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Variations in measured noise emission of wind turbines due to local circumstances

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Summary

When measurements are performed to determine the noise emission of onshore wind turbines, it is often found that the noise emission not only depends on the wind speed at hub height but also varies due to other aspects. Meteorological conditions and location specific circumstances like nearby objects and terrain conditions influencing the wind profile appear to be relevant. In this paper these situational factors are assessed.

Multiple close distance measurements in conformity with IEC61400-11 are performed at several wind turbine sites. From analysis of these measurements it is found that the occurring sound power levels deviate significantly day-by-day and per site, even with identical wind turbines. In the paper these deviations are related to the measurement method, changing atmospheric conditions and roughness length. Also the configuration of the wind turbine and location specific circumstances have a contribution in the found deviations.

Assessment of the sound power levels of wind turbines at project sites should be done taking into account the found spread of measured sound power levels. This spread is of concern when e.g. sample compliance checks are performed by the authorities by measuring the sound power level at dominant wind speeds. In the paper the practical implications are discussed.

1. Introduction

When nuisance is reported by residents due to the noise of a wind park local authorities may order a survey to check whether the noise limits at the nearby dwellings are met. With the European standard based on year equivalent noise limits (L_{den} and L_{night}) it is not possible to check these limits directly by measuring the sound pressure level at the nearby dwellings. In year round measurements disturbing noise would be dominant. Therefore the L_{den} and L_{night} are calculated. To check if the sound power levels provided by the manufacturer are also applicable for that specific situation, measurement at the project site of the occurring sound power levels is sometimes demanded.

Results of measurements at project sites show differences between the sound power levels provided by the manufacturer and the sound power levels measured at the project site. In paragraph 3.1 of this paper several measurement results are presented which are performed at project sites during varying conditions. In paragraph 3.2 measurement results performed at one wind turbine during varying conditions are given. In chapter 4 the found deviations are assessed and possible explanations are given.

2. Situation and method

2.1 Situation

The area in the north-west of The Netherlands is very suitable for wind parks because it is an windy area due to flat land and the nearby North Sea. This rural area is according to Dutch standards an area with low density of population and low background noise. However, still many sites are nearby dwellings. Nuisance due to solitary wind turbines and wind parks is reported frequently.

The local authorities often demand (driven by complaints of local residents) a survey to check whether the noise limits are met in practice.

In a time span of several years (2011 up until now) the sound power levels of many wind turbines were validated in practice by our company.

In figure 1 a typical situation of a solitary wind turbine in the aforementioned area is given.

Figure 1. Typical situation of wind turbine in rural area of The Netherlands

For this paper we made a selection of project sites where compliant checks were ordered by the local authorities ranging from solitary wind turbines of 800 kW up to more than 7 MW and wind parks. The surface area can be qualified as flat with occasional embankments and water channels. The surface is covered with seasonal agricultural crops or grass lands.

2.2 Method

Since 2011 the general noise limits in The Netherlands for wind turbines are 47 dB L_{den} and 41 L_{night} at the facade of dwellings, independent of the background noise levels.

In the Dutch law a Calculation and measurement method for wind turbines is prescribed for prognosis studies and compliance checks [1]. This method is based on the IEC 61400-11 edition 2 standard as well as the Dutch 'Guide for measuring and calculating industrial noise'. Contrary to the IEC61400-11 standard a 1 minute equivalent sound pressure level is used and the sound power level is related to V_{hub} (wind speed at hub height), calculated from the actual power output of the wind turbine and the applicable power curve. To obtain a year average noise emission the sound power levels are corrected with the statistical occurring wind speed at hub height.

For the selected wind turbines two comparisons on the datasets are made:
1) Comparison of guaranteed sound power levels with sound power levels determined at project sites
2) Comparison sound power levels of one specific wind turbine measured during different meteorological conditions

Dataset 1) consists measurements at project sites with an identical wind turbine type (800 kW, blade length 27 m). The hub height is 60 m for measurement 2 – 5 and 73 m for measurement 1.The sound power levels for dataset 1) are determined in conformity with the Dutch method for determination of the sound power levels. Per wind speed bin at least 6 valid measurements (with and without wind turbine in operation) are mandatory.

