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Noise from Wind Turbines
Measurement and prediction including low frequency noise

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Noise is a decisive factor when wind turbines are integrated in local communities. Therefore measurements and predictions have to be done as qualified as possible. Sound Power measurements and prediction are considered to be most precise in many countries. The newest version of the international noise measurement standard will be presented. Noise predictions will be discussed including the new Danish method for prediction of low frequency noise.

1 Introduction

As noise is a key factor in the process of integrating wind energy in the energy production, noise assessment is important. In many countries noise assessment is made through noise prediction according to standardised propagation models. For this type of assessment it is important to have a reliable noise prediction model and to have reliable input data for the prediction model. Around the world there is a general agreement that IEC 61400-11 is the most consistent and tested method for determining the sound power level of a wind turbine and is used combination with the propagation model ISO 9613-2 for prediction of noise from wind farms. ISO 9613-2 however is designed for sources at low altitudes and can lead to severe underestimation of wind turbine noise. Nord2000 appears to be a better choice. In Denmark a model for prediction of low frequency noise in-door has been introduced from 1. January 2012. This model is a simplified version of Nord2000 and includes standardised data for the noise insulation of Danish residences.

2 IEC 61400-11

The IEC 61400-11 have already changed several times since the first version published in 1998, [1], [2], [3] and [4]. The reason for this is the major changes in the technology and scale of wind turbines. The new version as described in [4] is intended to be more generic to avoid the need for rapid changes. The target is the large wind turbines but a separate annex is dealing with small scale wind turbines. In [6] Søndergaard gives an overview of the new version. The major changes between edition 2.1 and edition 3 are:

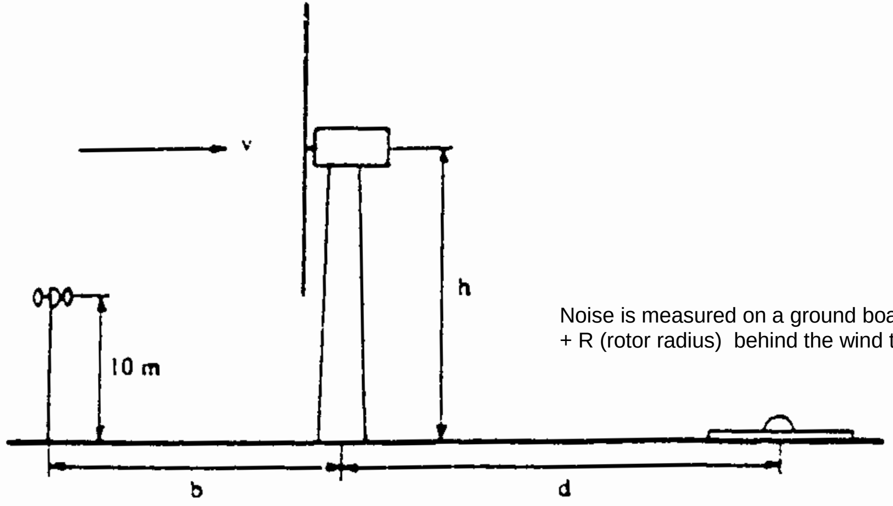
- Higher order regression analysis is replaced with bin-analysis and the bin size is changed from 1 m/s to 0.5 m/s.
- Analysis is based on 1/3-octavebands from 20 Hz to 10 kHz. All spectra are used.
- Averaging time is 10 s previously 60 s
- The reference wind speed is at hub height
- Detailed analysis of uncertainty on the results
- All spectra are used in the tonality analysis
- An annex for small wind turbines

The changes make the standard appear more complex than the previous versions but the entire measurement procedure is basically unchanged.

The analysis and reporting procedures are changed and in order to investigate the consequences of this, examples of tests of the method was presented in [7]. For simple situations the difference between results based on edition 3 and on edition 2.1 are small indicating the consistency of the standard. The frequency range required are 1/3-octave bands from 20 Hz to 10 kHz covering most of the low frequency range allowing for prediction of low frequency noise at the neighbours along with prediction of the normal frequency range from 50 Hz to 10 kHz.

2.1 The measurement setup

The measurement setup is shown in Figure 1 .



