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Low-frequency noise from large wind turbines – additional data and assessment of new Danish regulations

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Summary

Previous studies have shown that the noise has more low-frequency content, when wind turbines get larger, and with todays' megawatt turbines the low-frequency noise may cause annoyance for the neighbours. Therefore, low-frequency noise has been included in the noise regulations on wind turbines in Denmark. In this study, the data material has been increased to include more data on noise from modern production turbines up to 3.6 MW. In addition, the new Danish regulations are assessed. The previous result that the relative amount of low-frequency noise is higher for large turbines (> 2 MW) than for small turbines (≤ 2 MW) is confirmed. Due to the air absorption, the higher low-frequency content becomes even more pronounced, when sound pressure levels in relevant neighbour distances are considered. Even when A-weighted levels are considered, a substantial part of the noise is at low frequencies, and for several of the investigated large turbines, the one-third-octave band with the highest level is at or below 250 Hz. It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbours. The new Danish regulations are based on calculations of the indoor noise at the neighbours, but unfortunately, the calculation underestimates the level that would be measured, thus the regulation does not adequately prevent potential annoyance and sleep disturbance effects from future wind turbines in Denmark.

1 Introduction

As wind turbines get larger and larger, worries emerged, that the noise emitted by the turbines would consequently move down in frequency, and that the content of low-frequency and infrasonic noise would increase and reach a level, where it may be annoying for the neighbours. The daily press frequently reports on rumbling and annoying noise from large wind turbines, and it is often claimed that it propagates quite far. However, the scientific literature on infrasonic and low-frequency noise from large wind turbines is more limited.

Therefore, a Danish study including data from a total of 48 wind turbines was carried out [1] and it was indeed confirmed, that the noise from larger wind turbines emits relatively more low-frequency noise. Furthermore, the study showed that the claim from the Danish Environmental Protection Agency (Miljøstyrelsen) at the 2006 revision of the noise regulations [2], that an outdoor limit of 44 dBA is sufficient to protect neighbours from annoying low-frequency noise indoor is wrong. As a result the Danish regulations of noise from wind turbines have been revised in order to include limits on the low-frequency part of the noise [3]. However, these are based purely on calculations of indoor sound level from measurements close to the turbine and the question remains, whether these new rules are adequate to protect the neighbours.

After the aforementioned study was submitted for publication [1], data from additional 17 new wind turbines was published in [4]. In this study these data have been included resulting in a total of 65 wind turbines and thus giving a larger data material. The connection between emitted sound power and turbine size is investigated, source spectra are analyzed and discussed, and the new Danish regulations are assessed by estimating outdoor and indoor spectra at relevant neighbour distances using proper methods and comparing it to the levels estimated by the regulations.

2 Methods

2.1 Wind turbines

Data from measurements from a total of 65 wind turbines are included. 25 large turbines with nominal electric power above 2 MW and 40 “small” turbines with nominal electric power up to 2 MW. This includes the 48 turbines already analysed and published in [1] and 17 additional turbines (14 of them more than 2 MW) that have been erected in Denmark between 2008-2010. All turbines were three-bladed with the rotor placed at the upwind side of the tower.

All measurements were performed by Delta and more information on the data can be found in the original reports [4, 5, 6, 7].

2.2 Emitted sound power

The sound power emitted from the turbines was measured in accordance with IEC 61400-11 [8]. The principle of this standard is to measure the sound on a reflecting board placed on the ground beneath the turbine at a horizontal distance approximately equal to the turbine’s total height. The measured sound pressure level is converted to the sound power level of an imaginary point source at the rotor centre that would radiate the same sound in the direction, where the measurement is made. The result is denoted the *apparent sound power level*, where ‘apparent’ emphasizes that it is not the true sound power, but the power as ”seen” in the measured direction.

Apparent sound power level was determined for one-third-octave bands and as total A-weighted level, L_{WA}. In addition, a special low-frequency measure, L_{WALF}, the apparent A-weighted sound power level for the one-third-octave bands 10-160 Hz was derived. A-weighted sound pressure levels for this frequency range, L_{pALF}, are used by the Danish guidelines for low-frequency noise [9].

Data were obtained for all turbines in the down-wind direction, denoted the *reference direction*, at a wind speed of 8 m/s (10 m above ground). This wind speed is often used in noise regulations, and most analyses in the present article were made for this. All turbines were measured in the frequency range required by the standard, 50 Hz to 10 kHz, and most turbines were measured down to 31.5 or 25 Hz. Turbines 1-4 were measured down to 4 Hz.

2.3 Outdoor sound pressure levels at neighbours

Free-field sound pressure levels, L_p, for neighbour positions were calculated according to the method given by ISO 9613-2 [10], except that one-third-octave bands were used instead of octave bands.

The direction to neighbours is more horizontal than the direction, in which the apparent sound power level was measured, but in lack of more precise information, the sound power level plus directivity factor, $L_W + D_C$, was replaced by the apparent sound power level, L_{WA}, for the reference direction. The attenuation due to atmospheric absorption, A_{atm}, was calculated using data from ISO 9613-1 [11] for 10° C and a relative humidity of 80 %. The 'attenuation' due to ground effects, A_{gr}, was set to -1.5 dB, meaning that 1.5 dB is added to the direct sound from the turbine. The two remaining terms of ISO 9613-2 (attenuation due to a barrier A_{bar} and to miscellaneous A_{misc}) were set to zero. If the slant distance from rotor center to the observation point is denoted *d*, and the attenuation constant is α,

$$L_{\mathrm{p}} = L_{\mathrm{WA}} - 20\ \mathrm{dB} \cdot \log_{10}\left(\frac{d}{1\ \mathrm{m}}\right) - 11\ \mathrm{dB} - \alpha \cdot d + 1.5\ \mathrm{dB} \qquad (1)$$

This calculation corresponds to the one used for the total noise in the Danish regulations of noise for wind turbines [3].

