Buenos Aires – 5 to 9 September, 2016
Acoustics for the 21st Century…

PROCEEDINGS of the 22nd International Congress on Acoustics

Environmental Acoustics & Community Noise: EN-444

Characterization of the sound spectrum of the wind regarding environmental studies, focused in wind energy devices

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Abstract

Wind energy is not only growing in Uruguay, but it is expected to continue increasing for many years. Environmental licenses are required for the installation of wind farms. In this frame, an accurate quantitative comparison of environmental conditions with and without power generation is needed a feedback for adjusting the design of measurement campaigns. Sound pressure levels were obtained in frequency bands of third-octave width under different conditions, in either places without wind turbines (data for the baseline characterization) and with wind turbines in different In this paper, the spectra of sound pressure levels of winds of different speeds are presented. They have been obtained by direct measurement both in wind tunnel and field. Both kinds of measurements allowed having operating situations. These measurements were complemented by other data performed in the wind tunnel of the Faculty of Engineering. It is a wind tunnel designed to simulate the atmospheric boundary layer, taking into account the characteristics of turbulence intensity, scales of turbulence and power spectra. Wind speed fluctuations need to be measured; the instrument used in wind tunnels to achieve these data is a hot wire anemometer at constant temperature. The most frequent winds in Uruguay are those from SW and NE. For the same wind speed, higher sound pressure levels occur when wind blows from the SW. Both the temporal evolution of sound pressure levels in scale A and in BTO respond to changes in wind speed. The main energy is found between 12,5 Hz and 630 Hz, with a ‘floor value’ of about 10 dBZ per band. For frequencies exceeding 630 Hz, negligible noise levels were found both in field and in laboratory. Thus, wind effects should be expected to occur for frequencies up to 630 Hz.

Keywords: wind turbines; environmental acoustics.

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1 Introduction

The main objective of this paper is to contribute to the characterization of the sound spectrum of the wind overlooking environmental studies, especially in the area of wind energy.

In Uruguay, all power generation projects with installed power greater than 10 MW should be subject of an Environmental Impact Assessment process that is regulated by Decree 349/005. In case of the project is classified in two of three categories, an Environmental Impact Study should be done. Wind farms are usually in one of those two categories and therefore typically require a sectorial Environmental Impact Study, focusing on three issues: impacts on birds and bats, landscape impacts and increase of environmental sound pressure levels. These potential adverse impacts must be carefully analyzed. In particular, the expected increase of environmental noise levels often leads to conflicts with local people from the moment it is disclosed the intention to carry out an enterprise of this kind, long before it has a physical presence. The comparison of the sound pressure levels with and without power generation, i.e. wind noise against noise from wind turbines in operation, allows to quantitatively analyze the acoustic impacts associated with management measures (e.g. changing the startup speed of the machines).

Several audible spectral noise compositions generated by winds of different speeds are presented. They were obtained from data of sound pressure levels in third-octave bands. The interest in these spectra is related to the growth of wind farms in Uruguay, which is expected to continue to increase in the next years. Achieving a methodologic proposal for applying these spectra in environmental studies associated with the installation of wind farms is another objective of this work.

2 Methodology and activities

Available data from measurements made previously by the team have been capitalized in this work. Three different set of data have been used:

- Wind tunnel measurements for different air flow speeds.
- Field measurements at 12 points more than 5 km away of wind turbines in operation.
- Field measurements at distances between 100 m and 1000 m from operating wind turbines.

2.1 Equipment

To carry out the measurements two sound level meters class 1 (B & K 2250 and Casella 633C) were used; an anemometer field (Extech EN-300), GPS and two laptops for field work.

The wind tunnel where the measurements were done belongs to the Institute of Fluid Mechanics and Environmental Engineering (IMFIA), University of the Republic. The anemometer of this wind tunnel has the following characteristics:

- Wide range from 0.5 cm/s speeds up to Mach 1
- Sensors: tungsten wires, 3.8 µm
- Platinum blades, 20 µm
- Length ~ 2mm

2.2 Theoretical background

To characterize the distribution of average velocity in height, a logarithmic / potential profile is used. The distribution of average speed in the sub rough sub-layer (see Figure 1) depends on the location of the site considered regarding the obstacles that produce roughness on the floor.

