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Can we really predict wind turbine noise with only one point source?

David Ecotière, CEREMA/ERA 32, 11 rue Jean Mentelin BP9, 67035 Strasbourg Cedex 2, France

E-mail: david.ecotiere@cerema.fr

Summary

Several studies have shown that the sound from wind turbines can be divided into mechanical noise and aerodynamical noise. Mechanical noise is generated by different component in the hub, whereas the aerodynamical noise is generated by air movements on the blades and is the dominant noise source of modern large wind turbines. Although those primary noise sources are distributed at several locations (*e.g.* rotor location for mechanical sources and air blades for aerodynamical sources), current engineering methods for the prediction of wind turbine noise usually consider a wind turbine as an equivalent point source located at the hub location. The experimental practices and some theoretical studies show that this assumption is satisfactory for predicting global value of sound levels for distance larger than double blade length. Nevertheless, we show that this assumption is no longer valid if we consider the spectral content of the noise. The effect of the ground effect associated to the rotation of the main sources located on the blade can induce amplitude modulation of sound levels of several dB in some audible spectral bands. This phenomenon is not confined only in the vicinity of the wind turbine but can also be significant at distances of several hundred meters.

1. Introduction

The sound coming from wind turbines can be divided into mechanical noise and aerodynamical noise (Bowdler *et al.* 2012). Mechanical noise is generated by several components in the hub, whereas the aerodynamical noise is generated by air movements on the blades and is the dominant noise source of modern large wind turbines (Oerlemans *et al.* 2007). Although those primary noise sources are distributed at several locations (*e.g.* rotor location for mechanical sources and air blades for aerodynamical sources), many engineering studies for the prediction of wind turbine noise usually consider a wind turbine as an equivalent point source located at the hub. Using an analytical calculation, Makarewitz (Makarewitz 2011) has shown that this assumption is satisfactory for predicting global value of sound levels for distance larger than double blade length. Nevertheless, this calculation only treated global values of sound pressure level, without considering spectral aspects, and the influence of ground reflections was not taken into account.

Ground effect is well known for modifying the spectral content of the sound at a receiver because of the interferences created by the combination of direct and reflected rays (Attenborough *et al.* 2007). This effect is very sensitive to source and receiver positions: the distance, the height of receiver and of source are key values for predicting the location of ground dip interferences due to the ground effect. The main noise sources of a wind turbine are mainly located at the blade tip (Oerlemans *et al.* 2007) and the height of sources is constantly changing within a significant range. This induces a constant change of the interference pattern created by the ground effect, which can also induce amplitude modulation in some spectral band, only due to ground effect. We call here this phenomenon 'amplitude modulation by ground effect' (AM-GE). The aim of this paper is to investigate if this continually shift of

interferences by ground effect is significant enough to be perceived, and if the assumption of a unique point source is still sufficient for predicting the noise from a wind turbine, taking into account AM-GE.

2. Numerical setup

The aim of the simulations is to predict the time fluctuations of sound level spectrum at a receiver at 2m height, for several distances from the wind turbines and several meteorological downward conditions.

2.1 Source model

We consider the sound emitted by a unique wind turbine which the nominal electric power is 2 MW. The hub of the turbine is located at a height of 80m, and the rotor consists of 3 blades of length 45m. Only aerodynamical sources located on the blade are taken into account. As a first approximation these sources are modelled by three omnidirectional point sources located at the three blade tip. The sound power spectrum of each source consists of a broadband noise with a spectral characteristic of -4dB/octave (Møller *et al.* 2011, Botha 2013, Tachibana *et al.* 2014). The sound power level of each source is set at 100 dB(A), so that the combination of the three sources gives a sound power level of 105 dBA for the whole wind turbine, which is in agreement to data given by (Møller *et al.* 2011) for this kind of wind turbine. All sources are rotating together at 20 rpm.