2.4 Sound insulation

In order to allow calculation of low-frequency noise indoors, the low-frequency sound insulation was measured for ten rooms, two rooms in each of five normal living houses. For details about the measurements see [12]. All measurements were performed by Delta.

The house was exposed to sound from a loudspeaker placed on the ground and directed towards the facade of the house at a horizontal angle of incidence around 45° at the centre of the facade. The perpendicular distance from the loudspeaker to the wall was at least 5 m. The loudspeaker was supplied with broadband noise, low-pass-filtered at 250 Hz and equalized to compensate for the loudspeaker response. Outdoor sound pressure levels were measured at the facade at a vertical level approximately 1.5 m above the floor level of the receiving room. Free-field sound pressure levels were obtained by subtracting 6 dB from the measured levels. The outdoor setup and measurements share elements with the various methods of ISO 140-5 [13], but no single method is complied with as a whole.

At low frequencies, indoor levels may vary considerably within a room, and there is a general understanding that, for assessment of noise impact, measured levels should reflect high-level areas rather than the room average (see, e.g. Jakobsen [14], Simmons [15] and Pedersen et al. [16]). To fulfill this, indoor sound pressure levels were obtained as the power average of measurements in four arbitrary three-dimensional corners, i.e. where the floor or ceiling meets two walls. Corners close to possible concentrated transmission paths (e.g., ventilation ducts, windows, or doors) were avoided, though, and the selected corners were to represent all surfaces. Pedersen et al. [16] have shown that this method gives a good estimate of the level that is exceeded in 10 % of the room, i.e. close to the room maximum, but avoiding levels that only exist in a small part of the room.

The suitability of the 3D-corner method to estimate the maximum level that people would normally be exposed to in a room is supported by data from Brunskog and Jacobsen [17], who simulated 100 room/frequency combinations, each with two different reverberation times. They found that the 3D corner method hits quite centrally a target defined as the maximum level of the room excluding positions closer to the walls than 1 m (mean error below 1 dB, standard deviation of the error 3 to 4 dB depending on reverberation time).

The sound insulation was measured for one-third-octave bands in the frequency range 8-200 Hz, and it was calculated as the difference between outdoor free-field sound pressure level and indoor sound pressure level.

2.5 Indoor sound pressure levels at neighbours

Indoor sound pressure levels were obtained by subtracting the sound insulation from the outdoor free-field sound pressure levels, both in one-third-octave bands.

2.6 Statistics

Differences are tested in Student's t-tests. The highest p-values considered significant are 0.05. In two-sample tests, equal variance is not assumed, thus the Welch's adaptation of the t-test and the Welch-Satterthwaite degrees of freedom (d.f.) are used. One-sided tests are used, whenever the hypothesis contains a specific direction of the difference, whereas two-sided tests are used elsewhere. As an example, the hypothesis that the spectrum moves down in frequency for increasing turbine size, implies that relative levels for large turbines are higher at low frequencies and lower at high frequencies. Consequently, one-sided tests are used at low and high frequencies, whereas two-sided tests are used in the intermediate frequency range, chosen as 315-1600 Hz.

2.7 The new Danish wind turbine noise regulations, LF-noise

The Danish regulations on wind turbine noise were revised in 2011 [3] and now in addition to total noise limits also include limits and a special section on how to estimate the indoor low-frequency noise.

The general (i.e. not for wind turbines) Danish limit for low-frequency noise in dwellings is an indoor A-weighted level of 20 dB (evening and night) and 25 dB (day). Only frequencies in the 10-160 Hz frequency range (one-third-octave frequencies) are included. The level is measured as the power average of the levels in three positions, of which two are in the living areas of the room, where the noise complainant perceives the noise as particularly loud. The third position is near a room corner (1-1.5 m height, 0.5-1 m from the walls).

With the new Danish regulations, the 20 dB limit applies also for wind turbines at wind speeds of 6 and 8 m/s (wind turbines run around the clock). Unlike for other noise sources, the low-frequency noise is not measured but calculated from measurements close to the turbine of the emitted sound power. The indoor sound pressure level L_{pA} is calculated using the following equation:

$$L_{\mathrm{pA}} = L_{\mathrm{WA,ref}} - 20\ \mathrm{dB} \cdot \log_{10}\left(\frac{d}{1\ \mathrm{m}}\right) - 11\ \mathrm{dB} + \Delta L_{\mathrm{g}} - \Delta L_{\mathrm{a}} - \Delta L_{\sigma} \quad (2)$$

$L_{\mathrm{WA,ref}}$ is the apparent sound power level in the reference direction, basically measured according to IEC 61400-11 [8], d the distance from the nacelle to the neighbour, ΔL_{g} correction for the ground reflection, ΔL_{a} the air absorption equal to $\alpha_{\mathrm{a}} \cdot d$, where α_{a} is the absorption coefficient, and ΔL_{σ} the sound insulation. ΔL_{g}, α_{a} and ΔL_{σ} are given in Table 1.

Frequency (Hz)	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
ΔL_{g} (land) (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_{g} (sea) (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} (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
α_{a} (dB/km)	0	0	0	0	0.02	0.03	0.05	0.07	0.11	0.17	0.26	0.38	0.55

Table 1: Key figures for the new Danish regulations of LF-noise from wind turbines.

