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Influence of vertical temperature gradient on background noise and on long-range noise propagation from wind turbines

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Summary

The noise impact measurements of wind farms are often performed near inhabited areas, sometimes far away from the machines, at a distance where the influence of the meteorological conditions on the background noise levels and on the noise propagation cannot be neglected. The French standard NF S 31-114 recommends a classification of the environmental conditions into “homogeneous classes”, based on environmental and meteorological factors (e.g. external activities, dawn chorus, wind direction, seasons, etc).
Typically, noise analysis and reduction plans are established according to wind direction only. In this paper, we present a set of measurement results which show that the vertical temperature gradient may be a useful way to define “homogeneous classes” with a reduced dispersion of the measured data. This kind of classification has been used for a long time in rail, road and aircraft noise measurements.
Computer simulations have been performed (PE method) in order to better understand the influence of the temperature gradient on noise propagation of a wind turbine under a classical vertical logarithmic wind profile.

1. Introduction

The noise regulation in France is based on the concept of emergence, which is the difference between ambient noise (measured when machines are ON) and background noise (measured when machines are OFF).

Noise measurement is carried out near inhabited areas, and the noise descriptor is the $L_{50,10mn}$ of the $L_{Aeq,1s}$.

Wind measurements can be done in several ways, but the aim is to estimate the standardized wind speed, which is the wind speed converted to reference conditions (height 10 m and roughness length 0.05 m) using a logarithmic profile. With reference to a power law, the standardized wind speed can also be derived from 75 m height down to 10 m height using the wind shear factor α=0.16.

The guidelines for noise and wind speed measurements are described in the French standards NF S 31-114 and NF EN 61400-11.

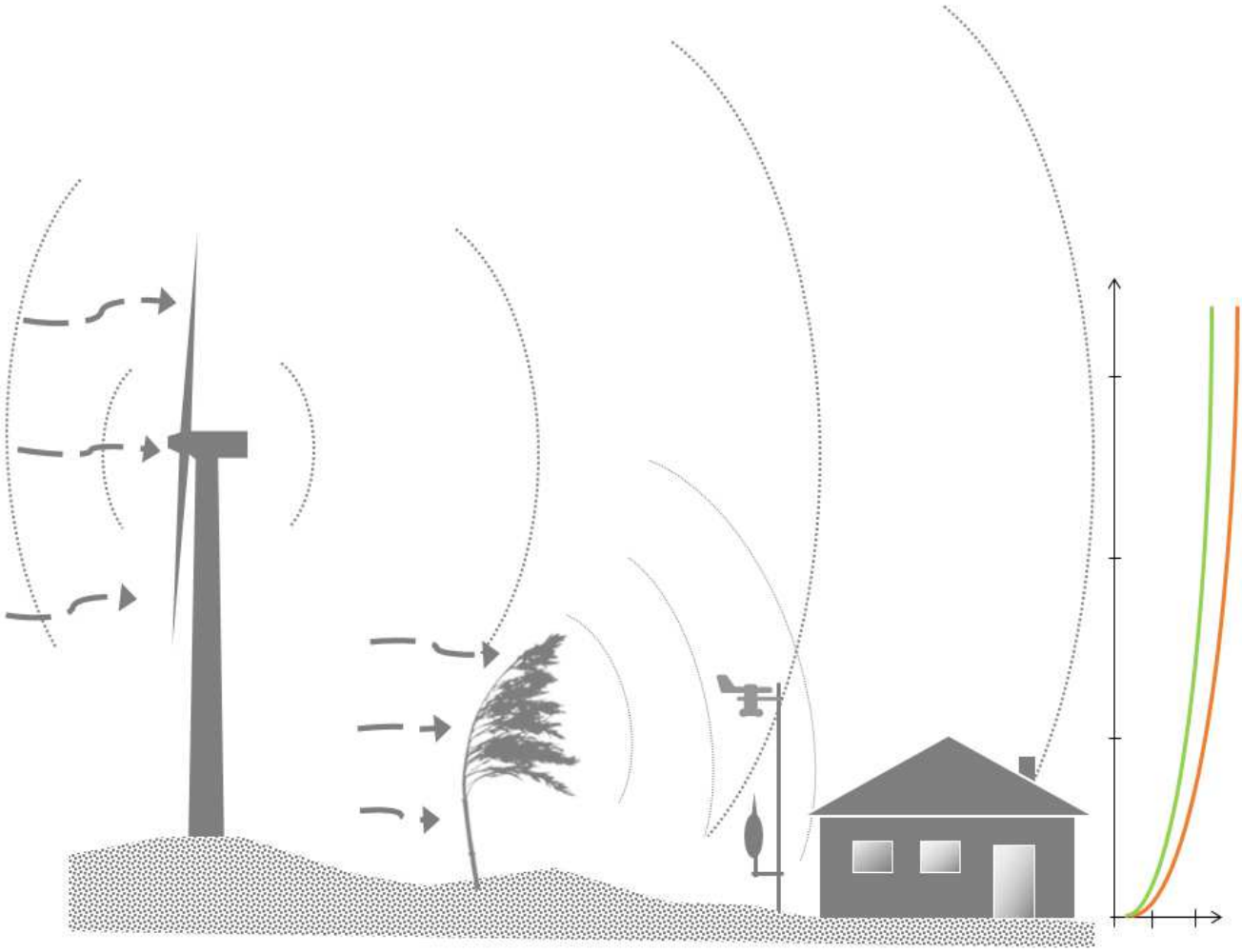
2. How the wind shear factor can influence background noise levels?