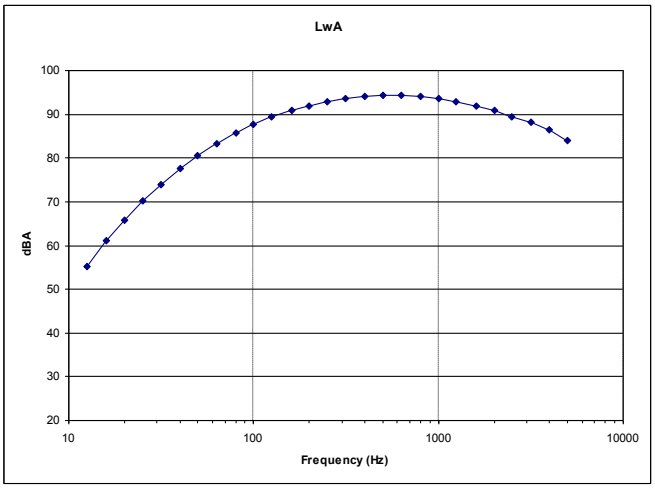

Figure 1: Sound power level of one aero dynamical source

2.2 Propagation model

The noise at the receiver is due to the broadband noise emitted by the three rotating point sources after propagating in a refracting atmosphere and above a flat ground.

The sound propagation is modelled with the sound rays model described by Salomons (Salomons 2001). This model can take into account ground reflections effects and also the effect of a refracting atmosphere due to downward meteorological conditions. This model has been chosen because of a satisfactory compromise between relevant results for ground and meteorological effects, and fast calculations for the propagation of a broadband noise in a downward refracting atmosphere. This geometrical acoustics model consists of i) calculating the path's characteristics of all sound rays between one source and the receiver (length, travel time, ...) ; ii) calculating the receiver sound pressure contribution of one source by summating the contributions of all sound rays between one source and the receiver, taking into account the phase difference between each ray ; iii) calculating the total sound pressure level at the receiver by summating the sound pressure contribution of all the sources.

The complex acoustic pressure due to one source can be written at the receiver as (Salomons 2001):

$$p = \sum_{m=1}^{N_{rays}} A_m e^{i\varphi_m} \ , \qquad (1)$$

where N_{rays} is the total number of rays between source and receiver. The phase φ_m of ray *m* is given by $\varphi_m = \omega t_m = \omega \int c^{-1}(z) ds$, where s is the curvilinear position along the ray, ω is the pulsation, and $c(z)$ is the sound speed that depend on the elevation above the ground. The amplitude A_m of ray *m* is given by

$$A_m = f_m \, A_{atm} \, Q_m^{\;N_m} \frac{S}{R_1}, \tag{2}$$

where S is the source amplitude, and R_1 is the length of the direct ray between the source and the receiver. Q_m is the spherical reflection coefficient of the ground for the ray *m* (see below) and N_m is the number of reflections of the ray *m*. f_m is a focusing factor that accounts for the fact that in a refracting atmosphere with curved sound rays, some concentrations of sound rays can occur (Salomons 2001). A_{atm} accounts for the atmospheric attenuation and is calculated using data from ISO 9613-1:1993 for 20°C and a relative humidity of 60%. The meteorological effect is taken into account through the gradient of a linear vertical profile of the sound speed. Linear profile is not the most realistic one, but it is sufficient here as a first approximation for introducing realistic situation due to meteorological effect downwind the wind turbine.

2.3 Ground

The spherical reflection coefficient of eq. (2) is given by

$$Q_m = R_p + (1 - R_p)\, F(w). \tag{3}$$

R_p is the plane wave reflection coefficient

$$R_p = \frac{Z_c \sin(\theta) - 1}{Z_c \sin(\theta) + 1}, \tag{4}$$

with

$$F(w) = 1 + j\sqrt{\pi}\, w\, e^{-w^2}\, erfc(jw), \tag{5}$$

and

$$w^2 = \frac{1}{2} jkr_i \, (\sin(\alpha) + \frac{1}{Z})^2. \tag{6}$$

θ is the incidence angle of the reflected ray on the ground. *erfc* is he complementary error function and can be computed using (Poppe and Wijers 1990). Z_c is the characteristic impedance of the ground. The model of Miki (Miki 1990) is adopted here:

$$Z_c = 1 + 5.5\left(\frac{f}{\sigma}\right)^{-0.632} + j \cdot 8.43\left(\frac{f}{\sigma}\right)^{-0.632}, \tag{7}$$

with the specific flow resistivity $\sigma = 300$ kNsm^{-4} for grass. f is the acoustic frequency.

