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Propagation phenomena associated with noise due to the operation of large-sized wind turbines

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Abstract

Noise pollution due to the operation of large-sized wind turbines is a current important issue in Uruguay: there is about 1000 MW of installed capacity of wind energy generation in the country. This work was developed in the Department of Environmental Engineering IMFIA of the Faculty of Engineering of the Universidad de la República (UdelaR), Uruguay, in the framework of a project funded by the National Agency for Research and Innovation (ANII-FSE 10942). The phenomena of generation of aerodynamic noise in these energy generation devices have been presented in detail in another paper of our team. Here, phenomena related to the propagation of aerodynamic noise of large-sized wind turbines are theoretically analysed. A propagation model in free atmosphere, considering the phenomena of geometrical divergence and atmospheric absorption is proposed. The prediction of sound pressure levels is performed by third octave bands. The values of atmospheric absorption coefficients are obtained according to ISO 9613-1 standard for all frequencies of interest. The adjustment is focused on the exponent of the depletion law, which is not square neither linear nor homogeneous in the different third-octave bands considered. The model has been validated with empirical data for distances greater than 300 m from the source. A good fit for different atmospheric stability conditions was achieved.

Keywords: wind turbines; environmental acoustics; environmental impact assessment

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1 Introduction

Uruguay is a small country located in South America. Currently, it has the highest rate of wind power generation per capita in the world. The rapid development of wind farms in the country encourages the study of the acoustic impact they can generate. The recommended predictive methodology is established in ISO 9613-2 [1], but as it is well known, it can lead to underestimates of more than 10 dB depending on the atmospheric stability conditions [2]. Several prediction methodologies have been developed, but none of them have technical consensus yet.

In this paper, the study of acoustic impact of large-sized wind turbines is centered on propagation phenomena of aerodynamic noise. A propagation model for free atmospheric propagation is proposed. It works by normalized frequency bands and it takes into account the phenomena of geometrical divergence and atmospheric absorption [3, 4].

While calculating atmospheric absorption is based on the methodology proposed by ISO Standard 9613-1 [5] in the frequency range of interest, the decay law for geometric divergence proposal is not quadratic or linear, nor homogeneous in the different frequency bands [3, 4].

This methodology has shown a proper adjustment to field data taken in different measurement campaigns close to different wind farms. The methodology consists of three instances: estimating the of the acoustic power emitted by the machine, estimating sound pressure levels at short distance from it and propagation of these levels at long distances from the source.

The model has been validated with empirical data taken at distances from 300 m to 1600 m from the source, achieving a good fit for different atmospheric stability conditions.

2 Aerodynamic noise generation

Aerodynamic noise generation at wind turbines can be classified into three types, according to the main process that causes the fluctuation in the pressure field:

I. The turbulence of the incoming wind, that causes the temporal variation of the pressure field around the blades.

II. The viscous forces in the boundary layer over the solid surfaces of the turbine, such as blades, tower and hub. Viscous forces in this layer are not negligible compared to the inertial forces (related to the medium air flow). The release of the boundary layer at the trailing edge causes a permanent releasing of eddies with negative gauge pressure at their cores.

III. Due to the power exchange between the wind and the rotor, two families of eddies linked to each blade are generated: one of them has helical motion and the other one is centred on the rotation axis and its length scale is about the length of the diameter of the rotor.

Also, the processes related to these fluctuations in the pressure field that causes wind noise in wind turbines, can be considered as a turbulence issue. The generation of eddies is, then, the result of the abovementioned noise generating processes. Each of these vortexes is related to a certain energy level and a length scale; it can propagate along great distances. These eddies are usually classified according to their scale as follows:

I. Macroscale: it is the scale related to the largest vortices. If U, L and T are the scales of speed, length and time associated, the Reynolds number of the vortexes is the same as for the main flow.

II. Intermediate scale: it includes lower scales than the macroscale ones; there is still no power dissipation. The range of scales included here is called "inertial range".

