Wind Turbines Noise: Predictions and Measurements

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Abstract: Wind turbines noise generation is a complex phenomenon due to the effects of air interaction during the rotation of the blades and the noise emission is one of the problems encountered during wind turbines operation. The theoretical evaluation of noise propagation due to wind turbine is due applying the ISO 9613 standard. In this paper the numerical simulations of the noise propagation of wind towers are compared with the experimental measurements performed inside houses. The acoustic measurements were carried in two different houses. In the first case the house is located near a wind farm consisting of 3 MW towers. In the second case the house is located near a 200 KW wind tower. The application of the theoretical model according to ISO 9613 provides the interior of the houses a noise emission value equal to Lp = 37 dBA. The acoustic measurements provide a value exceeding even 50 dBA, a value that changes according to the speed and direction of the wind. The application of the numerical model underestimates the actual measured value.

Keywords: - Wind turbine, wind farm, noise propagation, house, ISO 9613, dBA.

1. INTRODUCTION

Wind energy gives a contribution to reducing the use of fossil fuels in the electricity production. In ancient times the first examples of wind exploitation to produce energy were the mills in Persia and later in the Middle Age this technology was introduced in Europe [1, 2]. Figure 1 shows old mills in North Europe.

Figure 1. Old mills in North Europe

Today, windmills can still be seen in Northern Europe, Southern Italy and Spain. The first industrial wind towers for electric production were built in the United States in the 1950s. Today, wind energy is the most competitive renewable energy source to produce electricity, with it both limiting the use of fossil fuels and reducing the effects of atmospheric pollution. It is, therefore, a rapidly growing market. In 1996, global wind power accounted for around 6,100 MW; while MW; while in 2017 it was about 540,000 MW. The areas with the most significant growth are Asia (with China and India), Europe and the United States.

Wind farms were initially realized in isolated areas, but continuous increased of investments have led to them being expanded thus creating numerous problems such as noise pollution [3-6]. In Italy the first wind towers in Italy were built in 1990 and within a decade, there was a significant increase in the number of wind farms.

Italy has a significant number of sites that could be suitable for the installation of wind farms, especially in the southern areas and on the islands, where there are strong winds. Wind towers have a horizontal axis with three blades and a nacelle (that rotates to face the wind) housing the gearbox and electronic equipment. Noise emission is one of the problems encountered during wind turbines operation. Wind turbines noise generation is a complex phenomenon due to the effects of air interaction during the rotation of the blades and the systems inside the nacelle [7-9]. The main noise components generated are: aerodynamic noise produced by the rotating blades (this noise tends to be broadband) and mechanical noise produced by the electromechanical parts (generator, turning over-gear, cooling systems and other components), but this component has a noise level lower than the first and a few dozen meters away, is not perceptible.

When the blade passes near the tower (a passage occurs on average every second), a variation of sound level is generated, it is defined amplitude modulation; those noise variations are the most important factors for the noise annoyance. People describe noise as a variation of the perceived sound level and show greater sensitivity "to modulated noise than to steady noise", and the effects of the amplitude modulations are the principal factor of the wind turbine noise. When compared to other noise sources, the degree of annoyance of sound from wind turbines is high. Major noise sources (road, rail, and air traffic, industry) in general do not cause severe annoyance below a sound pressure level of 40 dBA. At a sound pressure level of 50 dBA only 6% of the exposed residents are highly annoyed, whereas for wind turbines, severe annoyance occurs at lower levels below 40 dBA [10-12]. Figure 2 shows the comparison between the disturbance relationship for transport noise and noise generated by wind turbines detected with a series of noise measurements, with statistical surveys on the local population living closed to wind farms, compared to other anthropic noise (road traffic, trains, aircrafts). The noise generated by wind towers operation is considered more annoying than other anthropic noises.