Source: Cataldo, 2016 [1]

Figure 1: Sub-layers of the boundary layer

This region covers from the ground to a height equal to 1.5 to 3 times the average height of the roughness elements. Above the roughened sub-layer extends the logarithmic sub-layer, in which the distribution of height average speed follows a law logarithmic type (equation 1).

$$U = \frac{u^*}{k} * Ln\left(\frac{Z-d}{Zo}\right) \quad (1)$$

- U: average speed at height Z
- u*: friction velocity
- Zo: roughness length (0.06 m)
- d: height displacement plane (for rural areas d=0)
- k: Von Karman constant (0.41)

To obtain the characteristics of turbulence intensity, scales of turbulence and power spectra, measurements of fluctuations of wind speed are required; to do them, the most used equipment in wind tunnels is hot wire anemometer to constant temperature.

A hot wire anemometer is a heated filament, which is exposed to a flow passage. This filament is connected to an electrical circuit that is able to monitor variations in electrical resistance by the action the of flow air. Then, a relationship can be established between the relevance flow rate and the resistance observed in the heated filament.

To extrapolate the wind records from the height at which the anemometers are in wind farms (66 m), a logarithmic profile was applied.

3 Available data

3.1 Measurements in the wind tunnel

Measurements were made for different air flow rates. In the IMFIA there is a wide experience in this kind of measurements.

The energy spectra were obtained from the records of wind velocity at the wind-tunnel. Then, they were used to determine the octave or third-octave band sound pressure spectra generated by the wind. For the purpose of simulating the behavior of the wind, average speeds of 3 m/s, 6 m/s, 7.5 m/s and 12 m/s were considered, that cover a typical range of average wind speeds.

3.2 Field measurements

Several sound pressure levels measurement campaigns were conducted during 2015 – 2016, at three different private companies which have large wind turbines (nominal power of 1.8 MW) in a hilly area. Records at several operating conditions of the machines at different speeds and wind directions were obtained.

Sound pressure levels records were taken at a 1.5 m height, simultaneously with records of wind speed and direction at a height of 10 m. Also, the records of wind speed and direction were obtained from the wind farm anemometer, located at 66 m height close to the wind turbines.

The measurement points covered four different geographic locations:

- A hilly zone, far from external sources such as people houses or roads, to avoid introducing disturbances in the measurements.
- A flat zone close to the sea, where 10 large wind turbines are installed. The choice was based on having a good accessibility to it and to do sound pressure measurements at different distances without the influence other wind turbines. Here, one of the sound level meters was located just under the wind turbine, thus obtaining a continuous recording for about 4 to 5 hours. The other sound level meter registered 30 minutes

every 100 m to 500 m; for greater distances, the operation of the second turbine, located at 1000 m from the equipment, could be perceived.

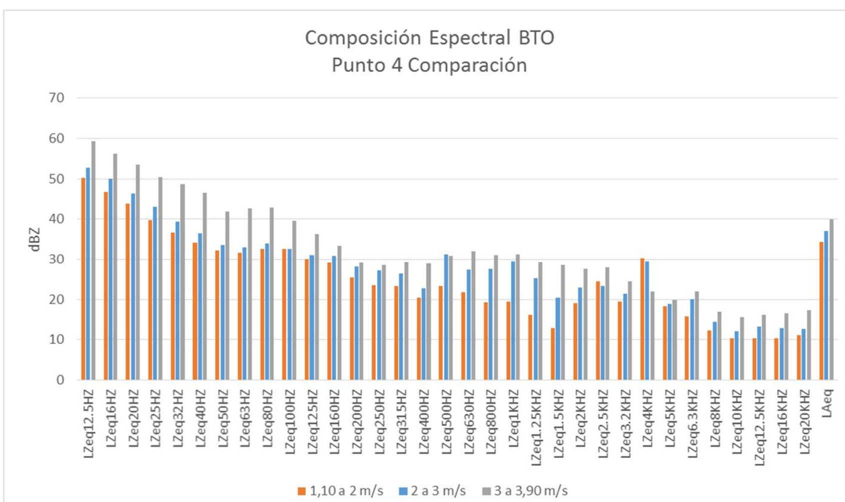
- Another flat zone where two wind turbines of 1.8 MW are installed. During the measurement campaign, both wind turbines were operating. In this campaign a long-term measurement was performed, placing one sound level meter about 250 m from the closest turbine and about 550 m from the second one. Also, measurements of 30 minutes were performed at 100 and 200 m from the first wind turbine (in this case, wind turbines are spaced approximately 400 m). Two records about 20 minutes long each, were obtained on a national way, located about 500 m from the turbines.
- A site close to a private company which has only one wind turbine. This feature makes it interesting for this study, since the records taken are not affected by other equipment or external sources that could disturb the measurements.