III. Microscale: is the smallest scale, in which the energy dissipation occurs. Unlike what happens in the macroscale, these vortices have an isotropic character, indicating that the flow has "forgotten" where it comes from.

The turbulent cascade hypothesis is to be considered. According to it, the larger vortices are melting in smaller scale vortices with increased kinetic energy. Thus, there is a spatial scale of vortexes that cannot continue to transfer power to another smaller scale of them. At this point, the cascade ends and the energy from the last vortex is finally dissipated. This smallest vortexes scale is known as the Kolmogorov scale. The so-called Kolmogorov frequency or dissipation frequency is the passing frequency or generation frequency of the smallest scale of eddies, which scale is the Kolmogorov scale.

The spectrum S(k) is defined as the density of kinetic energy of the turbulent eddies of radius 1/k. In the inertial range, it is assumed that the value of S(k) only depends on k and on the transmission power ε from the mean flow.

By the application of Buckingham theorem the following relationship is obtained:

$$S = f(k, \varepsilon) \rightarrow F\left(\frac{S}{k^{-5/3}\varepsilon^{2/3}}\right) = 0$$

In the inertial range, then:

$$S = Ck^{-5/3}\varepsilon^{2/3}$$

At the Kolmogorov scale, the diameter η depends on the viscosity ν and ε. By the application of Buckingham theorem the following expression is obtained:

$$F\left(\frac{\eta}{\nu^{3/4}\varepsilon^{1/4}}\right) = 0 \rightarrow \eta = C\frac{\nu^{3/4}}{\varepsilon^{1/4}}$$

where the value of the constant C is about 1.

3 Atmospheric conditions

3.1 Strong atmospheric instability

When there are instability atmospheric conditions, it could be assumed that the cascade process should be complete, so that energy dissipation will occur for the smallest spatial scale vortices. The distance at which the dissipation phenomenon occurs shall be noted as L.

For distances greater than L It shall be assumed that the flow conditions are the same as they are upstream the machine. The ratio between the current air speed up and downstream of the machine tends to 1 for greater distances; the difference between these speeds is practically negligible at a distance of about 6 or 7 diameters, i.e., about 540 m.

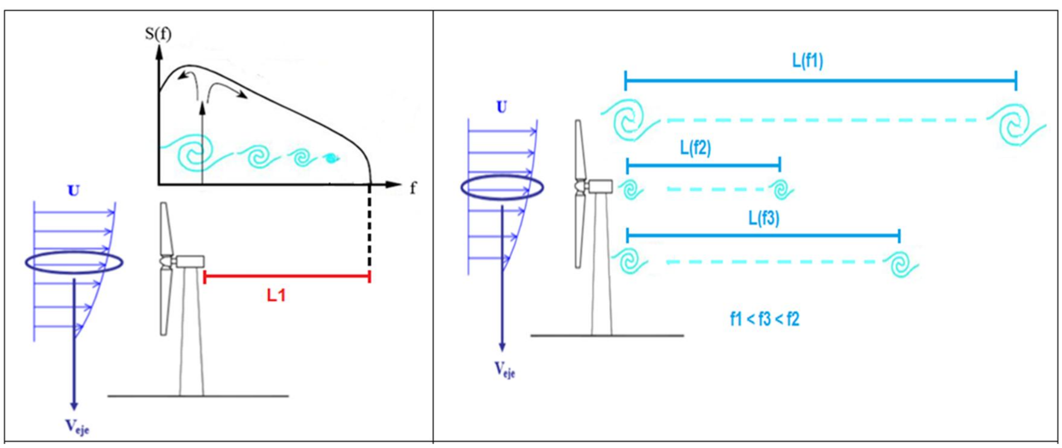
As the main hypothesis is strong atmospheric instability, the value of L is the shortest one to fully carry out the whole energy cascade process. For any other atmospheric conditions, a greater distance should be spent.

3.2 Strong atmospheric stability

The strong atmospheric stability condition corresponds to class F according to Pasquill-Gilfford stability classes. In this case, the effect of turbulence should be negligible. The only mechanism with incidence on energy depletion in any frequency band –in addition to the geometric divergence or attenuation by distance- is the atmospheric absorption.

