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ABSTRACT
The ISO9613 Standard is commonly used for noise mapping of wind turbines. This guideline is not a perfect solution as no wind turbine is a typical industrial source and ISO9613. It was written without taking into consideration such high sources (>90m) where the main noise comes from blade tips cutting air. Following the ISO9613 Standard a wind turbine can be characterized as a point source located at a nacelle height (>90m). To assess possible maximum impact of a wind farm, maximum sound power level (>100dB), which is reached at wind speed >8m/s, should be taken into calculations. In contradiction to maximum power level used when modelling is methodology for regular measurement of noise at dwelling areas - wind speed at 4m must not exceed 5m/s as wind stronger than 4 m/s has a real influence on measurements. The Assessment of noise impact by wind farms is complicated as modelling and measurements have conflicting requirements. The new CNOSSOS-EU guideline does not help to solve this situation and wind turbines are not treaded separately from any other industrial sources. Results are quite similar, however, wind turbines seem to be quieter under new regulations.

Keywords: Wind turbines and wind farms, international standards

Wind turbine – industrial construction for electricity production
By the word wind we understand air movements causing reciprocal movement of air masses of the earth's atmosphere. A vital role in wind formation is played by the uneven heating of the earth's surface by the sun and the differences in terrain level. Description of the wind in meteorology is determined by two variables: wind speed – given in m/s or km/h and direction which is often given in degrees.

A wind turbine is used to convert kinetic energy of blowing wind into electricity. The main elements of a modern wind turbine are: the rotor and the nacelle, both placed on the tower. The most important part is the rotor of a wind turbine responsible for conversion of wind energy into mechanical energy. It is mounted on a shaft driven by a generator. The rotor usually rotates at a speed of 15-20 rpm while the typical asynchronous generator produces electricity at speeds over 1500 rpm.

Therefore, it is necessary to use the gearbox to increase the speed. Gearless mechanisms utilizing a ring generator are used in some turbines. Three-blade rotors, constructed of fiberglass reinforced with polyester, are the most common. In the rotor’s hub a servomechanism allowing you to set the blade’s angle (pitch) is installed. The nacelle must be able to rotate 360 degrees so it can always be set against the wind.

An engine, which can turn the nacelle with the help of a gear, is installed at the top of the tower. For small turbines, where the mass of the nacelle is relatively small, setting against the wind enables a directional rudder integrate with the nacelle. A special microprocessor system manages the process of blades adjustment on the base of input data (eg. wind speed and direction). What is more, inside the nacelle there are: a transformer, bearings, lubrication systems and a brake which stops the turbine in case of emergency situations.

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Wind turbine, like every technical device, emits noise which in case of wind turbines is characterized by continuity in time, monotony and low intensity that can adversely affect the human psyche.

Noise emitted by a wind turbine may come from two sources:

1. The noise of mechanical origin - created through the work of a generator, a gearbox and a rotor. Due to efforts made to reduce noise pollution many large power plants are currently produced as gearless machines. Therefore, the wind turbine as a point source of mechanical origin can be heard only in close vicinity (usually up to 150 m) and is indistinguishable from the background noise (among others: wind noise) from a farther distance.

2. The noise of aerodynamic origin - formed as a result of the rotation of rotor blades which are doing the rotation and overcome the aerodynamic drag. This noise is a broadband noise with a spectral density of acoustic energy, rather uniform in the audible frequency bands [Wind Power, Current possibilities of the use - T. Boczar].

Picture given below shows measured values of sound pressure levels for each element of 2 MW wind turbine and the two paths for noise emission: air - borne ("transmitted through the air") and the structure - borne (transmitted by the structure);

a) "transmitted through the air" (called Air-borne, marked a/b) - means that the noise propagates directly from the surface of elements or in the air;

b) "transmitted by the structure"(called Structure-borne, marked s/b) - noise emission is
generated by other structural components before it is absorbed by air.

The sound power level of an individual wind turbine, due to the significant contribution of aerodynamic noise, is closely related to wind speed at which the turbine operates.

1. **The ISO9613-2 Standard used for wind turbines**

The ISO9613-2 Standard is used for noise mapping of wind turbines around Europe as no other standard has been developed to prognose the impact of noise originating from planned wind turbines (wind farms). This standard was recommended in the Directive 2002/49/EC of the European Parliament and the European Council on 25 June 2002. The directive concerns evaluation and control of environmental noise as the valid standard in the performance of calculations and predictions of acoustic impact of industrial plants and other sources on the acoustic climate of the environment.