4 Main results

4.1 Main results in field

The most relevant results of the study in the different measurement areas are presented.

Eight points of area 1 were analyzed, in which simultaneously sound pressure measurements and measurements of wind speed and direction about 10 m high were performed. For Point 4 of this area, a range of wind velocity was obtained from 1 m/s to 4 m/s. In this analysis spectrum of following are compared: 1 m/s to 2 m/s, 2 m/s to 3 m/s and 3 to 4 m/s.

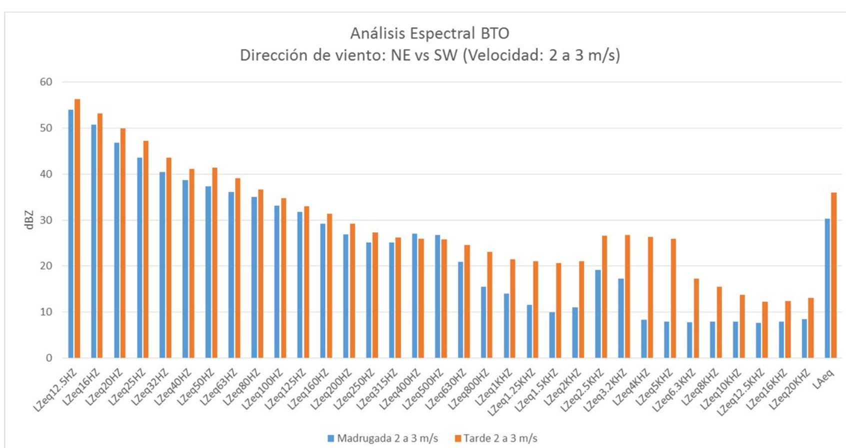


Source: González & Lisboa, 2013 [4]

Figure 2: Comparison of wind noise spectra for different wind speeds

In Figure 2, the obtained spectra in one-third octave band for two different wind directions are presented, comparing the three speed ranges mentioned. Comparing the generated spectrum for the velocity range of 3 to 4 m/s with the spectrum produced by the velocity range of 1 m/s to 2 m/s, there are differences of 10 dBZ to frequencies in 80 Hz; for bands between 100 Hz and 500 Hz the difference drops to 6 dBZ, whereas at bands 630 Hz to 1.5 kHz it increases to 12.5 dBZ. An opposite shape can be observed to the 4 kHz band: for the range of lower velocities, the sound pressure levels exceed the range of higher speed in 8 dBZ. This is related to the time of the day; as the lower speeds take place during the afternoon, when the ambient noise is higher, this difference could have been generated by an external source, such as birds. Velocities in the range of 3 m/s to 4 m/s occurred in the early morning, when ambient noise is usually lower. At higher frequencies, (5 kHz to 20 kHz) levels are very similar, and are below 20 dBZ in most cases; that means they are no detectable levels. Comparing the spectrum generated by speeds from 1 m/s to 2 m/s to that corresponding to a speed range of 2 m/s to 3 m/s, they have very similar shape, with slightly higher levels for the range with wind velocity between 2 to 3 m/s. Regarding A-weighted levels, the differences for the ranges of wind velocity between 1-2 m/s and 3 to 4 m/s are about 6 dBZ, while the difference between the range of wind velocity within the range of 2 to 3 m/s with the higher velocity range (3 to 4 m/s) is 3d BA. As for the wind direction during the measurement on point 4, the most frequent direction was the East.

In one of the measurement points of the first area, a particular situation occurred, in which over a period of time the prevailing wind direction was NE with speed in the range of 2 to 3 m/s, this measurement is compared with a record the same range wind velocity but from SW direction. Intending to verify the potential impact of the direction and velocity of wind in its spectral composition, it was decided to compare these two directions because, the SW is the direction of the winds of greatest intensity in Uruguay; it is wind usually related to cold air; NE winds (the most common ones), it is a warmer and wetter wind but with less intensity than the SW.

