Chapter

Prediction of Environmental Sound Pressure Levels from Wind Farms: A Simple but Accurate Model

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Abstract

The prediction of the environmental sound pressure levels of wind farms does not yet have a global consensus on how to achieve an easy-to-build model with accurate results. This chapter aims to present the sound pressure level prediction model developed at Universidad de la República (Uruguay). Its main characteristics are: taking into account atmospheric stability to determine the acoustic power of the machines; describing the generation of noise along the blades due to turbulent phenomena; and calculating the noise propagation at different distances from the tower taking into account atmospheric absorption, turbulence energy dissipation, and geometric divergence. It does not have any special IT requirements. A new approach to calculating geometric divergence is considered. The results show more than 80% of the cases within the range of ±3 dB, for wind farms throughout our country. The need to use not only A-weighted sound pressure levels but also octave frequency band levels is indicated.

Keywords: wind turbines noise, wind farms noise, wind energy, noise prediction model, aerodynamic noise

1. Introduction

Uruguay is a small country located in South America. According to the 2010 Strategic Energy Development Plan for Uruguay, the diversifying of the energy matrix should be prioritized. Alternative and renewable energy sources rose to be exploited at a major scale. Because of its windy climate, wind energy is now one of the most important sources in our country: currently, Uruguay has more than 1500 MW of installed power lying on this green energy source.

The fast growing development of wind power in Uruguay has encouraged research on many environmental issues, especially those related to wind turbines operation. In many countries—Uruguay included—the method of ISO Standard 9613-2 is the preferred tool for predicting environmental sound pressure levels due to stationary noise sources. However, it is well known that it can incur on great underestimations when sources are large wind turbines, especially under certain atmospheric conditions [1].

This paper is focused on the prediction of environmental sound pressure levels due to the operation of large wind turbines, emphasizing in the prediction model developed by the Research Group on Noise Pollution at the Faculty of Engineering (UdelaR). For its development, the theoretical analysis of the phenomena involved on noise emissions was complemented with tests at the University wind tunnel and, of course, with sound pressure levels measurements at some wind farms in Uruguay. The aerodynamic phenomena involved in acoustic emissions were analyzed with the Research Group on Wind Energy at the Faculty, which has been working on wind energy for nearly 30 years.

The application of the prediction model allows obtaining the expected sound pressure levels at different points. Only airborne sound propagation is considered, as the importance of ground propagation does not involve an important amount of acoustic energy for onshore wind farms.

2. Some limitations of the usual prediction methods to represent wind turbines noise generation and propagation

Environmental sound pressure levels related to stationary sources are usually predicted as prescribed by the ISO Standard 9613-2. It is not only a standardized method of calculation, but it has been for a long time the recommended one in the European Union [2]. This is a strong argument at some developing countries. Convincing the decision-makers about the need of developing another prediction method to achieve more reliable results in the case of wind turbines is not an easy task.

This section aims to point out the main hypothesis of the ISO Standard 9613-2 [3] and to discuss their applicability to wind turbine noise.

2.1 The origin of the calculation method

In 1981, CONCAWE (a group of oil companies, aiming toward the research on the conservation of water and air quality in Europe) hired C. J. Manning for developing a prediction model of environmental sound pressure levels [4]. Some novel prediction methods were inspired on it, as the ISO Standard 9613-2 was.

According to CONCAWE, the environmental sound pressure levels at remote places due to a noise source can be obtained by solving the following expression:

$$L_p = L_W + D - K \quad (1)$$

Where L_p is the sound pressure level in the short time for the octave band i, L_W is the acoustic power level for the octave band i, D is the correction due to directivity of the source, and K is the sum of the attenuation terms.

The ISO Standard 9613-2 general expression is just the same:

$$L_{pi} = L_{Wi} + D - A_i \quad (2)$$

The definitions of Eq. (1) are valid for Eq. (2). A_i are the attenuation terms (atmosphere absorption, ground absorption, presence of obstacles or noise barriers, etc.). The subscript i refers to the values for the octave band i.

Both calculation methods assume the divergence law to be quadratics, thus the emitter is supposed to be a point source. Also, both calculation methods promote their application by frequency octave bands. Nevertheless, if there is not enough information to work by bands, ISO Standard 9613-2 will accept calculating in A-weighted sound pressure levels using all formulae and coefficients corresponding to the octave band centered at 500 Hz. If the acoustic emissions have high energy content in low frequencies, this way of calculating will cause a great underestimation of immission sound pressure levels.

CONCAWE's model uses the meteorological categories proposed by Parkin and Scholes instead of the currently preferred Pasquill-Gifford ones. ISO Standard 9613-2 does not consider calculating differences due to different meteorological conditions when the main calculation hypothesis is satisfied: wind speed between 1 and 5 m/s at a height between 3 and 11 m above the ground and averaged over a short period of time or moderate temperature inversion with its base at ground level. These conditions are not always met when the source is a wind turbine.

In this century, it has been verified that the differences between environmental sound pressure levels predicted by ISO Standard 9613-2 and those that do occur due to the operation of wind turbines would be very important: underestimations of 15 dB or more have been reported during the occurrence of certain combination of environmental conditions [5, 6].

Then, ISO Standard 9613-2 calculation method has been submitted to a deeper analysis.

2.2 Understanding the ISO Standard 9613-2 limitations

Aerodynamic noise generation during operation of wind turbines is inherent to them in nature: the major acoustic emissions from large wind turbines are caused by the interaction between the air flow and the blades. The acoustic emissions occur all along each blade, most of them at low frequencies. Then, the height of the noise source is from about 40–130 m above the ground. The incident wind speed largely varies between these two heights, so that the wind turbine becomes a heterogeneous and complex sound emission source.