Dataset 2) consists measurements at one project site with a wind turbine of 2.5 MW, hub height 85 m and a blade length of 60 m. Measurements on this site were done in conformity with IEC 61400-11 edition 3 (with wind speed bins of 0.5 m/s, equivalent sound pressure level of 10 s etc.). Measurement no.6 en 7 (see table 2) are performed with the same wind turbine configuration. Measurements 8 – 10 are performed with another configuration but this configuration was unaltered during the measurements.

2.3 Measurement conditions

At every project site noise measurements were done to determine the sound power levels per wind speed bin. Measurements were done for at least several hours in the day or evening period during changing wind speeds in the range of 5 to 11 m/s (at hub height). The wind speed at hub height was derived from the actual power output (1 minute average for measurement 1-4 and 10 s for measurements 5 - 9) and the applicable power curve.

In table 1 the meteorological conditions during the measurements of dataset 1) are summarized.

Tabel 1 – Meteorological conditions at project sites with identical wind turbine types

Parameter	Measurement no.		
	1+2	3	4
Timespan	19:00 - 22:30	16:45 - 20:45	17.00-22.00
General wind direction	0 degrees	210-240 degrees	210-240 degrees
Temperature	7 °C	17 °C	14 °C
Pressure	1021 hPa	1008 hPa	1011 hPa
Relative humidity	79%	90%	80%
Cloud cover	Clear sky	Heavily cloudy	Heavily cloudy

The wind speed is standardized to 15 °C and 1013 hPa for measurements 1 to 5 (in conformity with the Dutch standard) although the majority of the measurements were performed already around these standard conditions.

In table 2 the meteorological conditions during the measurements of dataset 2) are summarized.

Table 2 - Meteorological conditions at one wind turbine at different days

Parameter	Measurement no.				
	5	6	7	8	9
Timespan	18:00 - 23:45	12:00 - 18:00	10:30 - 16:30	11:00 - 17:30	09:30 - 12:00
General wind direction	210-300 degrees	317 degrees (North West)	281 degrees (West)	200-240 degrees	210-220 degrees
Temperature	4,6-5,7 °C	5.4 - 11.0°C	4.3 - 12.1°C	8,6 -11,1°C	10,3-11,1 °C
Pressure	1011 hPa	1027 hPa	1024 hPa	1021 hPa	1023 hPa
Relative humidity	71-82%	75%	81%	80-97 %	84-90 %
Cloud cover	Partly cloudy	Half cloudy	Few clouds (2/8)	Heavily clouded	Heavily clouded/foggy

3. Measurement results

3.1 Wind turbines of same type at different locations

In figure 3 the measured sound power levels of four different measurements at three different project sites (and the same production model wind turbine) are given.

