# Comparison Between Measured and Calculated Values in Relation to Noise From Wind Turbines

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## Abstract

The noise from wind turbines is generally assessed according to ISO 9613 in order to preserve the internal noise levels of the nearest sensitive receptors. Following the standard requirements, the wind turbines are considered point sources with an attenuation decay equal to 6 dB by doubling the distance. These indications should be taking into account also the air absorption at different octave bands and the gradient effects due to outdoor environmental conditions. This paper deals with the comparison of some acoustic measurements carried out in Campania (Italy) with the theoretic outcomes obtained in line with the standard ISO 9613. Different types of wind turbines have been assessed, based on a variety of power supply, distance between source and receiver and gradient of wind speed and direction. The surveys have been undertaken inside the nearest sensitive receptors with the conditions of open windows. The results highlight a drift between results, where the calculated are found to be lower than the measured-on site, underestimating the real environmental conditions.

## 1. Introduction

Wind energy contributes significantly to reducing the use of fossil fuels in the production of electricity, having the benefit of little surface area of occupation. The first wind towers built for the transformation of wind energy into electricity occurred in the United States during 1950s and thereafter it spread rapidly during the 1970s, following the fossil energy crises. Nowadays, wind energy is the most competitive renewable energy source to produce electricity, contributing to both limiting the use of fossil fuels and reducing the effects of atmospheric pollution. Therefore, it is considered a growing business market. The uprising growth at global scale can be translated in numbers as summarised in Table 1.

Table 1 – Global growth of wind power in the last decades

| Time | Wind Tower Production (MW) |
|---|---|
| 1996 | 6100 |
| 2001 | 24000 |
| 2017 | 540000 |

The areas with the most significant increase are Asia (China and India), Europe (especially France, Spain and Germany) and the United States. In Italy the first wind towers were built in 1990. Based on the geographical morphology, Italy has a significant number of sites suitable for the productivity of wind power, especially in the south and on the islands, where strong winds are dominant. Many wind farms have been built nearby existing residential properties, rising nuisance concerns for the occupants living in the surrounding areas (Sardaro et al., 2019; Shaheen et al., 2016). Noise emission by the operation of wind turbines is potentially causing sleep disturbance and other disease, depending on time of exposure and level of noise. According to the World Health Organization (WHO), limits from nuisance have been established in relation to night-time period (Guillemette & Larsen, 2012). In particular, thresholds of 40 dB(A) for outdoor areas and 30 dB(A) within bedrooms are considered the recommended limits to avoid sleep disturbance which may be potentially causing distress and having negative impact on health (Raman et al., 2016).

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Specifically, the noise coming from wind turbines is due to both the effects of air interaction during the blades rotation and the systems inside the nacelle (Wagner et al., 2012). As such, the components of the generated noise are the following (Zajamsek et al., 2014):

- Airborne emission due to the blades' rotation, characterised by a broadband spectrum; and
- Structural-borne emission produced by the electro-mechanical pieces, like the generator, turning over-gear, cooling systems and other components).

Based on a comparison between the two, the levels of the second type of noise are lower than the first one (Bowdler et al., 2011; Burton et al., 2001). By calculating predictions according to ISO 9613 (ISO) the wind turbines are considered as point sources, and the major contribution of the total sound energy is considered to be issued by the gearbox. Generally, the higher the electric power production, the higher the sound pressure levels emitted by a wind tower. By detailing the noise at the gear box, a variation of sound levels is generated whereas the blade crosses the pole during the rotation. This variation can be defined as an amplitude modulation and is one of the most important factors of annoyance since the human hearing is more sensitive to impulsive than steady (or tonal) noise (Doolan et al., 2012; Rogers et al., 2006; Van den Berg, 2004). When compared to other noise sources (e.g. aircraft, railways, etc.) the degree of annoyance of noise from wind turbines is consistent (Pedersen et al., 2004; Waye & Öhrström, 2002).

This paper deals with the acoustic measurements of noise generated by wind turbines of different power supply undertaken inside sensitive residential properties; the measured results have been compared with the outcomes of the numerical predictions calculated in accordance with ISO 9613 (ISO, 2006). The two main scenarios (with the noise source on and off) have been compared with each other and with the predictions carried out by model simulations (Krijgsveld et al., 2009; Ladenburg, 2009; Lee et al., 2011; Shepherd et al., 2011; Voicescu et al., 2016).