The ISO9613-2 Standard was designed for typical industrial sound sources (machines or plants) with noise emitted independently on environmental conditions. Typical industrial sound sources are plants with machines, cooling fans, air conditioning systems inside.

According to ISO9613-2 Standard any sound source has to be represented by an elementary (point) source. Octave bands are limited to 8 bands (from 63Hz to 8kHz). Along with the ISO1996-2 Standard :1987 a wind speed at height 3m-11m should not exceed 5m/s.

It is quite difficult to compare an industrial wind turbine (2,0-3,5MW) with industrial machines even though the mechanical noise, which comes from a wind turbine, is negligible - aerodynamic noise is leading. Aerodynamic noise produced by wind turbines is produced mostly by blade tips cutting air with high speed. Any additional changes in noise characteristics can be added by turbulences, material problems with a blade, blade tips, etc.

Wind turbines produce wide range frequency noise with dominant bands 250Hz, 500Hz, 1kHz.

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*Source: Tomasz Boczar – Wind Energy, Present possibilities of the use”*  
*Picture 3 Noise generated by individual elements of wind turbine*
Wind turbines reach maximum sound power level much higher than suggested limitation at the ISO9613-2 and ISO1996-2 standards (wind speed at height 3m-11m should not exceed 5m/s).

The ISO 9613-2 Standard which is a base for assessment of noise impact of wind turbines (wind farm) requires the following data to be implemented in order to be able to calculate the noise propagation outdoor:

- Terrain model – if necessary (very much dependent on local situation and landform)
- Sound power level of wind turbine represented by a total value or octave/third octave bands (preferably octave/third octave bands as it is much closer to reality).
- Height of a wind turbine
- Environmental conditions – temperature, relative humidity
- Ground absorption “G” factor assessment (in case of sound power level in octave bands) – disputable factor which have an influence on final results. No particular rules how to assess it.
- the factor should be taken between 0-1 (0 – hard ground like concrete, 1 – highly absorbing terrain – meadows). Especially for wind turbines which are located in rural areas with a lot of meadows, forests, arable lands, etc. where ground absorption factor changes with seasons
- Meteorological corrections Cmet

Source: www.enercon.com

**Picture 4 Octave bands for sound power level for different wind turbines**

**Picture 5 Sound power level vs wind speed**
1. **Noise modelling for wind farms in a software**

Modelling of noise impact from a wind turbine (wind farms) is nothing else but calculation of noise emission in a regular mesh converted into a colourful map (noise map).

Modelling software with implemented the ISO9613-2 Standard helps in such calculations but needs to be very well fed to receive reliable results (data for sound source, local weather conditions, landform).

The most important is data connected to a wind turbine. This is very complicated as the process of wind farm planning and installations takes about 5-7 years. This means initially accepted turbines are mostly changed into new constructions with better performance and efficiency. Any precise acoustical information about wind turbine taken into consideration at the very first stage is not valid after 2-3 years and the project is still in the middle of realization. This problem does not only refer to a wind turbine height or total value of the sound power level but also to data in octave/third octave bands. It is the same total value of sound power level but significant differences in low frequency bands and final results are totally different.

![Definition of the sound emission level](image)

**WT(108,4dBA)**  \[\begin{array}{l}
\text{Overall level dB:} [\text{A: 108.4, L: 110.6}]
\end{array}\]

**WT*(109,4dBA)**  \[\begin{array}{l}
\text{Overall level dB:} [\text{A: 109.4, L: 111.2}]
\end{array}\]

Source: Own elaboration on the base of Software IMMI 2015, Woelfel,
**Picture 6 Different octave bands for two wind turbines**
How to treat used wind turbines for new planned projects? They should not be treated as new turbines with sound power level taken from the catalogue but special measurements on the base of the EN61400-11 Standard (Wind turbine generator systems, Part 11: Acoustic noise measurement techniques) should be carried out to determine actual sound power level used later for noise propagation calculations.

Acoustic impact of wind turbines is closely related to weather conditions, i.e. temperature, humidity, wind speed (the higher speed, the higher sound power - to a certain level). Changes in temperature and humidity have a direct influence on a range of acoustic impacts. In most cases wind conditions are much better at night than during the day, thus the impact is greater at night than during the day. This dependence should be also reflected in long term meteorological correction Cmet, average temperature and average humidity.