2.4 Methodology of numerical calculations

We simulate the sound emitted by the wind turbine by calculating the total sound emitted from the 3 sources at the receiver at instants separated by 12,5 ms and during a period that corresponds to a 1/3 rotation of the rotor. The influence of distances from 100m to 800-1000m is investigated. The influence of meteorological downward conditions is also investigating by changing the sound speed gradient from 0 to 0.5s-1.

3. Results

3.1 Sound levels

Mean sound pressure levels are presented on Figure 2 for 3 distances from the wind turbine and several meteorological downward conditions. The influence of the ground can be seen in the modification of the spectra. As expected, the influence of the meteorological effect is

negligible close to the wind turbine (100m), but it is influencing the spectrum shape in different ways at larger distances.

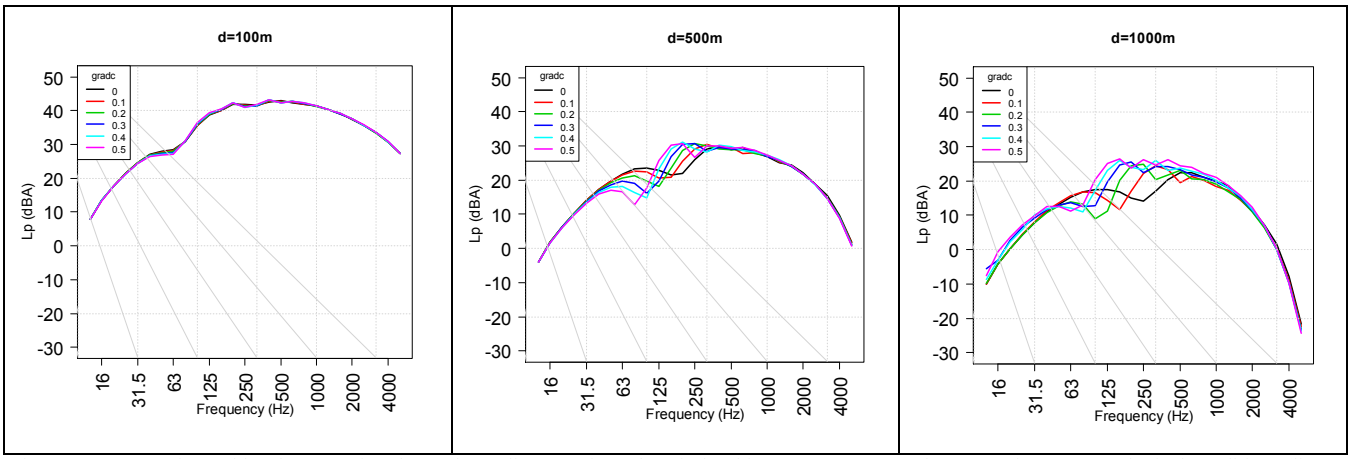

Figure 2: Spectra of sound level at a receiver located at 3 distances from the wind turbine (100m, 500m and 1000m), for 5 meteorological conditions (linear sound peed gradient from 0 to 0.5 s^{-1}). The receiver is at 2m high.

Figure 3 shows that the amplitude modulation caused by ground effects (AM-GE) is smaller than 0.2dBA for global sound levels, even at short distances. The AM-GE is decreasing with the distance and is negligible at neighbours usual distances. We can conclude here that AM-GE is negligible when considering global sound level, and that a unique equivalent point source can be used for modelling the sound propagation when only a global value of sound level is required.