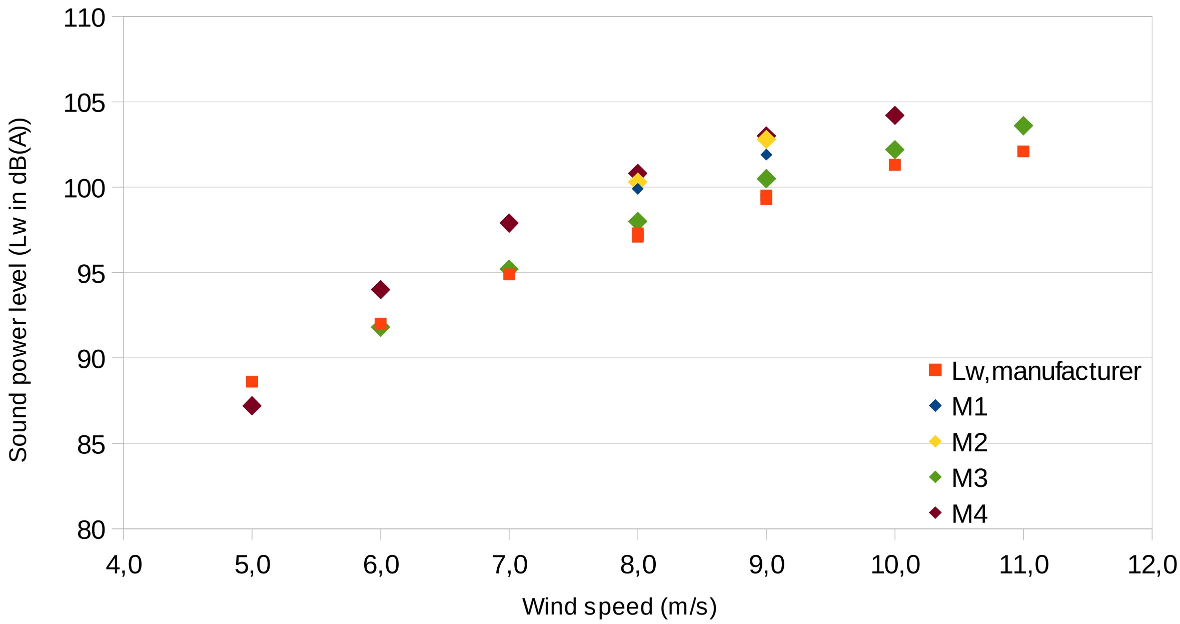

Figure 3 Sound power levels based on measurements at the project sites (measurements 1 to 4) compared to sound power levels supplied by the manufacturer.

The difference between the guaranteed sound power levels of the manufacturer and the measured sound power levels range from -1.4 to +4.5 dB(A) per wind speed bin. The standard deviation of the found spread is +1.8 dB(A). Figure 3 shows that at wind speed bins 5 and 6 m/s at hub height the deviation from the guaranteed sound power level is quite small (minus 1 to plus 2.0 dB(A)). At the wind speeds of 7 - 11 m/s the deviation is significantly higher. Since this range of wind speeds occurs during approximately 50% of the time these sound power levels contribute for a great part to the year average emission.

In figure 4 the measured A-weighted third octave band spectra are given for measurements 1 to 4.