Calculations are made for the third-octave frequency bands 10-160 Hz and the levels summarized to give the A-weighted low-frequency sound pressure level L_{pALF}

3 Results and discussion

3.1 Emitted sound power

3.1.1 L_{WA} and L_{WALF}

Figure 1 shows L_{WA} and L_{WALF} for all turbines as a function of turbine size. The horizontal axis is logarithmic in order to match the vertical decibel axis, which is inherently logarithmic. Simple power relations between emitted acoustic power and nominal electric power of the turbine will thus correspond to straight lines, and regression lines are included in the figure.

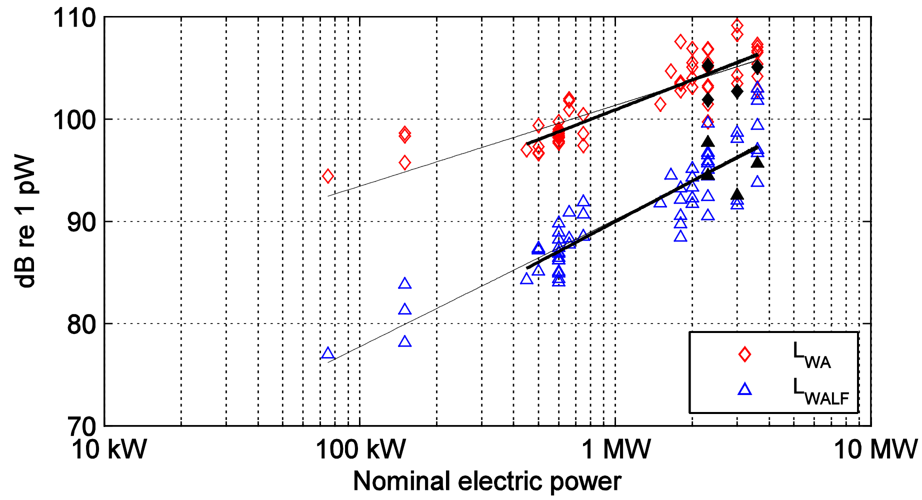

Figure 1. Apparent sound power levels (LWA and LWALF) in the reference direction as a function of turbine size. Wind speed 8 m/s. Regression lines: All turbines included (thin lines), four turbines below 450 kW excluded (bold lines). Black-filled marks are for Turbines 1-4, which are prototypes.

It is – not surprisingly – seen that both L_{WA} and L_{WALF} increase with increasing turbine size. It is also noted that L_{WALF} increases more steeply than L_{WA}, meaning that the relative amount of low-frequency noise increases with increasing turbine size. The difference in slope of the regression lines for all data (thin lines) is statistically significant. Since the four smallest turbines may not be representative for modern turbines, regression lines have also been calculated without these turbines (bold lines). The slopes are slightly higher than with all turbines included, and the difference is smaller but still statistically significant.

The relative amount of low-frequency noise can be expressed as $L_{WALF} – L_{WA}$, and a linear regression of this yields a significant positive slope with all turbines included as well as with the four smallest turbines removed.

It is also seen in Figure 1 that there is some variation between turbines of the same size. Turbines of the same size may be of the same or different makes, or, for a few turbines below 2 MW, the same physical turbine measured at different occasions and/or in different modes.

3.1.2 One-third-octave-band spectra

One-third-octave-band analyses of the apparent sound power are shown in Figure 2.

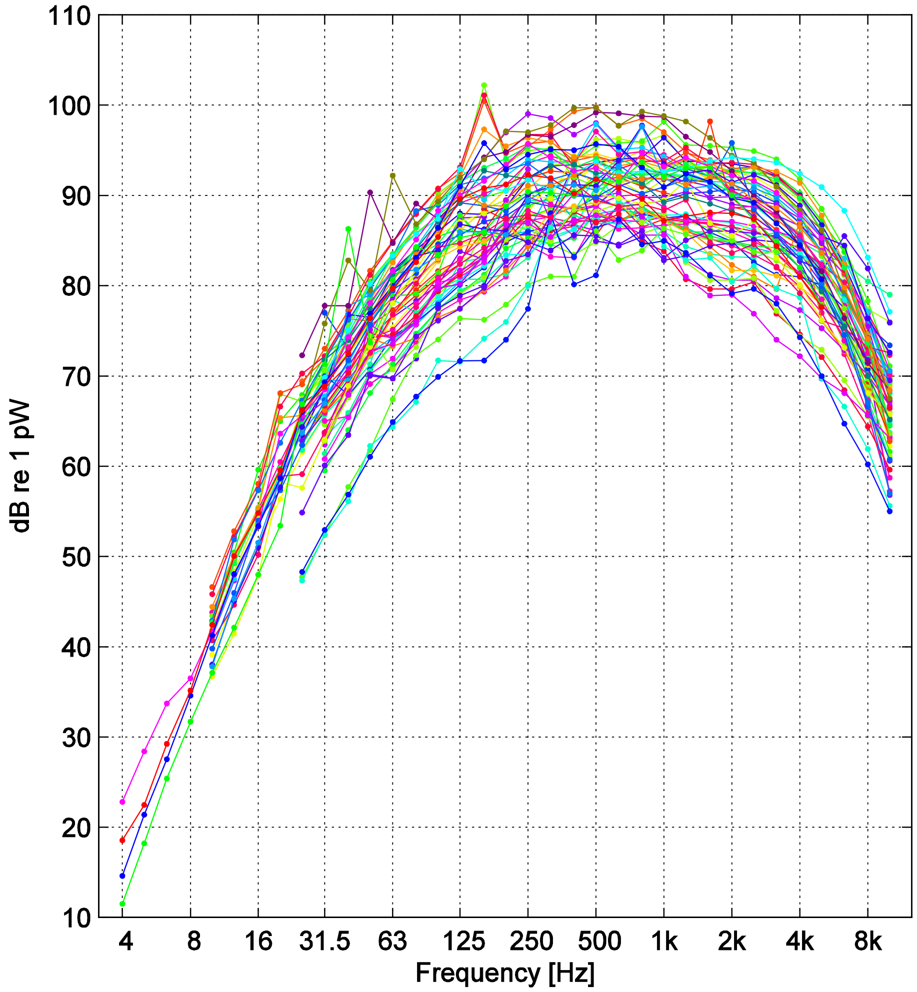

Figure 2. A-weighted apparent sound power levels in one-third-octave bands. 62 turbines with nominal electrical power 75 kW to 3.6 MW.

