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A proposal for the prediction of sound pressure levels due to wind turbine operation

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Summary

The prediction of environmental sound pressure levels related to the operation of wind turbines is still a concerning issue. During the last decade some different proposals have been made to enhance the results from the old prediction methods. We present the prediction model developed at the Environmental Engineering Department of the Faculty of Engineering (Universidad de la República, Uruguay), which has shown a good agreement with measured data at about ten different wind farms along the country. First of all, the atmospheric stability class according to Pasquill-Gifford and the wind velocity are taken into account for determining the acoustic power of the device. Then, a first module for describing noise generation along the blades due to turbulent phenomena (incoming wind turbulence and blades boundary layer release) is applied to compute sound pressure levels at 100 m far from the tower. Some coefficients have been experimentally obtained through wind tunnel tests. At last, a propagation module completes the prediction model to compute sound pressure levels at different distances from the tower. The propagation module considers not only geometric divergence but atmospheric absorption and turbulent dissipation (both phenomena depend on the frequency). The final sound pressure levels at a given reception point are obtained by superposing the sound pressure levels due to different wind turbines operation and the environmental noise due to the wind. Every computing is done in octave bands and the final results are expressed as L_{Aeq} values. The development of the prediction model has been done with measured data from 4 wind farms built on flat terrain. During calibration process some adjustment was needed for better prediction of noise propagation from wind farms built on complex terrain. This easy-to-use method has been programmed in Matlab®. The obtained results show almost 80 % cases within in ±3 dB range.

1. Introduction

One of the main problems that still make it difficult to predict the environmental sound pressure levels due to the operation of large wind turbines is the frequent disconnection between those who model aerodynamic phenomena and those who work in environmental acoustics.

In the development of this model, the Research Group on Noise Pollution of the Faculty of Engineering (UdelaR) has worked very closely to the Research Group on Wind Energy of the same Faculty. This second Group has been working on wind energy for more than 25 years. Actually, the strong growth of wind energy in Uruguay is closely related to their effort: in about only 10 years, the country has reached an installed wind energy power greater than 1500 MW. As Uruguay has about 3.400.000 inhabitants, what means less than 20 inh/km^2, it currently has one of the highest ratio of installed MW per capita in the world.

For developing our calculation procedure, the theoretical analysis of the different phenomena that are involved on noise generation, was complemented with tests at the University wind tunnel and, of course, with sound pressure levels measurements at some wind turbine farms in Uruguay.

This paper aims to present the main features of our prediction procedure and its results.

2. Noise sources

2.1 Mechanical noise

At the beginning of the development of large scale wind energy generation, there were many possibilities of improving the acoustic performance of the machines.

Currently, no significant problems are due to mechanical noises, which have been almost eliminated thanks to design improvement processes.

But aerodynamic noise generation during operation is inherent to wind turbines in nature. Their major acoustic emission is caused by the interaction between the wind and the blades. Most of these emissions occurs in low frequencies.

2.2 Aerodynamic noise

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 (Van den Berg, 2003; Hernández Castellani et al., 2016):

I. The turbulence of the incoming wind, that causes a 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 on 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.

These phenomena are related to three different geometric scales (Van den Berg, 2003; Cataldo, 2016).

I. Macroscale: it is the scale related to the largest vortexes. If U, L and T are the scales of velocity, length and time associated, the Reynolds number of the biggest 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: it is the smallest scale, in which the energy dissipation occurs. Unlike what happens in the macroscale, the smallest eddies are isotropic, as if the flow has "forgotten" where it comes from.

The turbulent cascade hypothesis is then to be considered. According to it, the larger vortexes are dissipating in smaller scale vortexes 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. The 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 (Cataldo, 2016; Hernández Castellani, 2016).

According to their frequency and energy, the released eddies can produce audible phenomena, i.e. they can become noise sources.

3. Noise propagation

Two phenomena are intended to be the most important ones during noise propagation: the atmospheric absorption and the turbulence energy dissipation.

3.1 Atmospheric absorption

To take into account the atmospheric absorption, the calculation method of ISO 9613 Part 1 has been used. For very low frequencies, it has been supposed to be negligible.

3.2 Turbulence dissipation processes

The released eddies are related to a certain energy level and a length scale. They can propagate along great distances while the turbulent cascade occurs (Cataldo, 2016).