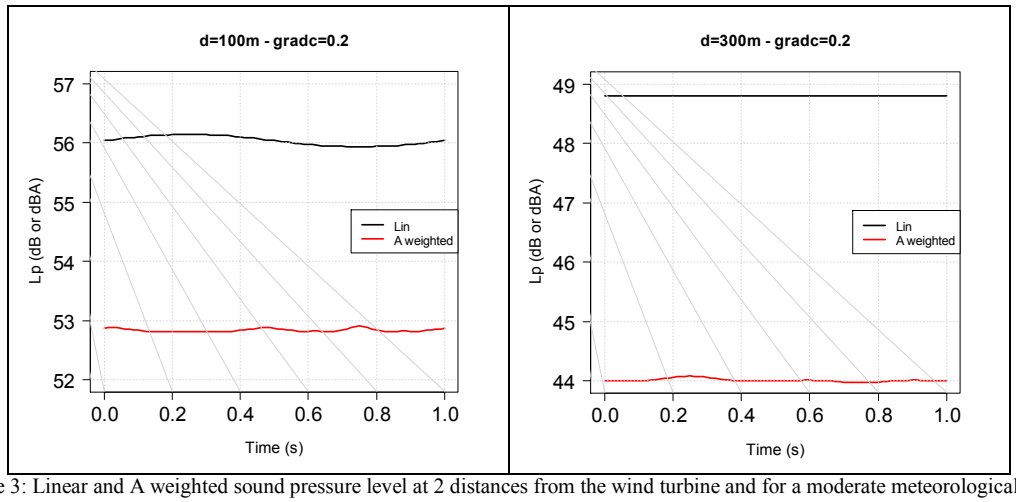

Figure 3: Linear and A weighted sound pressure level at 2 distances from the wind turbine and for a moderate meteorological effect.

3.2 Spectral amplitude modulation by ground effect

The evolution of the sound level spectrum is presented in Figure 4 for 3 distances and for a moderate meteorological downward condition. Non negligible changes in the shape of the spectrum can be noticed in the audible range [250 Hz-1000 Hz], up to a distance of 500m. Those changes are due to the modification of the continuous change of sources height.

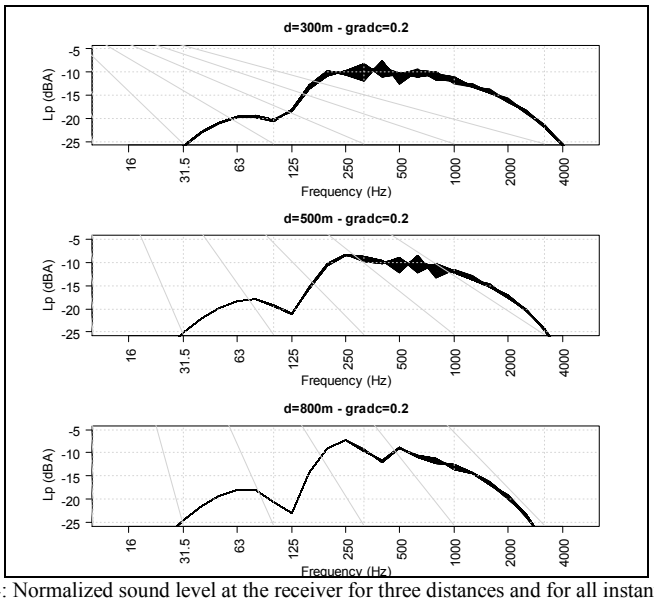

Figure 4: Normalized sound level at the receiver for three distances and for all instants from 0s to 1s.

The spectrograms obtained in the same conditions are presented in Figure 5. for a complete rotor rotation They show that maximum and minimum sound levels can shift from one 1/3 octave band to another along with time. This phenomenon is weak at large distance, but it is not negligible up to 500m.