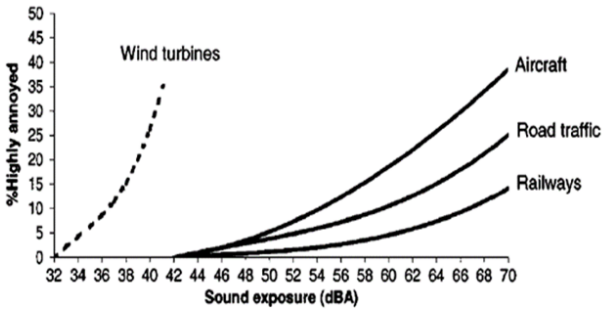

Figure 2. Comparison between the disturbance relationship for transport noise and noise generated by wind turbines

Usually the noise emitted by a wind turbine is a broadband noise and it is concentrated in the frequency range between 300 Hz – 2,000 Hz, in the interval in which the human ear is most sensitive and therefore the individual feels more discomfort. Figure 3 shows the comparison between the disturbance relationship for transport noise and noise generated by wind turbines. The acoustic measurements were carried out under different weather conditions as well as with different wind speeds and directions. Despite the sound levels measured near the houses not being excessive since they are of the order of 40 - 50 dBA, people living near the towers are annoyed by the noise generated by the particular sound components.

The same conditions were measured when the system was on and off. In this way, the noise due to the operation of the wind towers was evaluated. When the towers are off the measured equivalent sound level (LeqA) is about 30 dBA, while when the towers are operating the noise level is about 50 dBA. Although the turbine noise is produced in the outer part of the blades, in the simulation of the external sound according to ISO 9613 [13], the wind turbine is considered as a point source, so in this hypothesis the total sound energy is issued near the gearbox. With procedures expressed according to ISO 9613 were calculated the theoretical values of noise levels inside homes.

2. CASE STUDY

This paper describes a procedure to verify whether the ISO 9613 model applied to the theoretical simulation of the sound level at the receiver returns a value similar to the one measured.

As case study a wind farm that generates an annoying noise for people living nearby is considered. The sites under study is located in Southern Italy, where there is wind all year round with an average speed of about 8-10 m/s; only on a few occasions does the wind speed exceed 25 m/s (exceeding this speed, the rotation of the blades is interrupted so as to avoid any possible damage). The prevailing wind is from a south-west direction. For short periods of the year, the wind comes from the north. In the first case study the wind turbines are installed on a flat area, at about 1000 meters above sea level, on the Apennines.

The wind turbines are located within a few hundred meters of the homes. The wind farm has eleven turbines, with each turbine having a horizontal axis and a nominal power of 3.0 MW (Fig. 3). The towers are made of a single tubular post and a nacelle height of 90 m from the ground, equipped with three blades with a diameter of 112 m, average rotation speed 12 rpm. Figure 4 shows the aerial view of the wind farm indicating the positions of the towers and the surrounding residential buildings. The room in which the sound level meter was placed, is located on the first floor and has the following dimensions, height 3.0 m, width 2.0 m, length 3.0 m.

Figure 3. Wind turbine object of the acoustic measurements

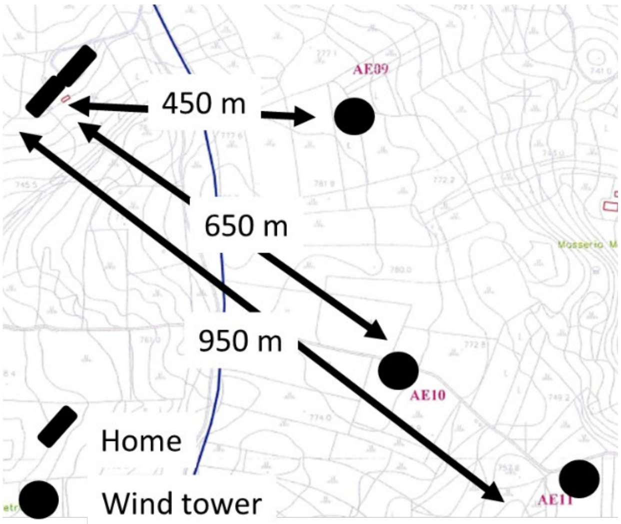

Figure 4. Aerial view of the wind farm showing the positions of the towers and homes.

Figure 5. Wind turbine object of the acoustic measurements

In the second case study the house in which the acoustic measurements were carried out is located in a small rural municipality. The area is a plateau within a large basin at about 700 meters above sea level, located in the central area in the South Italian Apennines. The height of the gearbox is 30 m, the rotor diameter is 20 m, and the blades rotation speed is 20 - 60 rpm (Fig. 5). The home is oriented along the north-south direction, the window from which the acoustic measurements were followed faces the east side, and the wind tower is visible from the window. The tower is located to the east of the house, and the land is flat and has modest vegetation. The distance between the home and the tower is 250 m (Fig. 6). The room in which the sound level meter was placed, is located on the first floor and has the following dimensions, height 3.0 m, width 3.2 m, length 3.6 m.