## 2. Sound Propagation Based On Simulated Predictions

The assessment of the acoustic impact generated by the operation of wind turbines is one of the concerns considered since the design phase. The predictions herein calculated have been assessed according to ISO 9613-2 (ISO, 2006; Wszołek et al., 2019), which considers the sound emission as a point source: a numerical model that can match the reality if the receiver is located at a large distance from the source. For the determination of environmental noise levels, the standard ISO 9613-2 provides a theoretical method to evaluate the sound attenuation based on free field conditions.

The calculation of the equivalent continuous sound pressure level ($L_{Aeq}$) is summarized in equation (1).

$$Lp = Lw + D_{i\vartheta} - A_{div} - A_{atm} - A_{gr} - A_{bar} - A_{misc} \quad (1)$$

where:

- $L_p$: sound pressure level, dB(A),
- $L_W$: sound power level, dB(A),
- $D_{i\vartheta}$: directivity factor,
- $A_{div}$: attenuation due geometric divergence,
- $A_{atm}$: attenuation due to atmospheric absorption,
- $A_{gr}$: attenuation due to the ground effect,
- $A_{bar}$: attenuation due to any barrier,
- $A_{misc}$: attenuation due to foliage, industrial sites, housing.

By simplifying equation (1) and considering the geometric divergence only, the sound pressure level becomes as indicated in equation (2).

$$L_p = L_w - A_{div} \quad (2)$$

where $A_{div}$ is calculated according to UNI ISO 9613-2, which is given in equation (3).

$$A_{div} = 20\ \log(d) + 11 \quad (3)$$

where $d$ is the distance between the sound source and the receiver. In line with the ISO 9613 (ISO, 2006), the sound pressure level at the nearest sensitive locations shall include the attenuation effect of the open window, or the difference between the sound levels measured outdoor and inside the building.

## 3. Acoustic Measurements

The acoustic measurements were carried out with a First-Class sound level meter LXT1 Larson Davis. The equipment was calibrated before and after the survey and no drift in calibration was noted. Sets of 5-minute were made at the 3-hour long term attended measurement locations, identified inside the nearest sensitive receptors. The measurements recorded overall A-weighted $L_{eq}$ and $L_{95}$ sound pressure levels, with the time averaging constant set to 'Fast' (Ciaburro et al., 2021). The sound level meter was installed on a tripod at a height of 1.4 m from the finish floor and a minimum of 2 m from any vertical surface. The acoustic measurements were carried out under the condition of having open window. The noise levels have been recorded for wind turbines in operation and out of any activity, in order to assess, under the same wind speed condition, the noise contribution from the wind farms in operation against the background noise levels without any activity running (Iannace, 2016; Iannace et al., 2019a; Trematerra & Iannace, 2017).

### 3.1 First Case Study

The first measurement campaign has been conducted in autumn, with a relative humidity equal to 50 %, a temperature around 10 °C, and a wind speed averaging between 8 m/s and 10 m/s, from South-West direction (Iannace et al., 2019a; Iannace et al., 2019b). With wind towers provided with 3.0 MW power supply. The rotation speed is about 12 rpm. The microphone was installed in a room having dimensions of 2 × 3 × 3 m (W, L, H). Given the different orientation, the wind turbines were operating singularly during the survey, such that each contribution has been calculated singularly (Iannace et al., 2020). The measured equivalent sound pressure levels at the receiving positions have been summarized in Table 2.

Table 2 – Measured results related to the first case study

| Activity of Wind Towers | $L_{eq}$ (dBA) | $L_{95}$ (dBA) | Average wind speed (m/s) |
|---|---|---|---|
| On | 45 | 39 | 8 - 9 |
| Off | 35 | 31 | 9 - 10 |
| On | 52 | 48 | 10 - 11 |
| On | 43 | 36 | 9 - 10 |

Table 2 indicates that the noisiest condition occurs when the wind speed fluctuates around 10-11 m/s; in this case the equivalent sound pressure level is equal to $L_{eq}$ = 52 dB(A). With similar wind speed conditions (9-10 m/s), when the wind turbines are off, the background noise level drops to $L_{eq}$ = 35 dB(A), up to 17 dB below. By comparing the sound pressure levels measured at the nearest sensitive receptor and the predictions as outlined by the standard requirements, it is possible to calculate the sound pressure level for each distance of the three towers from the receiver. Considering the distance of each wind tower equal to 450 m, 650 m, and 950 m, that a nominal power of each wind turbine is 3.0 MW (equivalent to $L_W$ =104 dB(A)), the predicted sound pressure levels emitted by a wind turbine according to ISO 9613 are summarised in Table 3. A total predicted equivalent sound pressure level at the receiver location would be equivalent to $L_p$ = 42 dB(A). Additionally, the effect of the open window shall be counted to be around 4-5 dB. Therefore, the sound level inside the sensitive receptor is equal to $L_p$ = 37-38 dB(A), meaning that the regulation underestimates the overall value if compared with the measured results.

