9]
- Nordic general prediction model for noise from industrial plants [10]

The two models have common characteristics and share among other things equations for ground attenuation. The advantage of both methods is that they are available in commercial software. However, the weather condition in the model has been fixed to moderate downwind and the model has been developed for moderate propagation distances and source and receiver close to the ground. A general weakness of empirical models is that they cannot be expected to produce reliable results outside the range of model variables where measurements have been available. It is well known that the two methods do not produce good results for high sources such as wind turbines.

Another type of models is ray models
The ray models are based on ray acoustics. For a homogeneous atmosphere without refraction accurate solutions exists for spherical waves propagating from a point source over a flat impedance surface (ground surface) or over a screen with one diffracting edge. For refracting atmospheres and more complicated terrain the ray model solutions will always be more or less approximate solutions based on the solutions for a homogeneous atmosphere. In the case of a refracting atmosphere the straight rays in the basic solutions are replaced by curved rays which have been found to yield satisfactory results for moderate refraction. In case of strong refraction where the assumption of the sound field being spherical is no longer fulfilled the ray model is known to produce less accurate results. The inaccuracies increase the closer to the ground the propagation takes place and the problem is therefore expected to be less important for wind turbines than for traffic noise sources.
The ray models can be divided into two groups:

- Numerical ray tracing models
- Semi-analytical ray models

In numerical ray tracing models a ray path is constructed numerically by making small steps along the ray path in such a way that the elevation angle of the ray satisfies Snell's law. A ray tracing algorithm is an iterative computational algorithm which calculates many ray paths and selects those that arrive at the receiver. An example of numerical ray tracing model can be found in [11].

In a semi-analytical ray model an algorithm is applied which directly calculates the ray without the iteration necessary for numerical ray tracing. However, a solution for direct calculation of the ray is only available for an atmosphere with a linear vertical sound speed profile leading to circular rays. Therefore more realistic sound speed profiles have to be approximated by linear profiles. It could be expected that numerical ray tracing models are more accurate than semi-analytical ray models as the correct ray path is calculated avoiding the approximation of the real sound speed profile by a linear profile. However, in practice the use of simple numerical ray tracing does not seem to increase the calculation accuracy significantly compared to a well adjusted semi-analytical ray model. Therefore, taking into account the considerable reduction in calculation time by the semi-analytical ray models, these models are often preferred for engineering purposes. The semi-analytical models can only be used for "normal" weather defined as weather which can be described by the Businger-Dyer profiles for wind and temperature or similar simple profiles. The semi-analytical models cannot be used for special weather (like e.g. "low level jets"). The Nord2000 model [12],[13] and the European Harmonoise/Imagine model [14] are both semi-analytical ray models although the former is using circular rays while the latter is based on the analogy of curving the ground instead. However, the curving of the ground is based on circles assuming linear sound speed profiles as well. It is expected that the accuracy of two methods are almost the same, also in the low frequency range. At present the Harmonoise method is not fully documented and has not been thoroughly tested in practical cases, and although a DLL with the propagation model exists some programming is needed before the DLL can be applied. Contrary to that, the Nord2000 method has matured for five years since the method was completed, and has been adjusted based on practical experience with the model through the five years, and a program is available at DELTA.

Wave equation models are numerical models based on the wave equation. Calculations may be performed in the frequency or time domain although frequency domain models are most often used. The only model relevant for to consider is the Parabolic Equation method (PE). However, PE will due to the calculation time and a lack of commercial software only be of relevance in special cases where strong weather effects at long distances have to be predicted accurately.

The general recommendation is to use Nord2000 method for prediction of outdoor sound propagation from wind turbines. The method is fast compared to the wave equation models and software implementations are available. A minor problem exists for frequencies below 25 Hz as the software only produce results in the frequency range from 25 Hz to 10 kHz.

The limitation of 25 Hz is entirely based on practical considerations as the theory is fully valid below 25 Hz. The problem can be overcome by changing the software or by extrapolating the predictions at the lowest frequency bands. In Figure 6 to Figure 9 the ground effect (sound pressure level above the ground relative to the free field sound pressure level) is shown for propagation over grass-covered ground and over hard ground (water) for 100 m high wind turbine. Results are shown for downwind as well as upwind propagation with a wind speed of 8 m/s. At distances above 500 m the ground effect is simple in the low frequency region without dips. In the upwind direction the effect of the shadow zone is present at 2000 m but not at 1000 m.

At low frequencies the ground effect is in all cases very close to the 6 dB obtained from the pressure doubling seen if the receiver is close to the ground. The simple solution is to use the value at 25 Hz at lower frequencies. A more accurate solution is to perform an extrapolation (linear with logarithmic frequency) based the values at 25 Hz and 32 Hz band with an upper limit of 6 dB. If the ground effect at 25 Hz is greater than 6 dB (in case of multiple ground reflection and very long propagation distances), this value is used below 25 Hz.

If a higher accuracy is needed for cases with long propagation distances or very special weather conditions, The Parabolic Equation method (PE) may be an option. A sufficiently reliable PE code is not available at DELTA. Only one commercial program based on PE is known (ATMOS developed by CSTB, France, price unknown).

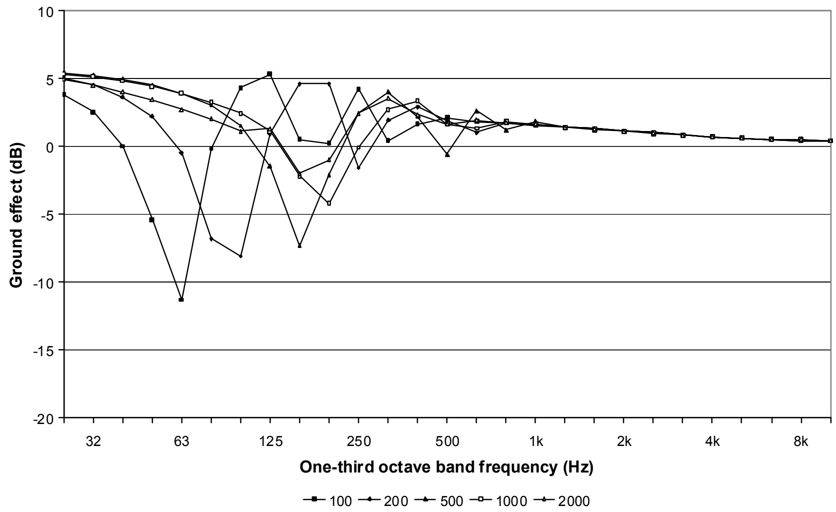

Figure 6

Ground effect from 25 Hz to 10 kHz according to Nord2000. Source height 100 m, receiver height 2 m, horizontal propagation distances from 100 m to 2000 m as shown in legend, downwind propagation over grass-covered ground, wind speed 8 m/s 10 m above ground

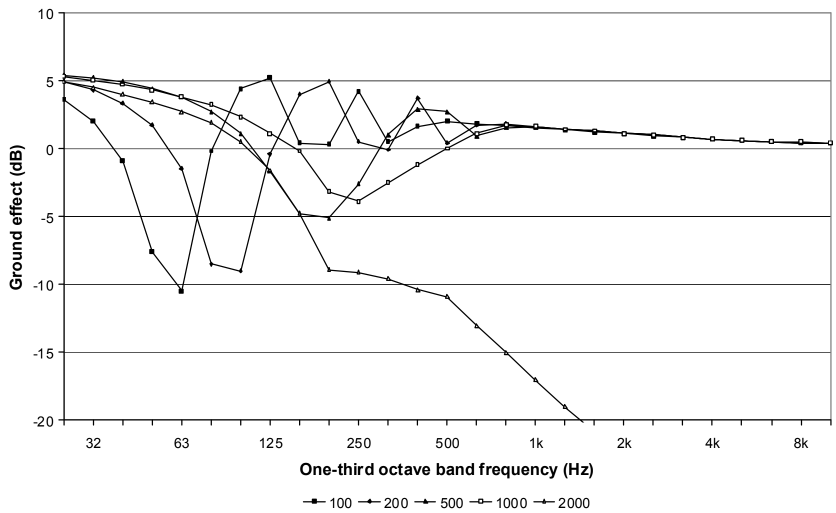

Figure 7

Ground effect from 25 Hz to10 kHz according to Nord2000. Source height 100 m, receiver height 2 m, horizontal propagation distances from 100 m to 2000 m as shown in legend, upwind propagation over grass-covered ground, wind speed 8 m/s 10 m above ground

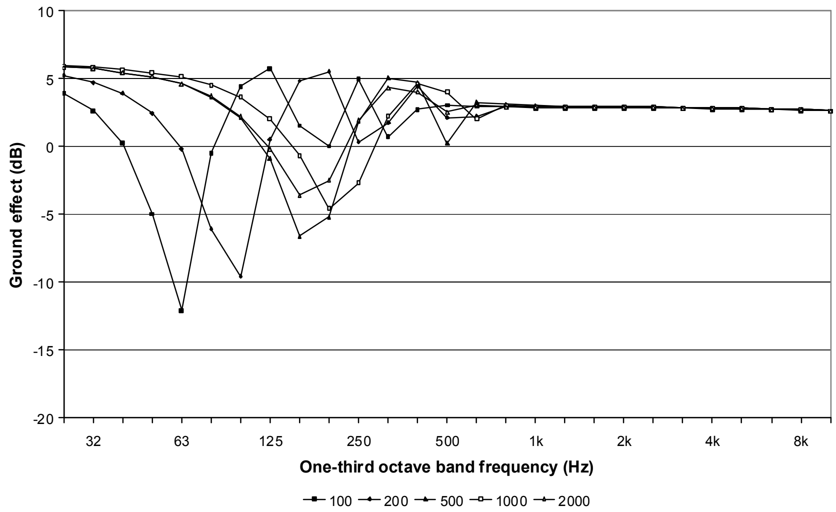

Figure 8

Ground effect from 25 Hz to 10 kHz according to Nord2000. Source height 100 m, receiver height 2 m, horizontal propagation distances from 100 m to 2000 m as shown in legend, downwind propagation over hard ground (water), wind speed 8 m/s 10 m above ground

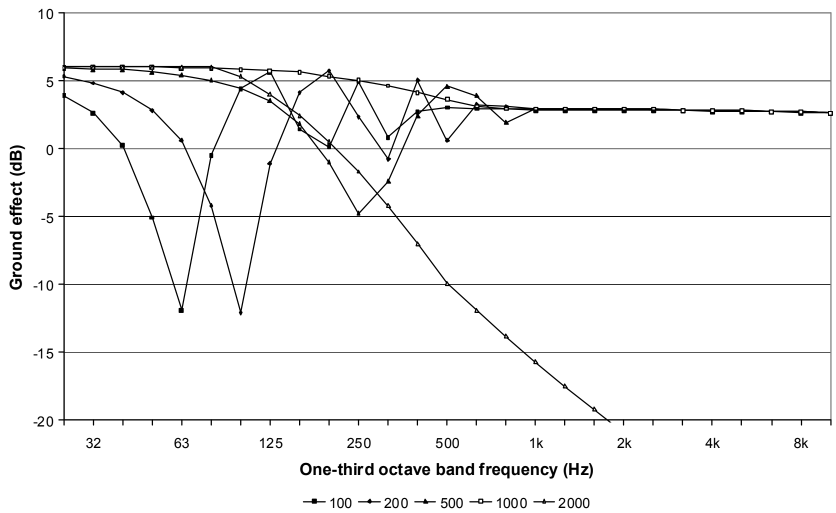

Figure 9

Ground effect from 25 Hz to 10 kHz according to Nord2000. Source height 100 m, receiver height 2 m, horizontal propagation distances from 100 m to 2000 m as shown in legend, upwind propagation over hard ground (water), wind speed 8 m/s 10 m above ground

Noise insulation measurement techniques

The aim is to specify a method for measurements of airborne sound insulation of building facades at low frequencies and investigate the sound insulation at low frequencies of a number of typical buildings in Denmark.

Two existing measurement methods for sound insulation of building facades served as background for the specified method.

ISO method

The international standard EN ISO 140-5:1998 [16] for field measurements of airborne sound insulation of façade elements and façades is intended for use in the frequency range from 50 Hz to 5000 Hz. The standard deals with eight different measurement methods, element methods for measurements of façade elements, global methods for whole façades, measurements using loudspeaker noise, and measurements with traffic as sound source.
The loudspeaker methods define a loudspeaker position outside the building with the angle of sound incidence equal to approx. 45^o. The outdoor sound pressure level is determined either directly on the façade element or 2 m in front of the façade. The indoor level is measured in at least five positions distributed throughout the room and spaced uniformly. The minimum separating distance between any microphone position and room boundaries is 0.5 m.

Low frequency method

The other method is described and used in the Working Report No. 10, 1997 from the Danish Environmental Protection Agency [17]. The method is dedicated to low frequency measurements of sound insulation. The results of measurements of low frequency sound insulation of several buildings described in the working report are used in a calculation method for the indoor noise level from high speed ferries at low frequencies.
The method uses a loudspeaker placed outside the building, and the outdoor sound pressure level is determined directly on the façade. The indoor level is measured in three positions. One position is in a corner at the façade, 0.5 - 1 m from the façade and 1 - 1.5 m above the floor. The other positions are chosen to represent typical habitation in the room, at least 0.5 m from walls and large pieces of furniture and 1 – 1.5 m above the floor. These three positions are in accordance with the Danish guidelines on environmental low frequency noise, infrasound and vibration [18]. The guidelines has a supplementary possibility in small rooms (less than about 20 m2) where the noise can be measured at two positions in different corners, 0.5 – 1 m from the adjoining walls and 1 – 1.5 m above the floor.

Specified method for measuring the outdoor/indoor level difference

The specified method differs from the method from the Danish Environmental Protection Agency only in the choice of indoor positions. In agreement with the project partner Department of Acoustics, Aalborg University, their findings about indoor measurements of sound at low frequencies [19] were worked into the method for measurements of airborne sound insulation of building facades at low frequencies. This introduces measurements in three-dimensional corners. In the 3D positions the microphone is placed only 0.01 – 0.02 m from a three-dimensional corner where two walls and the ceiling or the floor meet. It has been found that these

positions give a better estimate of the low frequency high-level areas in a room than other methods.
The specified method for measuring the outdoor/indoor level difference for a building façade at low frequencies can be summarized as follows:

- A global loudspeaker method, airborne sound insulation of the whole building façade. No corrections for the area of the test specimen.
- Loudspeaker placed on the ground outside the building with the angle of sound incidence equal to approx. 45^o to the centre of the façade. The distance at right angels to the façade should be at least 5 m.
- Broadband noise limited to the low frequency range up till 250 Hz. Equalized to compensate for the loudspeaker characteristics.
- Measurements in one-third-octave bands with centre frequencies from 8 to 200 Hz.
- Outdoor microphone fastened directly to the façade (+6 dB measurement) approx. 1.5 m above the floor in the receiving room.
- Indoor microphone positions shall be 3D positions. Four randomly selected positions shall be used in the receiving room. Positions very near to windows or façade doors should be avoided. The 3D positions should be chosen to represent more than one wall and both ceiling and floor in the room.
- The sound pressure levels from the four indoor positions are averaged on energy basis.
- Background noise shall be measured and corrections for background noise applied. At all frequencies corrections are limited to 1.3 dB corresponding to a difference of 6 dB.
- The level difference for each position shall be calculated as the difference between the outdoor level minus 6 dB and the background noise adjusted indoor level. The correction for the façade-reflection to the free-field value is specified as minus 6 dB although the influence of the façade is frequency dependent at low frequencies. This matter is discussed in [17].
- The level differences from the four positions are averaged on energy basis.