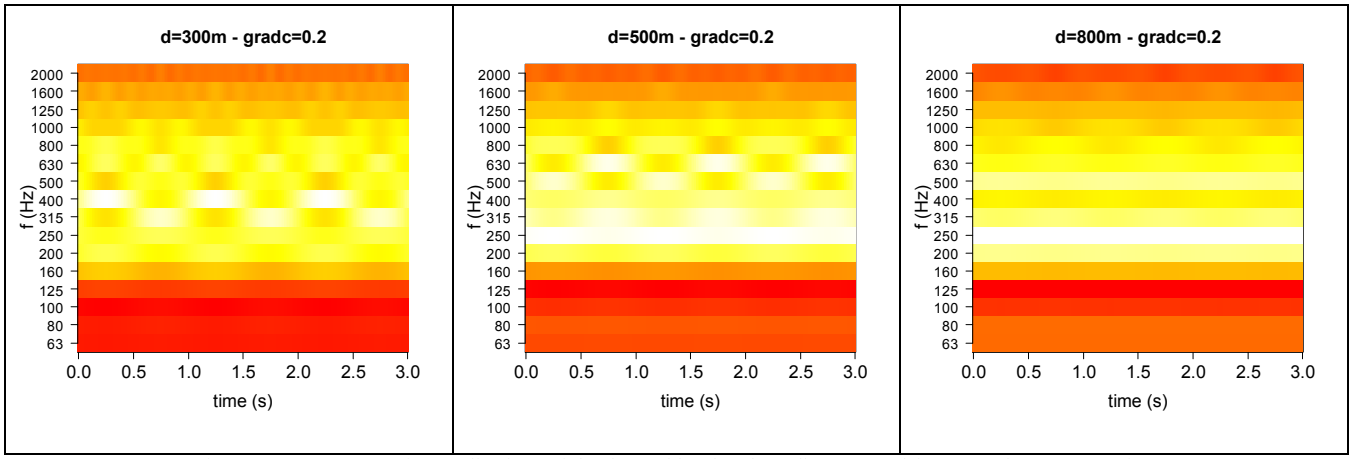

Figure 5: Spectrogram of normalized A weighted sound level at three distances and for a complete rotor rotation.

The sound energy in 1/3 octave bands can vary with time, and fluctuations of several dBA can be noticed for mid-frequencies bands (Figure 6). These periodic shift of energy from one 1/3 octave band to an adjacent band may be perceived by wind turbine neighbours and the induced spectral modulation could contribute to noise annoyance.

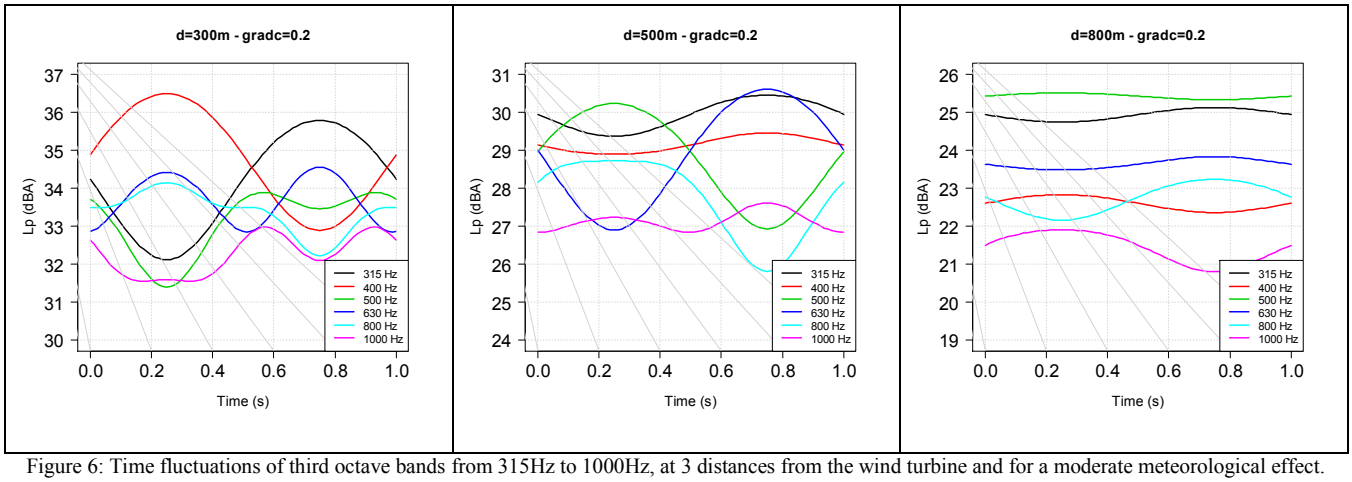

Figure 6: Time fluctuations of third octave bands from 315Hz to 1000Hz, at 3 distances from the wind turbine and for a moderate meteorological effect.

3.3 Influence of the distance and of the meteorological effect on the AM-GE

In order to quantify the significance of the AM-GE, the depth of the amplitude modulation Δ_{AM-GE} is estimated for each 1/3 octave band using the difference between the maximum and the minimum of the sound level during 1/3 period of the rotation of the rotor. Figure 7 shows the AM depth for 4 distances and 4 downward meteorological conditions. 1/3 octave bands sound levels lower than 20dBA have been skipped in order to keep only sound levels that could emerge from a background noise.