2.1 Effect of the wind speed on the background noise

The background noise (when machine are OFF) may be very low in the rural areas when road traffic and anthropic noises are negligible e.g. during night periods. In those situations noise induced by the wind in the vegetation (which strongly depends on the wind speed near the ground) has an important contribution on the background noise.

On the other hand, the ambient noise (when machines are ON) depends on the wind speed at hub height. It's easy to understand how the wind shear factor (α) can influence the background noise measurements: for a given wind speed at hub height, a low α will induce high wind speed near the ground (and therefore "high" background noise), and a high α will induce low wind speed near the ground (and therefore "low" background noise).

The figure below illustrates those effects.



V_{hub}	V_s	Shear factor α	$V_{10m\ meas.}$	Noise level
10 m/s	7 m/s	0.16	7 m/s	40 dB(A)
10 m/s	7 m/s	0.32	5 m/s	30 dB(A)

Figure 1: Illustration of the effect of the wind shear factor on background noise levels

2.2 Measurements results

Two measurement campaigns (1 month duration each) were performed before the installation of the machines, with 6 noise sensors and a meteorological mast with 4 sensors (h=100m, 70m, 50m and 20m). Measurements took place during 2 separate periods.

Results are presented below using the classical scatter plot as required in the French standard ($L_{50,10mn}$ / Standard wind speed Vs):

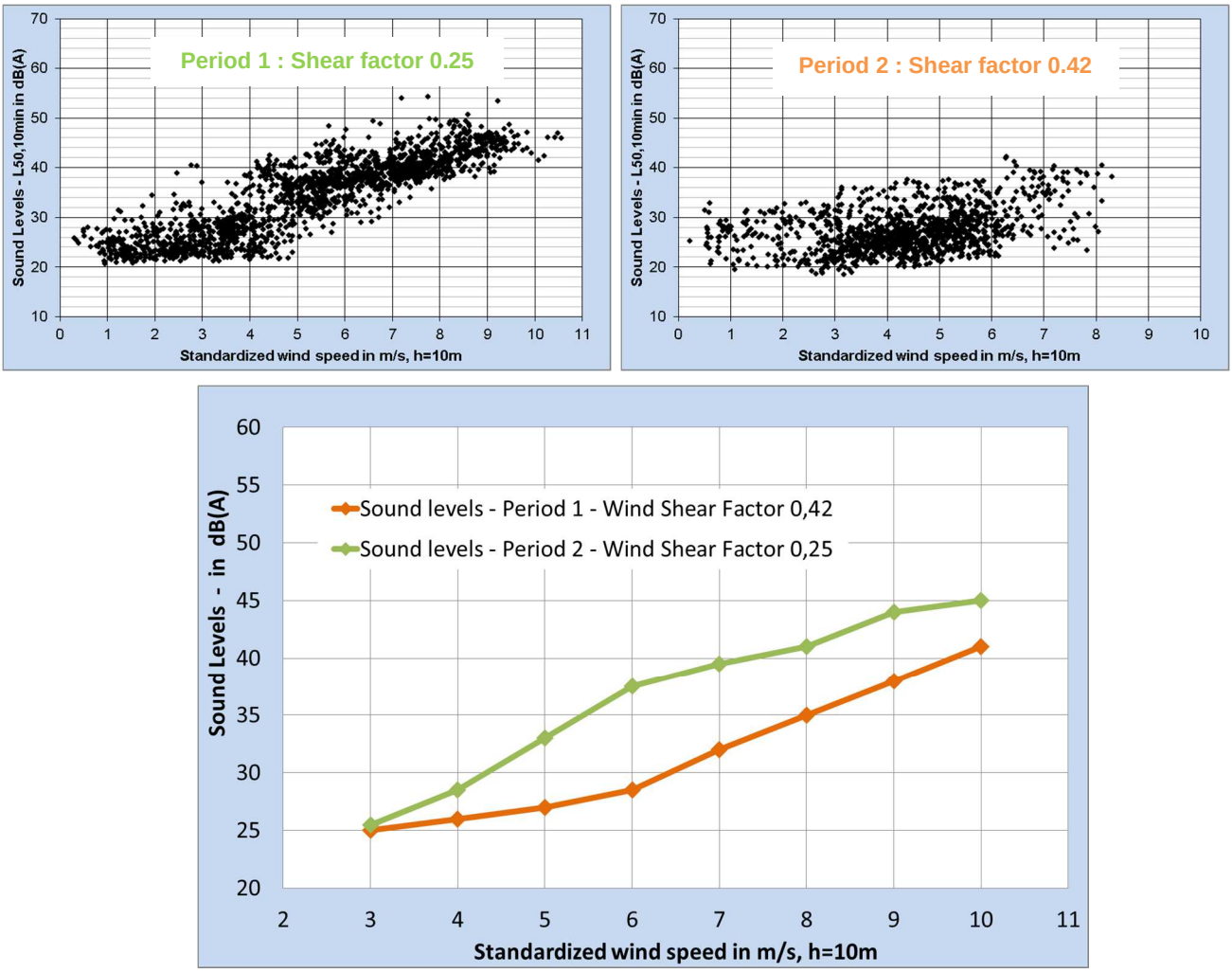


Figure 2: Background noise level measured during 2 periods with different shear factors (shear factor corresponds to the average for each measurement campaign)