There is no correction for the indoor room-acoustic environment, e.q. no corresponding reference value (normalized, standardized).

An example of a 3D position is showed in Figure 10.

Figure 10

Example of a 3D position with the microphone placed in the three-dimensional corner where two walls and the ceiling meet

Measurements have been performed in five different types of single-family houses, representing possible buildings situated in areas near large wind turbines in the open land in Denmark. For each house measurements of the sound insulation of the façade have been made both for the living room and for a small-sized room.

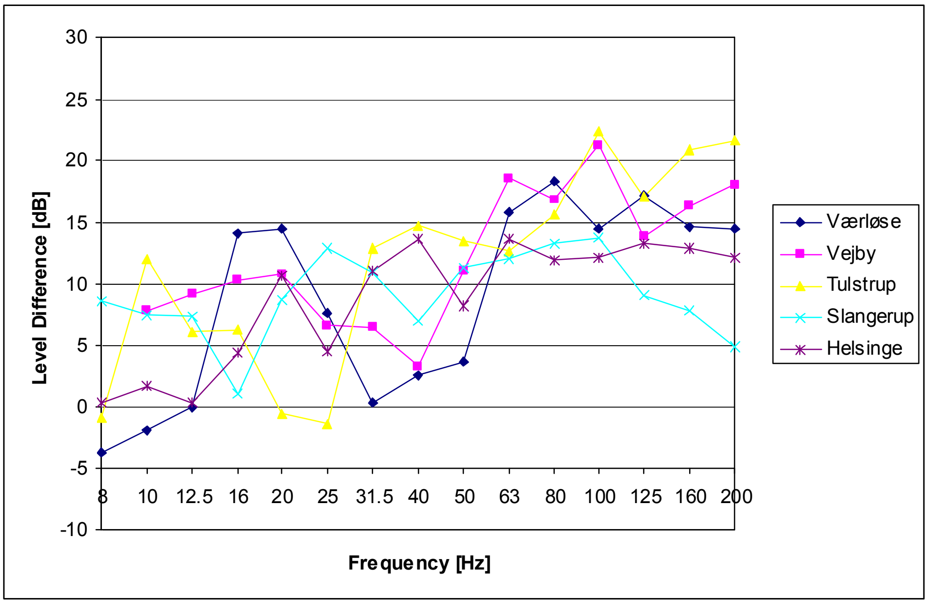

Figure 11 Measurement results for five living rooms. Outdoor/indoor level differences in dB per one-third-octave measured with the specified method.

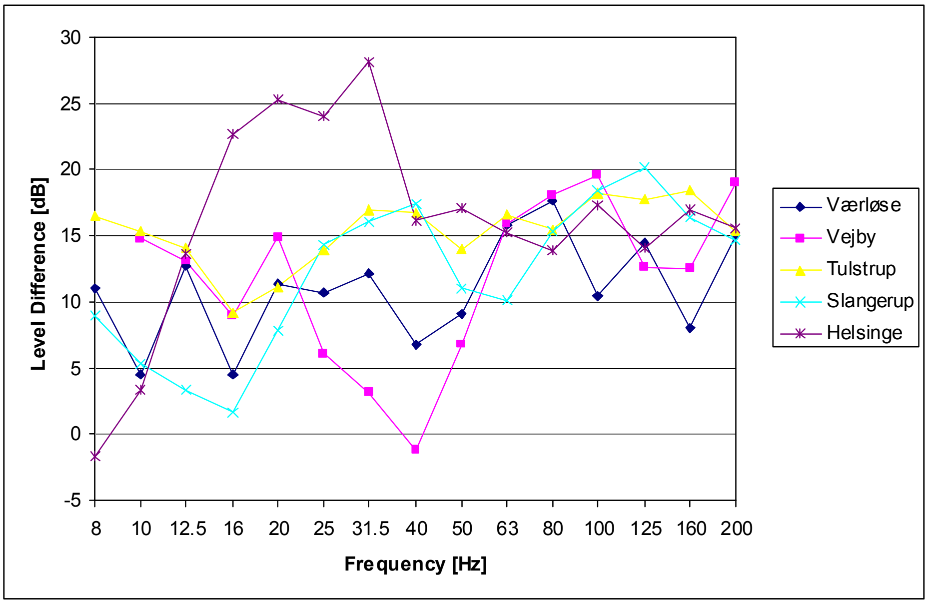

Figure 12 Measurement results for five small-sized rooms. Outdoor/indoor level differences in dB per one-third-octave measured with the specified method

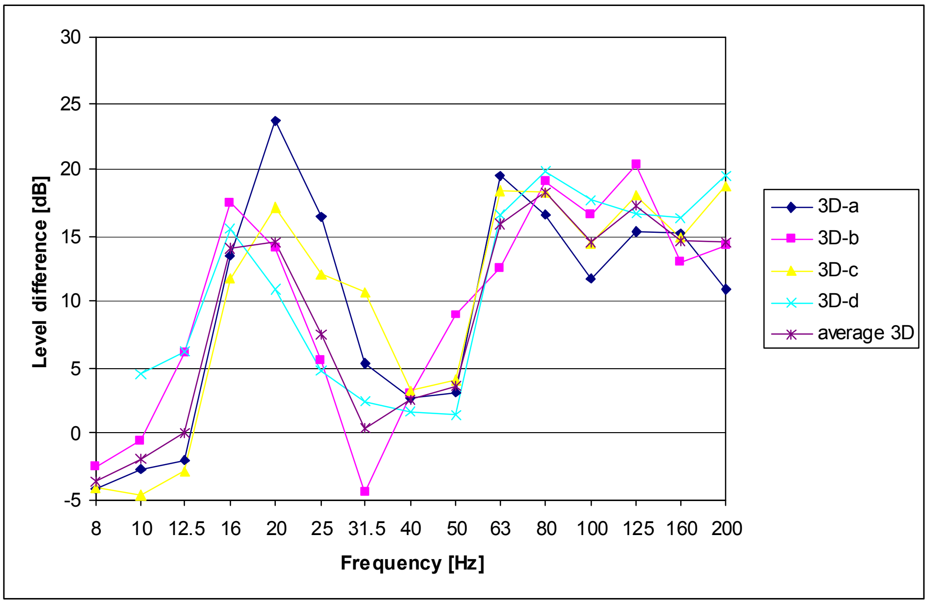

Figure 13 Results from a single living room showing the variation between the 4 3D-positions

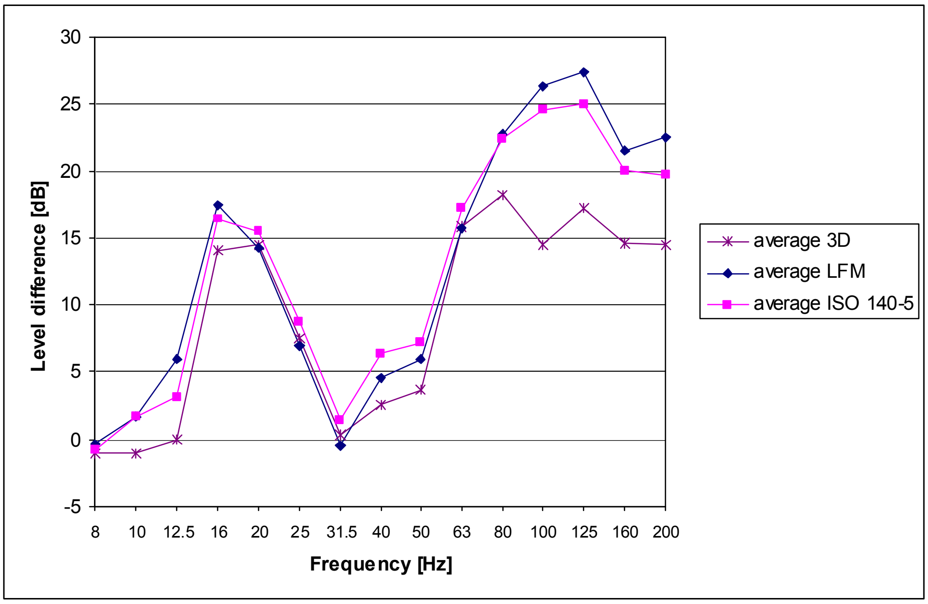

Figure 14 Comparison of the level difference determined from the 3 set of measurement positions

In Figure 14 the level difference from one of the living rooms are compared for the 3 set of measurement positions. This is a general tendency that below 63 Hz the results are almost the same and above 80 Hz the level difference determined from the 3D corner positions is lower by approximately 5 to 10 dB resulting in a higher predicted noise level inside the house ensuring that the parts of the room where the noise is experienced as significant are represented.

The spread in the level difference from house to house and room to room is too large to group the houses and more houses should be investigated to give a significant statistical basis.

Using this method to determine the insertion loss of a house at frequencies below 200 Hz requires a lot of signal power and a low background noise level. Especially at 8 Hz and 10 Hz a sufficient signal to noise ratio is difficult to obtain and correlation techniques like MLS should be used.

Evaluation on the development of noise at low frequencies from small to large wind turbines

This part of the project gives information on the noise at low frequencies for wind turbines already in operation based on results from 37 accredited measurement reports. The measurement reports represent the period from 1992 to 2006 and wind turbines from 75 kW to 2 MW.

As the time span of the measurements is more than 10 years the measurements have been made according to different measurement methods [1], [20] and [21]. The basics of the measurement methods are the same.

Measurement reports

Most of especially the earliest measurement reports do not have information of the noise below 63 Hz and the results are given in 1/1-octave bands. 37 measurement reports are selected and used in this analysis. The noise is given in 1/3-octave bands down to at least 31.5 Hz and for some down to 25 Hz. In a single case the lowest frequency was 50 Hz.

Sound Power spectra.

The measurement reports all have sound power spectra at 8 m/s at 10 m height which is the reference wind speed in [20] and [21]. In [1] the results are given at integer wind speeds from 6 - 10 m/s.

In Figure 15 the Sound Power spectra at 8 m/s is shown.

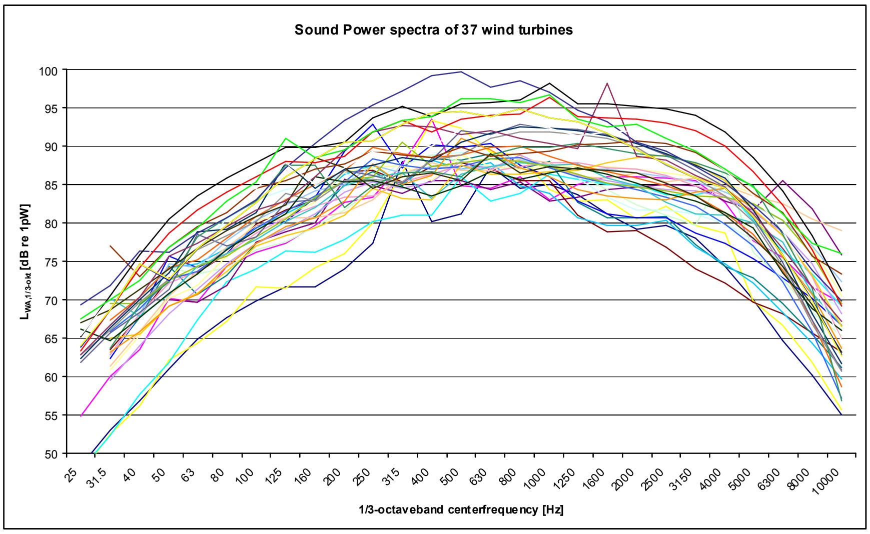

Figure 15 Sound Power spectra of 37 wind turbines at 8 m/s

It is not easy to compare the spectra directly and in Figure 16 the spectra are all normalized to LAW = 0 dB. This makes it possible to compare the shape of the spectra to see if there is more or less low frequency noise in some of the measurements.

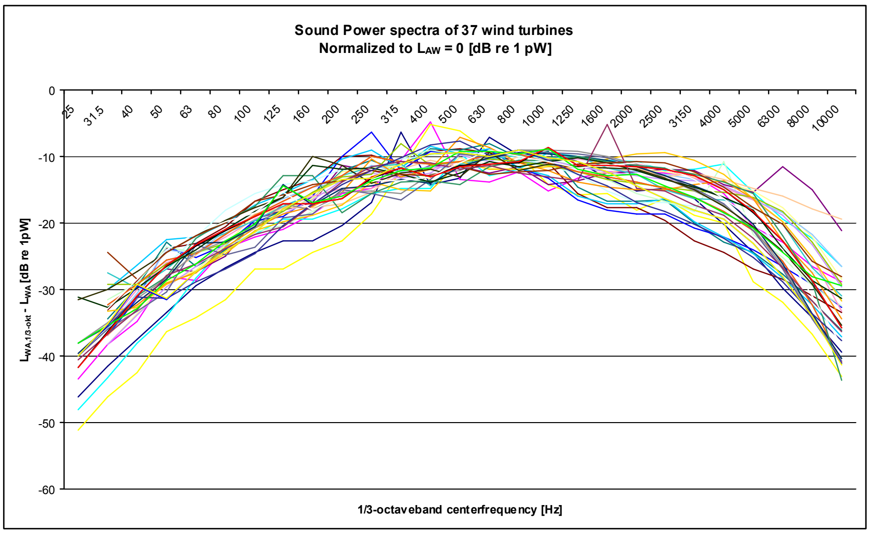

Figure 16 Sound Power spectra normalized to L_{AW} = 0 dB

The fact that some of the spectra are dominated by tones, seen as peaks in the spectra tends to give a larger spreading of the results.

To be able to look at the trend in the development of low frequency noise the measurements are grouped according to rated power and averaged in Figure 17

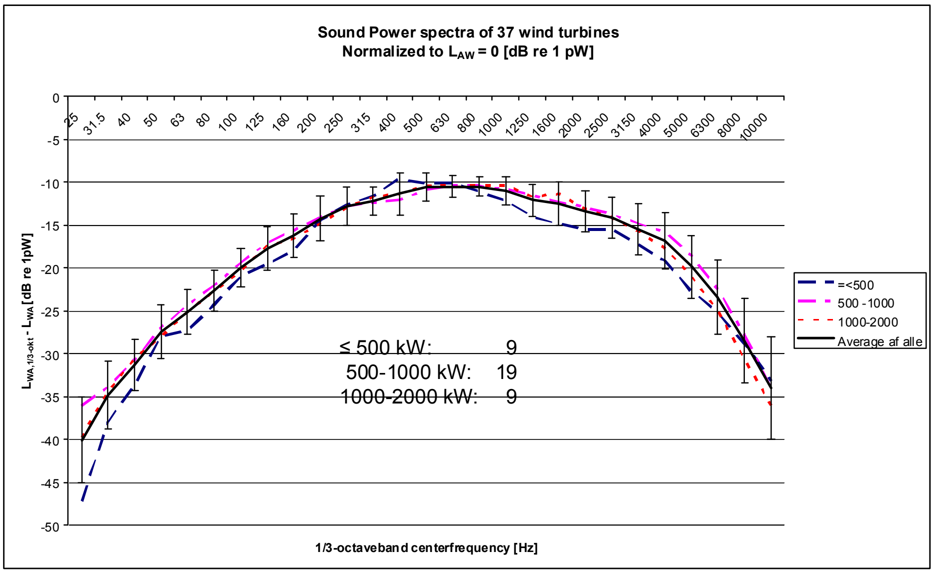

Figure 17 Sound Power spectra grouped according to rated power and averaged

The spectra in Figure 17 show that the spectral shape of the noise from wind turbines has not changed significantly over time. The Sound Power level has changed and this affects the amount of noise in general as well as low frequency noise emitted to the surroundings.