Wind speed from power and power curve and nacelle anemometer

Noise is measured on a ground board at d=h (hub height) + R (rotor radius) behind the wind turbine

Wind speed from mast mounted anemometer for background noise measurements. In edition 3 the anemometer is situated behind the wind turbine

Figure 1 Measurement setup according to IEC 61400-11

The setup of the measurements is unchanged and the required amount of data is almost unchanged. This means that the effort in making the measurements is almost unchanged. It is still the weather that determines the measuring time.

Basically the measurements are quite simple. Corresponding values of the noise and the wind speed at hub height are measured for the wind turbine running and stopped and the noise at the centre of bins 0.5 m/s wide is determined after correction for background noise. The noise is measured with the microphone on a ground board at a distance determined as the hub height and half the rotor diameter behind the turbine. Supplementary measurement positions at the same distance but at other directions are optional.

The wind speed is determined by measuring the produced power of the turbine and calculating the wind speed at hub height through a power versus wind speed curve for the wind turbine. For segments of the power curve where the slope is low, typically above 95% and below 5 % of rated power the wind speed measured by the nacelle anemometer is used. During the measurements the nacelle anemometer is calibrated against the wind speed determined through the produced power.

When measuring the background noise the wind speed is measured by a mast mounted anemometer typically at 10 m height. The mast mounted anemometer is also calibrated against the wind speed determined through the produced power. It is not allowed to use the nacelle anemometer during background noise measurements as the in-situ calibration is only applicable for the situation with the turbine running.

Even though this seems simple the discussion on determining the wind speed has been one of the major discussions in the standard from edition 1 and forward. Examples of measurement results are shown in plots from the Acoustica measurement and analysis system WT ver. 5.4.4. It can be seen that the regression curve is very sensitive at the ends of the dataset indicating that this type of analysis is not working well and that a bin-analysis will be more robust.