Each year wind turbines become taller and more powerful (also referring to noise generation). Starting from towers 60m many years ago to 150m height now. Adding the length of blades turbines can exceed totally 200m height. Longer blades come to higher speeds of blade tips (generating more noise). This means that more power – up to 5-6MW electricity production, and more noise – sound power level reaching 108dB(A)-110dB(A), comes along with bigger turbines. If possible noise modelling of a planned wind farm should also be taken into consideration with these changes.
Longer blades rotating with the same rotational speed – 15-20 rpm leads to higher speed of blade tips and more aerodynamic noise.

Example:

Wind turbine – tower 90m, blade 45m, blade tip speed – 339 km/h
Wind turbine – tower 140m, blade 63,5m, blade tip speed – 478 km/h

The ISO9613 standard does not differentiate especially high located sound sources (120-150 m), sources with varying directions and varying sound power level dependent on weather conditions, sources moving along with wind direction, sources generating aerodynamic noise depending on blades rotational speed and condition of blades.

Noise modelling of wind farms accepts some simplifications to provide results which should be carefully verified when project is carried out.

For noise analysis of wind turbines we assume that wind turbine is a point noise source (to be able to use the ISO9613 Standard). It means, according to the ISO9613 Standard, each linear dimension of the source is less than half of the distance between the geometric center of the source and the nearest point of observation. This assumption neglects position of a blade tip but meets...
ISO9613-2 Standard requirement. For big turbines a blade tip rotates along the circle with diameter 120-130 m.

From the point of modelling view and standard requirements wind turbine (wind farm) should be considered as long term noise source instead of short term assessment (short term worst conditions).

Long term parameters for noise modelling are:
- Ground factor – carefully calculated that is based on local changing conditions and seasons during a year
- Average temperature (annual) – the latest data is not always available (sometimes only 30 years old data is available)
- Average humidity (annual) – the latest data is not always available (sometimes only 30 years old data is available)
- Wind turbine represented by omnidirectional sound source
- Meteorological correction – according to the Directive 2002/49/EC of the European Parliament and the European Council of 25 June 2002 or other approach if local conditions are special
- Average wind speed for a wind turbine whuch has direct influence on sound power level
- Wind calculations or annually averaged wind rises are implemented
- Wind turbine operating at the same sound power level during the day and the night

There are no rules or even reliable assessments how to calculate aging of wind turbines and possible changes in sound power level with time.

Reliable calculations are very important as results are the base for a location of wind turbines. Calculated noise impact must not influence noise protected areas. Reliable approach gives reliable results.

1. Noise measurements at wind farms

Environmental noise measurements of wind farms are difficult as appropriate standards are not designed for such industrial constructions as wind turbines.

The ISO1996-2 Standard limits wind speed during noise measurements to 5m/s measured at 3m-11m height.

Another suggestion is to verify if wind has significant influence on measurements. In most cases noise measurements on wind farms are short term measurements (maximum 1 day).

Here we can find first conflict as noise measurement should be limited to 5m/s measured at 3m-11m height but a wind turbine reach maximum sound power level at 8m/s-9m/s measured at 10m height. The difference in wind speed measurement at height 3m and 10m is not more than 1m/s. Moreover, from wind turbines manufacturers data as well as own experience appears that the difference in wind speed at 3m-4m height and a nacelle height is ca. 2m/s-3m/s.

Wind speed is a crucial factor for noise measurements as low wind speed is perfect for noise measurements but wind turbines do not reach full sound power level. On the other hand, wind speed above 4m/s with gusts, which is typical for open areas, has an influence on noise measurement but is problematic to determine and remove from measurements. This is more complicated for noise measurements with wind and wind speed more than 4m/s. This additional stress on the microphone membrane has a direct influence on measurements, impossible to be assessed reliably.

Some solutions to this problem provide protective foams but not all sound level meters have corrections for them and they are not calibrated with the system in most cases.

It seems that some solutions can bring long term noise measurement for wind farms with specialized equipment to find changes of noise impact in different weather conditions (varying wind speed, different wind directions, different temperature, relative humidity and changing vegetation with seasons). The noise measurement equipment should additionally allow for: raw data recording for further analysis, wind speed and direction logging, rain detection, etc. to be also able to trace changes in weather conditions). Of course results should be correlated with information about wind turbines production to find worst conditions for noise impact and compare them with measurement results.