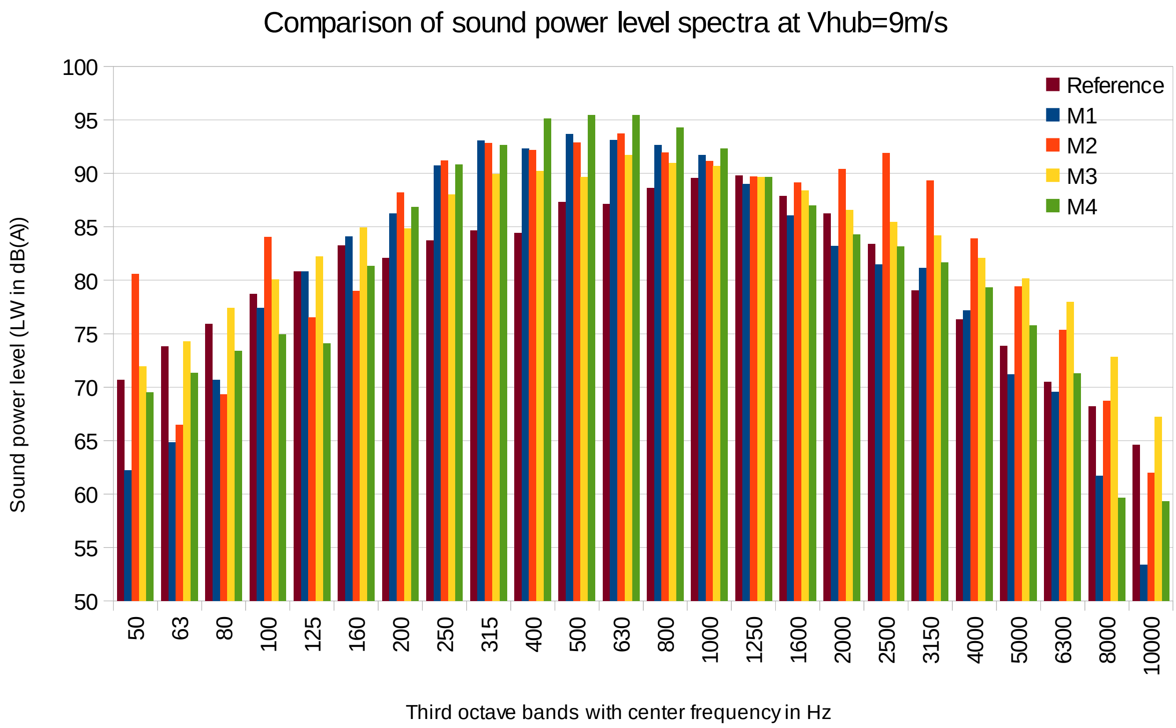

Figure 4 Comparison of measured third octave band spectra of measurements 1 - 4

From figure 4 can be concluded that in the frequency range 160 to 800 Hz and 2,5 – 10 kHz a significant increase occurs compared to the reference sound power level (supplied by the manufacturer). Analysis of all measurement data shows that within measurements M2 en M3 significant disturbing noise occur in the frequency range of 2,5 – 10 kHz, since the difference between the measured sound pressure levels with turbine in operation and with turbine shut down is less than 3 dB. This disturbing noise is caused by a row of trees close to the wind turbine and measurement position. However, the energy in these octave band is small. The broadband value (dB(A)) is at maximum 0.5 dB(A) lower if the third octave band from 2,5 to 10 kHz are neglected.

In the frequency range of 160 – 800 Hz also a significant increase occurs. This frequency range contribute greatly to the total sound power levels in dB(A). In chapter 4 possible causes are further investigated.

3.2 Comparison of sound power levels day-to-day

In figure 4 the average sound power levels measured at one wind turbine at different days and different meteorological conditions are given. The occurring wind speeds during these measurement days were approximately the same. The configuration of the wind turbine was during the different measurement days unaltered (same blade configuration and management). The sound power levels are normalized (and anonymised) to 100 dB(A) at 8 m/s for the dataset with lowest sound power level at 8 m/s. The underlying dataset consists of at least 10 measurements of 10 s per wind speed bin for total noise (wind turbine in operation) and background noise (wind turbine shut down).

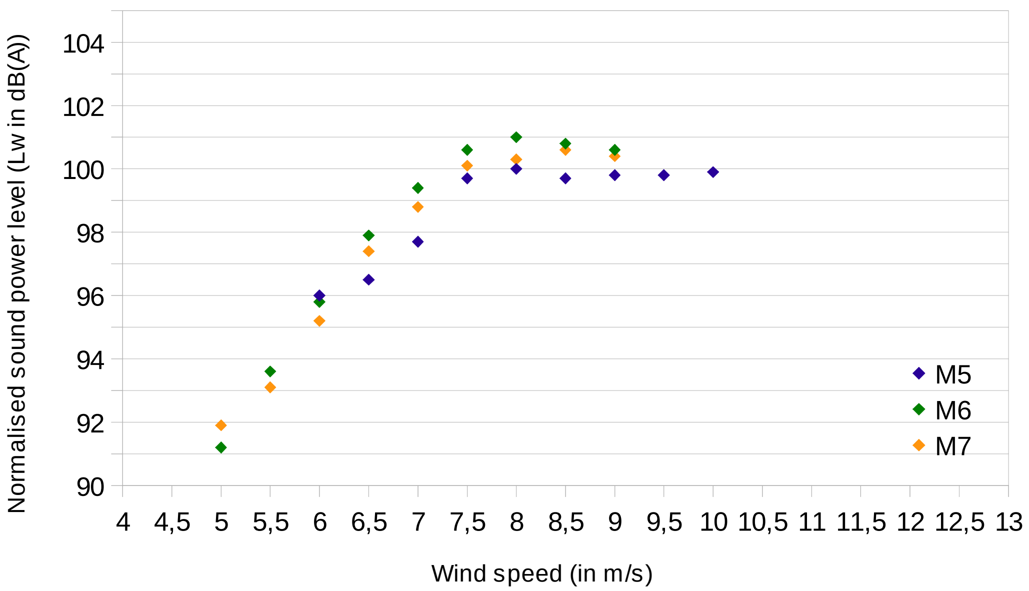

Figure 5 Sound power levels based on measurements at a wind turbine at different days and unaltered configuration of the wind turbine (measurements 5-7)

The deviation of the measured sound power levels at different days range from 0,5 to +1,7 dB(A). The standard deviation of the found spread is +0,4 dB(A).The deviation in this dataset is at the lower wind speed bins of 4,5 to 6 m/s smaller than at the higher wind speeds between 6,5 and 9 m/s although in this wind speed range more data points are collected.

In figure 6 the A-weighted third octave band spectra are given for the wind speed bin at 7,0 m/s for measurements 5 - 7.