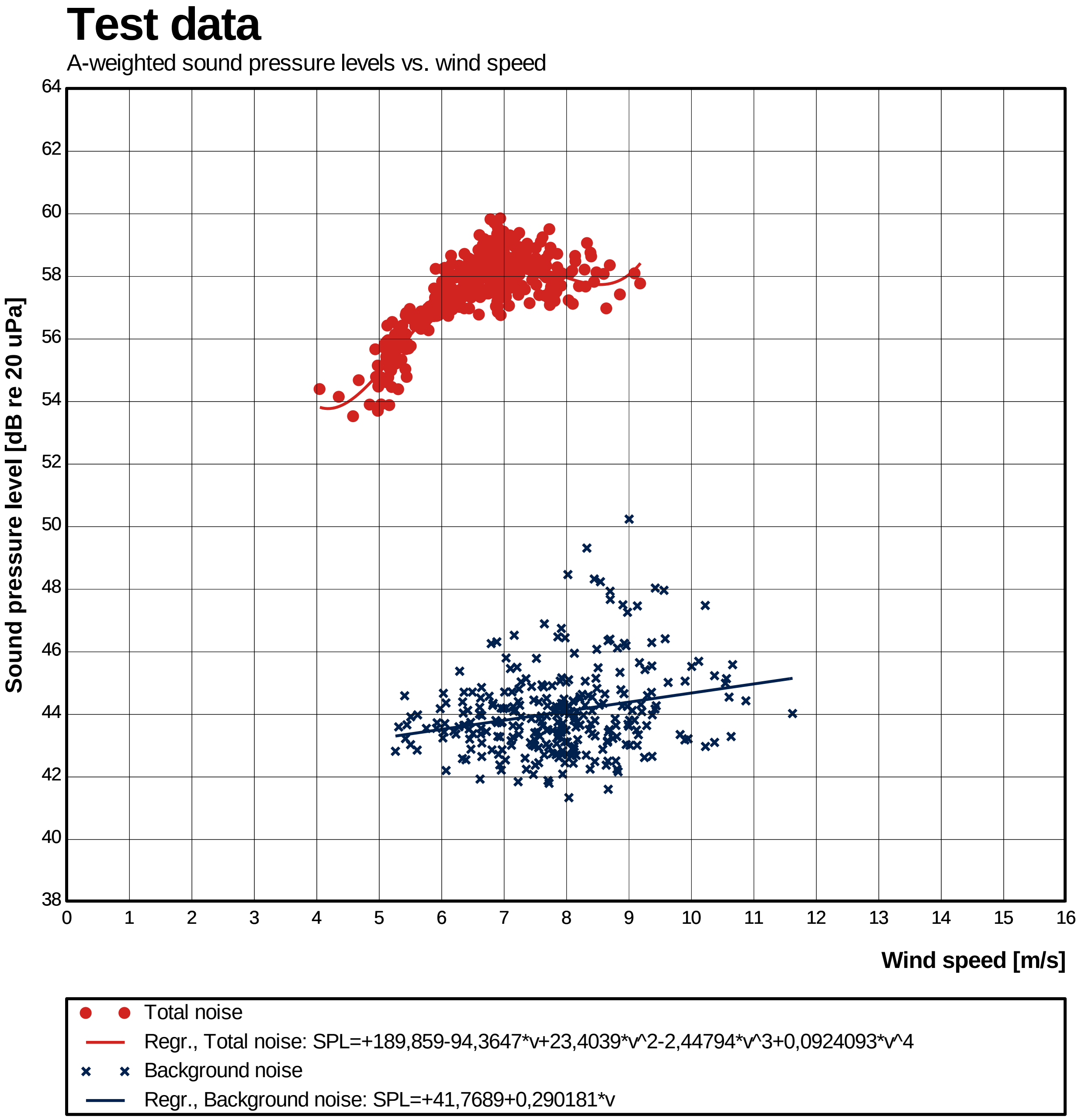


Figure 2 Measurement results given as Total noise and Background noise as a function of wind speed. A 4th order polynomial regression is used for the total noise while linear regression is used for the background noise

3 Noise prediction

3.1 ISO 9613-2

ISO 9613-2 is an empirical model developed for noise propagation under simple meteorological conditions (moderate downwind and neutral temperature gradient), moderate distances and with source and receiver close to the ground. The model is used for industry noise and similar and experience shows that it works well for these situations where most sources are at low heights and the distances are relatively short. However as the model is implemented in several software packages it is easily accessible and therefore also used for wind turbine noise.

The range of geometry and meteorology the model is developed does not seem to include wind turbines and wind turbines noise and tests shows that ISO 9613-2 is not the right model for wind turbine noise.

3.2 Nord2000

Nord 2000 is a semi-analytical ray model model developed in the Nordic countries. The model deals with the influence of meteorological parameters like wind speed, wind direction and temperature gradient and can handle elevated sources and complex terrain. The model is described in detail in [8].

A series of tests where Nord2000 predictions were compared with loudspeaker noise propagation measurements are reported in [9] for flat and complex terrain and varying meteorological conditions. In general there were good agreement between measurement results and the results of Nord2000 predictions. A very interesting subject is how results predicted by Nord2000 will deviate from the prediction by ISO-9613-2 which is the most commonly used method for wind turbine prediction today.

To illustrate the difference between the two prediction methods, two cases are selected from [9] with downwind propagation over flat grass-covered ground at Høvsøre (Test site for large wind turbines in Denmark). The source is a loudspeaker at 30 m and 50 m height and the signal is broadband noise filtered in 1/1-bands to increase the signal strength. Except for the high source position the ISO method is supposed to be valid in this propagation case. The results from these cases are recalculated to 1/1 octave bands and shown in Figure 3 and Figure 4 and predicted result by the ISO method has been included The two figures show the excess propagation effect (which is the ground reflection) and a considerable underestimation by the ISO method around 500 Hz and 1000 Hz can be seen. This is a well-known experience for very high source positions. Comparison at lower frequencies is difficult due to background noise from the measurements as can be seen at 63 Hz in Figure 4. Larger deviations in the prediction would of course have been observed if the ISO 9613-2 method had been used to predict some of the cases where the method is not valid such as the upwind cases at Høvsøre and some of the complex terrain cases at a wind turbine site at Hitra in Norway.