There are some limitations for the use of ISO Standard 9613-2 to predict environmental sound pressure levels due to large size wind turbines [1]. Some of the general ones are the following:

- The hypothesis about wind speed and atmospheric stability is not always fulfilled.
- Atmospheric conditions (neutral, instability, or under an inversion layer) have a great incidence both on generation and on propagation of noise [6].
- At the typical distances of interest, a wind turbine cannot be supposed to be a point source [7].
- The Standard supposes the distance from source to receiver to be between 100 and 1000 m.
- The average height of source and receiver should be between 0 and 30 m (then, the maximum height of the source will not exceed 60 m if the receiver is at 0 m height).

- Source and receiver should be placed over a plain surface (a surface with a continuous slope, i.e., the method is not valid for complex terrain).

- If the calculations are done based on A-weighted sound pressure levels (as it is allowed by the Standard), a greater underestimation should be done at low frequencies.

Some experimental findings also refer to better results when not considering ground attenuation effects during propagation [8].

But there are also two of the major assumptions that are at the very beginning of the conceptual framework of environmental acoustics that are not fulfilled by the physic/fluid mechanic phenomena involved in the aerodynamic sound generation from wind turbines [9]:

- The hypothesis that acoustic processes are adiabatic, because they occur very fast and involve only very small amounts of energy. Most of vibration phenomena can be well described as adiabatic ones, but this is not the case of the aerodynamic noise related to wind turbines' operation. Noise generation is related to turbulent phenomena, which are not adiabatic but very dissipative ones.

- The hypothesis of ideal fluid, which is opposite to the main phenomena that are related to release of eddies from a boundary layer; these phenomena only can occur if the air is considered as a viscous or real fluid.

These are thought to be the root causes for both CONCAWE and ISO methods not to being appropriate for predicting the environmental sound pressure levels related to wind turbines' operation, as they cannot describe the main involved phenomena on a right way [1, 9–11].

3. Improving the prediction method

In order to improve the current prediction method, we have proposed several modifications. We have focused on the noise generation phenomena, but we have also worked on two other points: the explicit consideration of the atmospheric stability condition and the dissipative nature of the main phenomena during propagation.

3.1 Wind velocity at the hub height: Considering atmospheric stability class

The wind velocity is usually measured at 10 m height above the ground. One of the main causes of underestimating the environmental sound pressure levels is related to calculating the wind speed at the hub height using a neutral atmospheric profile with basis on its value at 10 m. To avoid this problem, the atmospheric stability class (according to Pasquill-Gifford) has to be explicitly taken into account for this calculation. The atmospheric stability does not only influence the wind speed profile but also the turbulence intensity and, therefore, the acoustic energy depletion law.

If a stable or thermal inversion atmospheric condition occurs, not including it in the prediction method will conduct to:

Pasquill stability class		m	
Class	**Description**	**Usual bibliography values**	**Van den Berg experimental values [from 6]**
A	Highly unstable	0.09	0.15
D	Neutral	0.28	0.40
F	Highly stable	0.41	0.65

Table 1.
Values of m *according to Pasquill-Gifford stability class.*

- A great underestimation of the wind speed at the hub height, which would result in the underestimation of the emitted acoustic power level.

- A great overestimation of the sound pressure levels depletion, due to the lower atmospheric turbulence and hence, the lower energy dissipation during propagation.

If the atmospheric thermic profile is not known, the wind speed at the hub height should be obtained by supposing a strong atmospheric stability profile (class F according to Pasquill-Gifford), to be in the most demanding hypothesis for protecting the health of noise receivers.

Then, the wind speed at the hub height should be met by converting the measured wind speed data—that are usually taken at 10 m over the ground—using a proper method.

Using the logarithmic profile approach for wind velocity (Eq. (3)) is better than using the potential profile approach (Eq. (4)), even though there are good experimental values for the potential approach. Indeed, since several authors refer that the usual values of m may lead to underestimation of the acoustic power, using the experimental values met by Van den Berg [6] is strongly recommended when using the potential approach, in order to remain on the safe side (see **Table 1**).

Logarithmic profile approach:

$$u(h_{hub}) = \frac{u_*}{k}\left[ln\left(\frac{h_{hub}}{z_0}\right) - \psi_m\left(\frac{h_{hub}}{L_*}\right)\right] \tag{3}$$

Where:
$u(h_{hub})$ wind velocity at hub height
u_* friction velocity
k von Karman's constant
z_0 roughness length
ψ_m thermal stratification function
L_* Monin-Obukhov length
Potential profile approach:

$$u(h_{hub}) = u_{ref}\left(\frac{h_{hub}}{h_{ref}}\right)^m \tag{4}$$

Where:
u_{hub} wind velocity at hub height h_{hub}
u_{ref} measured wind velocity at a reference height h_{ref}

m coefficient depending on Pasquill-Gifford class of atmospheric stability (see **Table 1**)

The calculation procedure that we recommend to meet the wind velocity at h_{hub} height, taking into account its value at any other height h_{ref}, is as follows [10–12]:

1. If the stability class to which u_{ref} corresponds is known, the velocity at the hub height can be met by applying either Eqs. (3) or (4).

2. If the stability class to which u_{ref} corresponds is not known, a stable atmospheric profile should be assumed for calculating the velocity at hub height with basis on the wind velocity at a reference height (usually 10 m above the ground).

3. Once the wind velocity at the hub height (u_{hub}) has been obtained, a "corrected" wind velocity at 10 m in height should be calculated. This is the 10 m height wind velocity to be used for meeting the acoustic power level of the wind turbine from tables or charts provided by the manufacturer. **Figure 1** sketches the procedure.

Please note:

1. If the wind speed at the hub height is known, the wind velocity at 10 m must always be obtained assuming a neutral atmosphere (even when the stability class is known not to be neutral).