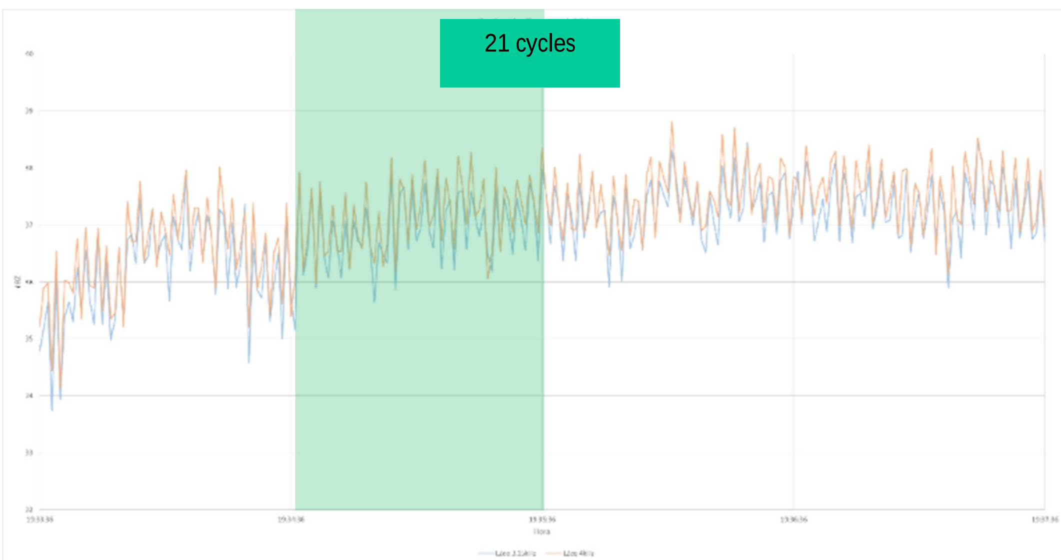


Source: González & Lisboa, 2013 [4]

Figure 3: Comparison of wind noise spectra for different wind directions: NE and SW

In figure 3, the graph of spectral analysis is presented in one-third octave band, comparing to the previous situation. One of the records was made during a morning where the prevailing wind direction was NE, while the other was in the afternoon, were the prevailing wind direction was SW. In this graph, you can see a slight difference of levels to the band 630 Hz inclusive, in which it has a difference of more 3dBZ for measurement performed during in the afternoon. From 800 Hz can be seen that have higher levels in the measurement performed during the afternoon, which is expected as early mornings noise in the environment is generally lower than during the day. This energy difference in the highest bands can be explained as they are related frequencies to birdsong. As for the level scale A, it is expected to be higher during the afternoon, and in fact in this case the level is 5.7 dBA higher.

By analyzing the recorded information every second, it was found that the frequencies of 3150 Hz and 4000 Hz have a behavior very similar to each other. These frequencies were related to the passage of each blade by the wind turbine tower. Such behavior could be verified in records taken up to 200 m from the wind turbine.



Source: Own elaboration

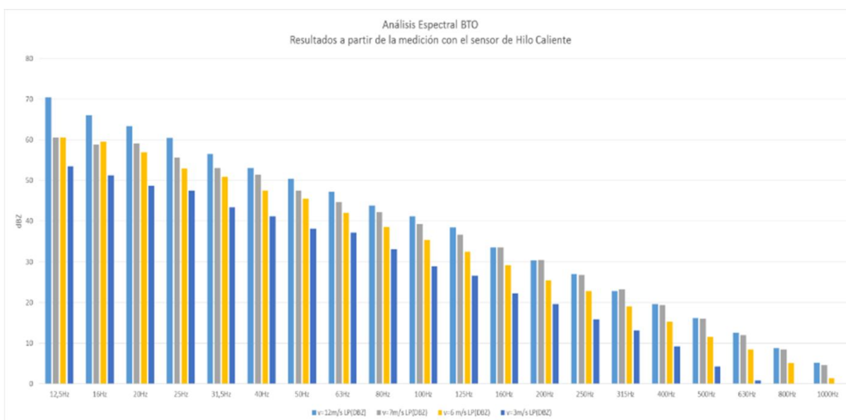
Figure 4: Time evolution of sound pressure levels in third-octave bands. Identification of the blade passage at a 100 m distance from the wind turbine.

In the graph of Figure 4, the time evolution of sound pressure levels is presented by third-octave bands. At the moment of this measurement, the turbine was rotating at about 9 RPM, since the passage of each blade by the tower was made every 2.9 seconds approximately; it is indicating that the blades (the three blades) pass by the tower 21 times in one minute. It can be observed that it is possible to count how many peaks occur in one minute of measurement e.g for the frequencies of 3150 Hz and 4000 Hz. This behavior was found in several of the records obtained at this study areas. In the case presented in Figure 4 (above), similar behavior can be observed at higher frequencies, but it is less clear as in the frequencies of 3150 Hz and 4000 Hz.