The Sound Power Levels of the 37 wind turbines are shown in Figure 18. The conclusion that the spectral shape has not changed significantly can be seen from the fact that the development of L_{WA} and $L_{WA,LF}$ is along almost parallel lines. $L_{WA,LF}$ is defined as the A-weighted sum of 1/3-octave bands from 10 Hz to 160 Hz of the Sound Power in [18]. Other definitions include the 200 Hz 1/3-octave band as well. Due to the spectral shape of the wind turbine noise, including the 200 Hz 1/3-octave band increases $L_{WA,LF}$ by approximately 2 dB but does not change the tendency given by the slope of the line in Figure 18.

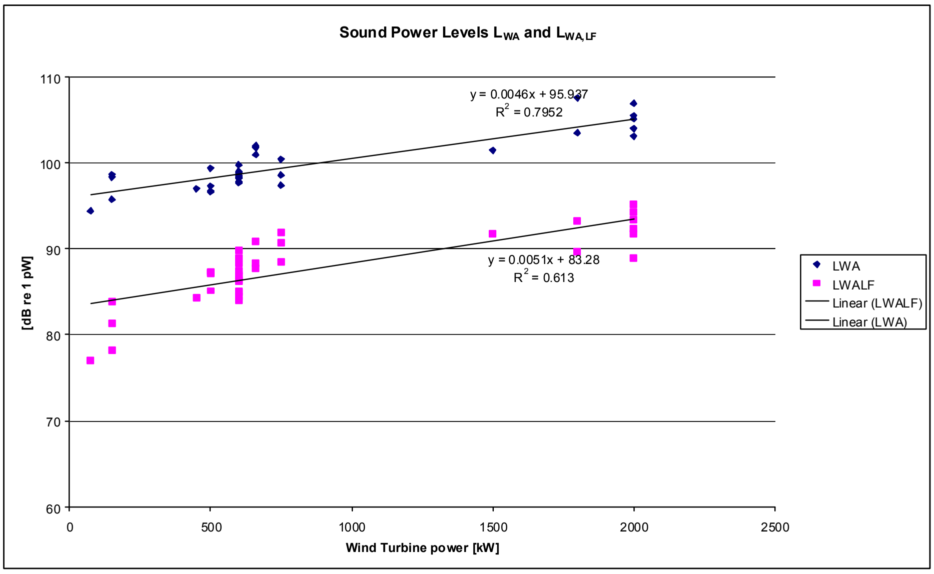

Figure 18 Sound Power Levels of 37 wind turbines

The Sound Power level pr meter radius and pr square meter area have been calculated by subtracting 10 times the logarithm of the radius/area of the rotor from the Sound Power levels for the data in Figure 18. The results are shown in Figure 19 and Figure 20.

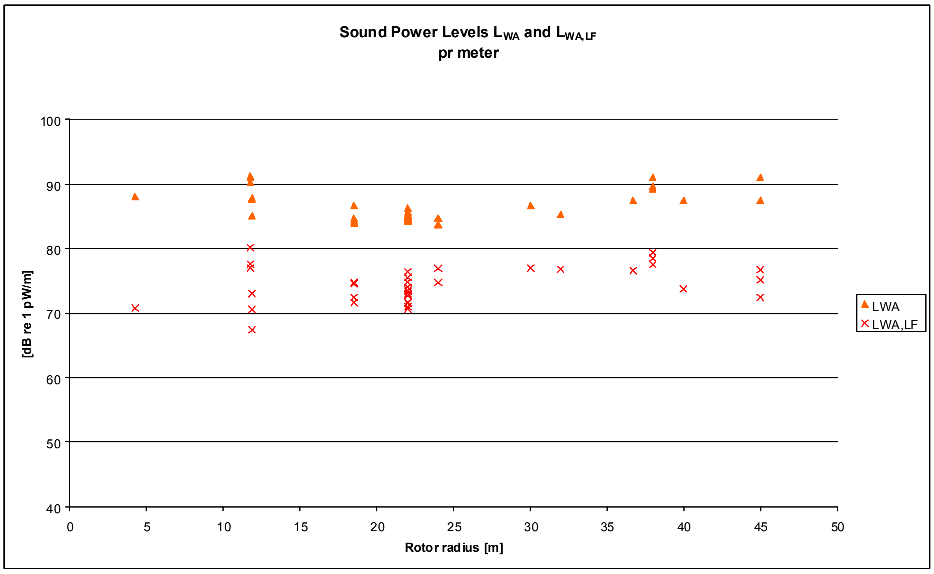

Figure 19 Sound Power levels pr m radius of the rotor.

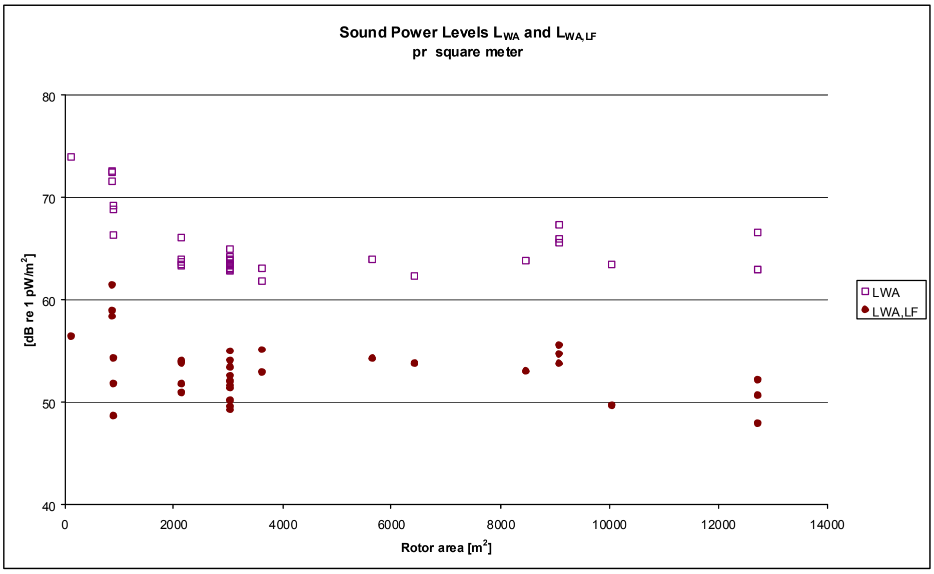

Figure 20 Sound Power levels pr square meter area of the rotor.

Apart from the smallest wind turbines where a significant part of the noise is radiated from the nacelle it seems that the overall noise correlates best with the rotor area while the low frequency noise correlates best with the rotor diameter.

Background noise

All the data presented are from accredited measurement reports and thus they are corrected for background noise. This however is not always an easy task as can be seen from Figure 21, where the background noise is up to 1 dB above the total noise at frequencies below 31.5 Hz. The data in Figure 21 shows the average value and standard deviation of 43 1-minute values for the total noise and 20 1-minute values for the background noise. The wind speeds vary between 7 and 9 m/s.

According to [1] and [20], data where the background noise is less than 3 dB below the total noise should not be reported, if the background noise is more than 3 dB but less than 6 dB below the total noise a correction of -1.3 dB should be applied. Normal correction is applied other wise.

This means that reported data at low frequencies are most often to be considered as maximum values.

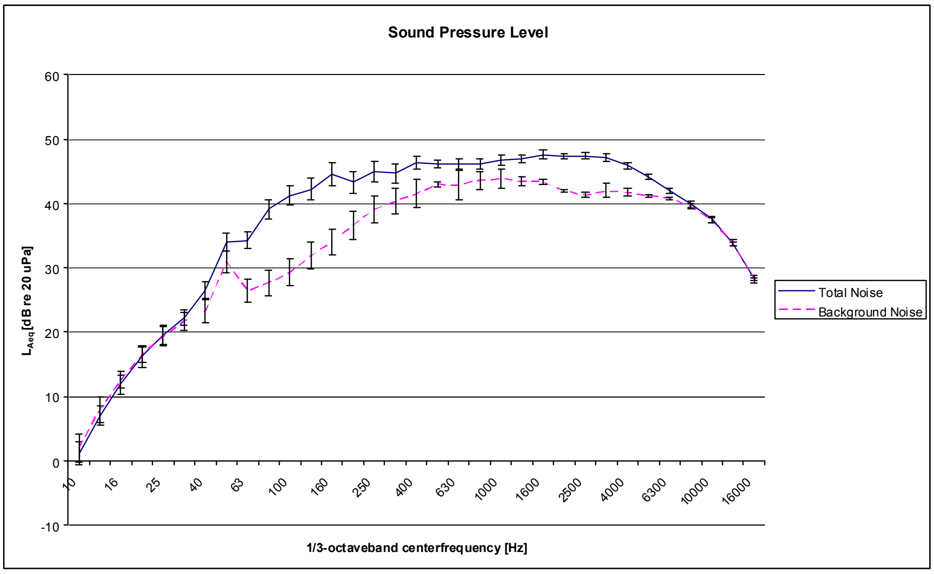

Figure 21 Spectra of total noise and background noise for a 1.5 MW wind turbine. A 50 Hz frequency from a nearby power line influences the measurements.

Conclusions

In the project methods for measuring and predicting the low frequency noise at the neighbours are presented. This is important as it should be possible to assess the low frequency noise from future wind turbines easing the planning process. Measurements on the prototypes available have or will be made and compared to the results for existing wind turbines.

From the analysis on existing wind turbines it seems that there is no tendency that the larger wind turbines is creating an excessive amount of low frequency noise compared to the overall noise level. Due to the fact that the rotor speed decreases the gear tones are moving towards the low frequency range. The manufacturers must be aware of this since tones at the low frequencies are not reduced with the distance at the same rate as tones at higher frequencies.

A series of project reports will be available at a later time

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Wind Farm Noise and Regulations in the Eastern United States

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Abstract

Recent advancements in the wind turbine technology, combined with available federal and state incentives, have greatly enhanced the development of wind powered electric generation facilities in the Eastern United States. Particularly ridges of the Allegany Mountains in New York, Pennsylvania, Maryland, West Virginia, and Virginia have become attractive sites for commercial wind farm developers. The fast development of commercial wind farms is currently an important issue in these regions due to environmental impacts.

The paper describes the demographic structure of the Allegany Mountains and presents an assessment of the audible noise at residences near actual wind turbines. The noise level recommendations of the USA Environmental Protection Agency (US-EPA) and local noise ordinances that apply to wind turbines are compared with the acceptable noise levels in various countries. The current status and trend of the wind power development in the Eastern USA, the expected benefits, and public concerns are discussed.

Introduction

Since the beginning of the 21st century, wind power development in the eastern part of the United States has grown significantly due to recent improvements in the wind turbine technology and financial incentives provided by the federal government and states. Data collected by American Wind Energy Association (AWEA) indicates that the total capacity of wind farms installed in 14 states east of the Mississippi river, which was 29 MW in 1999, has reached 843 MW in the end of 2006 (Flowers, L., 2007). Total 605 MW wind power plants were developed in New York, Pennsylvania, and West Virginia between 2000 and 2006. While the proportion of electricity generated by wind farms is still relatively small compared to the other sources, wind seems to be a potential clean energy alternative to the fossil fuels used in the region.

Environmental concerns about the wind power development include interactions with wild life, visual impacts, and annoyance due to the audible sound level. This paper focuses on the acoustic issues related to wind turbines and the associated public concerns in eastern United States.

Wind Power Development in the USA and Demographics

Wind farms are perhaps one of the most visible power generation facilities and have triggered significant public attention and discussions over the past several years. Because of substantial social interactions, demographic characteristics of the regions where the wind farms are located must be considered when evaluating the consequences of the wind power development.

Wind power development in the United States is summarized in Figure 1 (Wiser, R. et al., 2007). The map presents the wind projects above 1 MW that became online prior to 2006 and added in 2006.

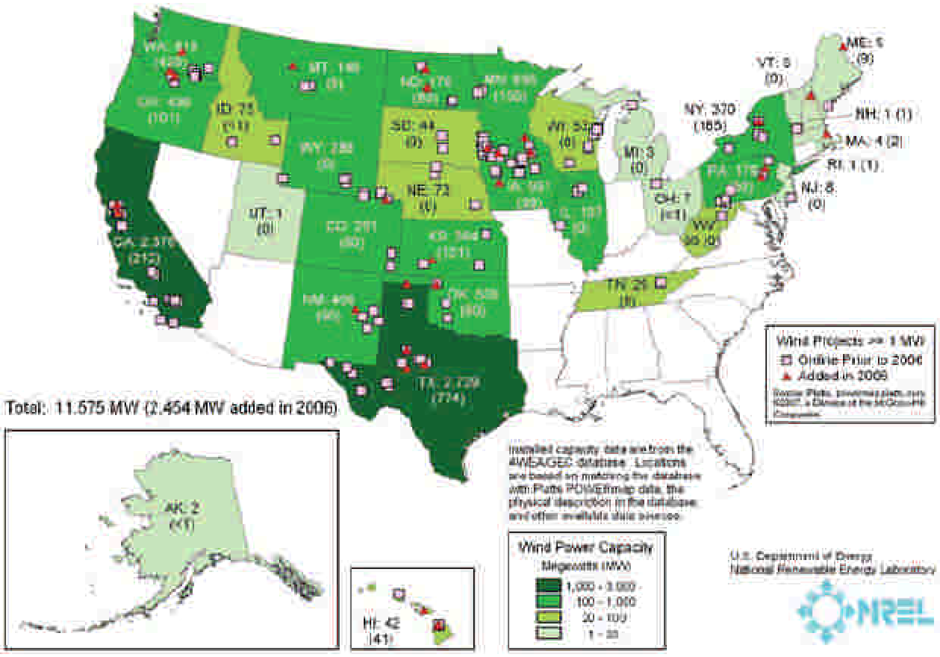


Figure 1 Installed wind power generation facilities as of December 31, 2006

Table 1 shows the major wind developments and the population density of the states grouped based on their location in respect to the Mississippi river. The wind development in the western part of the USA is significantly higher than the eastern part. On the other hand, the population density in eastern states is in general above the national density and significantly higher than the western states except California.

Wind development on the ridges of the Appalachian Mountains in New York, Pennsylvania, and West Virginia started after the year 2000. The wind farms are mostly located near agricultural and recreational areas where residences are sparsely distributed. The wind turbines are therefore close to many farms and residences and visible from small towns.