2. For obtaining the sound pressure level resulting from a wind velocity value measured at a height "H" (other from h_{hub}) in any given atmospheric condition "X": u_{hub} should be calculated assuming the class of stability "X"; then, the "corrected" wind speed at 10 m in height should also be calculated by assuming neutral atmosphere (class D). The acoustic power shall be read from the datasheet provided by the manufacturer; it will also be associated with that atmospheric stability class: $L_W^{''X''}$.

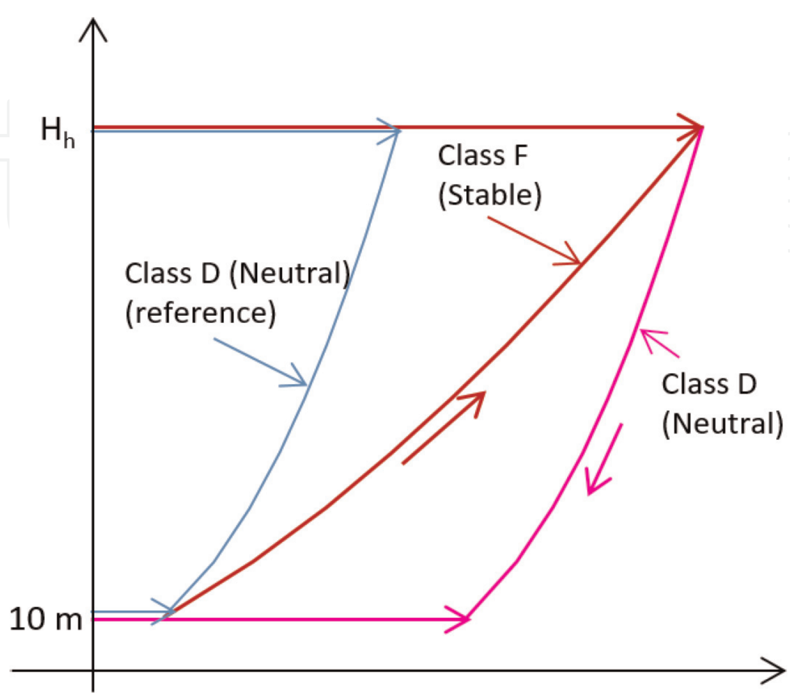

Figure 1.
How to reach the wind speed at 10 m height to obtain $L_{W,A}$ (redrawn from [10]).

f (Hz)	16	31.5	63	125	250	500	1000	2000	4000	8000
Add to L_{WA} (dB)	−44	−26	−21	−14	−7	−6	−6	−9	−12	−22

Table 2.
Reference spectrum of acoustic power of 2 MW wind turbines in octave bands (based on [13]).

Wind turbine manufacturers often provide tables or graphs relating the wind velocity at 10 m in height (u_{10}) to the acoustic power level (in dBA) emitted by the wind turbine in neutral atmosphere conditions. However, providing emission spectra in frequency bands is not so common. If this information is not available, a reference spectrum should be used, e.g., spectrum in **Table 2**.

Table 2 (based on [13]) presents the values to be added arithmetically to the acoustic power level of the wind turbine (L_{WA}) to obtain the acoustic power levels in each octave band, also in dBA ($L_{W,f,A}$).

3.2 Modeling noise generation phenomena

We aim to obtain the sound pressure levels due to the operation of a typical three-blade wind turbine, at a generic receiver point located downwind at a distance d.

Aerodynamic noise is generated by the interaction of wind with the blades of the machine. Most of the acoustic emissions occur in low frequencies, so the acoustic print of wind turbines can be found at large distances from the sources, making the problem more complex to manage.

3.1.1 General background

There are three main processes causing the fluctuation of the pressure field and then the acoustic emissions [14]:

1. The turbulence of the incoming wind, which causes pressure fluctuations around the blades; it is variable over time and it is called “incoming flow noise.”

2. 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 with the inertial forces (related to the medium air flow). The release of eddies with negative gauge pressure at their cores, developed on solid surfaces such as blades, tower, and hub due to viscous stresses, causes a continuous noise called “trailing edge noise.”

3. The power exchange between the wind and the machine that produces the release of two families of eddies linked to each blade; one of them has helical motion and the other one is centered 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 [14, 15]:

1. Macroscale: it is the scale related to the largest eddies. If U, L, and T are the scales of velocity, length, and time associated to these eddies, the Reynolds number of the biggest eddies is the same as for the main flow.

2. 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."

3. Microscale: it is the lowest 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 eddies are dissipating into smaller scale eddies with increased kinetic energy. However, there is a length scale at which the power transfer to a smaller eddies scale is not possible. At this point, the turbulent cascade ends and the energy from the last eddies is finally dissipated. The smallest eddies scale is the Kolmogorov scale; the so-called Kolmogorov frequency or dissipation frequency is the generation frequency of these smallest eddies [15]. According to their frequency and energy, the released eddies are able to produce audible phenomena, i.e., they can become noise sources (**Figure 2**).

The passage of the blades ahead the tower imposes a fluctuation of the sound level pressures emitted by the abovementioned phenomena. It results in an amplitude-modulated noise, called the "blade passage noise." It has a double nature, one related to the flow and one related to the geometry of the source. The modulation is the most related process to annoyance in wind turbine noise. This process is not modeled in detail: the informed sound pressure levels are the highest of those corresponding to the fluctuation.

3.1.2 Basic concepts concerning wind turbines

A first approach to describe the wind turbines operation is to model the rotor as an active disk, which absorbs kinetic energy from the incoming wind, resulting in a reduction in the flow speed downstream of the turbine.