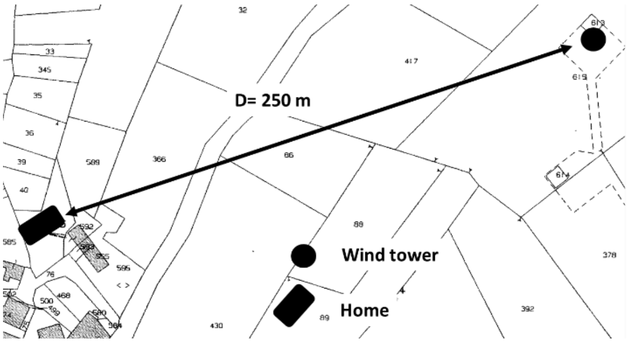

Figure 6. Aerial view of the measurement site.

3. CRITERIA FOR ASSESSMENT OF NOISE ANNOYANCE

The following regulatory approaches have been adopted to evaluate the annoyance produced by the operation of wind turbines in the living environment: [14, 15]:

- Differential criterion: the differential noise level is represented by the difference between the ambient noise level and the residual noise level. If the difference between the level of environmental noise (generated by the operation of the wind turbines) and the residual level (wind turbines turned off) is less than 5 dBA by day and 3 dBA by night, noise generation by wind turbines is considered negligible.
- Limit of the "normal tolerability". Background noise (L95) is evaluated when wind turbines do not work, and the equivalent level is evaluated when wind turbines are in operation. The normal tolerability limit is exceeded if the sound emissions exceed 3 dB the background noise. The background noise is the percentile value L95, that is the value that is exceeded 95% of the time, therefore equal to the almost minimum value of the instantaneous sound level.

4. SOUND PROPAGATION SIMULATION MODELS

One of the problems encountered during the installation of a wind tower is the theoretical assessment of the noise introduced into the living environment, as it is necessary to establish in advance whether the installation of the wind tower will cause disturbance to the people living in the chosen area. The most used model is based on ISO 9613-2: 2006 "Acoustics - Sound attenuation in outdoor propagation". This regulation considers the sound source points-forms. A wind turbine is a complex system that can be considered a point sound source only when there is a large distance between the source and the receiver. For the determination of noise levels inside a receiver point, the standard ISO 9613-2 provides a theoretical method to evaluate the sound attenuation, with the source - receiver distance, in outdoor propagation. The standard calculates the equivalent sound pressure level (Lp, dBA), assuming meteorological conditions that favor sound propagation (propagation downwind or in conditions of moderate inversion to the ground), by applying the following relationship:

Lp = Lw + DIθ - Adiv - Aatm - Agr - Abar – Amisc

Here:

Lp: sound pressure level (dBA);

Lw: sound power level (dBA).

Diθ: directivity; Adiv: attenuation due geometric divergence;

Aatm: attenuation due to atmospheric absorption;

Agr: attenuation due to the ground effect;

Abar: attenuation due to a barrier;

Amisc: attenuation due to foliage, industrial sites, housing.

The application of the calculation model of noise propagation appears to be precautionary, i.e., it provides an overestimation of the levels, when considering only the attenuation of the noise caused by the geometric divergence, not considering the other attenuating factors such as atmospheric absorption, as well as the presence of obstacles and vegetation. Numerical simulations based on engineering approaches are in many cases a rapid application. So, in a simplified way, the sound pressure level is given by the following formula:

- Lp = Lw – Adiv
- Adiv = 20 Log(D) + 11
- D is the distance between the sound source and the receiver.