Comments:

- The comparison between background noise levels for the same standardized wind speed (i.e.: same wind speed at hub height) shows clearly that the shear factor has a direct impact on the background noise results.
- It should be noted that shear factor depends on the period (day, night…), and may depend on wind direction (in case of non-flat ground and presence of obstacles) and seasons.
- As a conclusion the importance of the assessment of the wind speed gradient (or wind shear factor) can be seen. The measurements are usually done using a tall met mast with sensors at several heights.
- Unfortunately the wind shear factor is usually an unknown parameter, especially in the case of wind turbine noise control (after commissioning), because the met mast on site has been dismantled and the wind speed information retrieved from the wind turbines is seldom reliable.
- In the absence of a tall met mast, the use of a 10-m mast is recommended for two reasons. Firstly, it is necessary during the background noise measurements when the

wind turbines are stopped and no reliable wind speed information can be gained from the nacelle anemometers. Secondly, during the measurement of the ambient noise, the wind speeds measured at hub height by the nacelle anemometers and the wind speed measured at 10 m height can be used to determine the wind shear for each 10-min time period.

2. Relation between temperature gradient and wind shear

2.1 Concept of stability classes

The temperature gradient can be measured through the difference of temperature between 2 sensors located at different heights from the ground. In some cases, it may be a useful way to classify the stability of the atmosphere:

- Positive temperature gradient: stable atmosphere.
- Negative temperature gradient: unstable atmosphere.

Note: This classification can be understood as a rough simplification of the Pasquill stability classes, which are defined with 6 classes A to F.

Stability Class	Definition	Range of vertical temperature gradient (°C/100m)
A	very unstable	ΔT/ΔZ < -1.9
B	unstable	-1.9 ≤ ΔT/ΔZ < -1.7
C	slightly unstable	-1.7 ≤ ΔT/ΔZ < -1.5
D	neutral	-1.5 ≤ ΔT/ΔZ < -0.5
E	slightly stable	-0.5 ≤ ΔT/ΔZ < 1.5
F	stable	1.5 ≤ ΔT/ΔZ

Surface windspeed	Daytime incoming solar radiation			Nighttime cloud cover	
m/s	Strong	Moderate	Slight	> 50%	< 50 %
< 2	A	A - B	B	E	F
2 – 3	A - B	B	C	E	F
3 – 5	B	B – C	C	D	E
5 – 6	C	C – D	D	D	D
> 6	C	D	D	D	D

Figure 3: Meteorological conditions that define the Pasquill stability classes

The following “homogeneous classes” are then proposed:

- Homogeneous class n°1: Positive temperature gradient: stable atmosphere => possible high wind shear factor.
- Homogeneous class n°2: Negative temperature gradient: unstable atmosphere => possible low wind shear factor.

2.2 Potential temperature difference

The temperature difference between two layers of air is relevant for the energy flux between these layers. This difference is affected by several effects. One of these, the adiabatic transformation between the two layers, is not relevant for our purpose and can be compensated by considering the potential temperature:

$$\theta = T\left(\frac{p_0}{p}\right)^{R/c_p}$$

Where T is the absolute temperature, p_0a reference pressure e.g. 1.000 hPa, R is the gas constant of air, and C_p is the specific heat capacity at a constant pressure.

In order to better understand the significance of this potential temperature difference, let us consider a few practical situations.

During daytime, the solar radiation typically heats the ground. The potential temperature at the ground becomes typically higher than above ground and a heat transfer by convection mixes the boundary layer and leads to an unstable stratification. Under these conditions, the vertical wind shear will be typically small.

After sunset, the ground keeps radiating energy until its potential temperature becomes lower than that of the boundary layer.

During night-time, in the absence of heat transfer by convection from the ground, the stratification of the boundary layer stabilises. If a warm wind is blowing during the night, a warm layer of air will glide on top of a colder layer. The wind turbines may be operating at rated power, whereas the wind speed in the cold layer close to the ground will be very low. Under these conditions, the noise from the wind turbine might become prominent against the low wind-induced background noise.

The cloud cover plays an important role for the variations of the energy flux between the ground and the air layers. During daytime, a cloud cover would reduce the heating of the ground by solar radiation. On the other hand, during a clear night, the temperature of the ground would typically decrease rapidly and a very stable stratification might appear.

2.3 Measurement results

A measurement campaign of 10 days duration was performed after the installation of the machines, through the installation of 5 noise sensors and a meteorological mast with 2 ultrasonic sensors (h=2m and 10m) in addition to the anemometers near the hub of the machines.

Temperature measurements are transposed into potential temperatures in order to be compared together. The measurement results are presented below.