If v_1 is the incoming velocity and v_2 is the outcoming velocity, the velocity induction coefficient "*a*" is defined according to Eq. (5):

$$v_2 = v_1\,(1\text{–}2a) \tag{5}$$

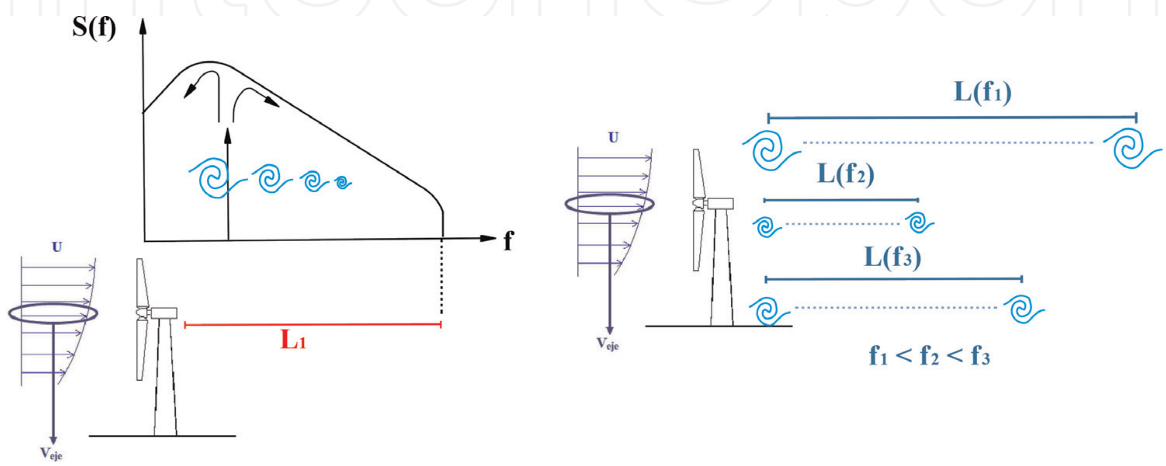

Figure 2.
Atmospheric conditions for propagation. From: [15].

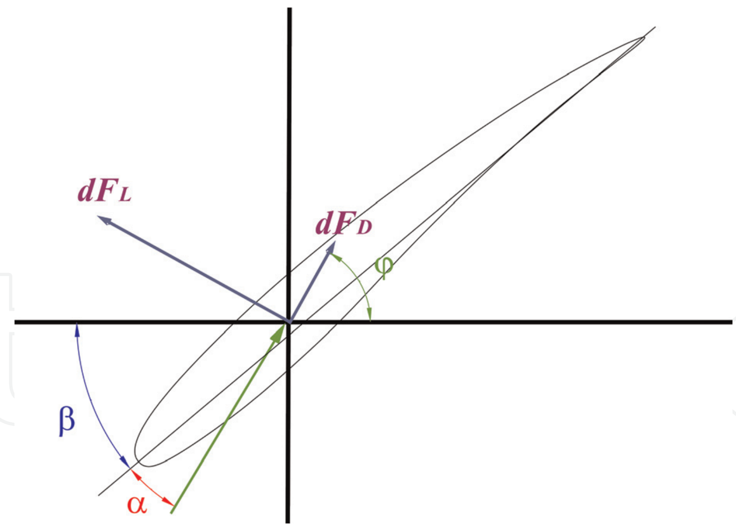

Figure 3.
Drag F_D and lift F_L efforts over the blade (from [15]).

Applying mass and energy balances to the incoming flow, and supposing an adiabatic and incompressible flow, the maximum amount of power absorbed by the disk is:

$$W = \frac{1}{4}\rho A(v_1 + v_2)\left(v_1^2 - v_2^2\right) \tag{6}$$

In Eq. (6), ρ is the air mass density, and A is the swept area or rotor area.

The power absorbed is maximized when a = 1/3. Then, Eq. (7) is the expression of the so-called “Betz power”:

$$W_{Max} = \frac{16}{27} \bullet \left(\frac{1}{2}\rho A v_1^3\right) \tag{7}$$

The wind turbine operates at its maximum power for each wind velocity, while the wind velocity is under the rate value. As consequence of the power exchange process between the wind and the machine, the flow downwind the rotor rotates around the turbine axis.

The force over the blade, consequence of the interaction between the flow and the blade, is split in two components: the drag effort (D) and the lift one (L) (**Figure 3**). The magnitude of these components strongly depends on the angle of attack (α), which is the angle between the chord of the blade and the incoming flow relative to the blade. When the drag component increases, the noise generation increases too. This usually occurs when the angle of attack α increases.

3.1.3 Theory of turbulence

There are several analytical expressions to describe the universal shape of the turbulence spectrum. One of that, the Von Karman’s spectrum, expresses the spectrum as function of a nondimensional ratio built with turbulence integral length scale L_u and the main flow speed v (Eq. (8)):

$$X = \frac{L_u f}{v} \tag{8}$$

According to Von Karman spectrum, we propose to estimate the energy content in a third-octave band centered at a frequency *f* according to Eq. (9), in which σ is the standard deviation of the flow speed:

$$S = 4\,X\,\frac{\left(2^{1/6} - 2^{-1/6}\right)\sigma^2}{\left(1 + 70,8\,X^2\right)^{5/6}} \tag{9}$$

3.1.4 Emitted acoustic power level

To meet the acoustic power level, we accept that each blade is composed of a group of discrete thin elements or slices. Each one would be sufficiently thin to be thought as a noise point source. Then, the total acoustic power emitted by one blade element should be obtained as the superposition of the acoustic power emitted by the incoming flow ($L_{W,IF}$) and the trailing edge ($L_{W,TE}$) as following (Eq. (10)):

$$L_W = 10\ log\left(10^{\frac{L_{W,IF}}{10}} + 10^{\frac{L_{W,TE}}{10}}\right) \tag{10}$$

The incoming flow noise is the result of the fluctuation of the lift effort on the blade, which makes the drag effort to fluctuate. We propose estimate of the pressure field fluctuation using McLaurin series, where first-order terms are related to the turbulent fluctuation.