The AM-GE depth is negligible for frequencies below 100Hz, except in the vicinity of the wind turbine (d=100m). The AM-GE can be significant in the frequency range [200Hz-1kHz] with spectral sound level fluctuation from 2dBA to 6dBA. For each meteorological condition, frequencies with maximum AM-GE depth are shifting to increasing frequencies with increasing distances. Moreover, the AM-GE depth is decreasing with increasing distances: no more AM-GE is significant at large distances (from 800m). Similarly, the AM-GE depth tends to decrease with increasing meteorological downward conditions.

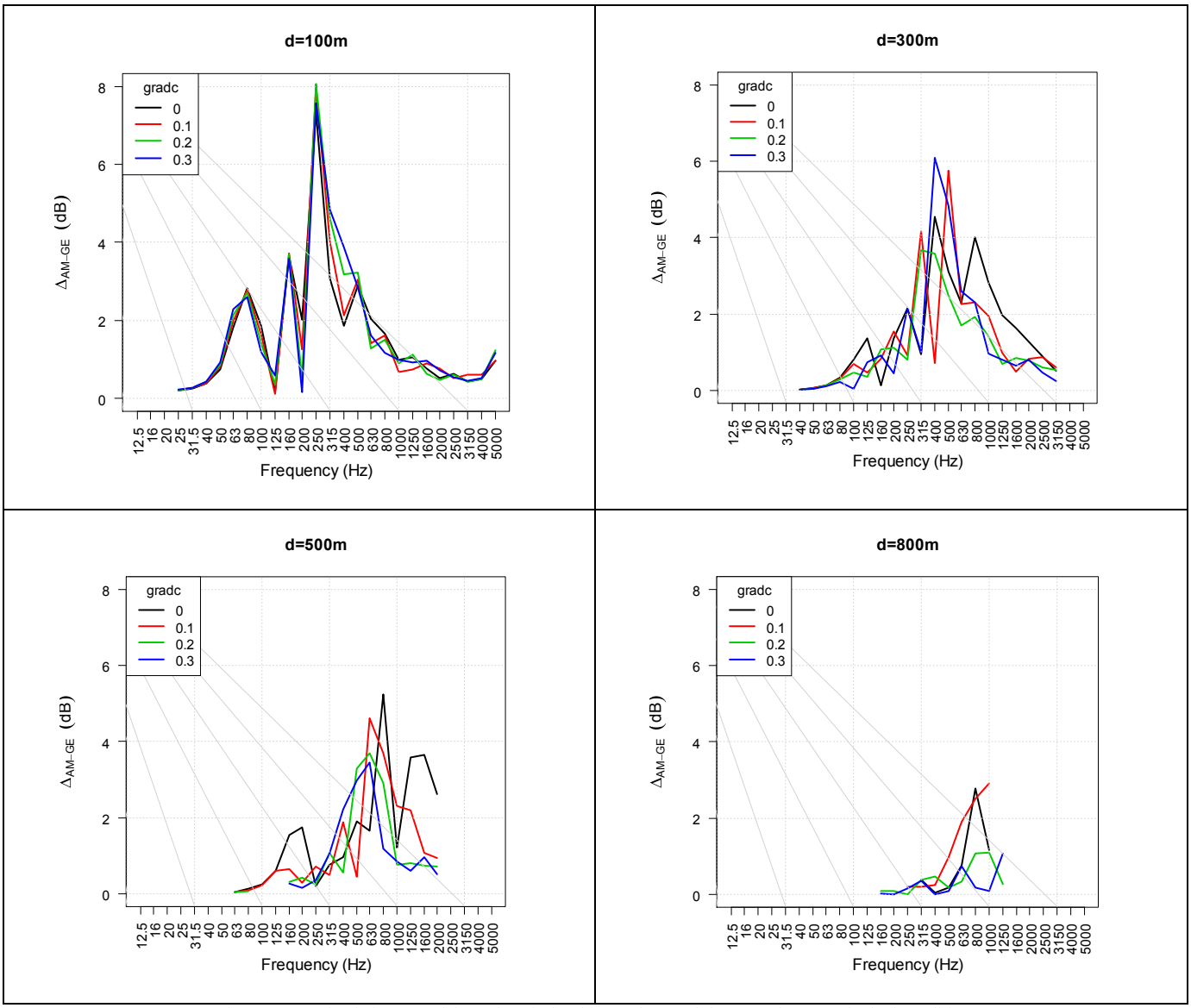

Figure 7: AM depth for several from the wind turbine and several downward meteorological conditions.

