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Prediction of environmental sound pressure levels due to large wind turbines

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Abstract

In the last years, Uruguay has strongly built wind power in its energy mix. Even if it is intended to be a "green energy", wind turbines can generate some adverse impacts on the environment. One of them is the related noise emissions. The aerodynamic wind turbine noise is generated as a result of three processes that make the pressure field to fluctuate:

1) Turbulence of wind, which is due to pressure fluctuations around the blades, is variable over time. It is called "incoming edge noise".

2) Release of vortexes from boundary layers developed on solid surfaces of the wind turbine, such as blades, tower and nacelle due to the viscous forces. It is intended to be a continuous noise that is called "trailing edge noise"

3) The passage of the blades ahead of the tower, which imposes a fluctuation of the levels of noise emitted by the abovementioned phenomena. It results in an amplitude-modulated noise. It is called "blade passage noise".

The incoming edge noise is caused by the fluctuation of pressure along the blade produced by the incoming turbulence. It can be described by combining the turbulence spectrum modelled by the approach of Von Karman and the aerodynamics theory. The trailing edge noise was determined by applying the turbulence spectrum from Von Karman to the boundary layer thickness, thus determining the pressure drop in the main vortexes. For a typical three-blade wind turbine, the noise immission level in any down-wind site can be intended as the result of the contributions of these three phenomena all along each blade. This theoretical model has shown accurately predictions of the sound pressure levels at distances between 300 m and 1000 m away from the machines.

Keywords: Aerodynamic noise, Wind farm noise

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1 Some basic generation concepts

In order to understand the aerodynamic noise production process, we will describe briefly the wind turbines operation.

1.1 A first model: The wind turbine as an energy receiver flow

A first approach to describe the wind turbines operation is to model the runner action by an active disk, which absorbs wind's kinetic energy, resulting in a reduction in the flow speed downstream of the turbine.

If V_1 is the Input velocity, V is the velocity at the blade and V_2 is the output velocity, then the velocity induction coefficient a is defined as: $V = (1-a)V_1$

Supposing that, the air flow is adiabatic and incompressible, and potential energy can be neglected, from the mass and energy balances to the flow through the active disk and the balance of forces the following expressions for output velocity and power (P) are obtained:

$$V_2 = 2V - V_1 = (1-2a)V_1$$

Equation 1

$$P = \frac{1}{4}\rho A(V_1 + V_2)\,(V_1^2 - V_2^2)$$

Equation 2

Where ρ is the air density and A is the rotor area.

This expression for total power is maximized when $a = 1/3$ in the "Betz power"

$$\boldsymbol{P_{máx} = \frac{16}{27}\left(\frac{1}{2}\rho A V_1^3\right)}$$

Equation 3

The wind turbines are controlled to operate at its maximum power.

As consequence of the power exchange process between the wind and the runner, downstream of the wind turbine the flow rotate around the turbine axis.

1.2 Kinetics in the blade: The airspeeds

In a second stage for describe the wind turbine operation the interaction between the wind and the blades is considered. Then, the blade is to discretized in an finite number of radial segments ("slices") of length $\mathbf{d}\boldsymbol{r}$.and with a section correspond to an aerodynamic profile.

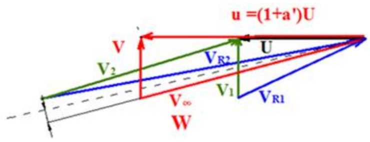

Figure 1: The airspeeds into the section. Source [6]

As it is usual in the study of axial turbomachinery, the vector average of $\overrightarrow{\mathbf{V_{R1}}}$ and $\overrightarrow{\mathbf{V_{R2}}}$ is calculated to analyse the blade dynamics

$$\vec{W} = \frac{\overrightarrow{V_{R1}} + \overrightarrow{V_{R2}}}{2}$$

Equation 3

$$W = \sqrt{(1-a)^2 V_1^2 + (\Omega r)^2 (1+a')^2}$$

Equation 4

The variable r is the distance from the axis to the considered slice.

1.3 Dynamics in the blade: Differential interaction

As consequence of the interaction between the flow and the blade a force is produced, usually split in two components named as drag (D) and lift (L), as figure 2 shows.