The effects on the wildlife, visual impact, and audible noise of the wind turbines have been the major issues discussed during the planning and approval process of the commercial wind generation facilities in eastern states, particularly in New York, Pennsylvania, Maryland, West Virginia, and Virginia.

Table 1 Major wind development and population density by states

	State	Installed Capacity, MW		Incremental Capacity 2000 to 2006	Population Density Persons/square mile
		End of 1999	End of 2006		
East of Mississippi	New York	0	370	370	402
	Pennsylvania	0	179	179	274
	Illinois	0	107	107	223
	West Virginia	0	66	66	75
	Wisconsin	23	53	30	99
West of Nississippi	Texas	180	2,739	2559	80
	California	1646	2,376	730	217
	Iowa	243	931	688	52
	Minnesota	273	895	622	62
	Washington	0	818	818	89
	Oklahoma	0	535	535	50
	New Mexico	1	496	495	15
	Oregon	25	438	413	36
	Kansas	2	364	362	33
	Colorado	22	291	269	42
	Wyoming	73	288	215	5
	North Dakota	0	178	178	9
	Montana	0	146	146	6
	Idaho	0	75	75	16
	Nebraska	3	73	70	22
	USA	2500	11,575	9075	80

Characteristics of Wind Turbine Sound

The characteristics of the wind turbine sound are studied in many publications in detail. The "White Paper" prepared by the Renewable Energy Research Laboratory (Rogers, A. L. and Manwell, J. F., 2002) classifies the wind turbine noise in four types as

1. Tonal noise, which is a combination of components at discrete frequencies

2. Broadband noise is characterized by a continuous distribution of sound pressure with frequencies greater than 100 Hz. It is usually modulated by low frequency fluctuations and described as a characteristic "whooshing" sound.
3. Low frequency noise is within the frequency range below 100 Hz.
4. Impulsive noise is described by short acoustic impulses or thumping sounds that vary in amplitude with time.

The operation of mechanical parts such as gearbox, generator, hydraulics, pneumatics and various control mechanisms generates mechanical noise. Rotating parts usually produce sound components at discrete frequencies related to the rotation speed, which result in tonal noise. Some mechanical parts can also generate broadband noise. This type of noise can be reduced by improving the design of the mechanical parts and using more effective acoustic insulation. However, the mechanical noise can be transmitted to the environment through the vibrations of the hub, rotor, and tower.

The interaction of the wind flow with the blades produces the aerodynamic noise. Aerodynamic noise is associated with various complex air flow phenomena and has both broadband and low frequency components. The interaction of the blades with the disturbed air flow around the tower results in low frequency and impulsive sound components. Changing wind speed around the blades can also produce low frequency and impulsive noise. This type of noise is usually bigger in downwind turbines, where the rotor is located on the downwind side of the tower.

Van Den Berg (2005) discusses the significance of the low frequency modulation of the broadband noise under stable atmospheric conditions. The study shows that the fluctuations become stronger especially during night time because of the stable atmosphere resulting in a bigger difference between the rotor averaged and near-tower wind speeds. Although the human ear is less sensitive to low frequency sound components, the modulation effect makes them more perceptible, creating a “whooshing” or “swishing” sound as described by residents who live near wind turbines.

The level of the sound generated by wind turbines depends on a number of factors such as

- Design characteristics of the wind turbine such as tower height, number of the blades, rotation speed, blade control mechanism – that is whether the blades are attached at a fixed or variable angle along their long axis (fixed or pitched)
- Distance to the source, sound blocks, obstructions, and uneven geometry of the terrain
- Sound absorption of the propagation medium between the source and location of the observer
- Acoustic characteristics of the ground surface affecting the sound propagation such as reflection, absorption of sound waves. Sound propagation depends on the physical properties of the ground surface, rock and soil composition, and vegetation covering the terrain.
- Frequency composition of the sound waves
- Weather conditions such as wind speed, direction, temperature, humidity, precipitation, etc.

Ambient Noise Recorded at a Residence near Wind Turbines

A number of tests were conducted between 2004 and 2005 near wind turbines located in Meyersdale, PA, to analyze the characteristics of the generated sound and determine the noise levels under various conditions.
The wind powered electric generation plant located in Somerset County near Meyersdale is a typical wind power facility (wind farm) with main characteristics similar to others constructed in the South Western Pennsylvania and Northern West Virginia over the last five years. New wind farms planned to be constructed in the region will have similar blade design, but possibly bigger turbines and higher towers.
The plant consists of twenty wind turbines installed on 262 feet tall towers on the mountain ridge. The NM72 type turbines are manufactured by Neg-Micon in 2003. The NM72 is a three blade upwind turbine generating electricity by an induction machine. It has a rated power of 1500 kW and an apparent power of 1667 kVA.
A number of tests were performed around a residence located at a distance of 900m (0.55 miles or 3000ft) to the windmills. Four windmills were visible from the residence. The tests are presented below in two parts: ambient noise recordings and sound level measurements.

The noise generated by wind turbines was recorded at a distance of approximately 3000 ft from the nearest turbine. Four turbines were visible at

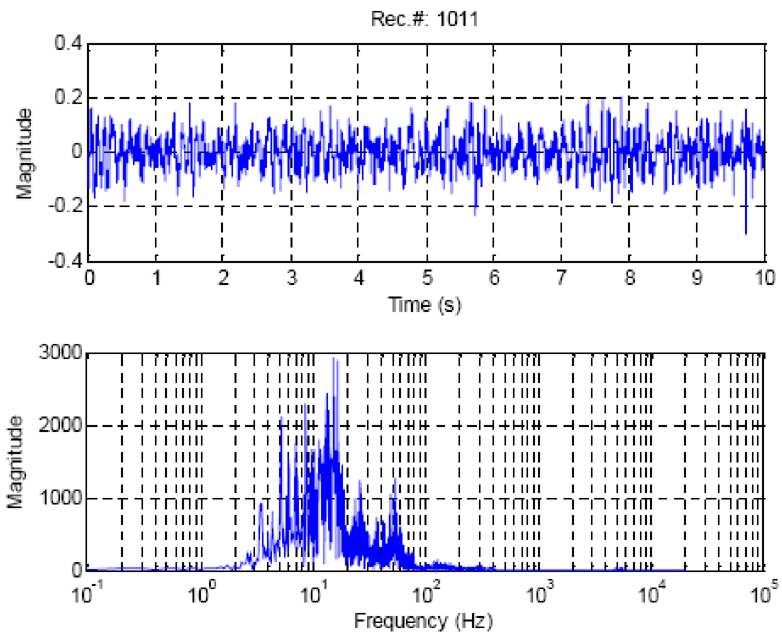
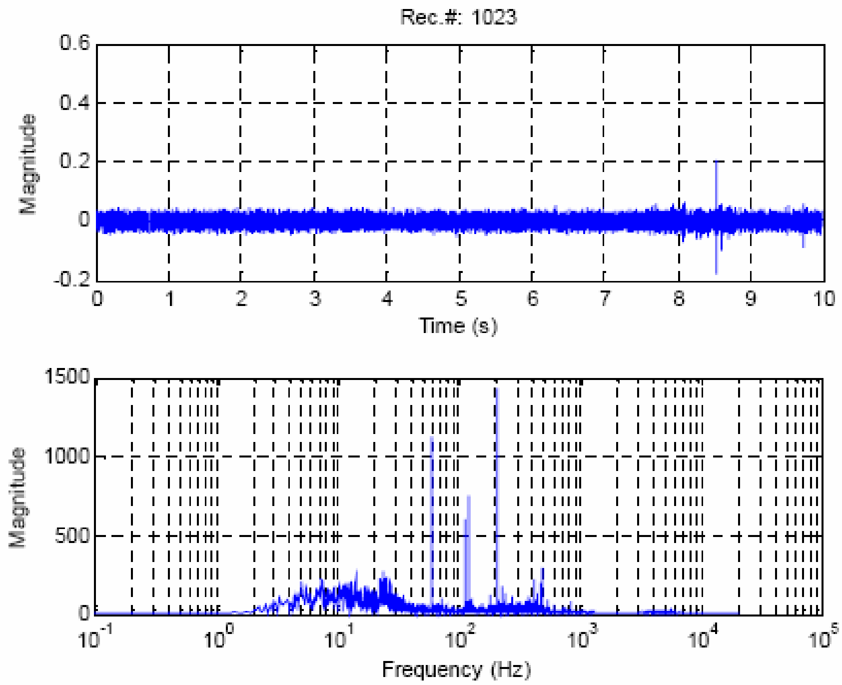


Figure 2 Sound recorded at a distance of 3000 ft from the wind turbines

the recording point, three of them were operating. Several recordings were made between 11:00 AM and 4:00 PM at different days. Wind speed was moderate (3 – 5 miles/hr) at the recording point (ground level) during the tests. A solid state digital recorder was used to obtain the waveform data. An example 10-s fragment is shown in Figure 2. The frequency distribution obtained by discreet Fourier transform indicates a dominance of low frequency components below 100Hz. Examination of the time variation of the sound waveform shows a periodic change of the magnitude, which is translated as “low frequency modulation.”

Figure 3 shows the ambient noise recorded in another location without wind turbines. Light traffic noise from distance was contributing to the natural sound of wind and trees. The time variation of the noise shown in Figure 3 is random and uniform over the 10-s recording time. The Fourier transform indicates significant tonal and broadband components above 100 Hz. This represents a typical suburban



residential ambient noise without industrial noise sources.

Figure 3 Ambient noise containing natural sounds and light traffic noise

The decibel level of the ambient noise was measured at the same location (3000 ft from the closest wind turbine). Figure 4 shows a set of plots obtained during short intervals at different times of a day.

The instrument used to record sound levels is an Extech Datalogging Sound Level Meter, model # 407764. The instrument can record up to 16,000 records to the internal memory with a sampling rate from 1 to 86,400 seconds per record. The sampling rate is selected depending on the type of test. The instrument is equipped with dBA and dBC weighting filters.

The international standard IEC 61400 (Wind Turbine Generator Systems – Part 11: Acoustic Noise Measurement Techniques) [5] indicates that the annoyance caused by noise dominated by low frequencies is often not adequately described by the A-weighted sound pressure level (p. 35, Annex A). According to the standard, this is likely the case if the difference between A and C-weighted sound level pressure levels exceeds approximately 20 dB. The plots in Figure 4 reflect the dominance of low frequency components since the difference between dBA and dBC levels is generally around 20 dB. This is also consistent with the spectrum analysis presented in Figure 2

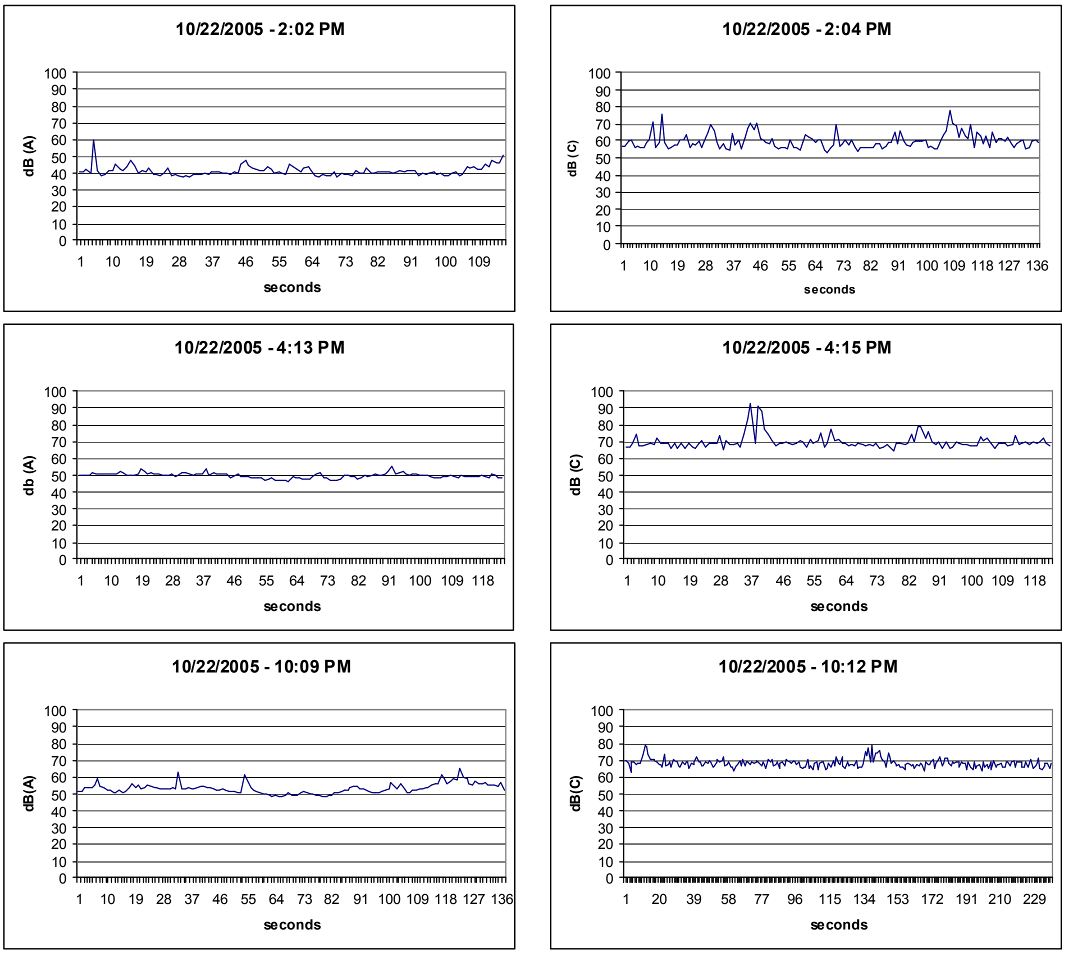


Figure 4 Noise level measurements at a distance of 3000ft from the nearest wind turbine

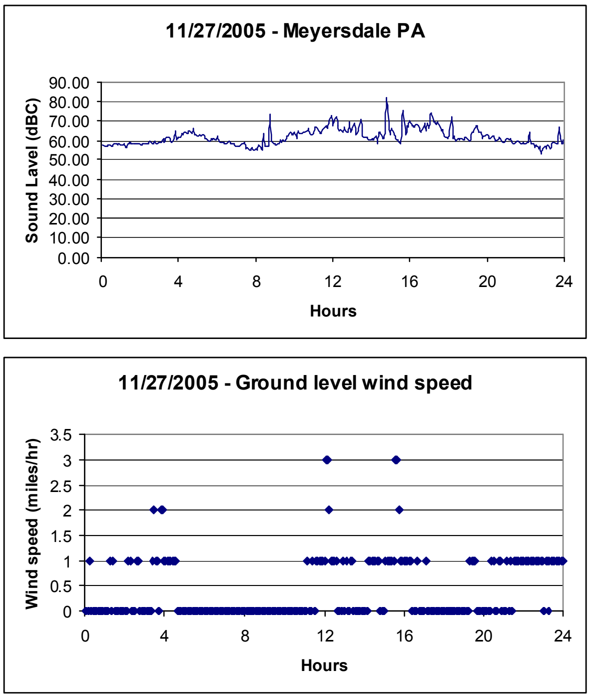
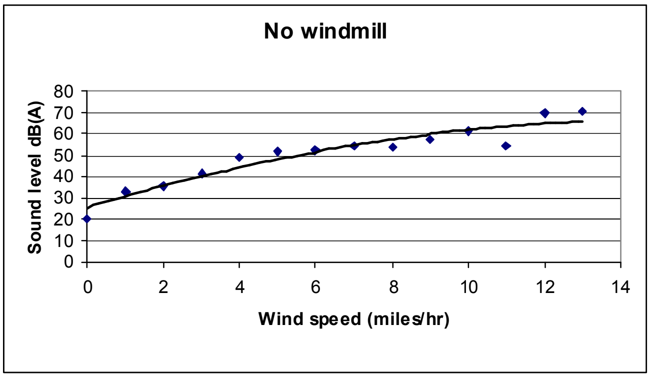


Figure 5 One-day record of noise level and wind speed

Figure 5 shows a one-day C-weighted noise pressure level recorded at the same location. The wind speed measured near the sound level meter is also plotted.