Table 3 – Predicted noise levels according to ISO 9613. First case study

| Distance of the Towers from Receiver | $A_{div}$ values (dBA) | $L_p$ values (dBA) |
|---|---|---|
| 450 | 64 | 40 |
| 650 | 67 | 37 |
| 950 | 71 | 33 |

## 3.2 Second Case Study

This second acoustic survey deals with wind towers provided with 60 kW power supply. The tower is located about 250 m from the nearest sensitive receptor, and it is composed of a 40 m high pole and three blades. The rotation speed is about 30 rpm. The rotation is discontinuous because it depends on instantaneous wind speed, that therefore generates an intermittent noise. The measured equivalent sound pressure levels at the receiving positions have been summarized in Table 4.

Table 4 – Measured results related to the second case study

| Activity of Wind Towers | $L_{eq}$ (dBA) | $L_{95}$ (dBA) | Average wind speed (m/s) |
|---|---|---|---|
| On | 45 | 40 | 8 - 9 |
| Off | 32 | 33 | 8 - 9 |
| On | 48 | 46 | 11 - 12 |
| On | 50 | 47 | 12 - 15 |
| On | 41 | 38 | 7 - 8 |

When the wind turbine is not in operation, the background noise level measured inside the sensitive receptor is equal to $L_{eq}$ = 32 dB(A), while results of the wind farm in operation is between $L_{eq}$ = 41 dB(A) and $L_{eq}$ =50 dB(A). Considering the theoretical methodology based on ISO 9613 standard, with a distance equal to 250 m, the sound attenuation indicated in equation (4) is the following.

$$A_{div} = 20 \log(250) + 11 = 59\ dB(A) \tag{4}$$

The nominal power of the wind turbine is 60 kW (equivalent to $L_W$ = 100 dB(A)); as such, the predicted sound pressure levels emitted by a wind turbine considered a point source in accordance with ISO 9613 is given in equation (5).

$$L_p = 100 - 59 = 41\ dB(A) \tag{5}$$

By applying a further attenuation for the open window equal to 4 dB, the predicted noise levels is $L_p$ =37 dB(A). For this second case study, the methodology outlined by the standard underestimates effective noise level and highlights a difference of up to 13 dB between the maximum measured results and the calculated value.

## 3.3 Third Case Study

The third acoustic survey has been performed inside a sensitive receptor that is 250 m distant from the wind towers. With wind towers provided with 1.0 MW power supply. A South-West wind direction has been recorded to have a speed of approximately 8-9 m/s. The rotation speed of these blades is equal to 15 rpm. The measured equivalent sound pressure levels at the receiving positions have been summarized in Table 5.

Table 5 – Measured results related to the third case study

| Activity of Wind Towers | $L_{eq}$ (dBA) | $L_{95}$ (dBA) | Average wind speed (m/s) |
|---|---|---|---|
| On | 45 | 31 | 8 - 9 |
| Off | 33 | 31 | 8 - 9 |

Table 5 indicates that when the wind turbine is in operation the equivalent sound pressure levels measured inside the sensitive receptor is equal to $L_{Aeq}$ = 45 dB(A), with a difference of 12 dB by considering the quiet condition (i.e., background noise level). Considering the theoretical methodology based on ISO 9613 standard, with a distance equal to 250 m, the sound attenuation is similar to what calculated in equation (4) to be equal to $A_{div}$ = 59 dB(A). The nominal power of this wind turbine is 1.0 MW, which is equivalent to $L_W$ = 104 dB(A). Based on these values, the predicted sound pressure level emitted by a wind turbine considered a point source in accordance with ISO 9613 is given in equation (6).

$$L_p = 104 - 59 = 45\ dB(A) \tag{6}$$

By applying a further attenuation for the open window equal to 4 dB, the predicted noise levels is $L_p$ = 41 dB(A). Similarly, this third case study highlights an underestimation of the predicted calculations of 4 dB compared to the measured value.

### 3.4 Fourth Case Study

The fourth acoustic survey has been performed inside the nearest sensitive receptor located 200 m from the wind farm. With wind towers provided with 1.0 MW power supply. The North wind direction has been recorded to have a speed equal to 15 m/s. The rotation speed for this wind turbines is equal to 15 rpm. The acoustic measurements were performed by placing the microphone in a room facing the wind turbines, with the window open. The measured equivalent sound pressure levels at the receiving positions have been summarized in Table 6 (Berardi et al., 2020).