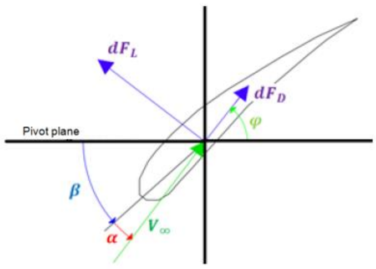

Figure 2: Dynamics in the blade

From Figure 2, the following expression is deduced:

$$\varphi = \beta + \alpha_p = Arctg\left(\frac{V(1-a)}{\Omega r(1+a')}\right)$$

Equation 5

Where φ is the relative velocity obtained as the blade angle (β) plus the attack angle (α). The lift component in a slice is

$$dF_L = C_L\left(\frac{1}{2}\rho l\, W^2\right) dr$$

Equation 5

And the differential pressure established between intrados and extrados is guessed as

$$dP \cong \frac{1}{l} C_L\left(\frac{1}{2}\rho l\, W^2\right)$$

Equation 6

The $\boldsymbol{C_L}$ coefficient (lift coefficient) depends on the profile geometry and the attack angle. $\boldsymbol{l}$ refers to the profile chord length.

2 Turbulence theory

The turbulence spectrum presents a universal form which there is several analytical expressions.

One of them is the Von Karman spectrum, which is expressed based on a non-dimensional ratio built with turbulence integral length scale L_u and the flow speed V as follow.

$$X = \frac{f L_u}{V}$$

While the von Karman spectrum is a non-dimensional expression of the spectrum (S) multiplying by the frequency and dividing by the total energy (σ, rms)

$$\frac{Sf}{\sigma^2} = \frac{4\,X}{[1 + 70{,}8\,X^2]^{5/6}}$$

Equation 5

From this spectrum, the energy content in a one-third of octave can then be estimated as:

$$S = \left(2^{\frac{1}{6}} - 2^{-\frac{1}{6}}\right)\sigma^2 \frac{4\,X}{[1 + 70{,}8\,X^2]^{\frac{5}{6}}}$$

Equation 6

3 Modelling noise generation

3.1 The leading edge noise

The edge noise (LWl.e.) is due to the fluctuation of lift effort on the blade, and, therefore, a good estimation of the pressure fluctuation can be made using Mc Lauren series.

$$\Delta P = \frac{\partial P}{\partial W}\Delta W + \frac{\partial P}{\partial \varphi}\Delta\varphi$$

Equation 7

The variation of φ and W are related to the turbulent fluctuation of the wind speed. For the longitudinal component the turbulent fluctuation is characterized with the standard deviation σ, which can be estimated at one height by knowing the atmospheric stability condition and the terrain roughness. As consequence, the spectrum of ∆P fluctuation would be proportional to the von Karman spectrum.

The turbulent scale of interest is around the length of the blade's chord, because that vortices produce the biggest amplitude fluctuation of the pressure field. As example the value proposed by Van Der Berg [2] is 0.6 of the chord's length. Vortices with smaller scales would produce a lower fluctuation of the pressure.

Then, the spectrum of the leading edge emitted noise will have the shape of Von Karman's spectrum, multiplied by this ΔP pressure value, for vortices length scale greater than the profile chord length.

3.2 The trailing edge noise

The noise of the trailing edge ($L_{Wt.e}$) is due to the turbulence produced in the boundary layer developed on the profile.

The scale of interest in this case is similar to the boundary layer´s thickness, and the intensity fluctuation is supposed to be linear with Reynolds. The thickness of the boundary layer is calculated according to [3].

3.3 Emitted acoustic power level

The total acoustic power emitted by one section of the blade should be obtained as the sum of the acoustic power emitted by the trailing edge and the leading edge, as follow Turning the expression in level terms:

$$L_W = 10 \times \log\left(10^{\left[\frac{(L_W)_{t.e.}}{10}\right]} + 10^{\left[\frac{(L_W)_{l.e.}}{10}\right]}\right)$$

Equation 8

4 Sound immission levels

The total sound immission level due to the emission of a wind turbine is obtained as the sum of each section of blade's immission level. In this calculation, it must be carefully taking into account the different height occupied by each slice, the mean and standard deviation of the velocity values which vary with the height and the atmospheric stability. The velocity field also is affected by the presence of the tower as an obstacle to the flow. All these parameters change in the time and then the emission levels vary periodically in time.