The plots shown above represent the sound of windmills combined with the natural ambient noise from wind, trees, bushes, and animals. Other noise sources such as traffic, machines, and commercial sources were occasional and minimal at the test location. In order estimate the contribution of the wind, noise levels are plotted in Figure 6 versus wind speed near the wind farm and at another rural location without windmill noise.

It should be noted that the wind speed at the test location may be very different than the wind speed at the turbine height. This explains why at lower wind speeds the noise level near wind turbines is much higher compared to the location where there is no windmill noise.



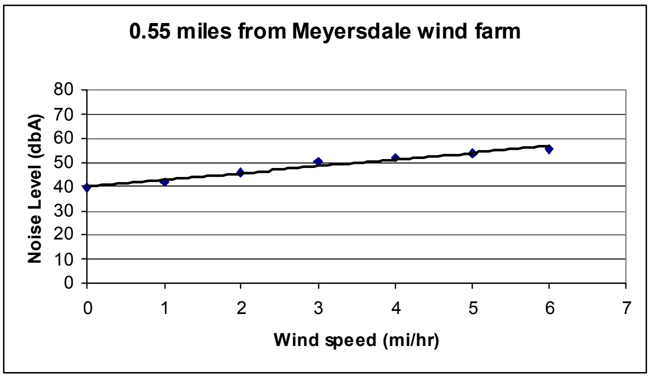


Figure 6 Noise levels with and without windmills

Assessment of the Nuisance Caused by Wind Turbine Noise

The tests performed near wind farms confirm the observations of several residents describing the windmill sound. The following psycho-physical characteristics of the windmill sound distinguish it from the typical urban and occupational noise.

- Windmill sound has dominant low frequency components
- The windmill sound is often periodic and rhythmic
- The very low frequency and infrasound components, for which human ear is normally not sensitive, are highlighted and become perceptible due to the low frequency modulation (fluctuations) of the broadband noise (Van Den Berg, 2005). This effect is usually described as swishing or whooshing sound.
- Low frequency modulation effect is stronger in stable atmosphere due to the interaction of the blades with the steady wind around the tower. This mostly occurs during night and early morning (Van Den Berg, 2005).

- The windmill sound is present day and night and can be disturbing at night because other sources of noise are reduced.

For the reasons listed above, the noise levels defined for urban and occupational noise may not represent the effects of the windmill sound. The A weighting network may be inadequate because of the dominant low frequency components and the modulation of the weak broadband noise.

Codes and Regulations Concerning Wind Turbine Noise

A nationwide applicable limit for windmill noise is not available in the USA. Instead of imposing standard noise limits, the US Environmental Agency (US-EPA) recommends that local governments develop their own noise regulations or zoning ordinances. The publication EPA-550/9-74-004 (EPA 1974) is one of the most detailed studies to date on disturbances and activity interference caused by various sources of noise. The publication presents data collected for 55 community noise problems between 1949 and 1974. The noise sources considered in the document are transportation vehicles, single-event operations (such as circuit breaker testing, shooting, rocket testing and body shop), steady state neighborhood sources, and industrial operations.

The day-night averaged A-weighted noise level is one of the parameters commonly used to assess the wind turbine noise. EPA added correction factors to the measured day-night sound level (Ldn) to obtain a normalized chart. The correction factor for a quiet suburban or rural community (remote from large cities and from industrial activity and trucking) is +10 dB. Whereas the night time noise is considered differently than day time, this parameter does not reflect the disturbing effects caused by the low frequency modulation of the background noise. In addition, the low frequency components are significantly suppressed in A weighting. In fact, IEC 61400-11 recommends the comparison of the A and C weighting to assess the presence of low frequency noise. The IEC standard recommends using C weighting if the difference is usually equal or above 20 dB.

Local governments in the USA are currently developing county noise ordinances based on the guidelines suggested by Environmental Protection Agency (EPA) and American Wind Energy Association. The ordinances are typically concerned with neighborhood, construction, and industrial noise. The strength of such regulations and ordinances is the consideration of the characteristics and tolerance limits of local communities. The residents living in counties where noise ordinances have not been established are currently unprotected from development of wind generation facilities near their homes and farms. The lack of noise limits increases the public reaction to wind farms, mostly motivated by subjective opinions.

The permissible noise levels applicable to wind turbines in various countries are listed in Table 2. While many countries do not specify the noise sources, Denmark clearly distinguished the noise limits for different sources. The noise limits for wind turbines are specified by the Ministry of the Environment (statutory order no. 304 of 14 May 1991) in open outdoor areas as 45 dB in open country and 40 db in residential and noise sensitive zones.

Table 2

Permissible L_{eq} Noise Levels in dBA applicable to wind turbines

(compiled from various sources)

Country	Commercial		Mixed		Residential		Rural	
	Day	Night	Day	Night	Day	Night	Day	Night
Germany	65	50	60	45	55	50	50	35
Netherlands (EPA)			50	40	45	35	40	30
Denmark (EPA)					45		40	
Australia	65	60			52	45	47	40
Ghana	75	65	65	60	65	48		
USA	No federal noise regulations, US-EPA established guidelines. Most states (including VA) do not have noise regulations. Local governments have noise ordinances (Rogers and Manwell, 2002).							

Conclusions

Sound generated by wind turbines has particular characteristics and it creates a different type of nuisance compared to usual urban, industrial, or commercial noise. The interaction of the blades with air turbulences around the towers creates low frequency and infrasound components, which modulate the broadband noise and create fluctuations of sound level. The low frequency fluctuations of the noise is described as “swishing” or “whooshing” sound, creating an additional disturbance due to the periodic and rhythmic characteristic.

A set of permissible limits for windmill noise that can be uniformly applicable over the nation is not available in the USA. Instead of imposing standard noise limits, the US Environmental Agency (US-EPA) suggests local governments developing their own noise regulations or zoning ordinances. Many countries developed national noise limits applicable to wind turbines.

Specific noise limits need to be developed by considering the characteristics of wind turbine noise. Especially the low frequency sound components and the modulation of the background noise resulting must be considered to represent the activity interference of the wind turbine sound. Adequate criteria to assess the wind turbine sound will greatly help the development of the wind industry by reducing the community reaction based on subjective opinions.

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WIND PROFILES OVER COMPLEX TERRAIN

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Abstract

Over an area with a complex topography the neutral wind profile is more difficult to predict then it is over flat terrain. Theoretical approaches have been given for relatively simple situations (such as an isolated hill or a ground plane with parallel ridges) and verified by measurements. As it does over flat land, atmospheric stability also influences the wind profile over complex terrain. As a consequence the ratio between higher (hub height) and lower (near ground) altitude winds depends on topography and atmospheric stability. Some general insights into this topic will be given and results of some measurements.

Introduction

At the first Wind Turbine Noise conference in Berlin, in 2005, several papers showed that the commonly used logarithmic formula does not correctly describe the wind profile in an atmosphere in a non-neutral state. In an unstable atmosphere this leads to an overestimate of the higher altitude wind speed, in a stable to an underestimate. From a noise perspective, the latter situation is more important as the discrepancy between a stable and neutral atmosphere is greater and has more effect on the noise output. Also, in the temperate climate zone the stable atmosphere is a common phenomenon after sundown, so this coincides with the time of day that noise levels usually must be lower. A stable atmosphere is thus the critical condition.
As a result of this shortcoming the relation between background sound (related to near ground wind) and turbine sound (related to higher altitude wind) often has not been determined properly as it was based on a 10 m altitude wind speed and a forever logartihmic wind profile. However, over flat land it is possible to give a correct description of the wind profile using the Monin-Obukhov similarity theory leading to a

stability correction added to the logarithmic profile. Holtslag [1984] gives a procedure to calculate the wind profile using near ground weather observations.

Over complex terrain the relation between wind speeds and wind directions at different altitudes is influenced also by the changes in ground height and as a result the situation is much more complex. Botha [2005] proposed to do away with the 10 m wind speed as the usual starting point to predict wind turbine noise levels and to relate all sound levels (from wind turbine and background) to the wind speed at rotor height. This proposal is superior to the practice of using only 10 m wind speeds in an apparently forever neutral atmosphere. Unfortunately it gives no insight into what actually happens below the rotor. To understand the impact of wind turbine noise it is important to understand, at least qualitatively, the behavour of the wind. This is demonstrated by Botha himself who concluded that in two of the cases he considered the atmosphere was predominantly neutral: this did seem to be the case at the location of the measurement on a mountain top, but it was not true in the valley below where the residents live.

This paper gives an overview of research results but represents only part of the knowledge available in this topic –*viz.* as far as it concerns the application to wind energy. It is limited to the changes in average wind speed due to topography and atmospheric stability and does not deal with turbulence, although this is an important feature of wind in complex terrain that has to be considered to be able to predict effects on wind turbines. To the author's knowledge as yet no information on wind in complex terrain is available that is directly applicable to the topic of wind turbine noise.

Flow over ridges in a neutral atmosphere

When a ridge is perpendicar to the main wind flow, the near ground air is forced upward. This air will not be compressed by the upward forcing when the slope is gentle which is the case when the dimensionless number NH/U is small. Here H is the maximum obstacle height, U is the average undisturbed wind speed, and N is the buoyancy frequency $N = \sqrt{(-g/\rho \cdot d\rho/dz)}$ [Baines 1995] where g is the graviational acceleration, ρ is air density and z is height. N is the frequency of free vertical, buoyancy driven oscillations of small amplitude and has a maximum value of approximately 0.01 rad/s which is approximately the inverse of 15 seconds. When a forced vertical movement is fast relative to N the air cannot follow this change and will be compressed.

As the air flows uphill the lower air is accelerated whereas at high altitude the wind speed will not (yet) be affected. In figure 1 results from Beljaars *et al* [1987] are shown from the relatively 'smooth' (roughness height 3 cm) isolated Askervein hill on South Uist, Scotland, that is elongated in the direction perpendicular to the wind at the time of measurement. The top of the hill is 120 m above the surrounding terrain, 400 m from the upstream foot of the hill and very nearly symmetrical; in the cross direction the hill has a length of almost 2 km. The vertical parameter in figure 1 is the speed-up ratio $\Delta s = (V_{10}/V_{10,upstream} - 1)$where $V_{10,upstream}$ is the (topographically) undisturbed wind speed at 10 m height. The figure shows the results of three different models with actual measurements at 10 m height above (local) ground for a neutral atmosphere. It shows that the wind blows strongest at the top whereas it is

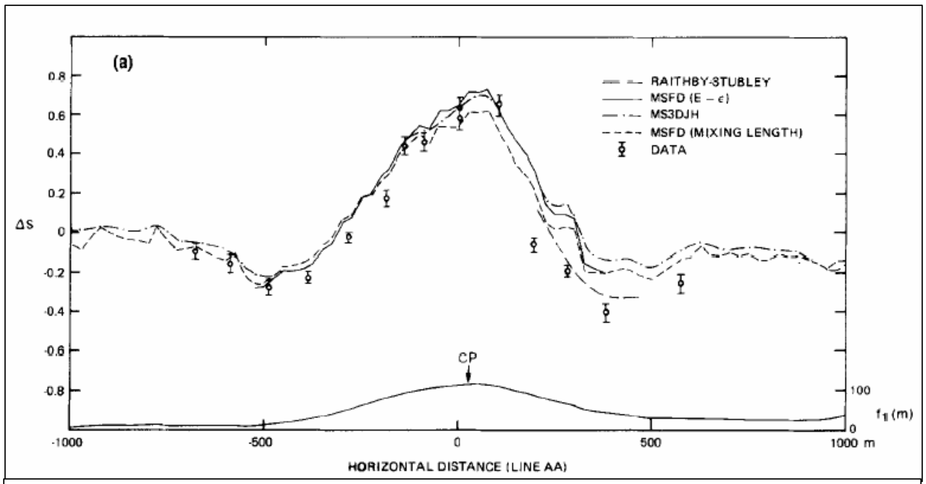

Figure 1: speed-up ratio, the change in 10 m wind speed relative to the upwind 10 m wind speed, plotted vs. distance in the streamwise direction from the top of Askervein Hill [figure from Beljaars *et al* 1986]

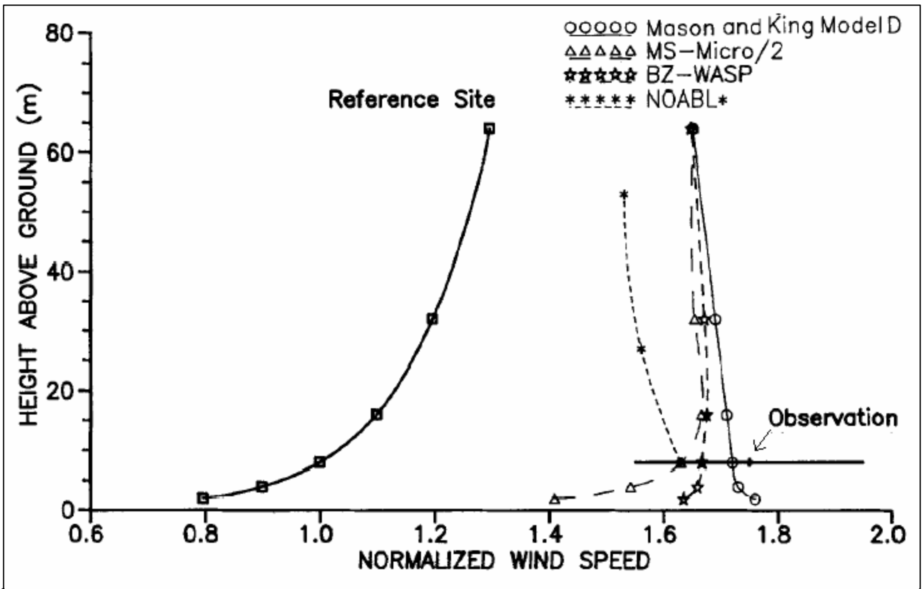

Figure 2: ratio of the wind speed to the reference upwind 8 m wind speed, plotted vs. height above local ground, in the (undisturbed) upwind reference point (left) and over the top of Blashaval Hill [figure from Walmsley *et al* 1990]

relatively calm at the foot of the hill due to a decrease of wind speed. Although the speed-up ratio at the top of the hill (almost 0.8, *i.e.* $V_{10}/V_{10,upstream} \approx 1.8$) refers to the up-stream 10 m wind speed, it is also a speed-up relative to a point at the same height without the hill. Over flat land, the wind speed ratio in a neutral atmosphere over 3 cm roughness would be V_{120}/V_{10} = 1.43. Thus, the hill creates an increase in wind speed at its top relative to that same altitude without the hill.