We studied the scale of distances from the source at what the cascade is expected to stop, which is closely related to atmospheric stability. Figure 1 shows the two extreme cases of atmospheric stability.

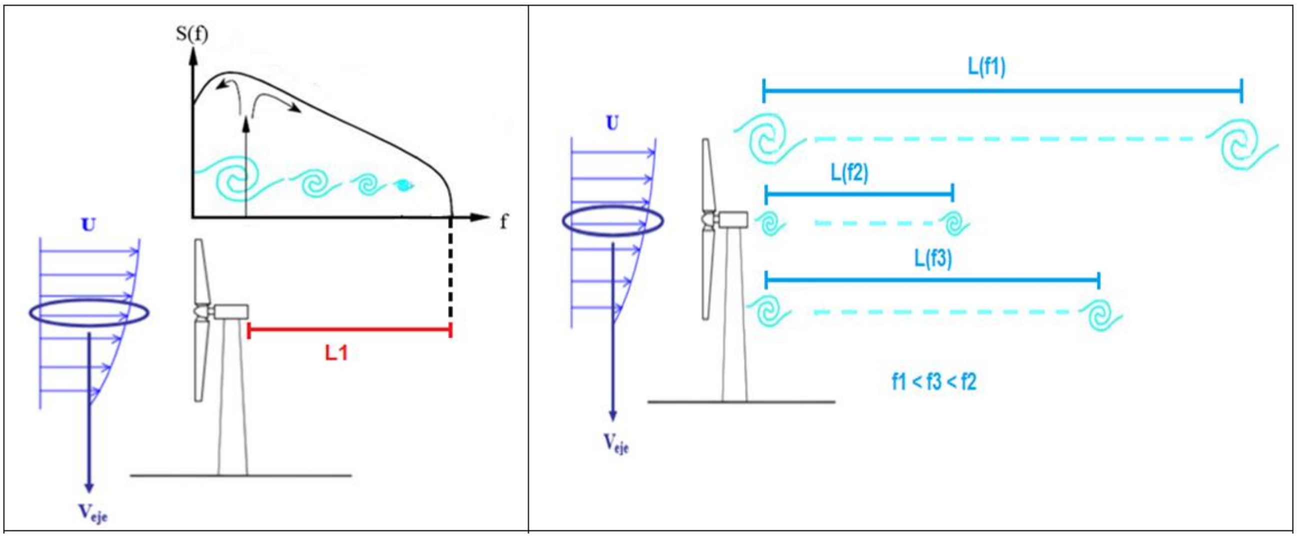

Figure 1: Atmospheric conditions for propagation (at left, strong instability; at right, extreme stability) From: Cataldo, 2016

As we have just integrated the atmospheric stability in the noise generation part of our prediction model (González et al., 2016a and 2016b), we could work here considering that the scale of distances mainly depends on the incoming wind velocity and the frequency of the released eddies.

As it is expected, we met different scales for different conditions. We grouped them into four classes according to wind velocity (lower or greater than 6.5 m/s) and distance to the wind turbine (lower or greater than 750 m). As a consequence, we obtained a set of depletion exponents for each one of these classes. We could also simplified the two sets of values for long distances, as they were equal or similar for most frequencies.

4. Our noise prediction proposal

As most of the research groups around the world did, we began working to understand ISO 9613:2 and CONCAWE Report 4/81 (Manning, 1981) limitations for the case of wind turbine noise (Van den Berg, 2006; González et al., 2011). Then, we begin working to overcome their weak faces.

The proposed model consists of two modules: the first one is related to aerodynamic noise generation; it allows to compute the sound pressure levels at 100 m from the wind turbine. The other module works with sound propagation; its input is the output of the first module and it propagates the levels of sound pressure up to the desired point.

The first module allows to calculate the acoustic power levels (in normalized third octave bands) associated with the aerodynamic phenomena of interaction between the wind and the blades. To do this, it takes the wind speed u in m/s from input data. If u is given at a height other than that of the wind turbine hub, the module itself computes the wind velocity at the hub height assuming that there is an atmospheric thermal inversion; the conversion is made following a potential curve with an exponent of 0.65 (Van den Berg, 2006).