The length scale of interest, for the incoming turbulence, is similar to the length of the blade chord, which corresponds to the length scale of the eddies that produce the greatest amplitude fluctuation on the pressure field. Van den Berg proposes to use a length scale equal to 60% of the blade chord for this length [8]. Smaller eddies would produce lower fluctuations on the pressure field. Then, the shape of the spectrum of the incoming edge noise, associated to eddies with length scale larger than the blade chord, will be the same as Von Karman's spectrum.

The trailing edge noise is due to the turbulent boundary layer separation over the blade. The length scale of interest in this case is about the boundary layer thickness.

We built a routine for obtaining the emitted acoustic power level by third-band octave. Its aim is to obtain the predicted sound pressure levels at a point placed at 100 m downwind of the wind turbine tower. We discretize the blade in infinitesimal length blade elements. The coordinates of each slice in every moment could be thought as [x(t), y(t), z (t)]. Then, the propagation into the first 100 m from the tower axis is done assuming that each one of the blade elements is a nonstationary noise point source (**Figure 4**).

For the propagation from each blade element to the receiver location, our routine only considers the geometrical divergence and the atmospheric sound absorption as indicated at ISO Standard 9613-1 [16]. The output of this routine is the input for the propagation module [10, 11].

3.3 Modeling noise propagation

For computing sound propagation, the input data are the results of the computing at 100 m far from the tower of the wind turbine. Not only geometric divergence but also atmospheric absorption and turbulent dissipation are considered; 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

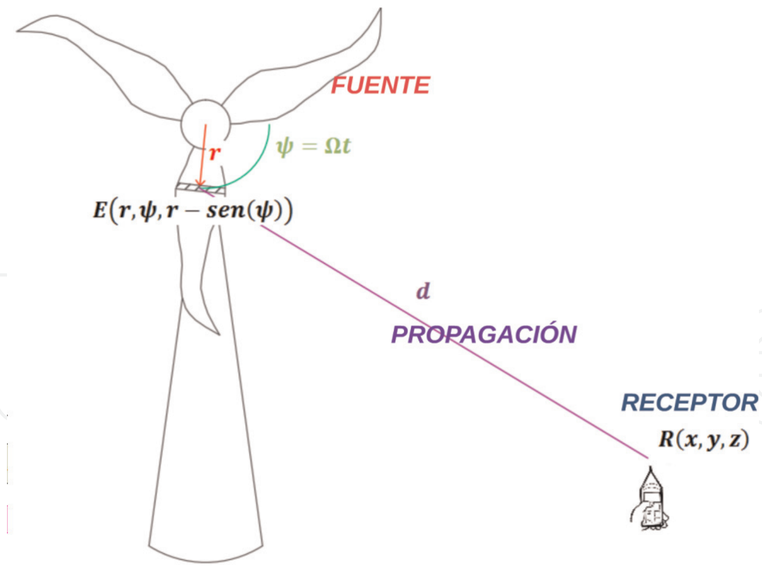

Figure 4.
Sketch of calculation of sound pressure levels in the first 100 m (from [10]).

turbines operation. All computations are done in octave bands, and the final results are expressed as L_{Aeq} values [11].

3.3.1 Atmospheric conditions and audibility of acoustic emissions

The analysis of the evolution of eddies generated due to wind turbine operation requires the use of the cascade process as it is usual in turbulent flow studies. According to it, the larger eddies are melting into smaller ones, increasing its kinetic energy. At some point, small eddies cannot continue to transfer power to smaller ones; so, they dissipate their remaining energy, thus ending the cascade process. The scale of these last eddies is the order of the Kolmogorov's scale.

Under atmospheric instability condition, the turbulence is very high and the eddies scale interval is broad; the cascade process is very efficient to dissipate the produced turbulence. For distances greater than the one at which that dissipation occurs, it shall be assumed that the flow conditions are the same as upstream the wind turbine. The ratio between the current wind velocity up and downstream the machine tends to 1 for greater distances, and the difference between them is practically negligible at a distance of about 6 or 7 rotor diameters downstream of the wind turbine (i.e., about 600 m).

In strong atmospheric instability conditions, the prior distance is the shortest one to fully carry out the whole energy cascade process. For any other atmospheric conditions, the dissipation process occurs in greater distances.

Under strong atmospheric stability conditions (i.e., class "F" according to Pasquill-Gilfford stability classes), the effect of turbulence should be negligible. The only mechanism that affects the energy depletion process in any frequency band—in addition to the geometric divergence or attenuation by distance—is the atmospheric absorption.

3.3.2 The atmospheric absorption

The effect of atmospheric absorption can be considered as the depletion of the acoustic energy of a wave over a given distance, due to energy loss caused by the viscosity of the propagation medium (currently, the atmosphere). To estimate the effect of the atmospheric absorption, the computation method of the ISO Standard 9613-1 was used [16].

The attenuation due to atmospheric absorption in dB of a pure tone with frequency *f*, from its initial level at a distance $d = 0$ to its level at d, can be obtained according to Eq. (11):

$$Abs = \Gamma_i(f) \cdot \frac{d}{1000} \tag{11}$$

Where Γ_i is the atmospheric absorption in the i-th frequency band in dB/km, and d is the distance from the base in m. The absorption coefficient Γ_i is a function of the relaxation frequencies from oxygen and nitrogen [16].

The generation and propagation phenomena of eddies can be described from a wave approach. Then, close to the source, the sound pressure levels should be estimated considering energy depletion by geometric divergence (*Div*) and by atmospheric absorption as shown in Eq. (12).

$$L_p = L_W - Div - \Gamma_i(f) \cdot \frac{d}{1000} \tag{12}$$

The threshold of perception at each frequency band should be another criterion for determining the distance upon which the sound is still audible. Hearing threshold levels were retrieved from ISO Standard 226 [17].