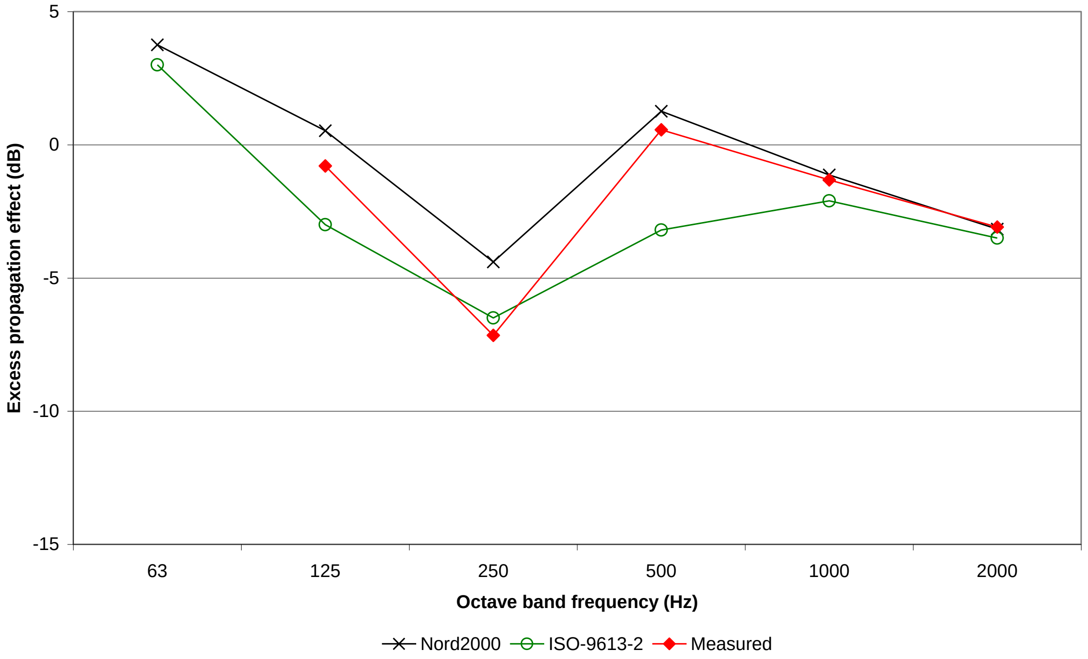


Figure 3 Measured (♦ red), predicted by ISO-9613-2 (○ green), and predicted by Nord2000 (X black) excess propagation effect. Downwind, distance 500 m, source height 30 m, and receiver height 2 m

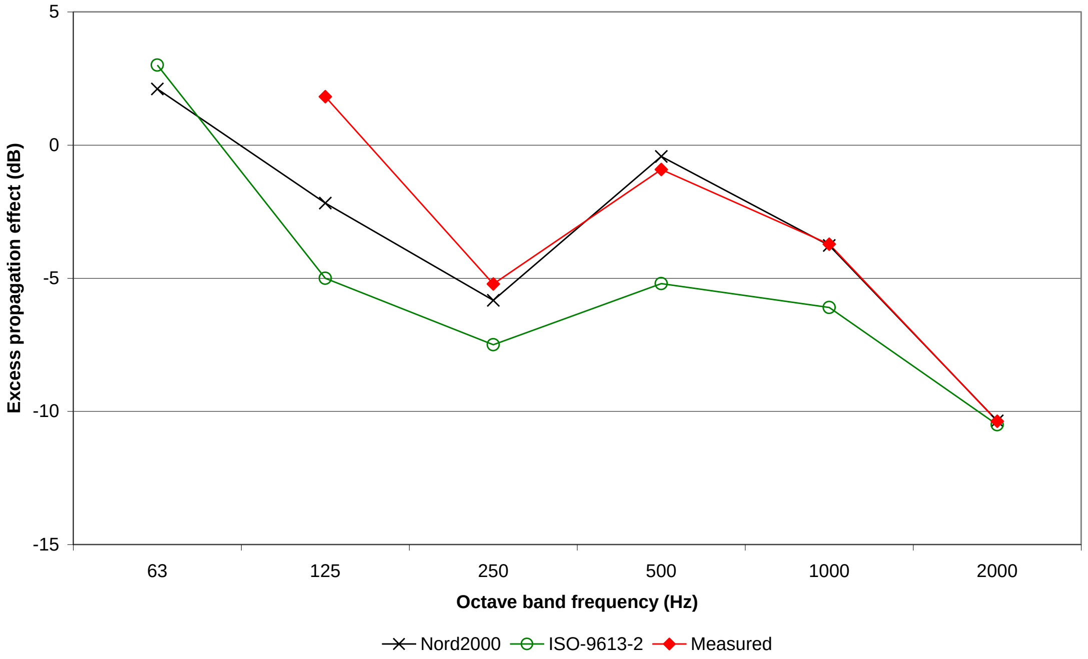


Figure 4 Measured (♦ red), predicted by ISO-9613-2 (○ green), and predicted by Nord2000 (X black) excess propagation effect. Downwind, distance 1500 m, source height 50 m, and receiver height 2 m