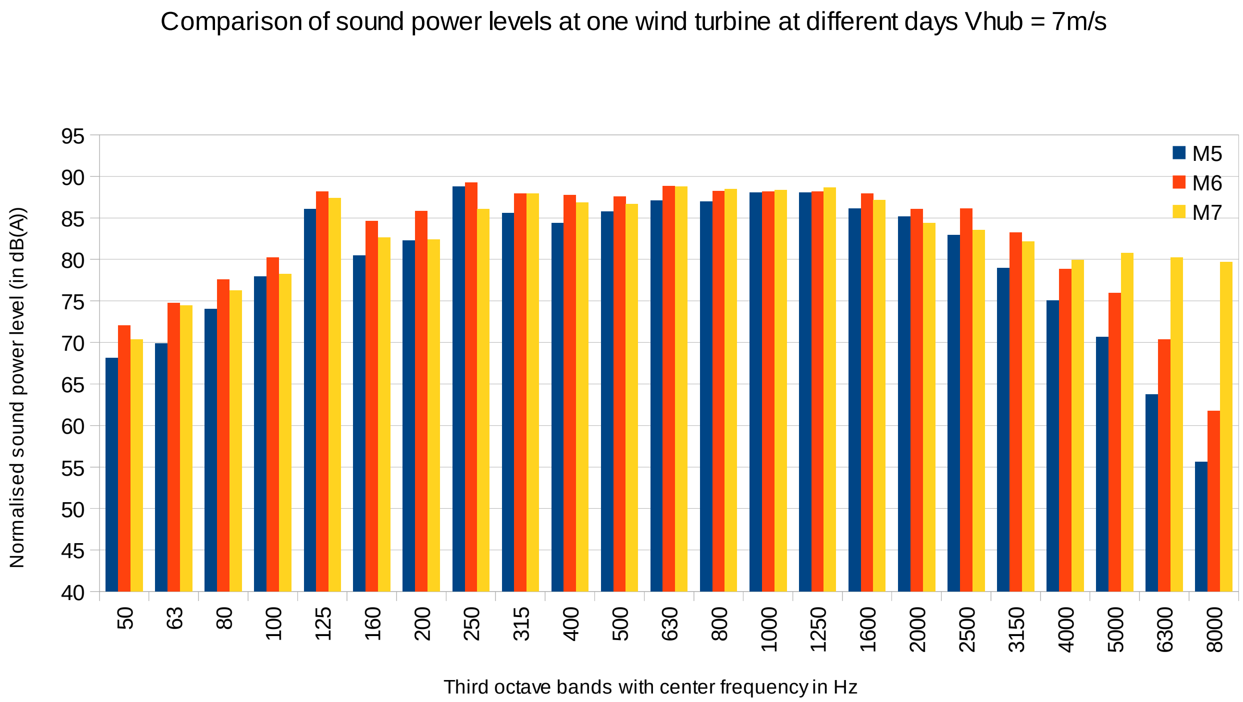

Figure 6 Measured sound power levels in third octave band spectra of one wind turbine during different days at V_{hub} = 7 m/s

Figure 6 shows that the spread of the sound power levels at one wind speed ranges from 1 to 5 dB (excluding the deviations at 5 kHz and higher since these sound power levels are determined without the necessary 3 dB difference between turbine in operation and turbine shut down). The contribution of the third octave bands of 5 kHz and higher to the total sound power level in dB(A) is however limited to 0,3 dB(A) at maximum, which is negligible. Therefore the found spread in dB(A) occurs mainly due to the energy in the 50 Hz to 800 Hz third octave bands.

Figure 7 shows the measured sound power levels from one wind turbine at two different days.