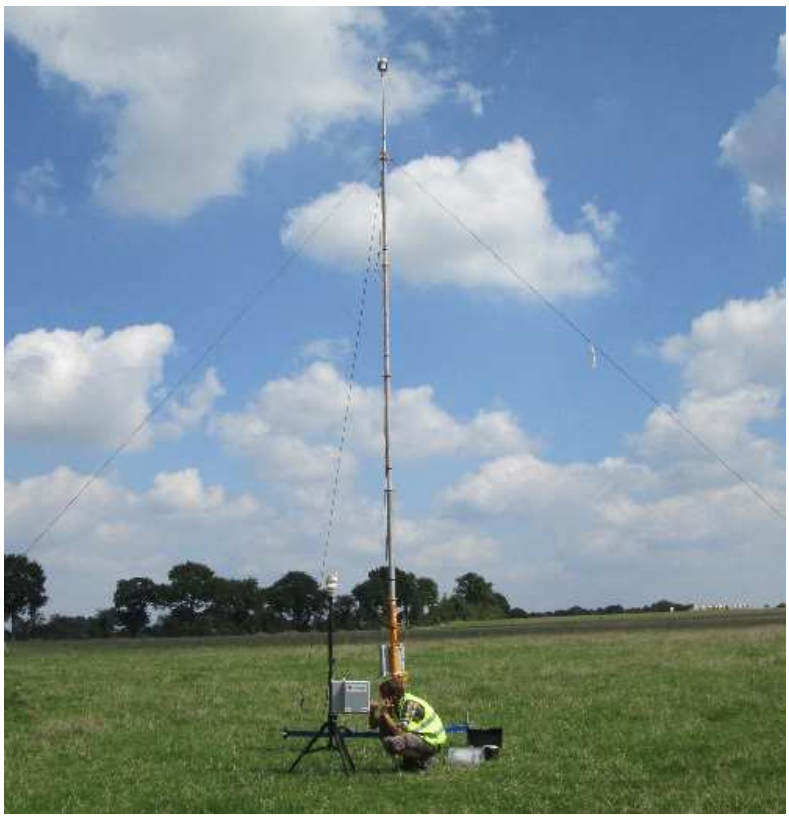
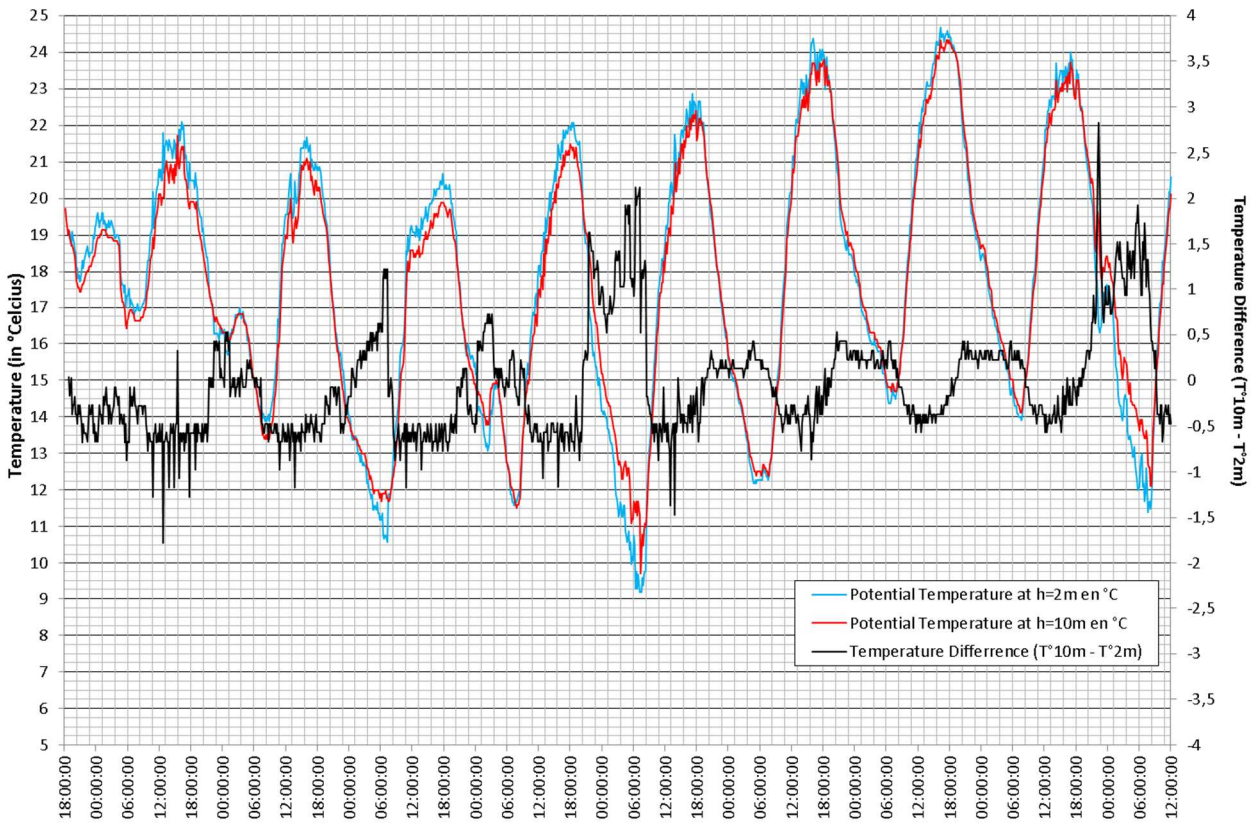


Figure 4: Met mast with ultrasonic sensors at h=2m and h=10m.