4. Conclusions

The constant movement of the aerodynamical noise sources of a wind turbine induces constant change of the interference pattern of sound levels at a receiver, only by ground effects. This has no influence on the global sound level and a single equivalent point source for wind turbine is enough for predicting global sound level at neighbourhood. It is not the case when considering the spectral content of the noise: 1/3 octave sound level fluctuations from 2dBA to

6dBA can be observed in the frequency range [200Hz-1kHz], up to 500m from the wind turbine. This effect decreases with the distance and becomes negligible from 800m (10 times the hub height). Meteorological effect tends to lower the AM-GE. As the permanent cyclic shift of interferences concerns audible frequencies, it could be a source of specific annoyance. It is not possible to predict this effect when considering a single equivalent point source at the hub. 3 point sources located at the end of each blade may be recommended if one want to predict AM-GE for distances lower than 800m (here 10 times the hub height). An alternative and more simple solution to characterize this effect may be to make two calculations, each one with a single point source located at the minimum and maximum height of the blade tip. Beyond 800m, the hypothesis of a unique equivalent point source located at the hub is still satisfactory as no amplitude modulation by ground effect remains.
Further work with more realistic meteorological effects (lin-log vertical sound speed profile for example), and a more accurate propagation model (PE (Lihoreau *et al.* 2006) or TLM (Guillaume *et al.* 2014) for example) will be considered in the future in order to extend and confirm those results for different positions of receivers and for different sizes of wind turbine.

References

Bowdler R. and Leventhall G. (ed.), *Wind Turbine Noise*, Multi-Science Pub. Co Ltd, 2012.

Oerlemans S., Sijstma P. and Mendez Lopez B., *Location and quantification of noise source on a wind turbine,* J. Sound Vib. 299, 869–883 (2007).

Makarewicz R., *Is a wind turbine a point source?,* J. Acoust Soc. Am. 129(2), 579-581 (2011).

Attenborough K., Li K.M. and Horoshenkov K., *Predicting outdoor sound*, Taylor & Francis, London, 2007.

Tachibana H., Yano H., Fukushima A., Sueoka S., *Nationwide field measurements of wind turbine noise in Japan*, Noise Control Engr. J. 62(2), 90-101 (2014)

Botha P., *Ground Vibration, Infrasound and Low Frequency Noise Measurements from a Modern Wind Turbine*, Acta Acust united Ac 99, 537 – 544 (2013)

Møller H., Pedersen C.S., Low-frequency noise from large wind turbines, J. Acoust. Soc. Am. 129(6) (2011)

Salomons E., *Computational Atmospheric acoustics*, Kluwer Academic Publisher., 2001.

ISO 9613-1:1993 *Acoustics - Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere*, ISO, Geneva (1993).

Poppe G.P.M. and Wijers C.M.J., More efficient computation of the complex error function, ACM Trans. on Math. Software, 16(1), 38-46 (1990)

Miki Y., *Acoustical properties of porous materials - Modifications of Delany-Bazley models*, J. Acoust. Soc. Jpn(E). 11(1), 19-24 (1990)

Lihoreau B., Gauvreau B., Berengier M., Blanc-Benon Ph., and Calmet I., *Outdoor sound propagation modeling in realistic environments: Application of coupled parabolic and atmospheric models*, J. Acoust. Soc. Am. 120, 110–119 (2006).

Guillaume G., Aumond P., Gauvreau B., Dutilleux G., *Application of the transmission line matrix method for outdoor sound propagation modelling – Part 1: Model presentation and evaluation*, Applied Acoustics 76, 113–118 (2014).