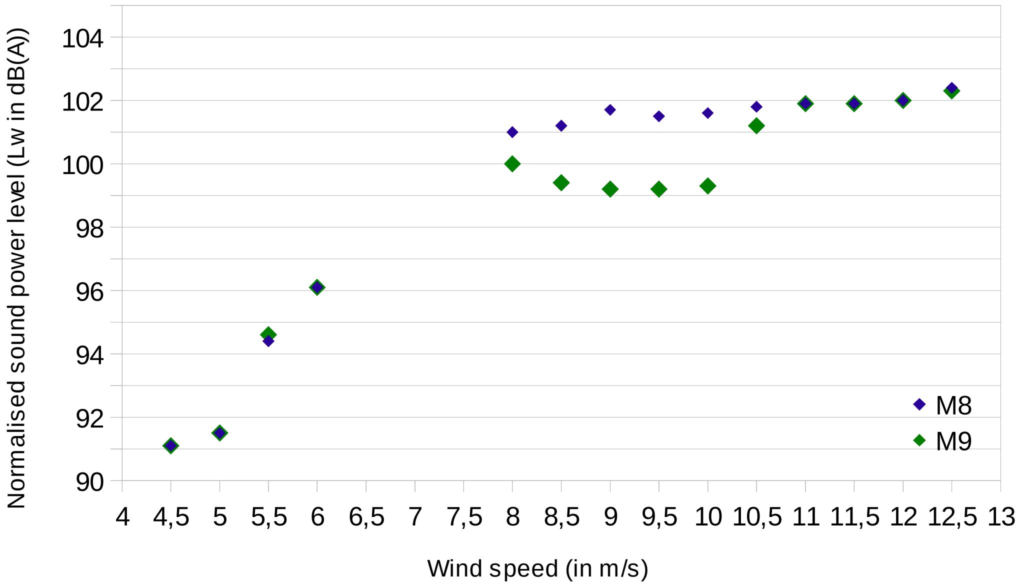

Figure 7 Sound power levels based on measurements at a wind turbine at different days and unaltered configuration of the wind turbine (measurements 8 and 9)

In figure 7 a remarkable pattern is shown whereby lower wind speeds (4,5-6 m/s) are almost identical, while 7,5 – 10 m/s deviates significantly (up to 3 dB(A)). Even more remarkable is that measurement 7 is performed the following day (even only 12 hours later) after measurement 6, with verified unchanged settings of the wind turbine.

In figure 8 the A-weighted third octave band spectra are given for the wind speed at 8,5 m/s for both measurements.

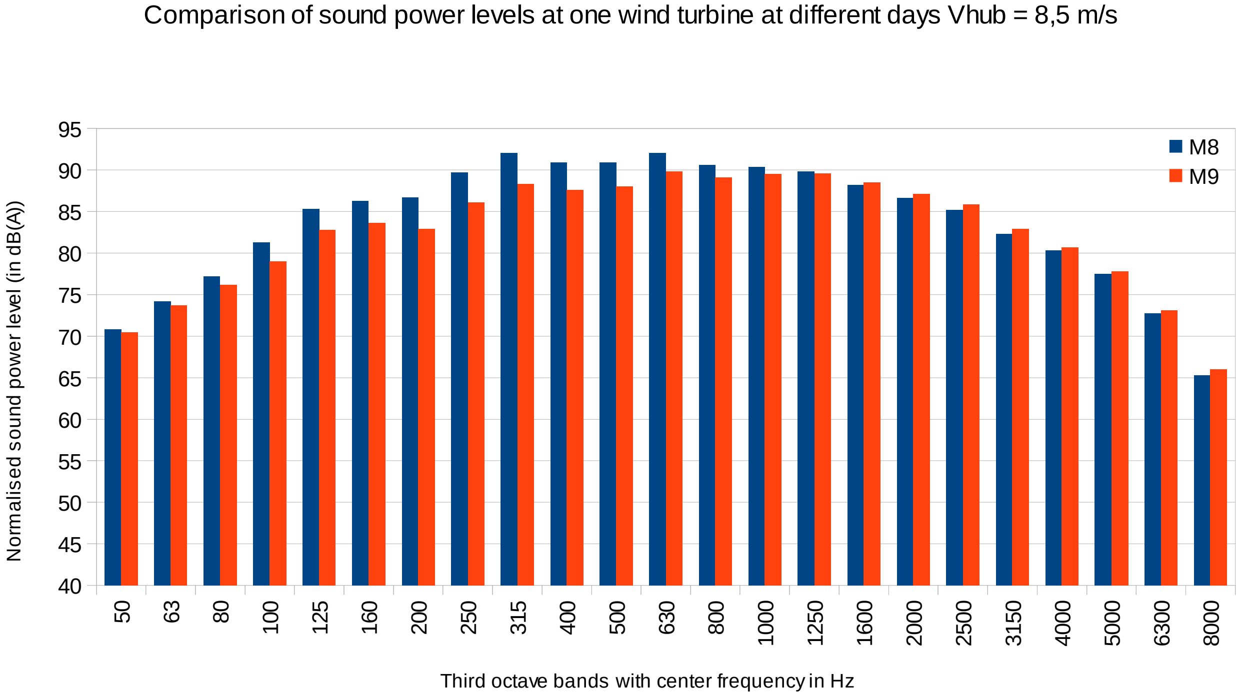

Figure 8 Measured sound power levels in third octave band spectra of one wind turbine during different days at V_{hub} = 8,5 m/s

Figure 8 shows that the found difference in sound power levels occurs mainly in the 100 Hz to 1 kHz third octave bands.