Regarding the infrasonic part of the spectrum, the G-weighted [18] apparent sound power levels, calculated from the one-third-octave-band levels, are 122-128 dB for the four turbines, where data is available. Even close to the turbines, e.g. in a distance of 150 m from the rotor centre, this will only give G-weighted sound pressure levels of 69-75 dB, which is far below the normal threshold of hearing [19]. This calculation does not account for possible near-field phenomena, e.g. from a closely passing blade.

At frequencies where data are available for all turbines, the level varies between turbines by 20 dB or more. This is to be expected, since the turbines cover a wide range of nominal electric power. In order to show possible spectral differences between turbines more clearly, the one-third-octave-band levels of all turbines have been normalized to the individual turbine's total A-weighted power. The result is shown in Figure 3.

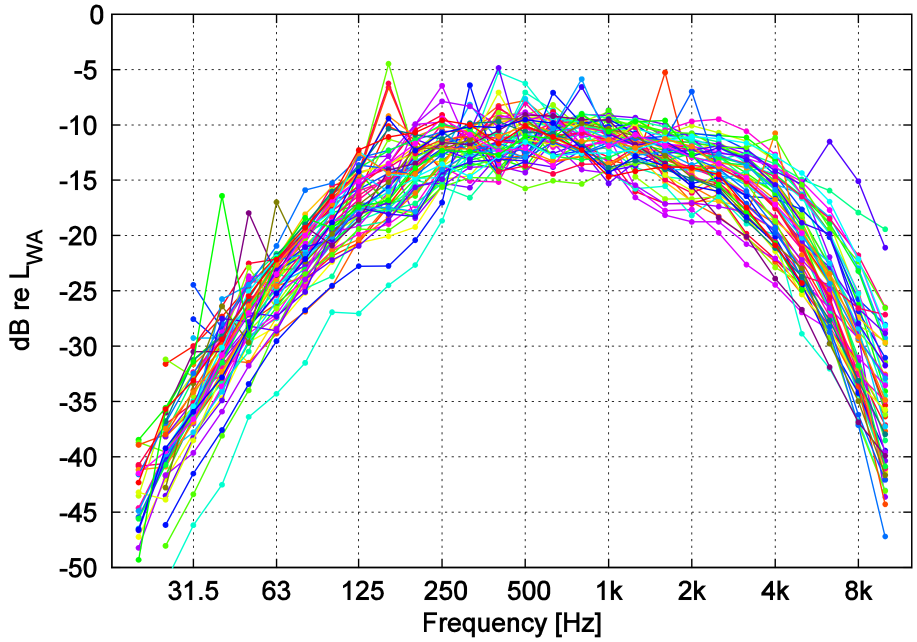

Figure 3. Normalized A-weighted apparent sound power levels in one-third-octave bands. 62 turbines with nominal electrical power 75 kW to 3.6 MW. (Normalized meaning that LWA for the individual turbine has been subtracted all one-third-octave-band levels).

A possible difference in spectrum between small and large turbines was investigated by dividing the turbines into two groups: Turbines up to and including 2 MW, and turbines above 2 MW. Figure 4 shows the mean and the standard error of mean for each of the two groups.

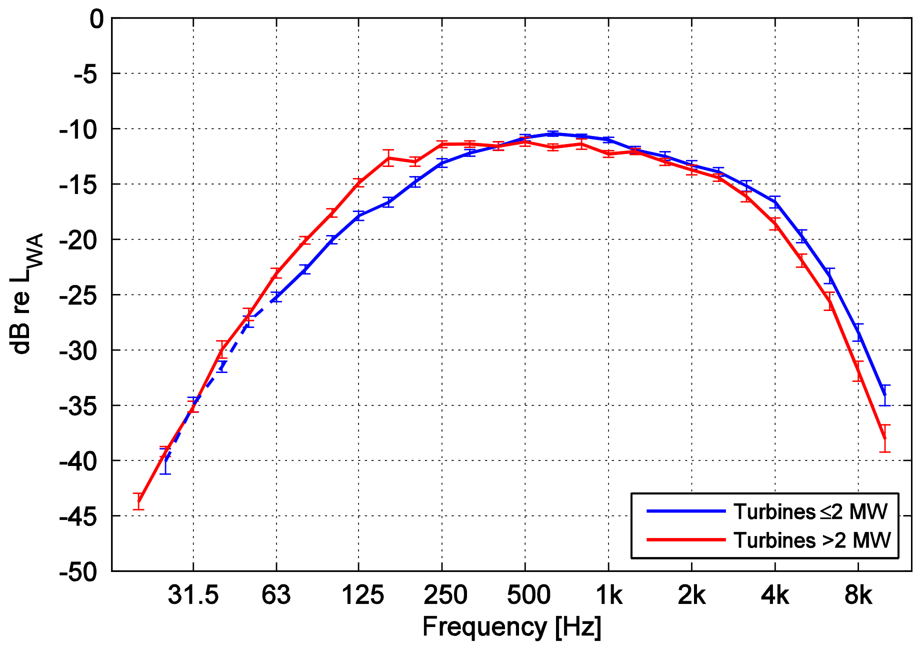

Figure 4. Normalized A-weighted apparent sound power levels in one-third-octave bands, means for two groups of turbines: ≤2 MW and >2 MW. Error bars indicate ± one standard error of mean.