The threshold of perception at each frequency band should be the criterion for determining the distance upon which the sound is still audible. Hearing threshold levels were retrieved from [7].

Figure 1 show the two extreme cases of atmospheric stability.



Source: Cataldo, 2016 [8]

Figure 1: Atmospheric conditions for propagation (at left, strong instability; at right, extreme stability)

4 The wave approach

The phenomena of generation and propagation of eddies can also be described from a wave approach. The, close to the source the sound pressure levels should be estimated considering energy depletion by geometric divergence (Div) and by atmospheric absorption [δLt (f)].

Then, the level of noise immission related to one blade is related to the level emitted by the same by the following equation:

$$L_P = L_W - Div - \delta Lt(f)$$

4.1 Atmospheric absorption

The effect of atmospheric absorption can be considered as the attenuation suffered by the acoustic wave over a certain distance due to energy loss caused by the viscosity of the propagation medium, which in this case is air. The uncondensed water vapour and the oxygen gas have absorption lines in different frequency bands.

To estimate the effect of atmospheric absorption, the computation method of ISO Standard 9613-1 was used. This Standard states that when a pure tone propagates in the atmosphere through a distance s, the amplitude of the sound pressure wave p_ (t) should exponentially decrease as a result of the atmospheric absorption. For plane sound waves in free space, it can be written:

$$p_t = p_i e^{-\frac{\alpha s}{10 \log e^2}}$$

The attenuation due to atmospheric absorption $\delta L_t(f)$ in dB in the sound pressure level of a pure tone with frequency f from its initial level at s = 0 to its level at a distance s, can be obtained as:

$$\delta L_t(f) = 10\, log \left(\frac{p_i}{p_t}\right)^2 = \alpha s$$

As it is stated in ISO Standard 9613-1, the attenuation due to atmospheric absorption is a function of the relaxation frequencies f_{rO} and f_{rN} from oxygen and nitrogen respectively. Their values should be calculated according to the following expressions:

$$f_{ro} = \frac{P_a}{P_r}\left(24 + 4.04 \times 10^4 h \frac{0.02 + h}{0.391 + h}\right)$$

$$f_{rN} = \frac{P_a}{P_r}\left(\frac{T}{T_o}\right)^{-\frac{1}{2}}\left(9 + 280he^{-4.170\left[\left(\frac{T}{T_o}\right)^{\frac{-1}{3}}-1\right]}\right)$$

Then, the attenuation coefficient α should be calculated by properly combining those equations.

The resulting expression for computing the value of α is:

$$\alpha = 8.686 f^2 \left(1.84 \times 10^{-11} \left(\frac{P_a}{P_r}\right)^{-1} \left(\frac{T}{T_o}\right)^{\frac{1}{2}} + \left(\frac{T}{T_0}\right)^{\frac{5}{2}} \times 0.01275 e^{\frac{-2239.1}{T}} \left[f_{ro} + \left(\frac{f^2}{f_{ro}}\right)\right]^{-1} + 0.1068 e^{\frac{-3352.0}{T}} \left[f_{rN} + \left(\frac{f^2}{f_{rN}}\right)\right]^{-1} \right)$$

For example, the computed values for T = 20 ºC and relative humidity 100 % are listed in Table 1.

Table 1: Computed values of α (T = 20 ºC, HR = 100 %)