4.1 First case study

As first case study is considered the towers distance from the home under investigation:

D= 450 m, D2=650 m and D3=950 m (Figure 1). Adiv is the sound attenuation (dB), which occurs during propagation from the sound source to the receiver. In this case:

Adiv1 = 20 Log(450) + 11 = 64.0 dBA

Adiv2 = 20 Log(650) + 11 = 67.2 dBA

Adiv3 = 20 Log(950) + 11 = 70.6 dBA

Lw is the sound power level (dBA), produced by the sound source: For a wind tower of nominal power of 3 MW, Lw = 104 dBA

So, the theoretical sound pressure levels emitted by a wind turbine, with the hypotheses of point source, according to ISO 9613, for each towers is:

Lp1 = Lw – Adiv1 = 104 - 64.0 = 40.0 dBA

Lp2 = Lw – Adiv2 = 104 - 67.2 = 36.8 dBA

Lp3 = Lw – Adiv3 = 104 - 70.6 = 33.4 dBA

The total sound pressure level in the receiver point is: Lptot = 42.2 dBA

With the ISO 9613 is possible to evaluate the sound pressure level at the receiving point located near a home. But for the evaluation of the disturbance inside the home it is necessary to estimate the effect of the attenuation of the open window, or the value of the difference between the sound level measured externally and the level measured internally in the home on equal terms. This value is reported by several authors and on average is estimated at around 4-5 dBA. Therefore, the sound level inside the house is equal to the sound level estimated in the receiving point subtracted from the attenuation value of the open window [16]. In this way we obtain a theoretical noise level emitted by a wind tower, inside the home, Lp=37 dBA.

4.2 Second case study

As the second case study is considered the tower distance D= 250 m (Figure 6). In this case Adiv is the sound attenuation (dB):

Adiv = 20 Log(250) + 11 = 59 dBA

Lw is the sound power level (dBA), produced by the sound source: For a wind tower of nominal power of 200 kW, Lw = 100 dBA.

So, the theoretical sound pressure levels emitted by a wind turbine, with the hypotheses of point source, according to ISO 9613, is:

Lp = Lw – Adiv = 41 dBA

Therefore, the sound level inside the house is equal to the sound level estimated in the receiving point subtracted from the attenuation value of the open window. In this way we obtain a theoretical noise level emitted by a wind tower, inside the home, Lp=37 dBA.

5. ACOUSTIC MEASUREMENTS

The following instruments were used: sound level meter LXT1 Larson Davis of "Class 1", calibrator Larson Davis CAL 200. The instruments used comply with the requirements of the standard IEC61672-2002. The sound level meters were configured to acquire the equivalent sound level of the linear sound, weighted "A", of the statistical levels with Fast constant time. The sound level meter was placed on the west side of building [17].

The sound level meter was installed on tripods, at a height of 1.40 m from the ground and 1.0 m from the window (the dimension are 0.8 m in width, 1.5 m in height). The room in which the sound level meter has been placed has the following dimensions (2.0 m in width, 3.0 m in length and 3.0 m in height). Only three towers are visible from the window of the room. The acoustic measurements were carried out with open window, which represent the maximum noise condition. The acoustic measurements were taken with the wind turbines both on and off, in order to evaluate, with the same wind speed, the noise contribution caused by the operating of the wind towers (ambient noise) as well as when they were off (background noise). The noise measurements were taken during autumnal, with average wind speeds between 8 m/s and 10 m/s. During the acoustic measurements, a series of previously agreed upon starts and stops were carried out. They were performed both when the towers were in operation and when they were turned off [18-22].

5.1 First case study

Figure 7 shows the time history of the sound pressure level during the measurement session.

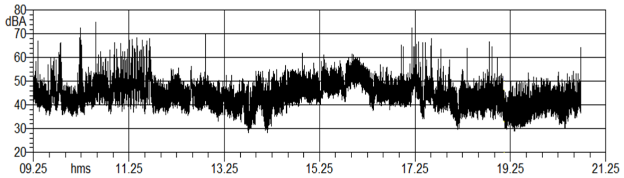

Figure 7. Time history of the sound pressure level during measurement session.

The time history shows a fluctuating trend to mean that the sound levels have recorded noisier conditions interspersed with quieter conditions. Since the surrounding environment has proved to be particularly quiet as no relevant anthropic activities have been detected, so the fluctuations of the levels are attributable to the different operating conditions of the wind farm.

Table 1 - Summary of the acoustic measurements.