The spectrum of the large turbines is clearly lower in frequency than that of the smaller turbines. The level difference is significant for all one-third-octave bands in the frequency range 63-250 Hz, 630 Hz, 1000 Hz and 4-10 kHz. (If the four smallest turbines are discarded, the difference is significant at the same frequencies plus 315 kHz).

The reason for no significant difference below 63 Hz is probably due to the fact, that the wind-induced noise in the microphone is higher for the measurements on the small turbines, since these were done without an extra windscreen.

The significant differences between small and large turbines are a moderate 2.2-4.0 dB, but systematic, and at low frequencies, even small differences may affect considerably the human perception of the sound [20]. In addition, if low frequencies have a notable impact on requirements of distance to the neighbours, small differences may have large impact on the needed distance.

Figure 5 shows the mean of turbines up to and including 2 MW and individual turbines above 2 MW. The spectra of the large turbines lie above the mean of the smaller turbines in virtually every single one-third-octave band below 315 Hz. Some of the turbines have a peak in one or more one-third-octave bands, which may be due to the presence of tonal components. Tones are likely to have their origin in the turbine mechanics, e.g. the gearbox or secondary equipment such as a generator cooling system (see e.g. Wagner et al. [21]).

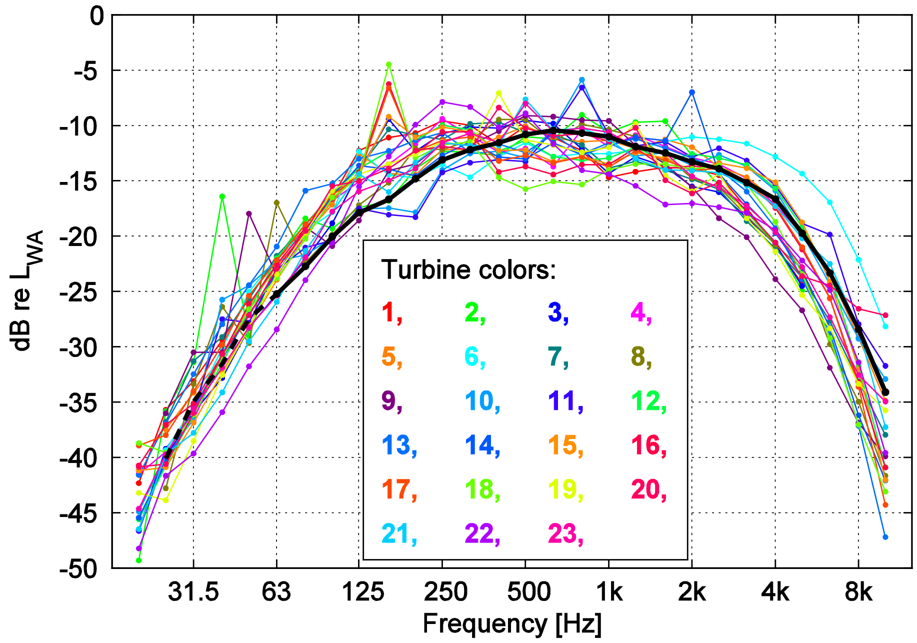

Figure 5. Normalized A-weighted apparent sound power levels in one-third-octave bands, mean of 36 turbines ≤2 MW (bold black line) and nine individual turbines > 2 MW.

At high frequencies, the picture is disturbed by an atypical pattern above 2 kHz for Turbine 6. There is no other data available from this turbine, for example for another wind speed or another direction, which could be used to verify that this is really noise from the turbine and not electrical noise as with some other turbines. Data for Turbine 6 above 2 kHz is therefore disregarded in all subsequent analysis, and without these data the difference between small and large wind turbines is also significant different at 3150 Hz.

3.2 Outdoor sound pressure levels at neighbours

For each of the large turbines, the distance needed for the A-weighted sound pressure level to decrease to 35 dB was derived. Pedersen and Waye [22] have shown that around this level, the percentage of highly annoyed persons increases above 5 %, and the percentage of annoyed persons increases above 10 % (Pedersen et al. [23]). Pedersen and Nielsen [24] recommended a minimum distance to neighbours so that the wind turbine noise would be below 33-38 dB. A limit of 35 dB is used for wind turbines, e.g. in Sweden for quiet areas [25]. It is also the evening/night limit for recreational areas in Denmark for industrial noise [26] (but not for wind turbine noise [3]). Table 2 shows the distances for the individual turbines as well as various key figures at the 35-dB distances.