4.1 Spread

The immission calculation should be done slice by slice, along the blade, for different runner angular position. In short distances (lower than 400m), the only appreciable decay is due to atmospheric absorption and geometric divergence.

$$L_P = L_W - \alpha d - 10 \times \log(4\pi d^2)$$

Equation 9

Where d is the distance between the source in this case between each slice and the receiver, and α is the ISO 9613:1 atmospheric absorption coefficient.

For distances greater than 500 metres, the model to show unacceptable errors.

4.2 Comparison with measured sound pressure levels

Two class 1 sound level meters (according to IEC 61672) were simultaneously used to measure the immision associated to wind farm noise. Both instruments belong to IMFIA-FING and they have their calibration certificates updated. The sound pressure levels measurements were performed at different distances from the source and with different wind speeds. The emission sources were wind turbines of different sizes in the two wind farms. In both cases of three blades.

The wind speeds at hub height were obtained from the wind farm meteorological station. Temperature and humidity were measured simultaneously with sound pressure levels; also the rotating speed of the machines was measured in field.

4.2.1 Case 1: "Fray Marcos"

Geometric data of the wind turbines are shown in table 1.

rotor radius	45m
hub height	90m
mean chord	1m
Tower radius	3m
hub-rotor distance	3m

Table 1: Wind turbines' dimensions

The roughness' ground at this place has been supposed to be well represented by a roughness length of $z_0 = 6\ cm$ (pasture's roughness), the zero displacement- plane height is zero. The intensity of turbulence profile was deduced from the ground.

Modelled and measured sound pressure levels are presented in Figure 5. The graphics on the left are for a 100 m and 200 m from shaft tower

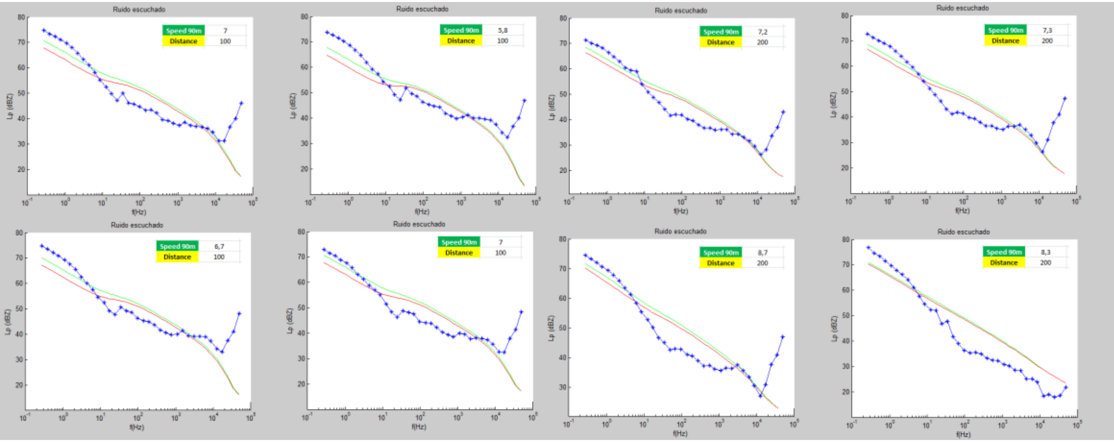

Figure 5: Chart comparison in Fray Marcos: maximum (green line) and minimum (red line) calculated sound pressure levels, measured sound pressure levels (blue line) in third-octave bands

Similar behavior between the theoretical curve and the measured curve in the range that interpretation is acceptable is observed.

4.2.2 Average error

The calculation was made prioritizing the results at low frequencies then, the average error is higher in medium and high frequencies, let say over 100 Hz. The calculated sound levels are higher than measured ones, as it figure 6 shows. The application of this model can be done for frequencies lower than 10000 Hz (Interval in which it is believed that the level that the sound level meter measures, is mainly due to the wind turbine).

The average error was calculated with data from 13 measurements in different conditions. Average error was calculated as: $Error = \ Average\ estimated\ level - Mesaurement\ level$

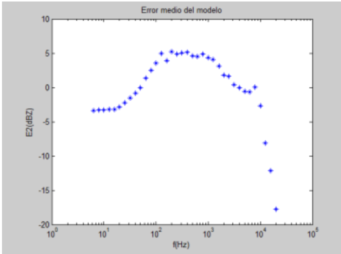

Figure 5: Average error

We can observe a difference of -5 dB for frequency lower than 10 Hz and +5 dB for frequencies between 100 Hz and 1000 Hz.