Walmsley *et al* [1990] obtained similar results for Blashaval Hill, Scotland. This hill has dimensions and roughness comparable to Askervein Hill. In figure 2 modelling results are plotted showing the wind speed above an upwind reference point undisturbed by topography, and above the 100 m high top of the hill, relative to the reference point wind speed at 8 m height. It shows that at the hill top the near ground velocity shear is strongly reduced compared to the near ground wind over flat land at the reference point. In fact at the hill top there is an increase close to the ground according to two models and a slight *de*crease in wind speed above $\approx$10 m according to all models. Beljaars *et al* [1986] give more detailed modelling results for the wind speed perturbation over periodic, sinusoidal ridges with a wave length (top to top or valley to valley) λ. In figure 3 results are plotted for three models (the MS3DJH model is the same as the MS-Micro/2 model used by Walmsley *et al*). On the abscissa is the dimensionless parameter $(z + z_o)/\lambda$, where z is height above ground and z_o is the roughness height. Three situations are given for (from left to right in figure 3) relatively longer or relavitely smoother hills, with values for λ/z_o of 10^3, 10^5 and 10^7, respectively. At λ/z_o =

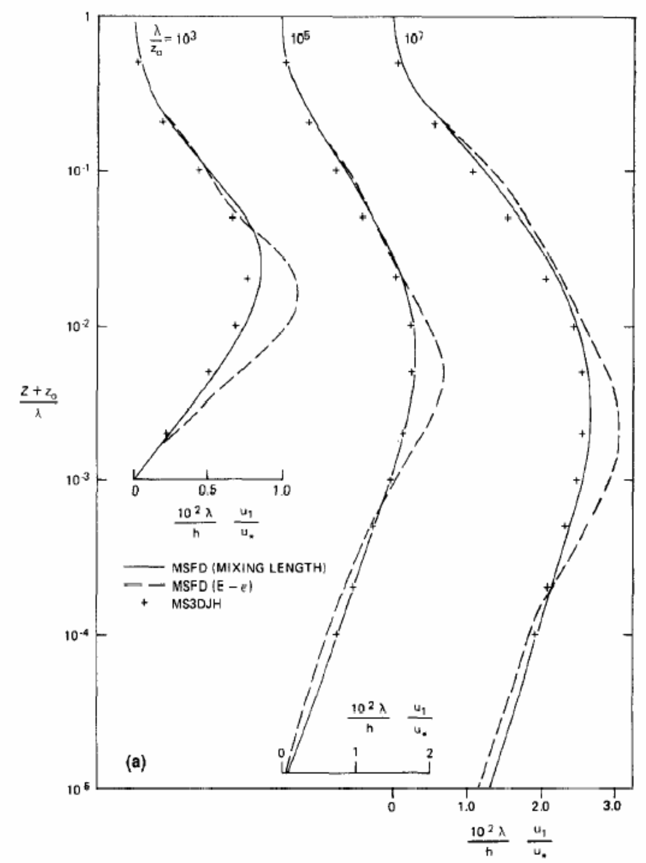

Figure 3: wind speed perturbation at dimensionless ‘height’ $(z+z_o)/\lambda$ over the top of a (periodic) ridge relative to the wind speed at the same height over flat land [figure from Beljaars

10^5 the maximum perturbation (relative to the profile at the same height above flat ground) in wind speed is at a height of $z \approx 0.005 \cdot \lambda - z_o$, which for an inter-ridge distance up to 1 km is less than 5 m. The perturbation vanishes at a height of appr. $\frac{1}{2}\lambda$.

When changes in ground height are small, the relief can be treated as increased rougness. Then, in a neutral atmosphere, the wind speed can be determined from the logarithmic wind profile, given a reference wind speed and the roughness and displacement height (defining a plane below which the model is not valid):

$$V_z \cdot \log[(z - d)/z_o] = V_{ref} \cdot \log[(z_{ref} - d)/z_o] \qquad (1)$$

Kustas *et al* [1986] applied this approach to a hilly region in the Swiss Voralpen ('Pre-alps') described as (non-periodic) statistically uniform terrain with hills of approximately 100 m height and distances between major peaks of about 1 km. They showed that in neutral conditions eq. 1 could be used to describe the wind speed and inferred that on average $z_o = 3.8 \pm 1.3$ m and d = 45 m. The displacement height is thus about half the (major) peak height; this approach can therefore not be used to describe the wind in the valleys.

Flow in valleys in a neutral atmosphere

We now take a closer look at the flow in the valleys between the ridges. From figure 1 it was apparent that for a single ridge the wind speed at the foot of the hill, upwind as well as downwind, is lower than it would be without the hill.

Baines [1995] gives an overview of modelling results for valleys modelled as single and periodic depressions. For a single depression and hydrostatic equilibrium (corresponding to a neutral atmosphere) the wind flows through the valley, but above a critical value of NH/U (where H is now the depth of the depression), the air at the bottom of the valley becomes stagnant. For an increasing value of NH/U the thickness of the stagnant layer increases. The critical value for a radially symmetric depression of the form $z_{ground} = -H/(1+(r/a)^2)$ is 0.85; for asymmetrical forms it is between 0.5 and 1. This means that for U/H < N/0.85 ≈ 0.012 there will be still air at the bottom of the valley. A vortex will develop in the valley above the upwind slope of the valley if the slope is steep enough. This occurs when NL/U < π where L is width of the downslope side of the valley; if (in a symmetrical valley 2L wide) NLU < $\frac{1}{2}\pi$, the vortex formed at the downslope will dominate most or all of the valley [Baines 1995].

In periodic valleys, between periodic ridges perpendicular to the wind, the behaviour of the wind is essentially a repetition of the single valley, air being swept from one valley into the other [Baines 1995], though each valley may have still air at its bottom when NH/U exceeds the critical value. The influence of a hill in the upwind direction is negligible, but increases when the atmosphere becomes more stable [Hunt *et al* 1984]. In the downwind direction the wake can influence the flow around a nearby hill, though for relatively low and smooth hills the flow of one hill can be superimposed on the next to determine the total flow [Hunt *et al* 1984].

When the wiond has a compionent in the direction of the valley, the wind below the ridges will be forced by topography to follow the valley, the more so if the valley is deep. Enger *et al* [1993] give a clear example of this from a north-south running section of the Colorado River Valley, USA, where the wind direction below the ridges that are 1 to 2 km above the valley floor, is either north or south, irrespective of the east-west component of the geostrophic wind.

Flow over ridges in a stable atmosphere

In the temperate climate zone an inversion usually develops at sundown that becomes more pronounced in the course of time. After sunrise it may remain present, but especially at high insolation it will disappear due to turbulent mixing. Above the inversion an adiabatic temperature gradient can be assumed, below it this gradient is inverted and temperature increases with height. This implies that above the inversion the atmosphere is neutral. Usually inversions have a height of up to several hectometers. Thus the situation at sufficiently high hill tops, which are closer to or perhaps above the inversion height, will be more similar to the neutral atmospheric state than the situation in the valleys is. A very broad hill top can be viewed as a plateau where the wind profile will adapt to the new, higher ground level; after a long fetch at the new height this will develop into a stable wind profile, irrespective of ground height.

Flow in valleys in a stable atmosphere

In a stable atmosphere the near ground air is relatively cool and heavy. With no wind this cool air will therefore flow towards the lowest point and the lower part of the

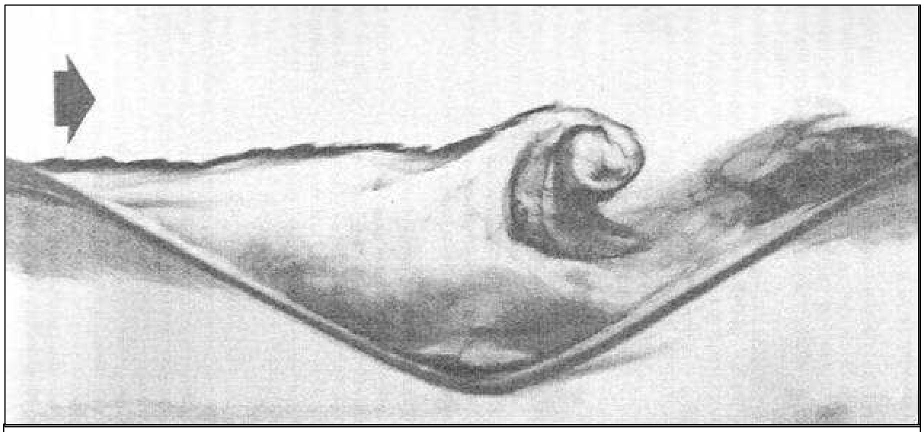

Figure 4: steady flow over a 'valley' filled with heavy (dark) fluid where NH/U =1.5 and H/L = 0.45; dye marks the separation between the flow over and in the valley. At the downwind side there is turbulent mixing (figure from [Baines 1995]).

valley will be filled with cool air. When there is some wind at higher altitudes, there will be a mixing layer between the stagnant valley air and the moving air above it. Figure 4, taken from Baines [1995], gives a laboratory example of steady flow over a depression filled with heavy fluid. Here the flow is strong enough to push some fluid from the upslope out of the valley. To push the heavy fluid entirely out of the valley the criterion NL/U << 0.5 must be met, where L is the half-width of the valley. When NL/U >> 0.5, the fluid will stay in the valley and not move. In between these values some heavy fluid will leave the valley and the remaining fluid will accumulate on the downwind slope (the dark patch at the right in figure 4). Enger *et al* [1993] illustrate this for the practical case of the Colorado River Canyon, showing a vortex on the downwind side of the canyon with wind speeds in excess of the geostrophic wind (7 m/s) and almost still air at the upwind slope.

Periodic ridges with a cross flow can be regarded as a repetition of single valleys, except that if cool air is pushed out of one valley it will enter the next [Baines 1995]. In a stable atmosphere cool air is in fact produced in the valleys, so the net loss of cool air in a valley is less than in a single valley and valleys further downwind will contain more cool air. In figure 5 this flow is plotted for three values of NH/U when the flow already has traversed several valleys and can be considered nearly steady. In figure 5 instantaneous streamlines as plotted as solid lines (dotted lines are potential density); in all three cases there is stagnant air in the valley. From the values of NH/U (with N = 0.01 rad/s and H = 500 m) one can conclude that the geostrophic wind speed is (from top to bottom) 7, 4 and 2 m/s, respectively. Fromn figure 5 one can conclude that when the geostrophic wind speed increases the height of the stagnant air pool in the valley decreases.

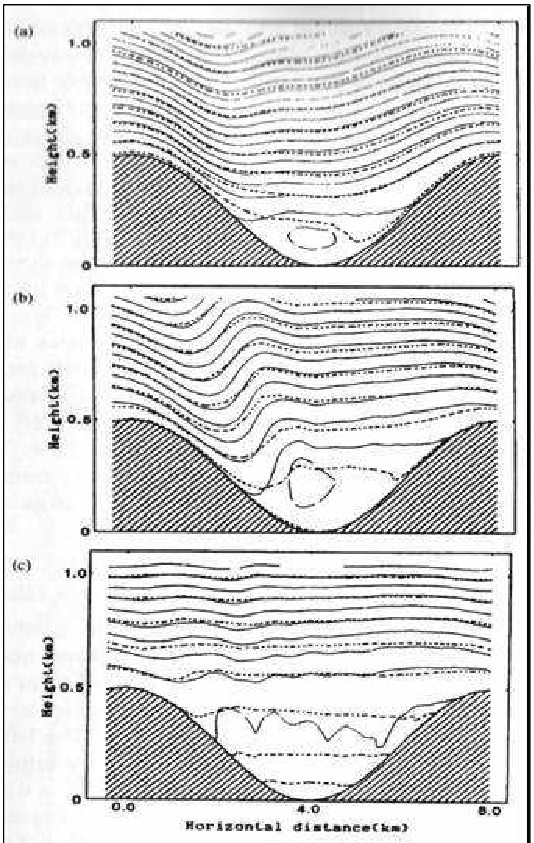

Figure 5: streamlines in the flow across a valley (solid lines) and contours of potential density (dotted lines) where NH/U has a value of 0.69 (a), 1.38 (b) and 2.44 (c) (figure from [Baines 1995], originally from [Kimura *et al* 1988])

In figure 6 a fine example of stable (evening) atmospheric conditions is shown on a popular leaflet of the Sydney CityRail. In the valley cool air is visible as fog as a result of condensation due to ground cooling. Also, on the plateau a thin layer of fog has formed.

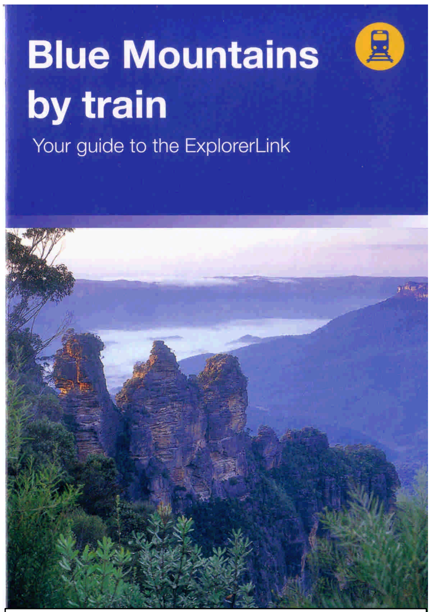

Figure 6: fog revealing the presence of stable air on a Sydney CityRail brochure

Downslope wind in a stable atmosphere

On a sloping surface the cooling of near ground air will cause it to flow downward. Thus the air on valley slopes will flow downward and fill the valley bottom. Brost *et al* [1978] have investigated this for a single sloping plane, and show how the thickness of the stable boundary layer depends on the direction of the wind relative to the slope. Although the authors conclude that the effect of slope on the flow is strong, these calculations were done for a slope of 0.002 which is lower than one would expect in hilly terrain. When the wind flows upslope the most stable layer develops; the flow reverses in direction when ascending from the ground up to a height where the prevailing wind blows. This was also found for the much steeper Colorado River Canyon, where the vortex developed on the downwind slope.

Case 1: wind measurements near Makara, NZ

For a projected wind farm close to the village of Makara, New Zealand, data were collected to be able to correlate the wind speed in a valley with the wind speed on top of ridges. Makara is a village in a valley running from SSW to NNE between approximately parrallel ridges up to 400 m above the valley floor. The wind farm is projected on the ridge west of the valley (and further away). Northern to northwesterly winds are predominant in the area, otherwise southern winds prevail; winds from other directions are rare.
The wind data presented here are from an anemometer mounted at 122 m height on a mast on Mount Kaukau, 10 km NE of Makara, on a location at 425 m above MSL, and were provided by the New Zealand Met Office (data fro. This anemometer is thus somewhat higher than the planned wind turbine rotors will be. Valley wind speeds (the ‘Makara valley data’) are from a 4 m high anemometer on a location appr. 80 m above MSL at 60 South Makara Road, and were provided by an amateur meteorologist. The anemometer is out in the open and not sheltered by any trees or

buildings. The data presented here are from hourly values in the period October 19, 2004 through December 31, 2005.