3.3.3 Geometric divergence

For the depletion of sound pressure levels due to distance, the adjustment is focused on the exponent (n) of the divergence law, which is neither squared nor linear as many measured sound pressure levels close to operating wind farms have shown.

As one of the main hypotheses of linear acoustics was broken (nonviscous effect), we intend not to be mandatory for n to be constant across every one of the considered third-octave bands: the exponents may be related to the distance scale at which eddies are expected to dissipate all their turbulence energy. Then:

$$Div = 10\, log \left(\frac{d}{d_0}\right)^{n(f_i)} \tag{13}$$

Here, $n = n(f_i, d, u)$ depends on the central frequency f_i of each octave band.

For the calculations of geometric divergence, the turbulent cascade approach is taken into account (**Figure 2**). The released eddies can propagate along great distances while the turbulent cascade occurs [15]. These distances are related to a certain energy level and a length scale. They are also closely related to atmospheric stability.

We calculated the length scale where the turbulent cascade is expected to end by considering it to depend on the incoming wind velocity and the frequency of the released eddies. This is based on prior consideration of the atmospheric stability during the calculation of noise emissions [10, 11].

Different sets of n values were achieved by fitting measured data. At first, we consider only the dependence of n related to the frequency. Then, we explored the dependences on the distance d, the wind speed u, and the atmospheric stability. The

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f (Hz)	16	31.5	63	125	250	500	1000	2000	4000	8000
Closer than 750 m, less 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
Closer than 750 m, 6.5 m/s or more	0.52	0.02	0.01	0.22	0.93	0.79	1.04	1.07	1.06	0.65
Further than 750 m	0.45	0.01	0.06	0.72	1.58	1.71	2.03	1.60	0.67	0.34

Table 3.
*Divergence coefficient "*n*" values for octave bands, according to the wind speed* u *and the distance* d*.*

best set of n values was selected by the application of the statistic Friedman test and the comparison of residues (differences) between measured to predicted sound pressure levels expressed as A-weighted broadband levels.

Field data were taken at a height of 1.2 m with class 1 sound pressure meters, close to three different wind farms over plain terrain; the distances of measurements covered from 100 m to about 2000 m.

The best set of values was found to be the one obtained for $n = n(\text{f, d, u})$. The explicit consideration of atmospheric stability in the propagation term did not result in an improvement in the simulated sound pressure levels.

The values of n(f, d, u) are given in octave bands according to whether the calculation distances are closer or further than 750 m and that the wind speed at the hub height is less or greater or equal to than 6.5 m/s (**Table 3**).

4. Validation of the model

4.1 Field measurements

Several sound pressure level measurement campaigns were conducted at three different wind farms with large wind turbines (rate power of 1.8 MW), covering several operating conditions.

Sound pressure level records were taken at 1.2 m height, simultaneously with records of wind speed and direction at 10 m height. In addition, the records of wind speed and direction were obtained from the wind farm anemometer, located at 66 m high and close to the turbines. To carry out the measurements, we used two sound level meters class 1 (Brüel and Kjaer 2250 and Casella 633C), an anemometer (Extech EN-300), a GPS, and two computers.

The measurement points covered four different geographical locations:

- A hilly zone, far from external sources such as houses or roads, to avoid introducing disturbances to the data obtained.
- A flat zone close to the sea, where 10 large wind turbines are installed.
- Another flat zone where two 1.8 MW wind turbines are installed.
- A location in the countryside close to a private company, which has only one wind turbine. This location was particularly interesting for this study, since the records are not affected by other turbines or any external sources.

A set of 59 measurements was used during the calibration and validation processes. The main findings showed that the model gave a good approach for the environmental sound pressure levels related to the operation of wind turbines for wind speeds over 5 m/s at the hub height.

In order to validate the model, another set of field data was used. It was another set of data of 49 cases from 10 wind farms in different locations in Uruguay:

- The four abovementioned places.
- A flat zone in the northern of the country, where 35 wind turbines are installed.
- Two hilly wind farms placed on the Southern part of the country, each one with around 25 wind turbines
- Three rather flat zones in the center/south-western part of the country, having from 20 to 35 wind turbines each one.

Some adjustments were needed for improving the prediction of noise propagation from wind farms built on uneven terrain.

4.2 Accuracy of predictions

The results obtained in the verification of the performance of the model are presented in **Tables 4–6**. Almost 80% of the cases are reproduced within ±3 dB range.

5. Further discussion

5.1 Computed spectra

As important as the percentage of accurate predictions is to state that not only the levels in scale A are predicted in a reasonably adjusted way, but particularly that

	Number of cases	Cases in ±3 dB	
		Number	%
d closer than 750 m	30	24	80
d further than 750 m	18	14	78
Total	48	38	79

Table 4.
Quality of results according to distance to the wind turbine.

	Number of cases	Cases in ±3 dB	
		Number	%
u lower than 6.5 m/s	12	10	83
u higher than 6.5 m/s	36	28	78
Total	48	38	79

Table 5.
Quality of results according to wind velocity at the hub height.

	Number of cases	Cases in ±3 dB	
		Number	%
d closer than 750 m, u lower than 6.5 m	8	7	88
d closer than 750 m, u higher than 6.5 m	22	17	77
d further than 750 m, u lower than 6.5 m	4	3	75
d further than 750 m, u higher than 6.5 m	14	11	79
Total	48	38	79

Table 6.
Quality of results according to distance to the wind turbine and wind velocity at the hub height.

the spectra obtained with the proposed model are also rightly adjusted to the measured ones [10].

Figure 5 shows some results for short and long distances. The blue bar is the measured sound pressure level; the pink bar is the computed sound pressure level using ISO 9613-2 with attenuation only due to geometric divergence and atmospheric absorption; and the dark red bar is the result of our prediction proposal. As it can be seen, our model achieves a good performance as a prediction tool.

5.2 Comparison with a nonnegative matrix factorization (NMF) estimation [18]

It is not usual to find references that use a variable depletion law according to the frequency.