Towers On	LeqA (dBA)	L95 (dBA)	Average wind speed (m/s)
Yes	44.5	38.5	8 - 9
No	35.0	31.0	9 - 10
Yes	52.0	48.0	10 - 11
Yes	43.0	36.0	9 - 10

From the time history is possible to identify the period in which the towers are not in operation, and therefore to go back to the value of the residual noise. Table 1 shows the values of the equivalent sound level weighted "A", the statistic level (L95) and the average wind speed for the different measurement intervals identified.

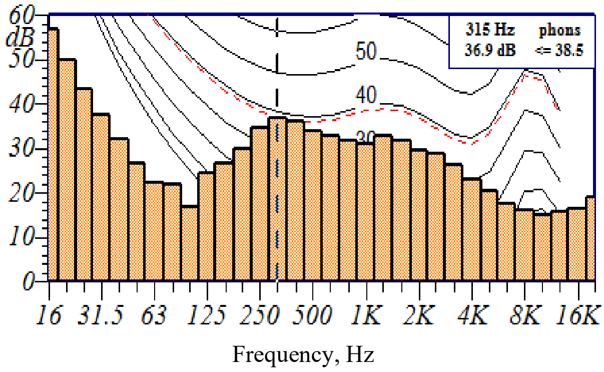

Figure 8. Minimum and average spectral levels in 1/3 octave bands between 16 Hz and 20 kHz.

Figure 8 shows the minimum spectral levels in 1/3 octave bands are used to identify any tonal components. In this case no tonal components were identified.

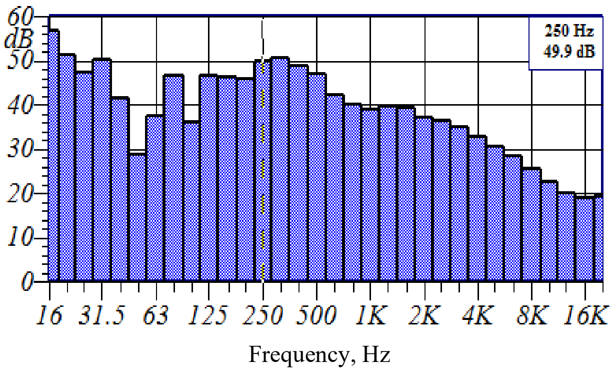

Figure 9. Average spectral levels in 1/3 octave bands between 16 Hz and 20 kHz.

Figure 9 shows the average spectral levels in 1/3 octave bands between 16 Hz and 20 kHz. The frequency ranges in which the maximum sound emission is found is between 125 Hz and 500 Hz. This time interval is the noisiest as all three turbines closest to the housing settlement have been in operation. In this way we were able to measure the environmental noise. In this time interval, the equivalent sound level weighted "A" measured was LeqA = 52.0 dBA, while L95 = 48 dBA, the difference between this two levels is only 4 dBA, in this way there is a little noise fluctuating.

To confirm the functioning of the towers, 1/3 octave bands analysis was conducted. Figure 9 shows minimum and average spectral levels in 1/3 octave bands between 16 Hz and 20 kHz. The condition of maximum sound emission corresponds to LeqA = 52.0 dBA. This condition represents the ambient noise. When wind changes speed, change also the noise measured inside home. In this time interval, the equivalent sound level weighted "A" measured was LeqA = 44.5 dBA and LeqA = 43.0 dBA. When all the turbines were turned off, it is possible to measure the background noise, which is equal to LeqA = 35.0 dBA, while L95 = 31 dBA. It is possible to establish that a difference of 18 dBA can be measured between towers on and towers off. Finally, it was considered the theoretical relationship for the evaluation of the noise introduced in the home due to the functioning of a tower, applying the ISO 9613 standard. In the hypothesis of point-sound source, it was found that the theoretical relationship gives a value of the sound pressure level of Lp = 37 dBA. Therefore, it underestimates the measured value of the sound pressure level inside the house. From the comparison with the theoretical values (ISO 9613), a difference of 13 dBA between measured and calculated values was obtained

5.2 Second case study

Figure 10 shows the time history of the sound pressure level during the measurement session. Figure shows the condition in which the wind turbine is in operating and when is stopped. While Table 2 shows the values of the equivalent sound level weighted "A", the statistic level (L95) and the average wind speed for the different measurement intervals identified.