Possible causes of the found deviations are further discussed in chapter 4.

4. Assessment of effects contributing to deviations

4.1 General

In general the following aspects may contribute to the found spread of measured sound power levels:

- Accuracy of the measurements (method, disturbances);
- Wind turbine conditions;
- Meteorological conditions;
- Objects and terrain influencing disturbances and wind profile.

In the following paragraphs possible causes for the found deviations are considered.

4.2 Accuracy of measurements

The sound power levels determined in practice at project sites deviate at some sites and some wind speeds significantly from the sound power levels of the manufacturer. The sound power levels are determined exactly the same measurement procedure as they are determined at the test field. Therefore comparison is possible, and several variables can be excluded as main cause. Close field measurements have in this regard advantages over far field measurements because deviations due to the effects of noise propagation are (as much as possible) eliminated.

It is remarkable that in almost all cases the sound power levels determined at the project sites are higher than the sound power levels delivered by the manufacturer.

The accuracy of measurements in conformity with IEC 61400-11 edition 2 and 3depends on several aspects but is typically due to site effects (‘type B’ uncertainty) between 1 and 3 dB(A). In appendix D of the standard (edition 2) the accuracy of the measurements are given. Since the wind speed at hub height is derived from the power output of the windturbine and the power curve, the accuracy of the power measurement equipment and the power curve contribute for the most part the actual accuracy.

Disturbing noise during the measurements may contribute to the found spread. However in these measurements the effects of foreground noise (temporary elevation of the sound pressure level due to local noise sources not related to the wind turbine) is excluded from the measurements as much as possible. Incidental disturbances could therefore not be a suitable explanation. The third octave band spectra show a significant increase at the octave bands higher than 2,5 kHz. In these octave bands the difference between the sound pressure level due to the wind turbine and background noise is less than 3 dB(A). At these octave bands background noise is dominant. The total contribution of these octave bands to the total sound power level is however limited to 0,5 dB(A) maximum. The increases at the lower third octave bands (200 Hz to 1 kHz) have the highest contribution to the total sound power levels. At these third octave bands the background noise is at least more than 6 dB(A) lower than the noise due to the wind turbine.

For the measurements at one wind turbine (Measurements 5 to 9) the aforementioned considerations apply as well, although in these measurements comparison is only made between the different measurement results. The actual accuracy of these measurements is even higher because the measurements were done with exactly the same instruments leading to a smaller margin for the measurement accuracy.

4.3 Wind turbine conditions

The deviations may be caused by wind turbine configuration due to:
1) Dimension tolerances;
2) Cleanliness of blades;
3) Management of the pitch angles of the blades.

Measurements 1 to 5 are done at the same fabricate and type wind turbine. Due to tolerances in the production process the dimensions of the blades may deviate from each other leading to possible increase of the sound power level. Measurements 6 to 10 are done at one specific wind turbine where a comparable spread of sound power levels is found. The effect due to dimension tolerances is therefore assumed to have a minor contribution.

It is known that blade cleanliness has an influence on the noise emission [Oerlemans, 2]. At the measured wind turbines no dust or dirt was visible at the blades. Unknown is if the blade roughness was increased by prolonged operation. The measured wind turbines were operational for less than a year and were not operating in specific dusty areas since the soil was during the measurements covered with crops or grass.

Rotational speeds were observed during the measurements and checked with the range of the specifications. The rotational speeds were in accordance with the specification of the manufacturer so the measurements performed at the project site were done without reduced (or increased rotational speeds). Therefore is a significant contribution to the increased sound power levels not likely.

Management of the pitch angles is for measurements 1 to 5 considered to be exactly identical. However this is not confirmed by the operator of manufacturer so it cannot be excluded as a possible cause. Measurements 6, 7 and 8 to 10 were done at one wind turbine with confirmed unchanged management of the blade pitch, as it was done at consecutive days.