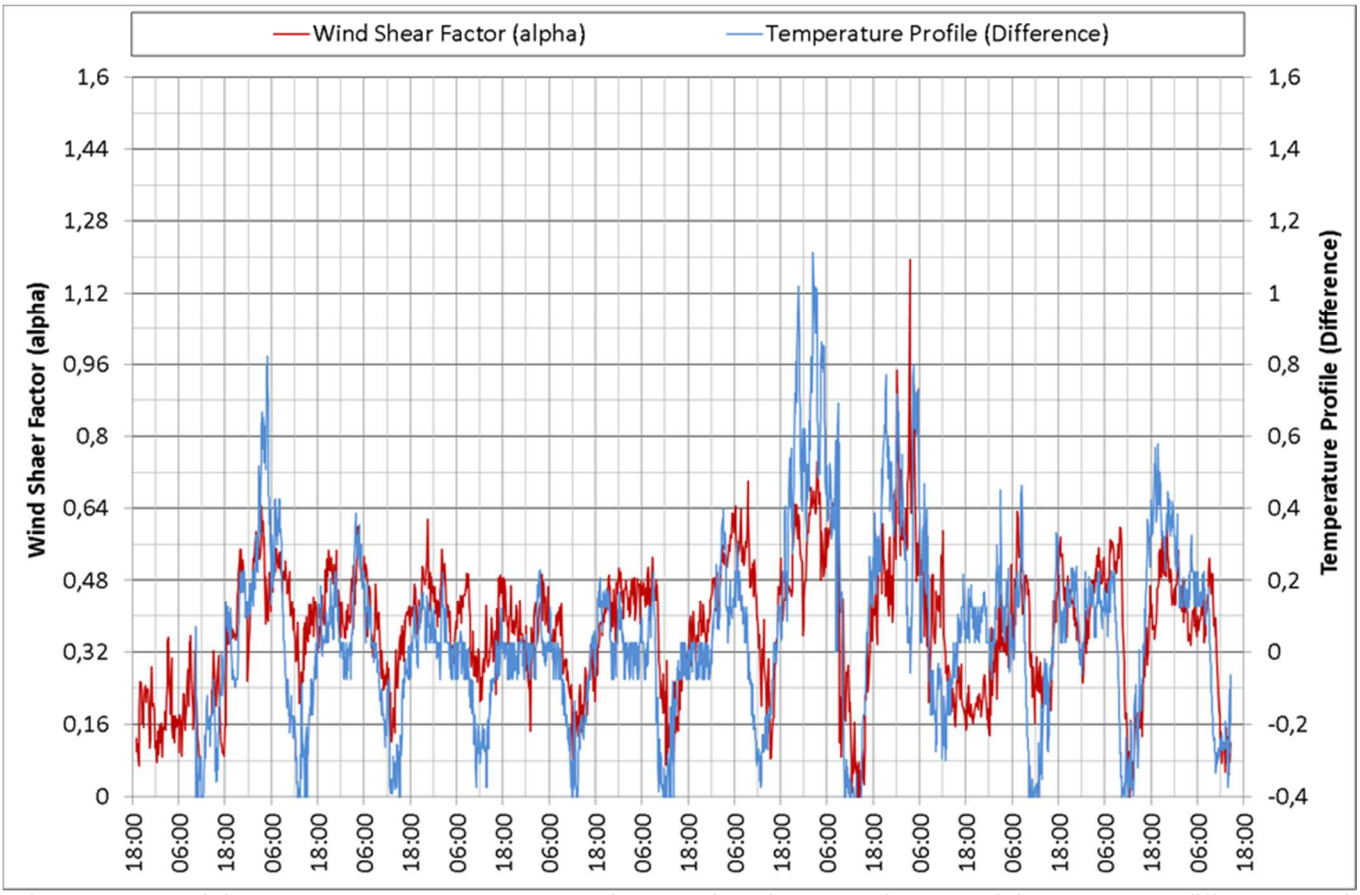


Figure 5: Potential temperature measurements and comparison between the potential temperature difference and the wind shear factor during noise campaign

Comments:

- The first graph shows important parallel variations of the temperatures at 2 and 10 m height between day and night; The potential temperature difference reveals the inversion of the heat flux and is often negative during daytime (10m temperature is lower than 2m temperature) meaning that the ground is getting warmer than the air layers, and positive during the night showing that the ground is getting colder than the air layers.