First in figure 7 results are shown from measurements over the year 2005 at Wellington airport, with a relatively flat and low surface, 10 km ESE of Makara. The anemometer is at 10 m above MSL. Figure 7 shows the averages per clock hour over all hours when the wind was northerly (which is the case for most of the time), over the four seasons. The fact that the wind picks up in the morning and abates in the evening is a direct result of a stable atmosphere (with low surface wind speed) that becomes unstable after sunrise (when surface wind increases). With southerly winds, when the air has moved over a long fetch of water where the differences between day and night time surface temperature are much smaller than on land, the difference between day and night wind speed is also smaller. From figure 7 it can be concluded that nighttime atmospheric stability is a common phenomenon in the area.

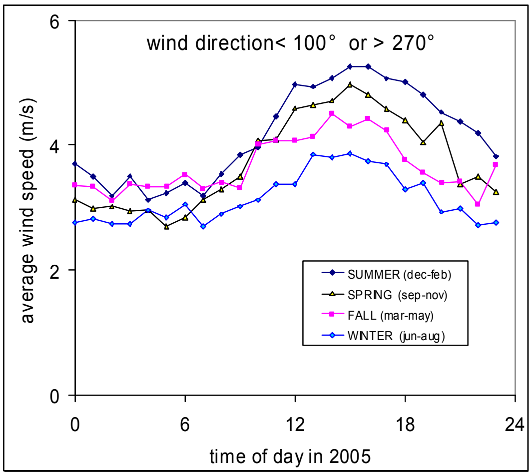

Figure 7: average wind speed at Wellington airport for ofshore winds (direction between West and East over North); averages per clock hour over all hours in 2005

In figure 8 the average wind speeds are plotted per season in the Makara valley and on top of Mount Kaukau. For the valley data the figure clearly shows the diurnal pattern of low near surface nighttime wind speed (stable atmosphere), increasing after sunrise (change to unstable atmosphere), and the reverse process around sunset. Also, as expected, the differences are greater in spring and summer because of increased heating of

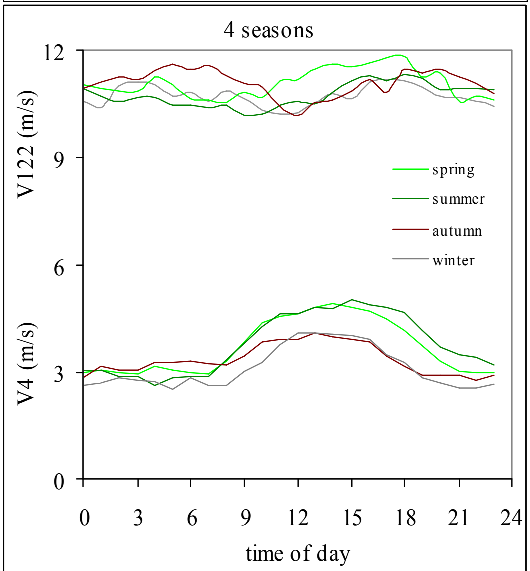

Figure 8: wind speed averaged per clock hour over Mount Kaukau (V122) and in Makara Valley (V4) over the seasons in period Oct.

the surface in daytime. In fact the results are very much similar to those of Wellington airport (figure 7).
For the mount Kaukau data the pattern is reversed, as is expected for higher altitudes: here the wind abates, though only lightly on average, in the morning and picks up again at night.

The wind farm developer has measured wind speeds at 40 m and 80 m altitude above the top (299 m) of Quartz Hill, 5 km north of Makara (these data were not made available). The wind shear, determined from wind speeds at 40 and 80 m height above Quartz Hill, is low: V80 is, on average, 5% higher than V40. Data from two heights at Mt. Kaukau (26 m and 122 m AGL) yield approximately the same results: on average the wind speed in daytime at 122 m is some 10% higher than at 26 m (at night this is 20%). This low wind shear is the combination of the higher altitude near-neutral atmosphere and the effect of acceleration of the wind when it ascends the slope.

In figure 9 the average ratio of the 122-m wind speed at Mt. Kaukau and the 4-m wind speed at South Makara Road is plotted for summer and winter. Also plotted are the ratio's that were exceeded for 10% and 90% of the time, respectively, showing values can significantly deviate from the average ratio for a considerable part of the time. In fact the valley wind speed was below 2 m/s for 31% of the total time (night and day), whereas such a low wind speed over the hill top is rare (2% of the time). The 31% corresponds to 60 to 70% (depending on season) of the hours between sunset and sunrise.

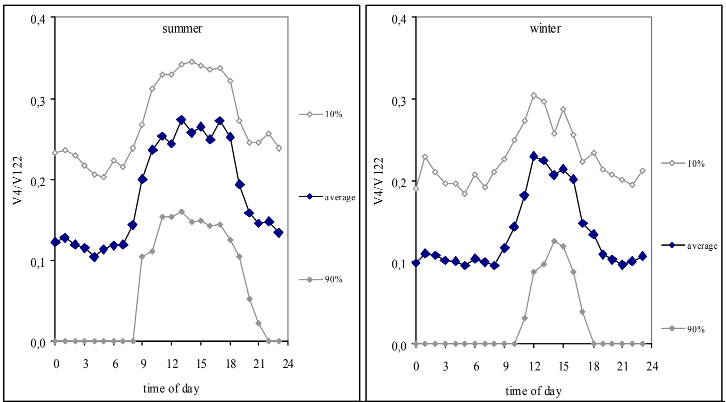

Figure 9: average ratio of the wind speed in Makara valley and over Mt. Kaukau and ratio's exceeded for 10% and 90% of the time in summer and winter; values per clock hour in period Oct. 2004

The results in figure 9 show that at night the wind speed in the valley is on average 20 to 25% of the hill top wind speed in daytime, but this decreases to appr. 10% at night time. These are averages: at night it is very common that the wind speed is zero or very weak (< 2 m/s). These values may be somewhat different when taking different locations, but the differences will be small as they only depend on small deviations from the general situation (the ridges vs. the valley floor). If this were not the case, then measurements from one location (such as Mt. Kaukau or Quartz Hill) would not represent the conditions in a larger area.

Case 2: observations in Taralga, NSW

Taralga is in an area with rolling hills and height variations up to several hundreds of meters, in New South Wales, Australia. A wind farm developer proposed to erect wind turbines on high places in the area. To determine the wind resource, several measurement masts have collected wind speed data. As was the case in NZ (above) these data were not made public, though in this case they could be analysed by the other parties. From the measurements the developer concluded that there was no significant wind shear. At one of the masts wind speeds were measured at 20, 35 and 50 m height. Our analysis of the wind shear between 35 and 50 m (calculated from the 35 and 50 m wind speeds, for 50-m wind speeds higher than the cut-in wind speed of the turbines), showed that 31% of all shear exponents were negative, which means that the wind speed decreases with height above 35 m. At the same time there was usually an increase in wind speed between 20 m and 35 m height.
In fact, the correlation between both sets of wind shear exponents was relatively low; the wind shear below 35 m determined 34% of the wind shear above 35 m, for the rest other factors are apparently important (correlation coefficient is 0.59 → variation is 0.34). Between 6PM and 7AM the proportion of time with a negative shear above 35 m was lower (15%), and there was less correlation between wind shear above and below 35 m (correlation coefficient is 0.53 → variation is 0.28).
The fact that there is often a change in wind shear somewhere between 20 m and 50 m over the hill can be understood from the flow over a hill as shown in the sections above, and demonstrates that the wind profile from ground level to projected hub height cannot be described correctly by the logarithmic wind shear formula that is valid over flat terrain. Taking simple averages of the wind shear between 20 and 50 m obscured the fact that for a significant proportion of time there is no steady increase of wind speed with height, but a maximum somewhere between 20 and 50 m height over the hill top. From these data it is not possible to determine the wind speed in the lower parts of the area.

Mr. Ross, a resident of this very quiet area, made interesting observations at his house that stands in a low part of the area with no direct neighbours and surrounded by hills on which the turbines were planned. He kept a diary of his weather observations of which a period of 87 days in April to July 2006 (the southern autumn and winter) will be shown here. Interestingly, a closeby wooded ridge, approximately 70 m higher than the house, provided an indication of the higher altitude wind speed: when it was very calm at his house he could often hear the rustling of the trees on the high part of the hill, and he could see (when it was light) the movement of the

leaved branches above a certain altitude. This was only seen at ‘night time’ (in a broad sense: with the sun low or down). In fact nature here demonstrates that a resident can experience no wind in the valley while at the same a wind turbine at the top would experience a high wind speed.
In figure 10 mr. Ross’ observations are summed up graphically: out of 86 days of observations (he was out one day) in 34 nights he observed rustling on the ridge, in various degrees of loudness, while at his house it was calm. These days are not scattered randomly but are more or less grouped according to the passage of weather systems that have a succession time of several days to a week. Also, in many of these days he observed fog in the low parts; in fact this is a visualization of the cool near ground air. He also observed more than a light clouding in seven occasions, which never coincided in time with the high wind shear.

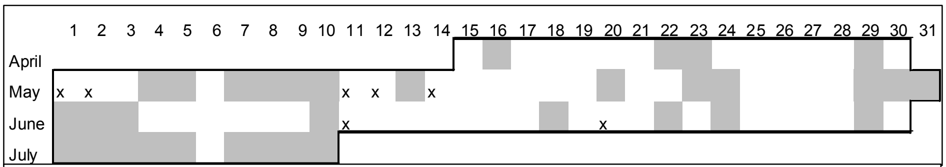

Figure 10: weather observations in the Taralga area over a period of 87 days; grey: night with no or very little wind at house, wind on high ridge; x: sky (partly) clouded; white: other conditions

Conclusion

Atmospheric stability and topographic forcing are important determinants of the wind profile in complex terrain. Due to topographical height variations the near ground wind can be slower or faster than the higher altitude wind. Over a hill the wind speed will usually be higher than it would be at that point in space without the hill. At the same time the wind speed in the valley will usually be lower than it would be without the hill. Topography can enhance or decrease the effect that atmospheric stability has on near ground wind. In general, at night a valley will be calm while the wind will keep on blowing at high tops.
From measurements on high places in complex terrain it is not possible to calculate the wind speed in lower parts; the commonly used logarithmic (neutral) wind profile cannot be used in complex terrain, even less so when the atmosphere is stable.

From an energy perspective the high places in complex terrain are therefore most attractive, though added turbulence and wind shear due to topographic forcing may increase the dynamical load on a turbine.
From a noise perspective this means that in valleys it can be very quiet, especially at night, while on hill tops the wind may drive wind turbines at high speed. Thus, the perception of wind farms by residents in hilly terrain is not very different from residents in flat terrain where atmospheric stability produces the same effect. An advantage of hilly terrain may be that it can help in shielding wind turbines aurally and visually, though this depends on position as it can also enhance perception.

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Taking into account of atmospheric conditions for a spatio-time localization of the aerodynamic sources on a moving blade by the method of acoustic imagery.

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Abstract

The rapidly increasing capabilities of computer hardware and electronic components allow to apply the acoustic imaging technique to today's large wind turbines. It is possible to separate and analyse the noise behaviour of the three major zones of noise radiation, which are the tower, the rotor hub and the blades. Locating accurately the origin of the main aeroacoustic radiations on a moving blade drives the beamforming technique to its limits. Advanced methods are required for the space-time localization of the blade and to operate the measurement devices. The blade localization with the beamforming technique can be improved by taking into account the influence of the climatic parameters (wind field, hygrometry, temperature). This publication presents our effort to quantify the effects of the wind.

Introduction

Wind turbines are more quieter since the first constructed. And those days, when fossil fuels are selling out, we are trying to find another way to produce energies. In order to develop this renewable energy, more and more wind turbine parks have been and are being established. So more and more techniques are improved to localise sources and preserved people from this discomfort. In this paper we used the beamforming technique in time domain. To enhance beamforming and precisely localisation of noise source, we have to consider the influence of climatic parameters and especially the wind.
So the first part is devoted to the analytical presentation of the problem. The second part shows theoretical and experimental results illustrating the differences in localizing aeroacoustic noise sources with or without correction to account for the influence of climatic parameters.

I. THE ANALYTICAL PRESENTATION OF THE PROBLEM

1. The beamforming technique

The acoustical imaging methods are based on the acquisition from a microphone array, also called an antenna. The method used in this paper is the beamforming technique. As indicated by this word, the processing consists in forming narrow beams to 'hear' a local point in the space. The most robust method to form a beam is the delay & sum technique. As shown below (Figure 1), each signal from the microphones is first delayed and then all the contributions are summed. The delays are calculated to compensate the difference of time propagation between the hearing point and the microphones. Applying these delays for all the microphones makes the wavefront is lined up with the antenna. The output is a time signal, representative of the original signal from the source. The time domain version of the beamforming (it exists also a frequency domain version) allows dealing with non-stationary sources. For example, it allows tracking aeroacoustic sources on blades. It is possible to obtain an acoustic image every 1ms.as results inside this paper show it The time domain also brings more flexibility in low frequencies, since it is not necessary to have one period of signal to localize a source. To obtain an acoustic image, one have to change the delays to scan a surface (called an 'acoustic image or focal plane' below).

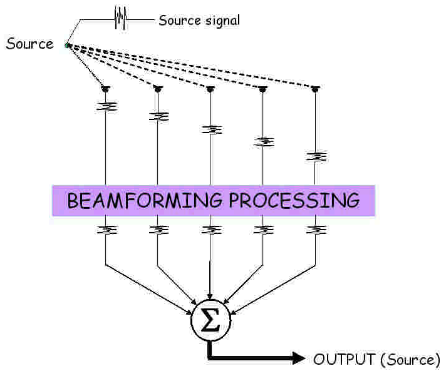


Figure 1: the 'delay & sum' processing

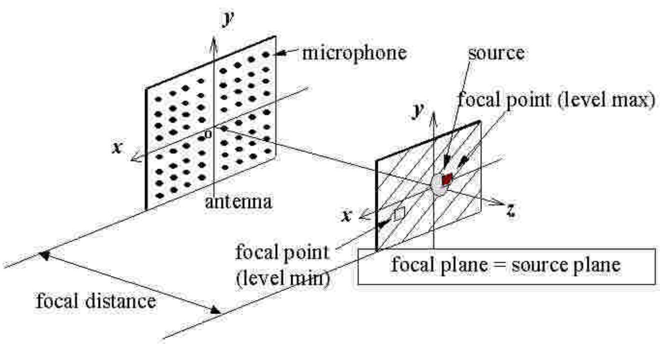


Figure 2: beamforming parameters

The study of wind turbines on a broad frequency band requires:
- a large size of acoustic antenna, and at the same time the space between microphones should be lower than the shortest half wavelength.
- a non regular repartition of microphones to reduce the number of sensors and given the best dynamic; it means the difference of levels between the source level and the highest level of lobes. But the repartion must be carefully optimized to avoid a high incidence of virtual lobes
- a sufficient density of microphones to limit virtual lobes and improve the robustness of the processing against background noise, providing a noise reduction of the acoustic image.