Table 6 – Measured results related to the fourth case study

| Activity of Wind Towers | $L_{eq}$ (dBA) | $L_{95}$ (dBA) | Average wind speed (m/s) |
|---|---|---|---|
| On | 52 | 49 | 15 |
| Off | 44 | 40 | 15 |

Table 6 indicates that when the wind turbine is in operation the equivalent sound pressure levels measured inside the sensitive receptor is equal to $L_{Aeq}$ = 52 dB(A), with a difference of 8 dB by considering the quiet condition (i.e., background noise level). Considering the theoretical methodology based on ISO 9613 standard, with a distance equal to 200 m, the sound attenuation expressed in equation (7) is given as follows.

$$A_{div} = 20\ \log(200) + 11 = 57\ dB(A) \tag{7}$$

Having a nominal power of 1.0 MW, which is equivalent to $L_W$ = 104 dB(A) the predicted noise levels based on theoretical concepts is given in equation (8).

$$L_p = 104 - 57 = 47\ dB(A) \tag{8}$$

With the open window attenuation, the final predicted noise level emitted by the wind turbine is equal to $L_p$ = 43 dB(A). On this basis, it has been demonstrated that a difference of 9 dB has been found between measured and estimated values.

### 3.5 Fifth Case Study

The fifth acoustic survey has been performed inside the nearest sensitive receptor located 450 m from the wind farm. With wind towers provided with 1.0 MW power supply. The North wind direction has been recorded to have a speed around 6-8 m/s. The rotation speed of the blades is equal to 11 rpm. The acoustic measurements were performed by placing the microphone in a room facing the wind turbines, with the window open. The measured equivalent sound pressure levels at the receiving positions have been summarized in Table 7.

Table 7 – Measured results related to the fourth case study

| Activity of Wind Towers | $L_{eq}$ (dBA) | $L_{95}$ (dBA) | Average wind speed (m/s) |
|---|---|---|---|
| On | 40 | 37 | 6 - 8 |
| Off | 35 | 31 | 6 - 8 |

Table 7 indicates that when the wind turbine is in operation the equivalent sound pressure levels measured inside the sensitive receptor is equal to $L_{Aeq}$ = 40 dB(A), with a difference of 5 dB by considering the background noise level. Considering the theoretical methodology based on ISO 9613 standard, with a distance equal to 450 m, the sound attenuation expressed in equation (9) is given as follows.

$$A_{div} = 20\ \log(450) + 11 = 64\ dB(A) \tag{9}$$

Given the nominal power produced by the sound source equal to $L_W$ = 104 dB(A) the theoretical sound pressure level emitted by a wind turbine according to ISO 9613 is summarised in equation (10).

$$L_p = 104 - 64 = 40\ dB(A) \tag{10}$$

With the additional open window attenuation, the final predicted noise level emitted by the wind turbine is equal to $L_p$ = 36 dB(A). On this basis, it has been demonstrated that a difference of 4 dB has been found between measured and estimated values.

## 4. Discussion

Different campaigns of measurements have been carried out inside sensitive receptors near to the wind farms. The nominal power of the wind turbine varied from 60 kW, 1.0 MW to 3.0 MW. The surveys were carried out in rooms having similar volume size and with the window open, with the microphone directly facing the sound sources. This paper has demonstrated that the difference between measured results and predicted values calculated in accordance with ISO 9613 is consistent, to be up to 13 dB. From the five case studies it has been shown how the predicted values are lower than the measured results therefore underestimating the effective impact that the wind farms have on the sensitive receptors. The effects of the disturbance due to the noise perceived inside the houses is a function of the difference in the noise level measured when the wind turbine is off or in operation. If from the analysis of the acoustic measurements between the sound source switched off or in operation, a difference is detected then we are in the presence of a disturbing noise, that is generates annoyance. It may happen that for wind speeds above 15 m/s the wind noise covers the noise emitted by the wind turbines, in this condition the noise emitted by the wind turbines is not perceived by the people living inside the houses, but this is a condition limit that happens a few times.

## 5. Conclusions

The theoretical assessment of the noise propagation from wind turbines in operation has been performed in accordance with the ISO 9613 standard requirements. The predictions are based on the simulation of a wind turbine as a point source and on the open window attenuation. The variety of case studies, characterised by different distance between source and receiver, has demonstrated that the predictions underestimate the effective noise levels of the wind farms as they have been measured on site. One of the main factors that the regulation shall take into account is the wear of the rotating elements that is cause of an increase of noise levels compared to the initial assessment carried out in laboratory conditions, before the wind farms are installed. This outcome highlights the limits of the existing regulation (ISO 9613) that shall be implemented with further considerations in order to produce results to be close to the acoustic measurements.

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