Noise measurements should be carried out close to inhabited buildings. It is difficult as owners of acoustically protected plots do not allow for measurements in majority. The solution is to measure at the border of a protected plot and to check whether or not the same result can be reached for the buildings and the plot.
Noise modelling vs noise measurements at wind farms

Modelling, according to ISO9613-2, of noise propagation for wind turbines includes some simplifications for input data like omnidirectional sound source, wind speed 10m/s or more at which maximum sound power level is reached. Wind turbine sound source is represented by elementary (point) sound source. What is more, long term parameters like temperature and relative humidity are used and ground attenuation factor reflects annual averaging.

Noise measurements at wind farms carried out according to the ISO1996-2 Standard and national standards are mostly short term measurements with following rules: wind speed should not exceed 5m/s, direction of wind is only checked, aerodynamic noise should be measured, temperature should not be lower than -5°C, no rainfall is required, while season for measurements is meaningless.

Both modelling of noise propagation and noise measurement for wind turbines are prepared according to international standards: ISO9613-2 for modelling and ISO1996-2 for measurements but some simplifications and individual interpretations can result in overestimation or underestimation of noise assessment for wind turbines.

There have been no good practices written so far that could clear the way for modelling of noise propagation for wind turbines and then clear the way for noise measurements at wind farms. Modelling and measurements should correspond together and be able to verify each other but different approaches for modelling and measurements in most cases lead to incomparable results.

CNOSSOS-EU vs ISO9613-2 for noise propagation for wind turbines


The most important attenuation factors for wind turbines noise modelling are: $A_{div}$, $A_{gr}$, $A_{atm}$. These factors have a crucial influence on final results because the path between a source and a receptor is not disturbed by any barrier.

The method of calculation integrated in CNOSSOS-EU does not provide results in upward-refraction propagation conditions (negative vertical gradient of effective sound celerity). It provides results per octave band, from 63 Hz to 4 000 Hz. The calculations are made for each of the centre frequencies. The ISO9613-2 Standard allows for calculations from 63 Hz to 8000Hz. However, majority of energy from sound power level of a wind turbine includes in octave bands from 250Hz to 2000Hz.

In CNOSSOS-EU only the attenuations due to the ground effect ($A_{ground}$) and diffraction ($A_{dif}$) are affected by meteorological conditions.

Attenuation factors $A_{div}$ and $A_{atm}$ are calculated in the same way for CNOSSOS-EU and ISO9613-2.

Ground attenuation $A_{ground}$ in CNOSSOS-EU has a quite similar approach like $A_{gr}$ in ISO9613-2, additionally ground absorption factor $G$ is explained in more details and can be calculated according to a real change of the terrain type between the source and the receptor (assessed Gpath).
CNOSSOS-EU for industrial noise calculations used for wind turbines is not a revolutionary standard in comparison to ISO9613-2. There are no special calculations or factors used especially for wind turbines. Wind turbines need to be taken into calculations as any other industrial installations. On the other hand, better clarification of some factors for instance ground absorption factor can be found.
Conclusion

The ISO9613 Standard is not designed for such industrial constructions as wind turbines but there is no alternative for this type of noise sources at the moment. All simplifications according to the standard ISO9613 which are necessary for modelling of noise propagation for wind turbines are an individual approach of each acoustician who prepares such a project. His individual knowledge and experience has an influence on a final result. There are no good practices for modelling of noise propagation for wind turbines which could help in this process.

Input data for modelling of noise impact for wind turbines base on long term data and favourable conditions for noise propagation (worst conditions) to simulate noise propagation in long term conditions with maximum sound power level and wind blowing from the source to a receptor.

The ISO1996-2 Standard is also not designed for wind turbines and national standard in Poland prefers short term measurements for new investments but, similarly to ISO9613, there is no special standard for noise measurement on wind turbines. Companies with experience in wind turbines measurements attempt to find suitable weather conditions to be as close to 4m/s-5m/s of wind speed during measurements. However, it requires time and knowledge about how to interpret results and discard measurements with high wind influence.

Both modelling of noise propagation and measurement of noise for wind turbines are prepared according to international standards: ISO9613-2 for modelling and ISO1996-2 for measurements but some simplifications and individual interpretations can result in overestimation or underestimation of noise assessment for wind turbines.

Modelling and measurements should correspond together but different approaches for modelling and measurements in most cases lead to incomparable results.

New calculation methodology implemented in CNOSSOS-EU does not bring anything designed especially for modelling of noise propagation for wind turbines. It means that wind turbines are still in regular industrial machines basket.

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