In conclusion, improving the resolution (with the dimension of the antenna) and the dynamic (the arrangement of microphones) makes a better separation of sources and a reduction of ghost sources: the spots are smaller and well identified. Thus all these parameters, resolution, dynamic and robustness, contribute to the precision of the processing in the localization of sources.

The acoustical imaging system

The complete system is composed of the microphone array, the acquisition system and softwares.
The antenna of 9 m x 9 m and with 121 microphones with a specific arrangement providing bandwidth 80 – 4000 Hz.
Because of dimensions of antennas, the practical deployment was studied carefully to simplify the set-up. The 9 x 9 m antenna is built from a structure which defines the framework.

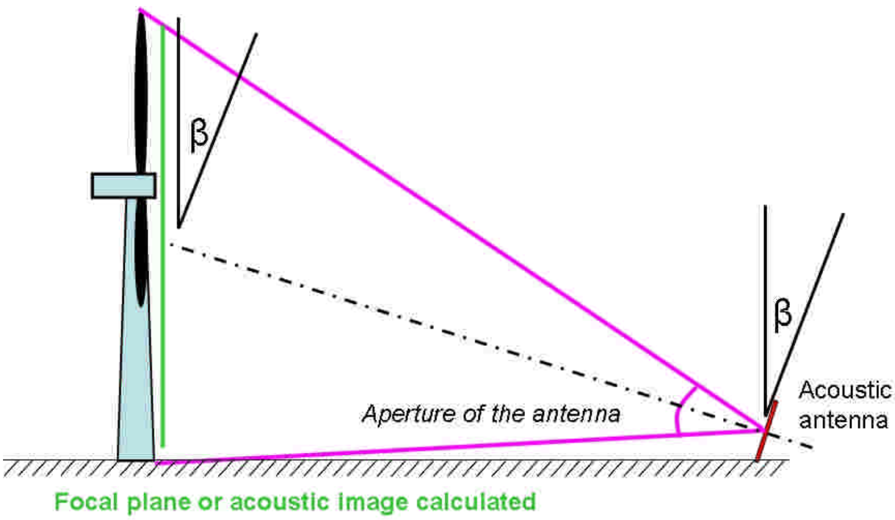
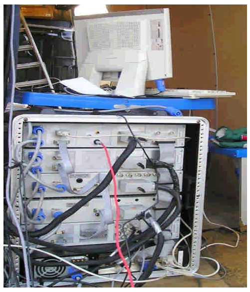


Figure 4: Position of the antenna relatively to the wind turbine

Orientation β of the focal plane is chosen in the calculation software to correspond to the plane of the object which is in study
The acquisition system records the time signal of each microphone. The complete system is autonomous in energy (it is powered by a 12 Volts power supply). The hardware is made to record signals with no limit in time, except that related to the hard-disk size of the computer. Thus the acquisition can last several hours or more.

A truck is enable to move full system around some positions to acquire a lot of configurations in the same campaign.

In the context of outdoor measurements, and especially in the case of wind turbines, it is important to acquire climatic parameters. The system also allows recording at the same time these data: the speed and the direction of the wind, the ambient pressure, the temperature and the humidity. And about the parameters from the wind turbine, Acoustic video System records blade angle, active power, generator speed, yaw position too. WindLaw software powered by ACB allows to analyse theses parameters in function of acoustic levels to determine interesting configurations in terms of acoustic images and wind speed or blade angle and so on. Also, a channel is dedicated to the tachometric signal coming from the wind turbine.



2. Influence of climatic parameters

The wind may influence the time propagation of sound between the sources and the sensors. Based on a given wind speed profile, it is possible to use a ray method to calculate the effective time propagation between sources and microphones. Indeed, a uniform flow doesn't modify the geometry of the propagation but produce only a set translation.
The two primary objectives of the acoustic measurements are to identify the noise-producing regions and quantify their strength. When the microphone array stands on the ground, the localized sources are related to the main parts of the wind turbine: the tower, the blades and the rotor. Here, we are interested in the localisation of the noise generated by blades in motion at 150m away from the antenna with a high precision.
In phase array testing, a number of microphones can be used together to extract the desired source location and level information and the beamforming technique is used to successively focus the phased array to each point in a grid and thereby measure the apparent source strength distribution.

Uniform flow

Suppose that the flow is uniform with a speed $\vec{V}$. In linear acoustics, to find the wave equation we use the linearisation of the Euler equations. But for a uniform flow, we have to consider that the linearisation of the speed vector at the first order is :

$$\vec{V} = \vec{v}_0 + \vec{v}_1 \qquad (2)$$

So, combinating the law mass and the momentum, the acoustic pressure, p, obey the convected wave equation :

$$\frac{1}{c^2}\left[\frac{\partial}{\partial t} + \vec{v}_0 \cdot \vec{\nabla}\right]^2 p = \Delta^2 p \qquad (3)$$

Acoustic propagation for phased array analysis can be analysed in the context of geometrical optics. In geometrical optics the form of the pressure is:

$$p = A(\vec{r})e^{-i\omega(t-\psi(\vec{r}))} \qquad (4)$$

Substituing Equation (4) into Equation (3) and knowing that the amplitude vary slowly in comparison to the phase, $\psi(\vec{r})$ is seen to obey the eikonal equation :

$$\frac{1}{c^2}\left[1 - \vec{v}_0 \vec{\nabla}\psi\right]^2 = \left|\vec{\nabla}\psi\right|^2 \qquad (5)$$

Solutions to Equation (5) can be found graphically. In the case of a compact source at the origin, the wavefront is a spherical surface that expands outward at the speed of sound while the center of the sphere is simultaneously convected downstream at speed v_0.

Consider the scheme below :

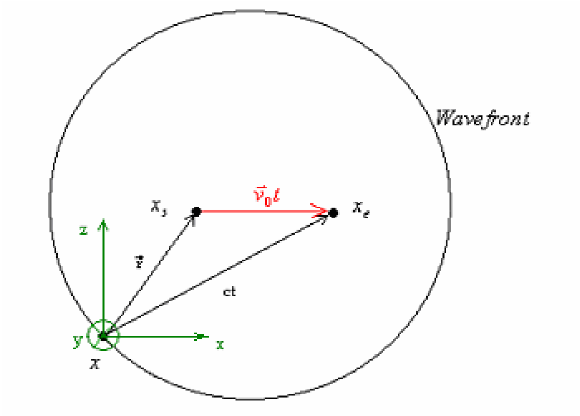


Figure 5 : The wavefront at time $t = \psi$.

Figure 4 shows that the radius of the sphere is ct, and the center is at $x_e = (\vec{v}_0 t, 0, 0)$

To find arrival time, $\psi(\vec{r})$, use is made of the triangle $x_s = Source$, $x_e = Convected \ \ Source$ and $x = Microphone$ in Figure 4.

Putting into practice vector's properties we obtain :

$$\left|\vec{r} + \vec{v}_0 t\right| = ct$$

And $$\left(c^2 - v_0^2\right) t^2 - 2\left(\vec{r} \cdot \vec{v}_0\right) t - r^2 = 0 \tag{6}$$

Finally, we obtain a quadratique equation in t, which root is :

$$\boxed{t = \frac{\left(\vec{r} \cdot \vec{v}_0\right) + \sqrt{\left(\vec{r} \cdot \vec{v}_0\right)^2 + \left(c^2 - v_0^2\right) r^2}}{\left(c^2 - v_0^2\right)}} \tag{7}$$

Injecting Equation (7) into Equation (5) we can see Equation (7) is a solution to the Eikonal equation.
Thanks to these techniques, we are able to determine the propagation time under wind's influence. Then when we apply the beamforming technique we can localise the noise generated by the blades.

Wind profiles

There is a relation between the wind speed v_h at a certain height h and the wind speed v_{ref} at a reference height h_{ref} (in our case 10m), which is the logarithmic wind profile, with surface roughness z as the only parameter. For height h the wind speed v_h is described as :

$$v_h = v_{ref} \left[\frac{\log\left(\frac{h}{z}\right)}{\log\left(\frac{h_{ref}}{z}\right)} \right] \tag{8}$$

This equation is an approximation of the wind profile when the air is mixed by turbulence resulting from friction with the surface of the earth, then considering uniform flow. But, the atmosphere during daytime and night-time is completly different because of the weather or temperature. As a consequence, the wind profile changes and can no longer be adequately described by Equation (8). In this paper we will use this equation to describe our wind profile. For further details see the G.P van den Berg's paper [6].

<u>2. Theoretical and experimental results</u>

By confidentiality condition, authors cannot describe some details (acoustic levels, scale, exact profile of blade …).
At first, we used "static" acoustic sources to calibrate in the space the antenna associated with the windturbine. Secondly, we have placed a known "dynamic"acoustical source at 5 meters from the end of one blade. We kept data of its generated sound noise during our measurements. we localized acoustical radiation from this "dynamic" source knowing its position everytime. Doing that allowed us to follow behaviours of the aeroacoustic noise sources and the generated sound by the known acoustical source in the same time and finally determine the right localization of the aeroacoustic noise sounds generated by the blades thanks to the unmovable source of the known acoustical source.
We have made images with certains parameters:

- The is faced to rotor the antenna (no rotation of focal plane by vertical axe).
- The wind blows at a speed of 35km/h at 10 meters height

- Distance about 158meters
- Dynamic acoustical source known radiating in high frequency range.
- Aerodynamic sources on the blade radiating at middle frequency range.
- β angle following horizontal axe to adjust focal plane on rotor surface.
- Wind speed for correction = 35 km/h at 10 meters height

Results show the acoustic source known on the blade without and with correction " wind effect", and in the same time the aeroacoustic sources on the blade in same condition. Furthermore, it is possible to choose a quick time exposure with the beamforming technique working in the time domain.

Results of the known acoustical source

Here, we have chosen a time exposure of 0.02 second and we obtain:

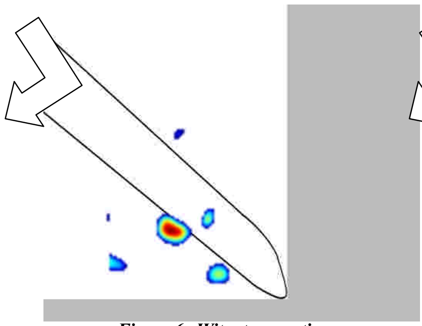


Figure 6: Witout correction

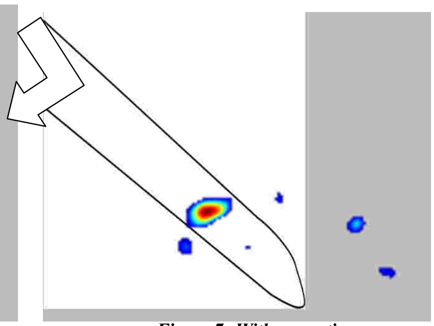


Figure 7: With correction

Results of aeroacoustical source generated by the blade

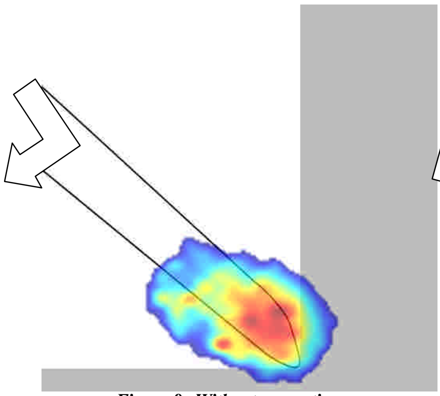


Figure 8: Without correction

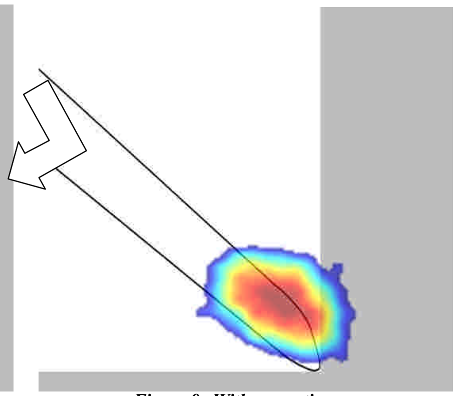


Figure 9: With correction

We can see on Figure 9 when we apply the algorithm correction, the aeroacoustical source are well focalizing on the intrados side.

Second example of results
Acoustic source known when the blade is in horizontal condition :

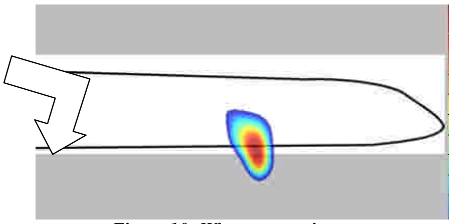


Figure 10: Witout correction

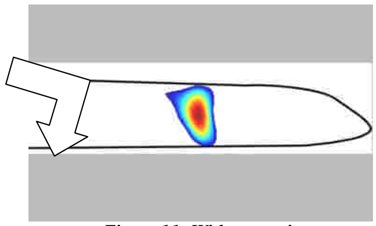


Figure 11: With correction

Exactly in the same time, but no same frequency range, aeroacoustic sources :

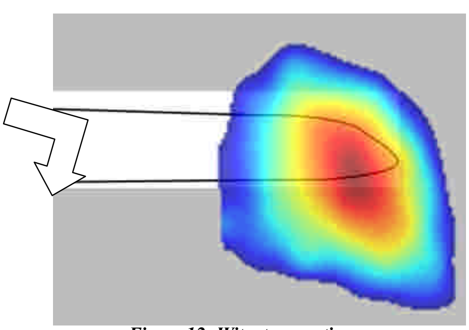


Figure 12: Witout correction

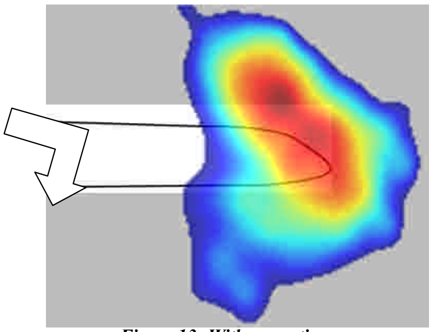


Figure 13: With correction

In this last case, aerodynamic noises come from the top of the blade.

3. Conclusion

In this paper, we wanted to determine at first the theoric acoustic influence on propagation from the wind. We showed that under wind's influence, propagation of sound is convected. Delays used for the beamforming technique are differents than those which are not influenced by the wind. So, algorithm including these new delays was implemented. Thanks to this algoritm and our software **APM®,** we created acoustical images figures 6 to 13.

In the case of studies of acoustical radiation on the side of the wind turbine, wind blowing from the side, this correction would provide larger gaps relating of localisation effects. The information of temperature could also be taken into account in further research.

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[5] Tomas J. Mueller : Aeroacoustic Measurments.

[6] G.P. van den Berg: Effects of the wind profile at night on wind turbine sound