Turbine	Distance	L_{pA}	L_{pALF}	L_{pALF}-L_{pA}	L_{pG}
	[m]	[dB]	[dB]	[dB]	[dB]
1	629	35.0	28.8	-6.2	59.1
2	647	35.0	26.7	-8.3	54.5
3	879	35.0	28.9	-6.1	55.0
4	822	35.0	27.6	-7.4	58.0
5	679	35.0	28.0	-7.0	
6	751	35.0	29.2	-5.8	
7	713	35.0	28.8	-6.2	
8	1.227	35.0	27.0	-8.0	
9	1.144	35.0	27.0	-8.0	
10	676	35.0	25.3	-9.7	
11	715	35.0	25.2	-9.8	
12	847	35.0	28.6	-6.4	
13	768	35.0	29.2	-5.8	
14	631	35.0	28.0	-7.0	
15	962	35.0	29.8	-5.2	
16	1.078	35.0	31.7	-3.3	
17	1.042	35.0	31.5	-3.5	
18	1.038	35.0	32.7	-2.3	
19	594	35.0	27.2	-7.8	
20	495	35.0	26.9	-8.1	
21	861	35.0	26.5	-8.5	
22	1.054	35.0	26.3	-8.7	
23	834	35.0	26.2	-8.8	
All turbines > 2 MW					
Mean		35.0	28.1	-6.9	
s.d.			2.0		
Turbines ≤ 2 MW					
Mean		35.0	25.1	-9.9	
s.d.			1.6		

Table 2: Key figures in the distance where the total A-weighted sound pressure levels is 35 dB. Distance is given as slant distance to rotor centre, which for the actual turbine heights is close to the horizontal distance. The four. turbines below 450 kW are not included for the small turbines.

The minimum distance, where a 35-dB limit is complied with, varies considerably between the large turbines, even when the turbines are relatively equal in size (2.3-3.6 MW). The distance varies from slightly below 500 m to more than 1200 m.

There is a significant difference between the low-frequency part of the noise in the order of 3 dB.

The one-third-octave-band spectra at the same distances are shown in Figure 6.

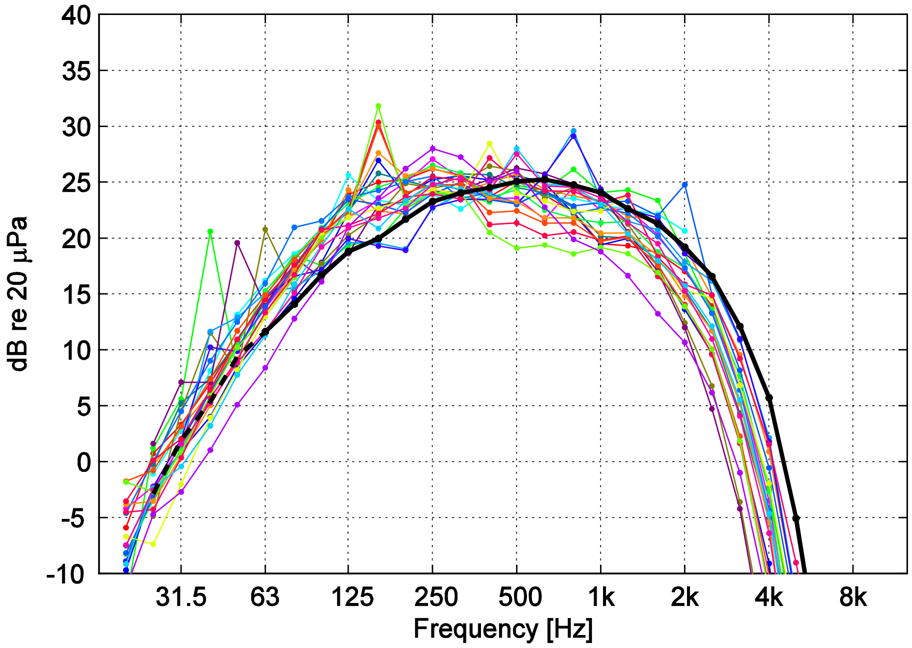

Figure 6. A-weighted one-third-octave-band sound pressure levels at the distance from a single turbine, where the total A-weighted sound pressure level is 35 dB (see Table 2). Turbine color code as in Figure 5.

At these distances, the air absorption plays a role. It affects mainly the high frequencies, and the result is that the shift of the spectrum towards lower frequencies becomes even more pronounced than for the source spectrum (compare with Figure 5).

It is important to note that, for several turbines, the highest one-third-octave-band level is at 250 Hz or lower, even when A-weighted levels are regarded (Figure 6). It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbours, and that the low frequency sound must be treated seriously in the assessment of noise from large turbines. The total low-frequency part of the spectrum is on average 7 dB below the total noise level for the large wind turbines, but for some turbines, it is only a few dB below.

In many cases, A-weighted outdoor levels in excess of 35 dB are allowed. As an example, for houses outside official residential or recreational areas, Danish regulations allow 44 dB [3]. For visual reasons, the Danish regulations has a setback distance for dwellings of four times the total turbine height, and at this distance, the level is often below 44 dB for a single turbine. However, 44 dB may certainly occur further away than four times the turbine height, when several turbines are together in wind farms.

Table 3 shows distances to small wind farms, where the A-weighted sound pressure level is 44 dB, as well as various key figures at those distances.

Turbine	Distance	L_{pA}	L_{pALF}	L_{pALF}-L_{pA}	L_{pG}
	[m]	[dB]	[dB]	[dB]	[dB]
1	530	44.0	37.9	-6.1	67.7
2	546	44.0	35.9	-8.1	61.1
3	831	44.0	38.1	-5.9	63.6
4	759	44.0	36.8	-7.2	66.9
5	585	44.0	37.2	-6.8	
6	672	44.0	38.4	-5.6	
7	631	44.0	38.0	-6.0	
8	1.241	44.0	36.3	-7.7	
9	1.142	44.0	36.3	-7.7	
10	579	44.0	34.5	-9.5	
11	624	44.0	34.5	-9.5	
12	791	44.0	37.8	-6.2	
13	695	44.0	38.4	-5.6	
14	528	44.0	37.2	-6.8	
15	934	44.0	39.0	-5.0	
16	1.078	44.0	40.8	-3.2	
17	1.033	44.0	40.6	-3.4	
18	1.033	44.0	41.8	-2.2	
19	487	44.0	36.4	-7.6	
20	375	44.0	36.0	-8.0	
21	805	44.0	35.8	-8.2	
22	1.045	44.0	35.5	-8.5	
23	771	44.0	35.4	-8.6	
All turbines > 2 MW					
Mean		44.0	37.3	-6.7	
s.d.			1.9		
Turbines ≤ 2 MW					
Mean		44.0	34.3	-9.7	
s.d.			1.6		

Table 3: Key figures in the distance where the total A-weighted sound pressure level is 44 dB. Wind turbine park with two rows of each 6 identical turbines, 300 m distance between turbines in both directions (200 m for small turbines). Observation point centered at the long side. Distance is given as slant distance to nearest wind turbine. The four turbines below 450 kW are not included for the small turbines.