- The second graph shows the comparison between temperature difference and wind speed gradient: we can see that when the temperature difference is negative, the wind shear factor is low, and vice versa.
- Experience shows that a wind-speed measurement at 10m height is sometimes significantly affected by the operation of the wind turbines in the vicinity of the met mast. On the other hand, the potential temperature difference appears to be more stable and more representative of the micrometeorology at the site.
- The temperatures can be measured at various heights. The 10m height is recommended because it is a standard in meteorology and can be used for correlation with other weather data sets. The 2m height has been chosen here because it corresponds to the height of the sound level meters. Another interesting information would be the temperature at hub height around the wind turbine nacelle but this information is unfortunately seldom available from the SCADA data or is too coarse (+-1°C) for the purpose. The measurement of the ground temperature is also recommended.
- The time evolution of the potential temperature difference is by definition a differential measurement in temperature and in time. It is hence relatively immune to offsets of the individual temperature measurements as well as to drift of the sensors, as long as both sensors have similar characteristics.
- The potential temperature difference appears then to be an easy way to classify the atmospheric stability, and therefore could be used as an additional criterion for the definition of the homogeneous classes which are required by the French standard.
- The acceptance measurements of wind farm projects give the opportunity to gain experience on the parallel evaluation of wind shear and potential temperature difference. The use of the potential temperature difference only could turn out to be also an effective means for the classification of the stability during green-field background noise measurements when no high met mast is available for the evaluation of the wind shear.

3.0 Noise simulations of noise propagation under a vertical temperature gradient

3.1 Concept

Noise simulations are performed in order to better understand the influence of the temperature gradient on noise propagation of a wind turbine.

A Parabolic Equation (PE) method is used, with one wind turbine which is modelled as a point source at h=100m and the receiver is placed at h=2m at a distance of 800m, 1000m and 1200m from the wind turbine. In this theoretical approach, the ground is assumed flat and reflecting.

The noise refraction effect in the atmosphere is due to the sound celerity profile which is assumed depending only on the vertical height z (m):

$$c(z) = \sqrt{\gamma RT(z)} + a_{log}.\ln\left(1 + \frac{z}{z_0}\right) cos\theta$$

Where $\frac{Cp}{Cv} \approx 1.4$ is the heat capacity ratio, $\mathrm{R} = 286.69\ \mathrm{J}.kg^{-1}.K^{-1}$ is the gas constant, a_{log} defines the vertical wind speed profile for a roughness $z_0(m)$, and θ is the angle between wind direction and source-receiver direction.

The graph below shows the vertical celerity profile $c(z)$:

- With a wind speed profile defined by $a_{log} = 0.8$, $z_0 = 0.05m$, an upwind situation ($\theta = 180°$) but without any temperature gradient (blue curve).
- With the same wind speed profile and a temperature gradient of +0,01°C/m (orange curve).

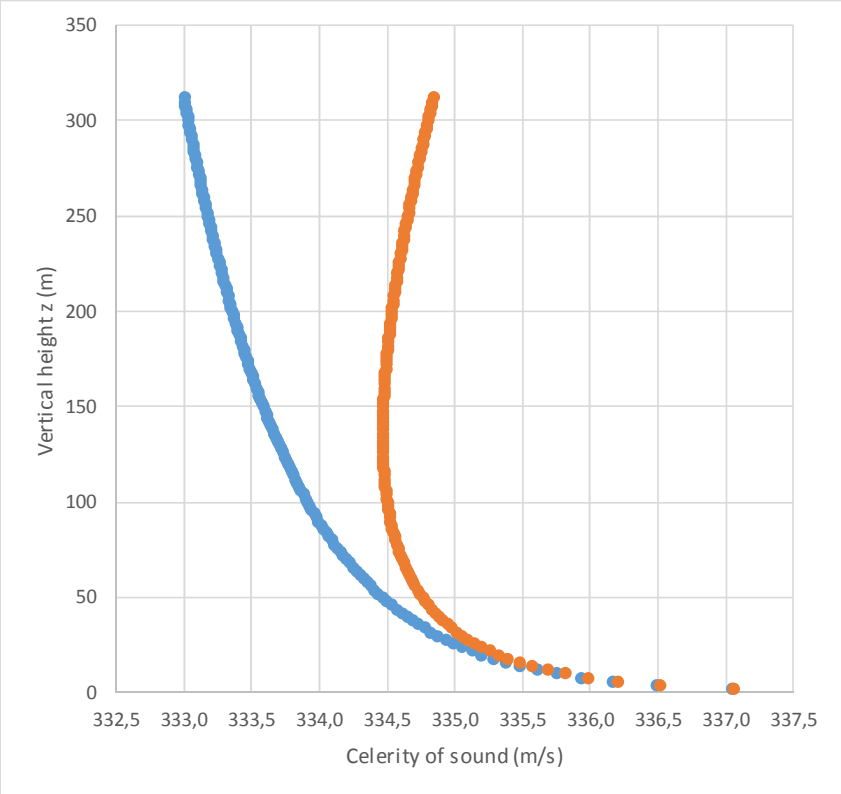


Figure 6: Vertical sound celerity profile c(z) in upwind conditions (a_{log}=0.8; θ=180°, z_0=0.05m) without temperature gradient (blue) and with positive temperature gradient (orange)

This example shows that in upwind condition, a positive temperature gradient can change the celerity gradient (which becomes positive for z > 130m approximatively). As the celerity profile is closely related to noise propagation, it can be expected that the temperature gradient could have an effect on long-range noise propagation of high height wind turbines. This is the scope of this parametric study.