Then, the module assumes that each of the blades is divided into n slices that behave as n point sources and for each of them calculates the sound emission associated with the noise of the incoming turbulence (noise at the attack edge), with the release of the boundary layer at the trailing edge and with the passage of the blade in front of the tower (these computing procedures are described in Deambrosi Papini et al., 2016; González et al, 2016a and 2016b; Hernández Castellani et al., 2016). The emission is propagated up to a distance of 100 m from the tower, supposing each segment of the blade is a point source; the contribution of every part of the blades are added to obtain the sound pressure levels in third octave bands that will serve as input data for the propagation module. For this computing, the values of drag and lift coefficients have been obtained from a set of tests at the wind tunnel of the Universidad de la República (Olazábal et al., 2018); these tests have been useful for improve the prediction results.

The propagation module takes the output of the generation module as an input and it propagates these sound pressure levels considering geometric divergence and atmospheric absorption. The absorption coefficients in third octave bands are obtained according to ISO 9613: 1.

The decay by geometric divergence is performed by using a depletion law in which the exponent n is not constant for all the bands, but n = n(f, d, u). The exponents are related to the distance scale at which eddies are expected to dissipate all their turbulence energy. The values of n(f, d, u) are given in octave bands according to whether the calculation distances are less than or greater than 750 m and that the wind speed at the hub height is less than or greater than 6,5 m/s (see table 1).

For distances greater than 750 m, the expected behaviour of noise is related to the frequency of the eddies but it is rather independent from the wind velocity. This means that the shorter distance scale phenomena are expected to have mostly ended.

For distances shorter than 750 m, the propagation phenomena are still conditioned by the wind velocity. Then the fact of not working within the usual general hypotheses (in particular because the phenomena under consideration are not adiabatic but dissipative (Núñez Pereira, 2013)) supports the position of assuming n as a variable. The eddies exhibit different behaviour for different wind velocities: they dissolve quicker for calmer situations but they can travel further for higher wind speeds. This is reflected by the values of n that our prediction model takes into account.

Table 1. Values of the exponent n = n(f, d, u) according to distance to the source and wind velocity

	16	31,5	63	125	250	500	1000	2000	4000	8000
d less than 750 m, u lower than 6,5 m/s	0,37	0,01	0,05	0,66	1,60	1,67	1,94	1,61	0,85	0,43
d less than 750 m, u higher than 6,5 m/s	0,52	0,02	0,01	0,22	0,93	0,79	1,04	1,07	1,06	0,65
d greater than 750 m	0,45	0,01	0,06	0,72	1,58	1,71	2,03	1,60	0,67	0,34

5. Results

The model was calibrated, validated and verified with measurements made in four wind farms. In the calibration and validation stages, a set of 59 data was used, while the subsequent verification included 49 cases from ten wind farms. The results obtained in the verification of the performance of the model are presented in Tables 2 to 4.

Table 2. Quality of results according to distance to the wind turbine

	Number of cases	Cases in ±3 dB	%
d shorter than 750 m	30	24	**80.0 %**
d greater than 750 m	18	14	**77.8 %**
TOTAL	48	38	**79.2 %**

Table 3. Quality of results according to wind velocity at the hub height

	Number of cases	Cases in ±3 dB	%
u lower than 6.5 m/s	12	10	**83.3 %**
u higher tan 6.5 m/s	36	28	**77.8 %**
TOTAL	48	38	**79.2 %**

Table 4. Quality of results according to distance to the wind turbine and wind velocity at the hub height

	Number of cases	Cases in ±3 dB	%
d shorter than 750 m, u less than 6.5 m	8	7	**87.5 %**
d shorter than 750 m, u greater than 6.5 m	22	17	**77.3 %**
d further than 750 m, u less than 6.5 m	4	3	**75.0 %**
d further than 750 m, u greater than 6.5 m	14	11	**78.6 %**
TOTAL	48	38	**79.2 %**

As important as the percentage of right predictions is to state that not only the levels in scale A are predicted in a reasonably adjusted way, but particularly that the spectra obtained with the proposed model are also rightly adjusted to the measured ones.

6. Conclusions

We have presented a proposal for the prediction of sound pressure levels related to the operation of large wind turbines. Our innovative point of view is to treat the exponent n used to compute the geometric depletion as a variable value depending on the distance to the wind turbine and on the wind velocity. The performance of this proposal is almost good, with about 80 % of the predicted results into an interval of ±3 dB from the measured values. It has an easy implementation and the needed data are easy to be obtained (geometrical and meteorological information).

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