4.2 Wind tunnel results

Several tests were done in the wind tunnel in order to obtain the one-third octave band spectra generated by wind at different average flow velocities inside the tunnel. The method for determining those average velocities is to use an air mass sensor where the voltage variations needed to maintain the sensor temperature constant are registered. Once those variations are obtained, we apply the King´s Law for determining the average velocity. From the velocities obtained from each test, we get the energy spectrum, this is S (m^2/s^2/Hz) vs Frequency (Hz). From this spectrum we determined the sound power spectrum in one-third octave band for each test.

In Figure 5 the one-third octave band spectra obtained for the average velocities measured inside the tunnel are presented. The chosen velocities are: 3 m/s, 6 m/s, 7 m/s and 12m/s, equivalent to 10,8 km/h, 21,6 km/h, 25,2 km/h y 43,2 km/h respectively, and which are typical wind velocities.



Source: Own elaboration

Figure 6: Wind noise spectra by third-octave bands, measured at the wind tunnel

In the graph above, we can see that the spectrum is presented until the 1000Hz band, this is because for higher frequencies the energy values were extremely low. The spectrum shape seems to be the same for different wind average speed, also we can observe that the difference in dBZ between the spectrum generated by an average velocity of 12 m/s and one of 6 m/s is of 5 dBZ, while the average difference of level between the spectrum generated by a wind velocity of 3 m/s is approximately of 12 dBZ. The largest difference is found in the lowefefrequencies, as the case of the 12.5 Hz band where the difference is of 10 dBZ for the first comparison case, and a difference of 17dBZ for the second case. The spectrum generated by the wind at a velocity of 7.5 m/s is very similar to the spectrum generated by a 6m/s velocity. The level´s difference is larger starting at the 80 Hz band, from where the spectrum tends to be very similar to the one generated by a 12 m/s velocity.

5 Conclusions

- Based on the analyzed field records, it can be concluded that:

- Time evolution both for A-weighted and for one-third octave band, go along with wind variations, for all wind speeds.
- According to the spectra obtained from velocities of 1 to 2 m/s, 2 to 3 m/s and 3 to 4 m/s, for the same wind direction, all of them have the same behavior until the 630 Hz frequency.
- The wind velocity range from 3 to 4 m/s has higher sound pressure levels than others of lower velocities ranges in practically all of the one-third octave bands.
- The moment of the day in which the measures are taken is very important, as during the afternoon some disturbances exists, but they are not present during the night or the dawn.
- For the same wind velocity range (2 to 3 m/s) but for different wind directions (SW and NE) it could been verified that until de 630Hz band inclusive, there is a 3 dBZ difference in favor of the SW wind.
- For the same wind direction (E), when comparing 3 to 4 m/s and 1 to 2 m/s wind velocity ranges, there is a difference of 6 dBA in scale A levels, meanwhile for 12.5 Hz band to 2 kHz band inclusive, there is an average difference of 9 dBZ.
- As for the third-octave bands, it was verified that to 160 Hz frequency including the different levels are equal to or less than 5 dBZ for all records obtained at different distances. This is expected since both the wind direction and the wind speed range during this campaign had no significant variations, so this result attributed to these frequencies are related to the wind. The frequencies of 3150 Hz and 4000 Hz have a very similar behavior during their evolution; it is linked to each blade passage through the tower.
- In one of the measurement campaigns carried out in zone 4, it was possible to register two wind turbine operating conditions. For a period of time the wind speed was less than 3 m/s at hub height, speed which the turbine begins to stop, and for another period of time the wind speed was in a range of 4 to 5 m/s a the same height, in which the turbine was operating normally. Records taken in this campaign clearly show those frequencies that have higher variations with changing wind speed; these frequencies are the lowest, of 12.5 Hz to 160 Hz.
- As for the higher frequencies, linked to passage of the blades through the tower (3150 and 4000 Hz) at the time when the computer was turned off, they possess a randomic behavior, however the time when the starts generating wind turbine

begins to observe a stabilization in its evolution, increasing levels with increasing wind speed and observing the pulsations above.

• Based on the records from the wind tunnel, it can be concluded that:

The generated spectrum is presented for third-octave bands from 12.5 Hz to 1000 Hz. For higher frequency bands, energy values were really very small. For As it was expected, the higher the wind speed increased energy levels will occur and that is reflected in the spectrum by third-octave bands.

different wind speeds the shape of the spectrum is rather the same.
For an average wind speed of 3 m/s energy from 400 Hz and the upper bands is really negligible (less than 10 dBZ).

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