Also here the needed distance varies considerably between the different large turbines (375-1241 m), and there is also a significant difference of 3 dB in the low-frequency part of the noise between small and large wind turbines.

3.3 Sound insulation

Figure 7 shows the measured sound insulation for 10 rooms.

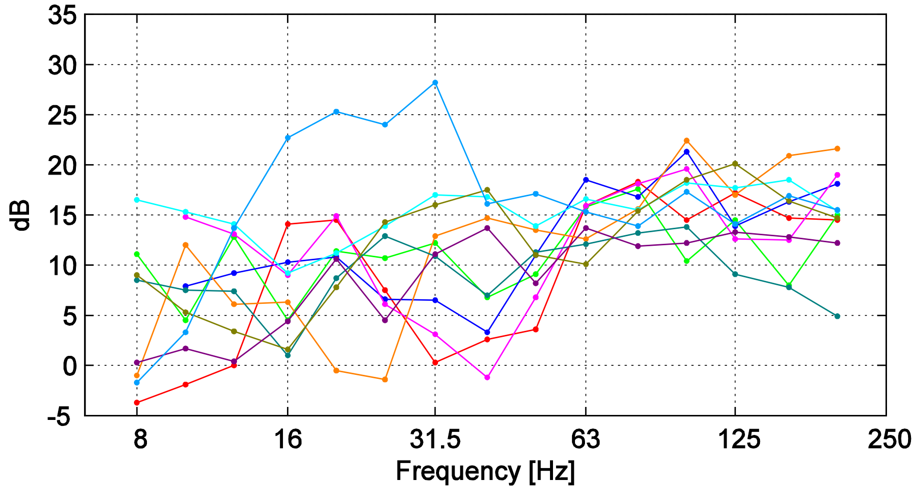

Figure 7: Sound insulation for 10 rooms.

At the frequencies 63-200 Hz, the rooms typically have a sound insulation of 10-20 dB. At lower frequencies the insulation becomes smaller and the difference between the rooms becomes higher. Some rooms have a very small and even negative insulation at specific frequencies. One room has an atypically high insulation in the range 16-31.5 Hz. This was a small room that is used for storing furniture and other things. It is therefore not a typical living area and the data for this room is therefore not used.

Note that for each one-third-octave band the indoor level refers to the highest levels that people will typically be exposed to in the room. The sound insulation numbers is therefore lower than traditional sound insulation numbers used for technical purposes, where typically the average of the room is pursued.

3.4 Indoor spectrum at neighbours

Figure 8 shows the indoor sound pressure levels for one-third-octave bands for all 207 combinations of 23 large wind turbines and 9 rooms in the distance with a total outdoor A-weighted sound pressure level of 35 dB. Note that the indoor levels are estimates of the highest levels that one would normally be exposed to in the room and not the average of the room.