We compared our attenuation curves with those presented in a paper published in 2021 [18]. The authors estimate the sound pressure level related to wind turbines with a nonnegative matrix factorization (NMF), a machine learning technique.

They present some attenuation filters in third-octave bands from 31.3 to 2000 Hz, for attenuation only and for attenuation considering three kinds of residual noise designed by the authors with basis on real noise samples. The filters were published in graphic format for three distances: 500, 1000, and 1500 m. We read the graphs and compared the attenuations proposed in [18] with the attenuation achieved for our prediction model in the same frequencies range.

The comparison was done using the Wilcoxon's test for differences between pairs. H_0 was the equivalence of the compared curves; accepting H_0 at 95% confidence means that our attenuation curves are equivalent to those from [18]. Test results are summarized in **Table 7**. We conclude that each one of our attenuation curves reasonably fit at least one case of the filters suggested by [18], the filter with residual noise 1 being the most similar to our proposal.

6. Summarizing our proposal for predicting sound pressure levels related to the operation of large wind turbines

Our proposed calculation process has two steps: at first, modeling the noise generation and its propagation in the short scale (less than 100 m); and propagating the output of the first step from short to large distances far away from the source. At the beginning of the process, the atmospheric stability class is to be taken into account by a correction to the wind velocity; this is very important, to avoid underestimations.

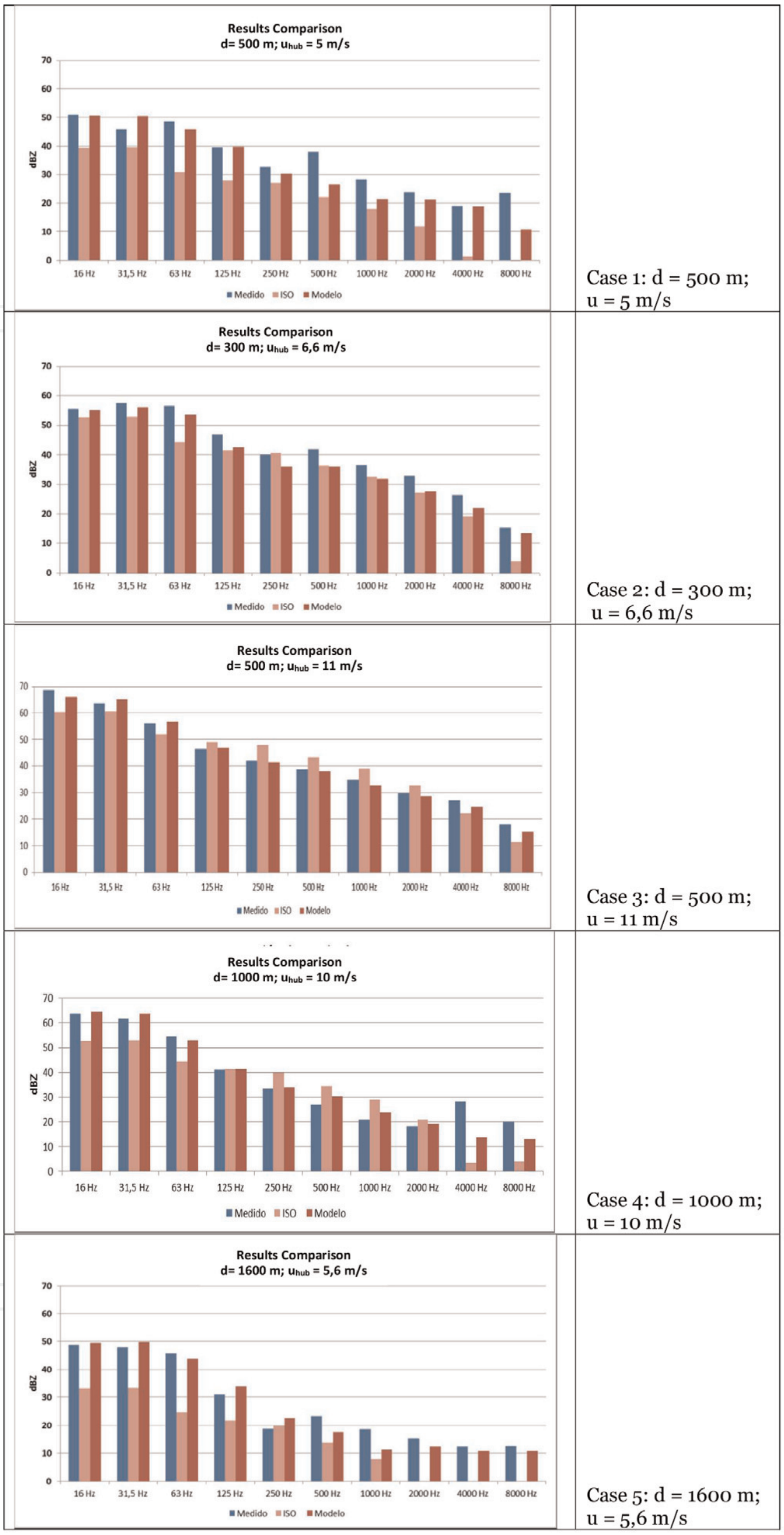

Figure 5.
Comparison of results; left bar: Measured sound pressure levels; center bar: ISO 9613-2 predicted sound pressure levels; left bar: Our prediction proposal. All sound pressure levels are in dBZ. (Adapted from [10]).

	Only attenuation	With residual noise 1	With residual noise 2	With residual noise 3
500 m, u less than 6.5 m/s	Accept H_0	Reject H_0	Reject H_0	Reject H_0
500 m, u 6.5 m/s or higher	Reject H_0	Accept H_0	Reject H_0	Reject H_0
500 m (all together)	Reject H_0	Accept H_0	Reject H_0	Reject H_0

	Only attenuation	With residual noise 1	With residual noise 2	With residual noise 3
1000 m	Reject H_0	Accept H_0	Accept H_0	Accept H_0
1500 m	Reject H_0	Accept H_0	Accept H_0	Accept H_0

Table 7.
Comparison between our attenuation curves and those from [18].