4.2.3 Case 2: “Kentilux”

Wind Farm Kentilux S.A. is located at about 45 km from Montevideo city, in the department of San Jose.

The dimensions of the wind turbines are shown in the table 2.

rotor radius	45m
hub height	80m
mean chord	1m
Tower radius	3m
hub-rotor distance	3m

Table 2: Aero generator’s dimensions

Around the wind farm the land is a cultivated with a roughness length of and a zero displacement plane height of   m.

The wind speed at hub height was obtained from the meteorological station, and temperature and humidity were measured. The rotor frequency was estimated by counting the RPM.

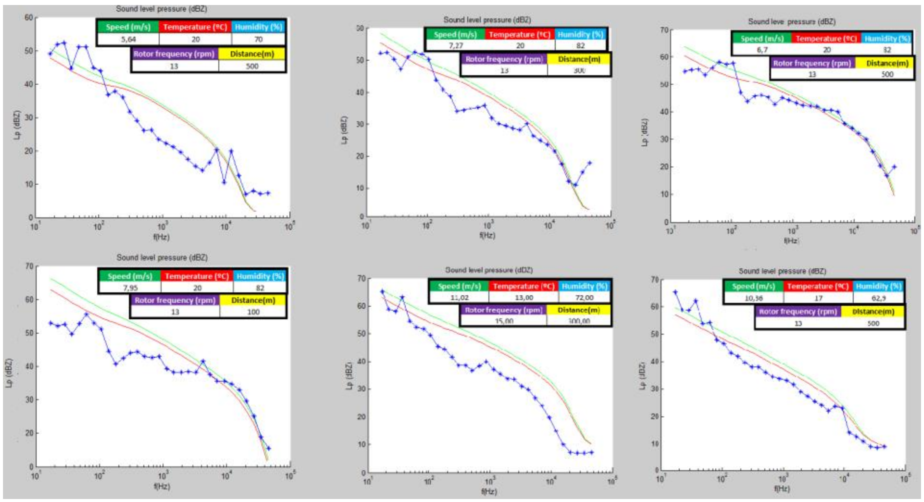

Figure 6: Chart comparison in Kentilux: maximum (green line) and minimum (red line) calculated sound pressure levels, measured sound pressure levels (blue line) in third-octave bands

We can observe that the model is better adjusted at short distances than at long distances.

4.2.4 Average error

Average error was classified in order to draw a conclusion about this wind farm. The average error was calculated with data from 20 measurements in different conditions. Average error was calculated as: $Error = \ Average\ estimated\ level - Mesaurement\ level$

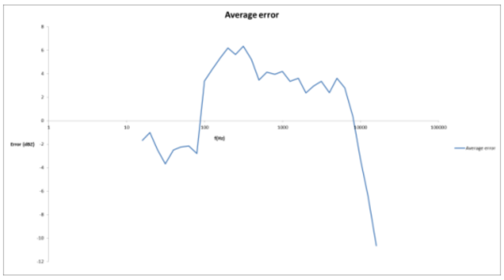

Figure 7: Average error

The error has similar distribution, but is less than the previous. Figure 5.

5 Conclusions

Main results

- The model can rightly reproduce the main phenomena involved in aerodynamic noise generation.
- The model has better results at higher frequencies but it overestimates the emission levels in medium frequencies and underestimates them at lower ones.
- The slope of the noise spectrum is slightly lower than the one that emerges from Von Karman spectrum with absorption mechanisms considered, even taking into account the wind noise.
- The difference between the minimum and maximum immision sound pressure levels is noticeable at low frequencies but they are negligible at high frequencies.
- Model effectiveness decreases with increasing distance.

Main possible error causes

- The most probable error causes could be as follow:
- The absorption and/or dissipation phenomena aconsidered (especially at mid frequencies).

- Difficulties for considering an accurate value for the standard deviation of wind speed, especially in conditions of atmospheric stability.
- Also, perhaps neglected low.
- Emission mechanisms that are not considered should be taken into account.

It must also be said that to visualize the modulating phenomena related to the blade passing by the tower, time evolution of sound pressure levels should be explicitly taken into account.

Even if the model has been able reproduce the most important phenomena related to aerodynamic noise generation, it still needs to be improved to allow its practical application in environmental noise impact assessments.

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