f(Hz)	α	f(Hz)	α
10	2.45×10^{-6}	**500**	1.56×10^{-3}
12.5	3.89×10^{-6}	**630**	1.76×10^{-3}
16	6.16×10^{-6}	**800**	1.98×10^{-3}
20	9.76×10^{-6}	**1000**	2.22×10^{-3}
25	1.54×10^{-5}	**1250**	2.55×10^{-3}
31.5	2.44×10^{-5}	**1600**	3.03×10^{-3}
40	3.85×10^{-5}	**2000**	3.76×10^{-3}
50	6.04×10^{-5}	**2500**	4.91×10^{-3}
63	9.41×10^{-5}	**3150**	6.71×10^{-3}
80	1.45×10^{-4}	**4000**	9.56×10^{-3}
100	2.21×10^{-4}	**5000**	1.41×10^{-2}
125	3.29×10^{-4}	**6300**	2.13×10^{-2}
160	4.75×10^{-4}	**8000**	3.26×10^{-2}
200	6.61×10^{-4}	**10000**	5.06×10^{-2}
250	8.79×10^{-4}	**12500**	7.91×10^{-2}
315	1.11×10^{-3}	**16000**	1.24×10^{-1}
400	1.34×10^{-3}	**20000**	1.95×10^{-1}

Note that the absorption coefficients at low frequencies (less than 100 Hz) are several orders of magnitude smaller than those for higher frequencies.

4.2 Geometric divergence

One of the main objectives of this paper is to find an expression for the geometric divergence, i.e., for the depletion of sound pressure levels due to distance. The adjustment is focused on the exponent of the depletion law, which is not square neither linear nor homogeneous in the different third-octave bands considered all along the computation.

The general expression can be written as follows:

$$Div = 10\log\left(\frac{d}{d_0}\right)^N$$

To begin the estimation process, it will be supposed that the sound pressure levels at a distance of 100 m downstream the wind turbine, are known. Also, it will be assumed that the following general expression can be used:

$$L_{pd} = L_{p,100m} - Div - \delta Lt(f)$$

Then:

$$L_{pr} = L_{p,100m} - 10\log\left(\frac{d}{100}\right)^N - \alpha(d-100)$$

5 The calculation process

5.1 Emitted acoustic power spectra

To obtain the emitted acoustic power spectra at a distance of 100 m downstream the machine, a normalized spectrum for wind turbines from 200 kW to 200 MW was used ([3]).

The way to use this chart is very easy: for each frequency band of interest, the level to be added arithmetically to the sound power level of the machine -expressed in dBA- is read on the vertical axis; then, the power level spectrum is obtained -also in dBA-. Table 2 presents the values to add to the sound power level when working by octave bands [3].

Table 2: Normalized sound power spectrum for a 2 MW wind turbine (values to be arithmetically added to the sound power level in dBA to obtain the sound power level by octave band, also in dBA)

f(Hz)	16	31,5	63	125	250	500	1000	2000	4000	8000
	-44	-26	-21	-14	-7	-6	-6	-9	-12	-22

The sound power level L_{wA} of the wind turbine should be obtained from the manufacturer datasheet as a function of the wind speed at the hub height or at 10 m over the ground [9].

5.2 Sound pressure level at a 100 m distance from the wind turbine

The A-weighted environmental sound pressure levels due to a wind turbine depend on several factors.

To avoid introducing weaker hypotheses about the sound pressure spectrum, it will be supposed that it has the same shape as the sound power spectrum of the machine. In other words, it is assumed that 100 meters away from a wind turbine effects of atmospheric absorption and other possible phenomena that may cause differences in the depletion laws of different frequencies sounds, are negligible.

Then, the sound pressure level at 100 meters downstream from a wind turbine should be obtained using the following expression (from field data processing):

$$L_{pA,100m} = 0{,}8462 L_{wA} - 37{,}715$$

The sound pressure levels spectrum in this point should be obtained arithmetically adding band by band the abovementioned corrections and finally, putting the obtained values in dBZ by adding the corresponding term.

5.3 Values of n(f)

Several sound pressure levels measurement campaigns have been performed from 2012 to 2016. Measurements were made at different wind farms, which have meteorological stations that provide data of wind speed, temperature and relative humidity.

Thus, the propagation process was done, beginning at 100 m from the wind turbine with the calculated sound pressure level $L_{pA,100m}$.