3.3 The Danish method for prediction of noise and low frequency noise from wind turbines.

An investigation by Søndergaard [10] finalized by Madsen [11] has shown that low frequency noise from wind turbines increases slightly with the size relative to noise in the normal frequency range. As a consequence of this the Danish Environmental Protection Agency has introduced noise criteria for the indoor low frequency noise level in parallel with the normal noise criteria at 6 m/s and 8 m/s. The noise criteria is 20 dB(A) calculated as the sum of the 1/3-octave bands from 10 Hz to 160 Hz calculated in a specified manner [12]. The method specifies the ground reflection and the insertion loss of buildings as a set of standardized data in 1/3-octaves from 10 Hz to 160 Hz. The rest of the method is similar to other methods. The ground reflection data are the average values from a series of Nord2000 data valid for distances typical for Danish situations from about a few hundred meters. The noise insulation data are selected to represent the level where 67% of Danish residences will have a better noise insulation than these data. This is also an accept that some residences will have lower insulation data and some people may have a higher level of low frequency noise than given by the noise criteria on 20 dB(A). The prediction method is given in equation 1 for normal noise and equation 2 for low frequency noise.

$$L_{pA} = L_{WA} \div 10 \cdot \log(l^2 + h^2) \div 11 dB + \Delta L_g \div \Delta L_a \qquad (1)$$

Where

l = distance from the foot of the wind turbine to receiver

11 dB =correction for distance, 10·log(4π)

ΔL_g = correction for ground reflection (1,5 dB for land based wind turbines and 3 dB for offshore wind turbines)

ΔL_a = correction for airabsorption ($\alpha_a \cdot \sqrt{(l^2+h^2)}$)

The prediction is made in 1/3-octave bands from 50 Hz to 10 kHz.

$$L_{pA} = L_{WA} \div 10 \cdot \log(l^2 + h^2) \div 11 dB + \Delta L_{gLF} \div \Delta L_{\sigma} \div \Delta L_a \qquad (2)$$

Where

l = distance from the foot of the wind turbine to receiver

11 dB =correction for distance, 10·log(4π)

ΔL_{gLF} = correction for ground reflection (Table 1)

ΔL_{σ} = sound insulation at low frequencies (Table 1)

ΔL_a = correction for airabsorption ($\alpha_a \cdot \sqrt{(l^2+h^2)}$)

The prediction is made in 1/3-octave bands from 10 Hz to 160 Hz.

Table 1 Parameters for prediction of indoor low frequency noise

1/3-oktav centerfrekvens i Hz	**10**	**12,5**	**16**	**20**	**25**	**31,5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**
ΔL_{gLF}: ground correction, land based wind turbine (dB)	6,0	6,0	5,8	5,6	5,4	5,2	5,0	4,7	4,3	3,7	3,0	1,8	0,0
ΔL_{gLF}: ground correction, offshore wind turbine (dB)	6,0	6,0	6,0	6,0	6,0	5,9	5,9	5,8	5,7	5,5	5,2	4,7	4,0
ΔL_{σ}: sound insulation (level difference) (dB)	4,9	5,9	4,6	6,6	8,4	10,8	11,4	13,0	16,6	19,7	21,2	20,2	21,2

Usually the normal noise criteria in the frequency range from 50 Hz to 10 kHz are the determining parameter and not the low frequency noise.

Denmark is the first country to introduce noise criteria for low frequency noise from wind turbines, but the method can easily be accepted in other countries. The noise insulation data however may have to be changed according to local building traditions.

4 Summary

Investigations show that ISO 9613-2 can lead to severe underestimation of noise from wind turbines depending on how the ground is modeled. Nord2000 seems to be a better choice and can include the effect of meteorological parameters like wind speed, wind direction, wind speed gradient etc. The main difference in the models are the ground effect and if ISO 9613-2 is used with hard ground the result will be a slight overestimation of the noise of the order of 1,5 dB for short distances. Prediction of low frequency noise can only be made with models like Nord2000 and Harmonoise.

Nord2000 is implemented in software packages like SoundPLAN and WindPRO ver 2.8.

References

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