3.2 Simulation results of the parametric study

The results are presented for receivers located at 800m, 1000m and 1200m from a 100m height the wind turbine. The only varying parameter is the vertical temperature gradient, which is varying from -0,015°C/m to +0,015°C/m.

The results are presented for upwind configuration only (in downwind conditions the results don't show any significant impact).

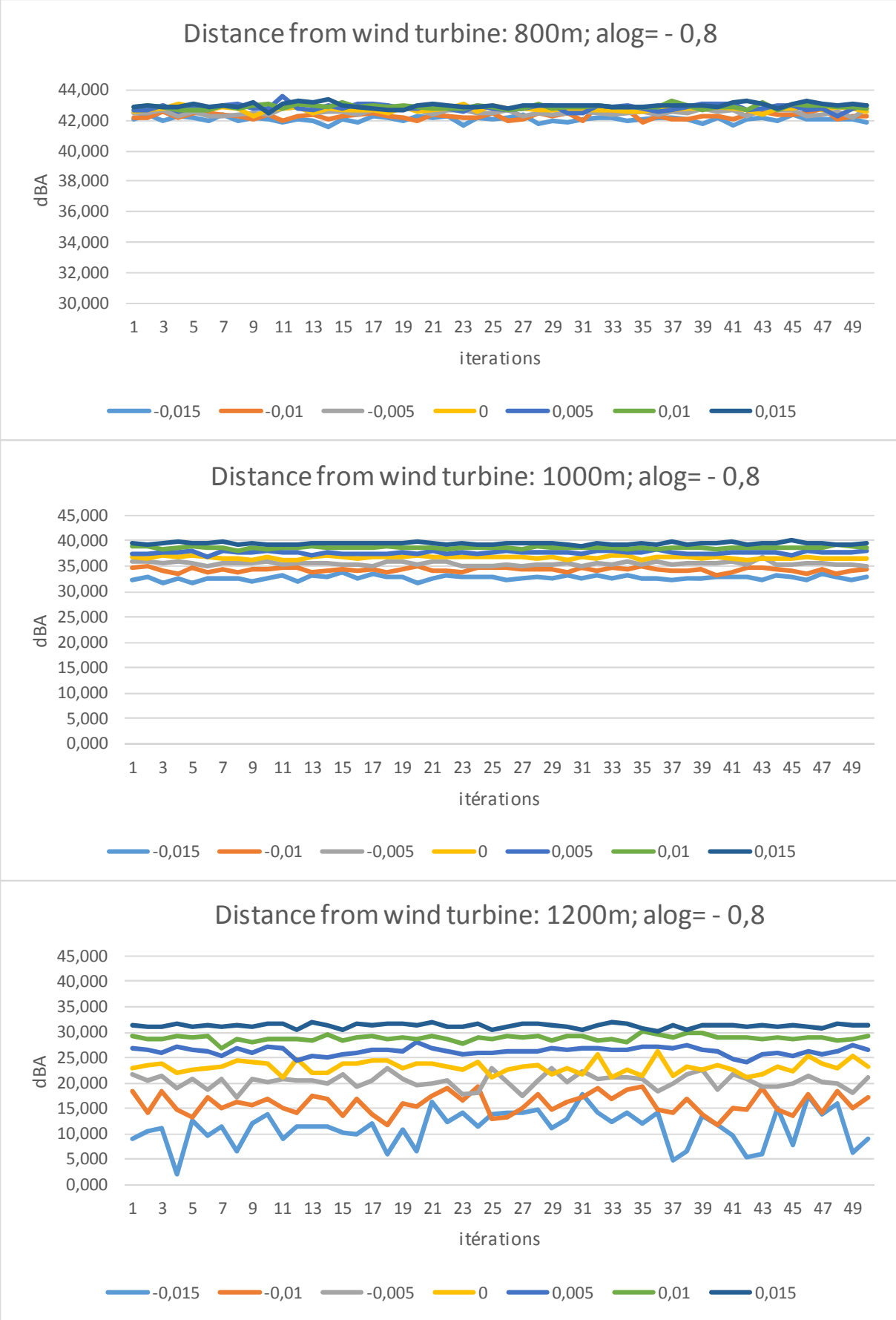


Figure 7: Noise simulation with PE at different distances from a 100m height wind turbine; f=250 Hz; upwind condition with a_{log}=0.8 and θ=180°; 50 iterations of calculation with a variance of refractive index of the turbulence $<\mu^2>=2.10^{-6}$; vertical temperature gradient is varying from -0.015°C/m to +0.015°C/m

Comments:

- In upwind conditions, the influence of the temperature gradient is negligible at a distance of 800m from the wind turbine, because the receiver is not located in the shadow zone.
- For distances of 1000m and 1200m the influence of the temperature gradient is more significant, because the receiver is now located near the shadow zone limit (which is approximatively 1000m). A positive temperature gradient moves the shadow zone to distances greater than 1000m (as shown on the following figure), and the noise level at the receiver is increased, with a maximum of 7 dB at 1000m and 20 dB at 1200m.