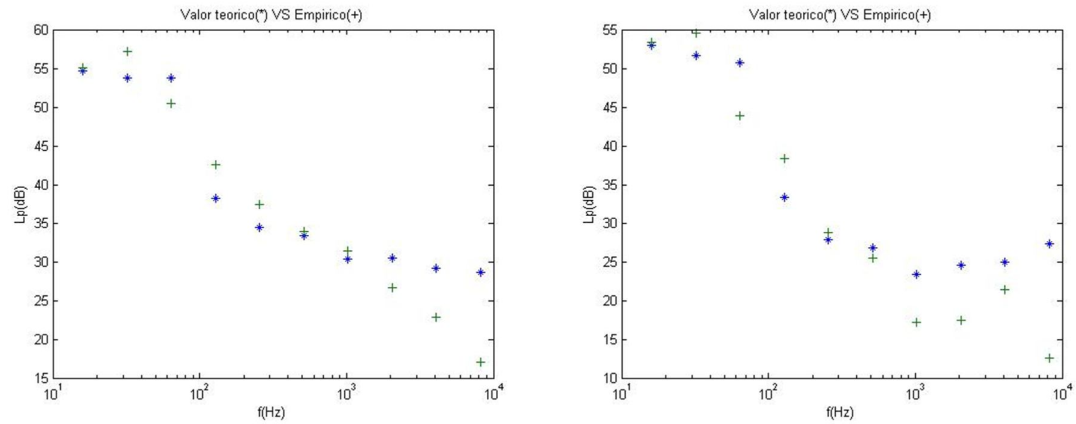
Several sets of sound pressure levels data measured at 500, 1000 and 1500 m allowed to obtain the values that are presented in Table 3. Also the corresponding standard deviation is included.

Table 3: Proposed values for N(f) (general values and better values according to atmospheric stability condition)

f(Hz)	**16**	**31,5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
General	**0.53**	**0.69**	**0.97**	**1.48**	**2.08**	**2.10**	**2.19**	**1.77**	**1.28**	**0.40**
St.Dev.	0.254	0.24	0.25	0.36	0.22	0.3	0.27	0.39	0.52	0.43
Stable	**0.00**	**0.52**	**1.17**	**1.87**	**2.28**	**2.27**	**2.44**	**2.30**	**2.01**	**1.00**
St.Dev.	0.00	0.07	0.14	0.06	0.12	0.06	0.06	0.11	0.25	0.24
Unstable	**0.43**	**1.23**	**0.71**	**1.09**	**1.99**	**2.56**	**2.18**	**1.69**	**1.13**	**0.00**
St.Dev.	0.04	0.04	0.15	0.03	0.08	0.13	0.16	0.06	0.16	0.00

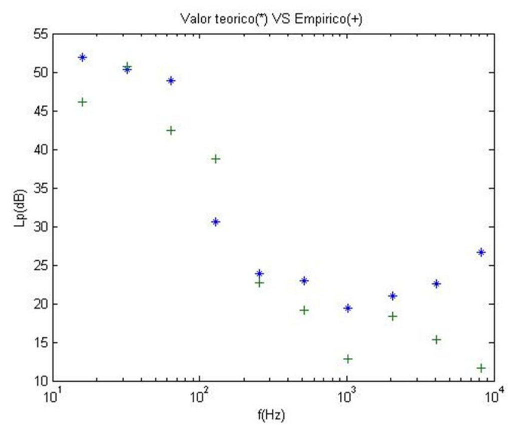
6 Results

The obtained results show a good accuracy between measured and simulated sound pressure levels for different calculation distances. Figures 3 and 4 exemplify several results.



Source: Own production

Figure 3: Measured and simulated sound pressure levels (left: 500 m form the source; right: 1000 m from the source)



Source: Own production

Figure 4: Measured and simulated sound pressure levels at 1500 m form the source

7 Conclusions

According to the results obtained for the coefficient N, such values vary for different frequencies, as stated earlier. This shows clearly that the expression of attenuation due to distance for this type of machine is not corresponding to a point source or a linear one.

This predictive approach exhibit a good fit to measured data; so it can be considered as a valid way to predict environmental sound pressure levels due to large wind turbines.

Acknowledgments

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