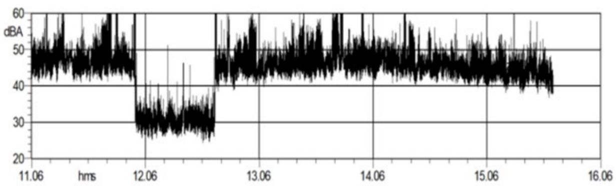

Figure 10. Time history of the sound pressure level.

Table 2 - Summary of the acoustic measurements.

Towers On	LeqA (dBA)	L95 (dBA)	Average wind speed (m/s)
Yes	44.8	39.5	8 - 9
No	32.2	22.5	8 - 9
Yes	48.0	46.0	12 - 11
Yes	50.0	47.0	15 – 12
Yes	41.0	38.0	8 - 7

Figure 11 shows the minimum spectral levels in 1/3 octave bands are used to identify any tonal components. In this case no tonal components were identified.

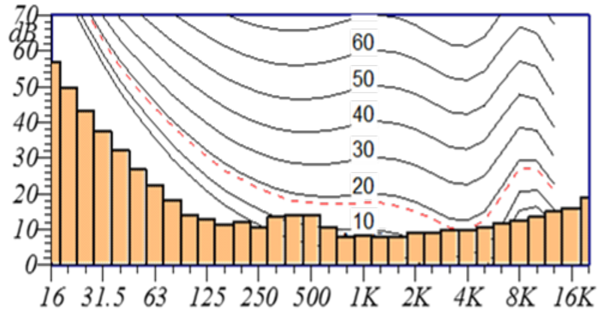

Figure 11. Minimum and average spectral levels in 1/3 octave bands between 16 Hz and 20 kHz.

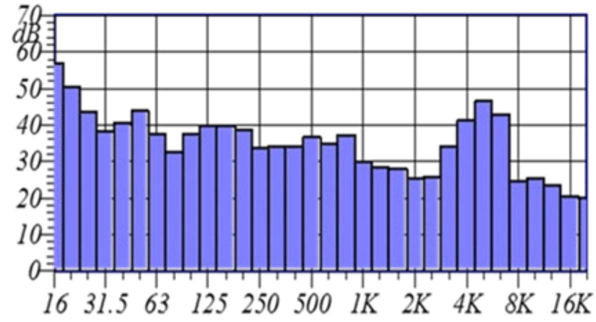

Figure 12. Average frequency spectrum of the measured sound levels in 1/3 octave band between (dB Lin), when the tower is on.

Figure 12 shows the average spectral levels in 1/3 octave bands between 16 Hz and 20 kHz. The noise emission is broadband, with an increase at the frequency of 4 kHz. When the wind turbine is off, the residual noise level, measured inside the home, is equal to 30 dBA, while when the wind turbine is on, the measured sound pressure level is equal to 45-50 dBA. The blade rotation speed is about 30 rpm.

The rotation of the blades is discontinuous, it depends from the instantaneous wind speed, and this generates an intermittent noise. Intermittent rotation with a speed of about 30 rpm can cause damage to the blade elements; moreover, for wind speeds in the range (6-10 m/s) in a range when the wind tower is not at the maximum power of electrical production, the noise generated is considered annoying. Finally, it was considered the theoretical relationship for the evaluation of the noise introduced in the home due to the functioning of a tower, applying the ISO 9613 standard. In the hypothesis of point-sound source, it was found that the theoretical relationship gives a value of the sound pressure level of Lp = 37 dBA. Therefore, it underestimates the measured value of the sound pressure level inside the house. From the comparison with the theoretical values (ISO 9613), a difference of 13 dBA between measured and calculated values was obtained

6. CONCLUSIONS

This paper reports the results of acoustic measurements inside houses near wind farms. The theoretical evaluation of noise propagation due to wind turbine is due applying the ISO 9613 standard. In this paper the numerical simulations of the noise propagation of wind towers are compared with the experimental measurements performed inside houses. The acoustic measurements were carried in two different houses. In the first case the house is located near a wind farm consisting of 3 MW towers. In the second case the house is located near a 200 KW wind tower. The application of the theoretical model according to ISO 9613 provides the interior of the houses a noise emission value equal to Lp = 37 dBA.

The acoustic measurements provide a value exceeding even 50 dBA, a value that changes according to the speed and direction of the wind. The application of the numerical model underestimates the actual measured value.

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