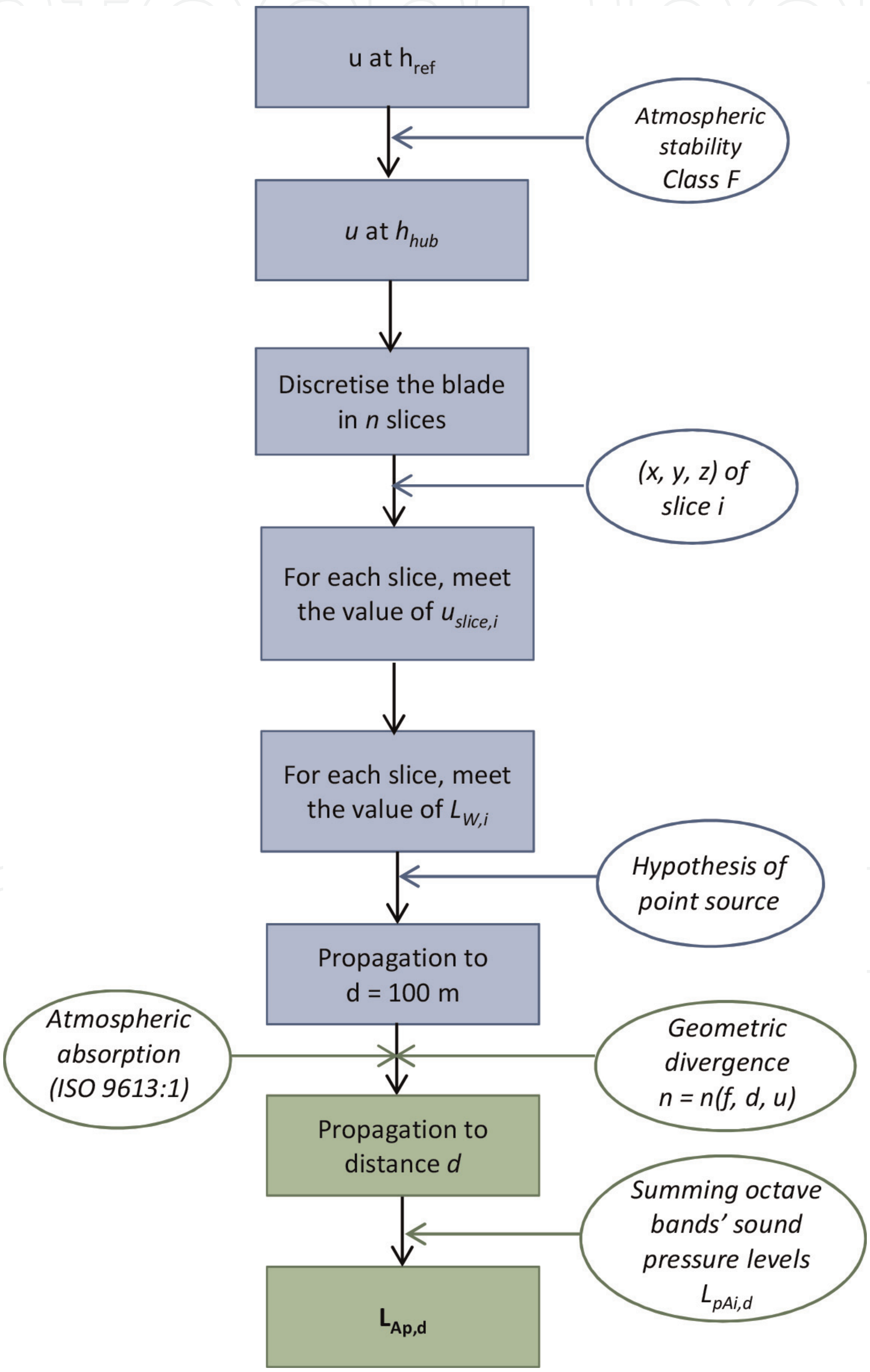

Figure 6.
Calculation process of this prediction proposal (adapted from [10]).

The first step of the calculation process divides the blade in infinitesimal length slices that behave as point sources, and for them the sound pressure level associated to the three mentioned generation processes for each source is calculated and summed logarithmically.

The propagation model takes into account the geometric divergence and the atmospheric absorption, considering n as $n(f_i, \text{d u})$. Our proposed "n" values have been presented in Section 3. The fact of not working under the usual hypothesis of environmental acoustics allows considering the coefficient "n" as variable.

Figure 6 shows a sketch of the procedure.

7. Final remarks

We presented an alternative proposal for predicting sound pressure levels from wind turbines. It is a simple method that has shown very good results, it is easy to build, and it does not need special hardware or software requirements.

The whole model was calibrated, validated, and verified, with field measurements made in different wind farms located in Uruguay. Field data for calibration and validation were taken at distances between 300 and 2000 m from the tower of the wind turbine.

Although this method can be used for different turbines, our results were obtained for 2 MW power rate turbines with between 80 and 90 m of hub height.

More, our prediction model seems to be a good one to be used in noise impact studies related to environmental impact assessments for getting the environmental license of wind farms before their construction.

We presented the accuracy of the predicted A-weighted sound pressure levels, which are good or very good in most of the cases; we also showed the obtained spectra fit accurately to the measured ones.

This fitting is more noticeable at low frequencies, the most problematic ones for noise phenomena in wind turbine, because the energetic content in those frequencies is potentially related to people's annoyance.

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Conflict of interest

The authors declare they have no conflict of interest.

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