4.4 Meteorological conditions

During the measurements several meteorological conditions varied significantly. The relative humidity (influencing air density) varied 70-97% (RH) and cloud cover (influencing atmospheric stability) varied from clear sky to fully clouded.

Inflow turbulence may occur due to specific meteorological conditions, for instance sunny days with heated ground surface leading to a buoyancy effect of air mixing with higher layers. Since most measurements were done with (almost) full cloud cover or were done in the evening at sunset or after sunset the effect of ‘turbulent mixing in the boundary layer’ [YY2] is assumed to be of lesser influence. Inflow turbulence is however considered as one of the most relevant aspects contributing to the increased sound power levels (see paragraph 4.5).

4.5 Objects and terrain disturbances

Upwind nearby objects and terrain disturbances like existing channels, rows of trees, embankments lead to increased (inflow) turbulence, and decrease the stability of the atmosphere. The roughness length of the surface near the areas of the project sites (measurement no. 1 to 4) ranges from 0.03 to 0.3, which deviates at some sites significantly from the reference roughness length of 0.05 from the IEC 61400-11 standard used to determine the sound power levels of the wind turbine by the manufacturer.

The nearby objects and terrain disturbances also may change the inflow angle and increase inflow turbulence. All wind turbines of the considered project sites have upwind objects, like homesteads, rows of tree, channels and soil bodies at a distance of less than 150 m.
The influence of objects near to the ground is greater when they are more near the wind turbine but may have an influence on the inflow turbulence and wind profile up to several kilometers [Ragheb, 3]. Increased inflow turbulence is found to increase the sound power levels [Søndergaard, 4], although others did not find a significant influence [Evans and Cooper, 5].

At the project site of measurement no. 2 and 3 the wind turbine was located near the homestead surrounded by a row of trees. During measurement 3 the row of trees were at a distance of less than 50 m from the wind turbine and the measurement location. At the project site of measurement no. 4 an embankment and homestead was present most probably leading to inflow turbulence. This inflow turbulence may even occur during specific meteorological conditions (wind direction and speed).

Measurements 5 – 9 were done at a site where upstream at a distance of 400 m a row of trees was present, while no other nearby objects (of considerable size) were present. This site was therefore without nearby disturbing objects. Nearby objects and terrain disturbances on these measurements is considered to be of minor influence.

4.6 Implications on compliance

The found increased sound power levels based on measurements at the project sites are between 0 and 4 dB(A) per wind speed bin. In the researched sites the found increase of sound power levels did not lead to exceedance of the noise limits at the nearby dwellings. However the found increase of sound power levels lead to an increase of the year average emission factor (L_E) of maximum 2 dB. Since the initial calculated L_{den} and L_{night} was about 1 to 2 dB lower than the noise limits, no substantial exceedance was found.

The found increase is however higher than is expected only on measurement uncertainty. In situations where neighbors are complaining about noise due to the wind turbine measurement of the sound power levels in practice may be a good starting point to check whether increased sound power levels occur.

In the planning phase it may in critical situations be necessary to avoid compliance issues and discussion afterwards. To be more certain that the noise limits in practice will be met a surplus of 1 to 3 dB(A) per wind speed bin could be considered in the calculation results before assessment with the noise limits is done.

5. Conclusions

From the measurement results of 9 measurements at different sites and meteorological conditions a significant spread is found in the occurring sound power levels. The found spread is higher than measurement accuracy only, therefore other relevant influences occur.

The wind turbine configuration was probably the same for 1-4 and confirmed the same for M5-9 so the found spread is probably not caused by different wind turbine configurations

Meteorological conditions varied quite heavily during several conditions which is a probable cause for relevant part of the found spread. Nearby objects and terrain influences were at some project sites present, probably leading to an increased inflow turbulence, because of nearby rows of trees and buildings. For measurements 1-4 inflow turbulence could well be the most relevant cause for the found increased sound power levels.

The found elevated sound power levels due to local circumstances can be between 1 and 3 dB(A). To avoid compliance issues one may consider to add a surplus of 2 or 3 dB(A) in the planning phase in the development of a wind turbine site before assessment with noise limits is done.

Since the contribution of the considered possible causes is yet unknown differentiation between specific local circumstances (size and type of nearby objects, predicted inflow turbulence) is not possible based on the datasets used in this paper. Further investigation to the contribution of these effects is necessary.

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