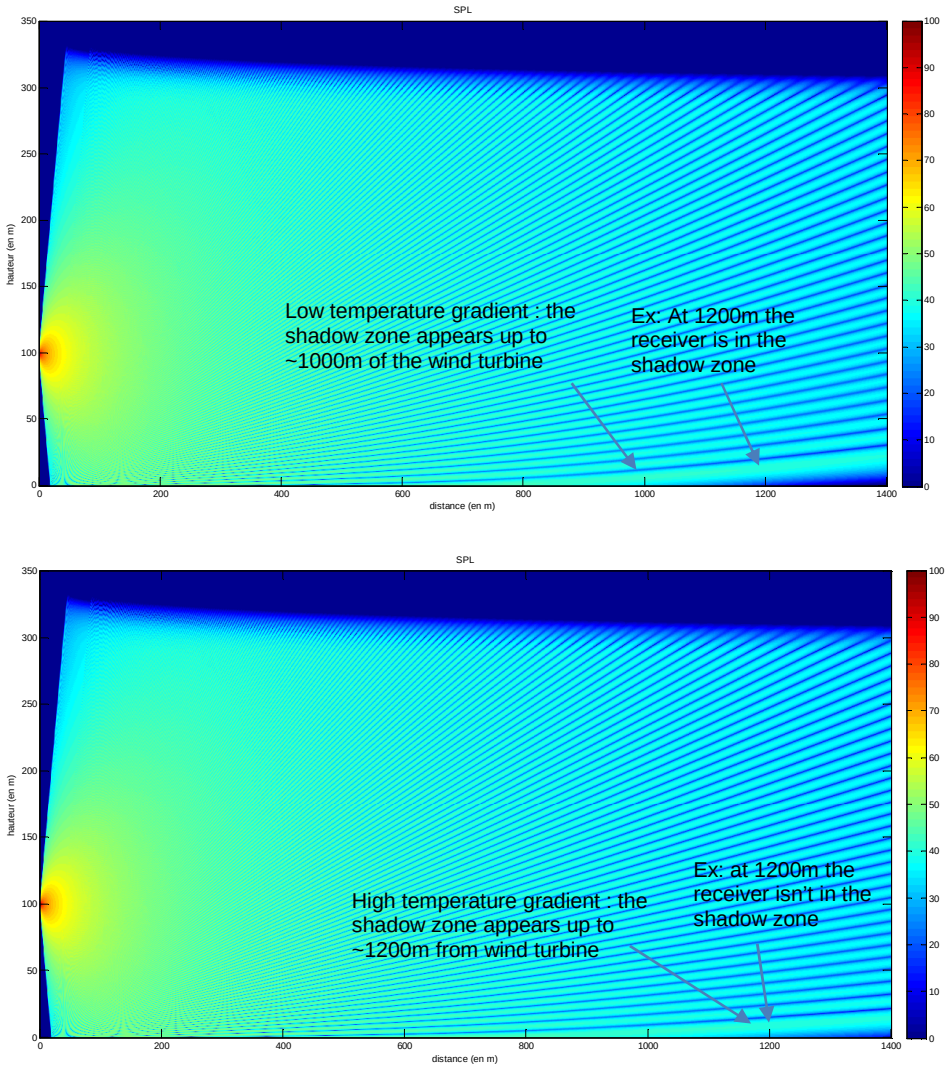


Figure 8: Vertical noise map for a_{log}=-0.8; f=250 Hz; vertical temperature gradients of -0,01°C/m and +0,01°C/m

However, the impact of the temperature gradient can often be neglected, because:

- This effect takes place only in upwind conditions.
- The temperature does not have any influence when the receiver is close enough to the wind turbine (distances lower than 1 km approximatively for a 100m height turbine).
- This effect hasn't been identified yet through noise measurements, maybe because of the large number of meteorological and acoustical datasets. Therefore we would recommend further analysis through long-range noise measurements (more than 1km distance from wind turbine) in parallel with detailed micrometeorological measurements (ex: with a 3-D sonic anemometer). More accurate noise simulations could be also performed (e.g. the point source is a coarse simplification for the large rotor diameter).

4.0 Conclusions

The vertical temperature gradients are relevant for the background noise levels as well as for the propagation of the acoustic noise from a wind turbine. They should be taken into account during noise measurement of wind farms. When the wind-speed gradient cannot be measured directly, the potential temperature difference can be measured instead. This method has been used with success over a large set of measurement campaigns, in order to define “homogeneous classes” of meteorological conditions with their corresponding noise levels.

A parametric study of the propagation of wind-turbine noise was also performed through computer simulations on a theoretical test case. It showed that the temperature gradient can influence noise propagation, but only in some specific cases: upwind conditions, and at long distance (between 1km to 1,2km in our test case). Further investigation would be necessary to check this effect, for example through long-range noise measurements, in parallel with detailed micrometeorological measurements.

Acknowledgements

Back in 2009-2010, one of the authors was in search for an efficient forecast and documentation method for the particularly critical situations in France where the risk of excessive emergence levels is high because of particularly high wind shears. His colleague Andreas Beeken suggested tracking the potential temperature difference as an indicator for the atmospheric stability.

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