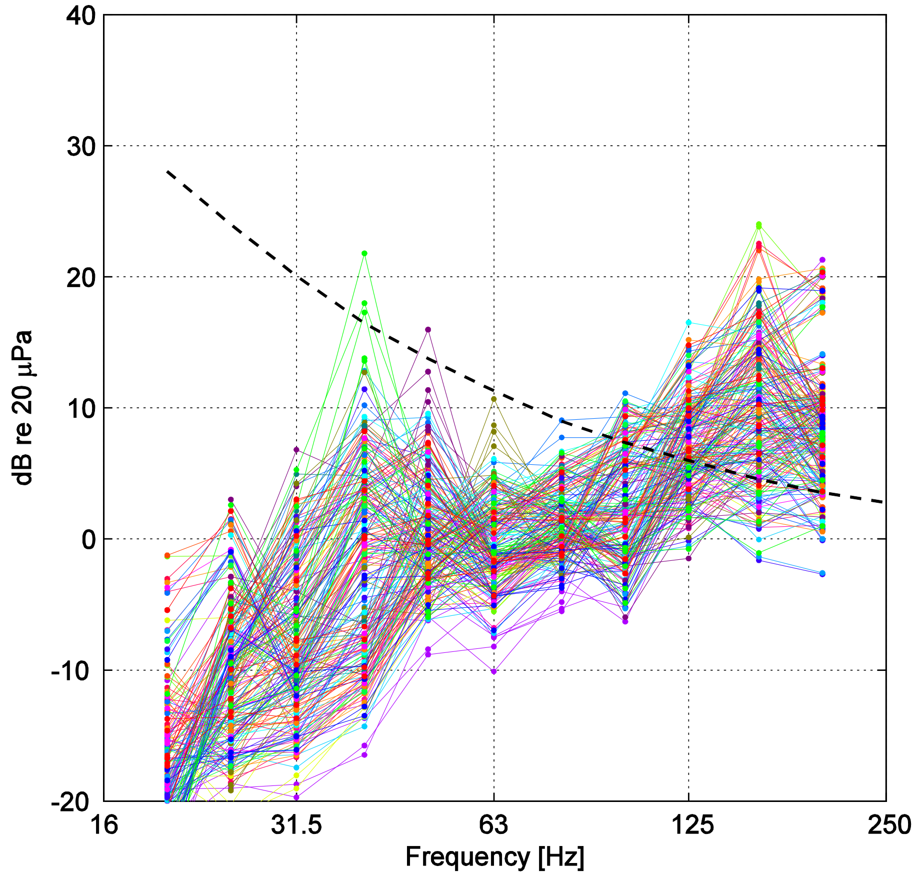

Figure 8: Indoor A-weighted sound pressure levels for one-third-octave bands in the distance for each turbine where the total A-weighted sound pressure level outside is 35 dB. 207 combinations of 23 large turbines and 9 rooms. The dashed line is the hearing threshold according to ISO 389-7 [27]. Colors indicate the turbine with same colors as in Figure 5.

Large variation is seen between different combinations of turbine and room. Most of the variation is due to the different insulation of the different rooms, except at 63 and 80 Hz, where both room and turbine contribute approximately equally to the variation. A group of high values at 40 Hz is caused by high sound power level of one specific turbine, while a group of high levels at 200 Hz is due to low sound insulation of one specific room.

From a comparison with the hearing threshold (dashed line), it can be seen that the low-frequency noise can be heard in many turbine/room combinations especially at the high end of the low frequencies. The sound will not be very loud, but low-frequency noise can be annoying although the levels are not far above the hearing threshold, and some people can be annoyed by the noise shown in Figure 8.

Figure 9 shows the indoor level for the situation in Table 3, where the outdoor A-weighted sound pressure levels from a wind turbine park is 44 dB.

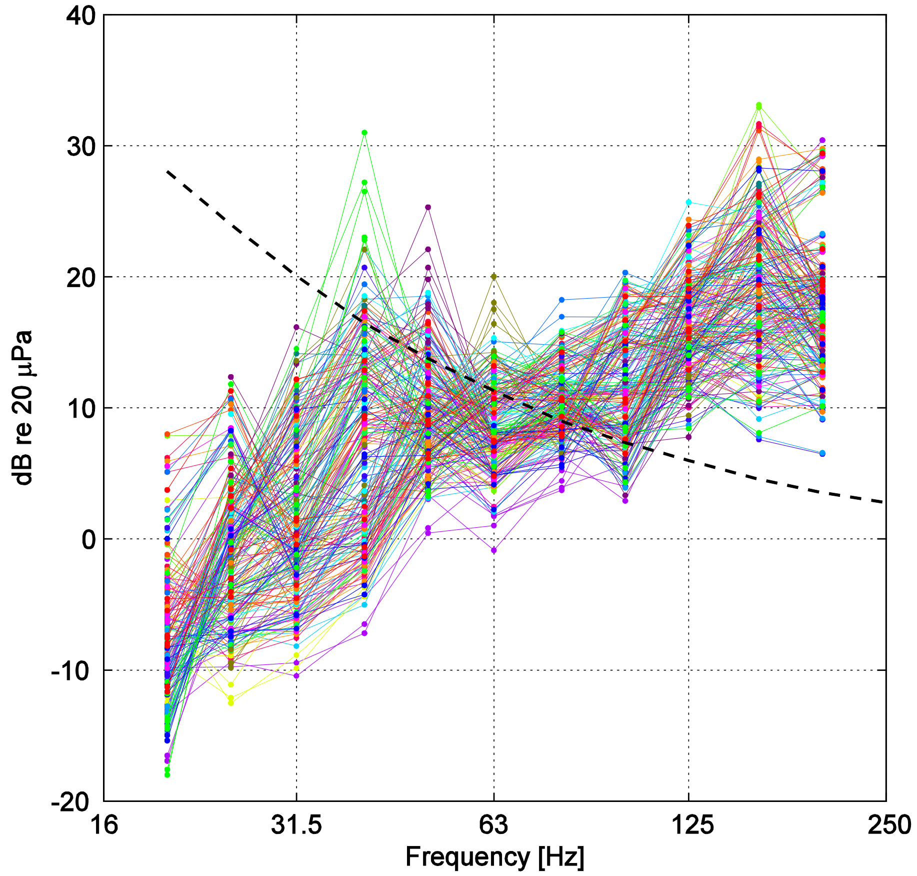

Figure 9: Indoor A-weighted sound pressure levels for one-third-octave bands in the distance from a turbine park where the total A-weighted sound pressure level outside is 44 dB. 207 combinations of 23 large turbines and 9 rooms. The dashed line is the hearing threshold according to ISO 389-7 [27]. Colors indicate the turbine with same colors as in Figure 5.

For this situation, there will be audible low-frequency sound somewhere in all the rooms and for all turbines. In more than half of the combinations (122 out of 207), the normal hearing threshold is exceeded with more than 15 dB in at least one one-third-octave band, and there is a risk that a considerable part of the neighbours will be annoyed by the noise.

It is not possible to directly find the L_{pALF} by adding the one-third-octave-band levels in Figure 8 and Figure 9, as the different one-third-octave bands can have their maximum in different positions in the room. Nevertheless, 100 of the 207 turbine/room combinations in Figure 9 exceed an A-weighted sound pressure level of 20 dB for at least one one-third-octave band in the 10-160 Hz range, and it is reasonable to assume, that the total sound pressure level for this frequency range, L_{pALF} will exceed 20 dB for even more turbine/room combinations.

3.5 Indoor levels according to Danish regulations

Figure 10 shows the indoor level calculated using the Danish regulations for the situation in Table 3, where the outdoor A-weighted sound pressure levels from a wind turbine park is 44 dB.

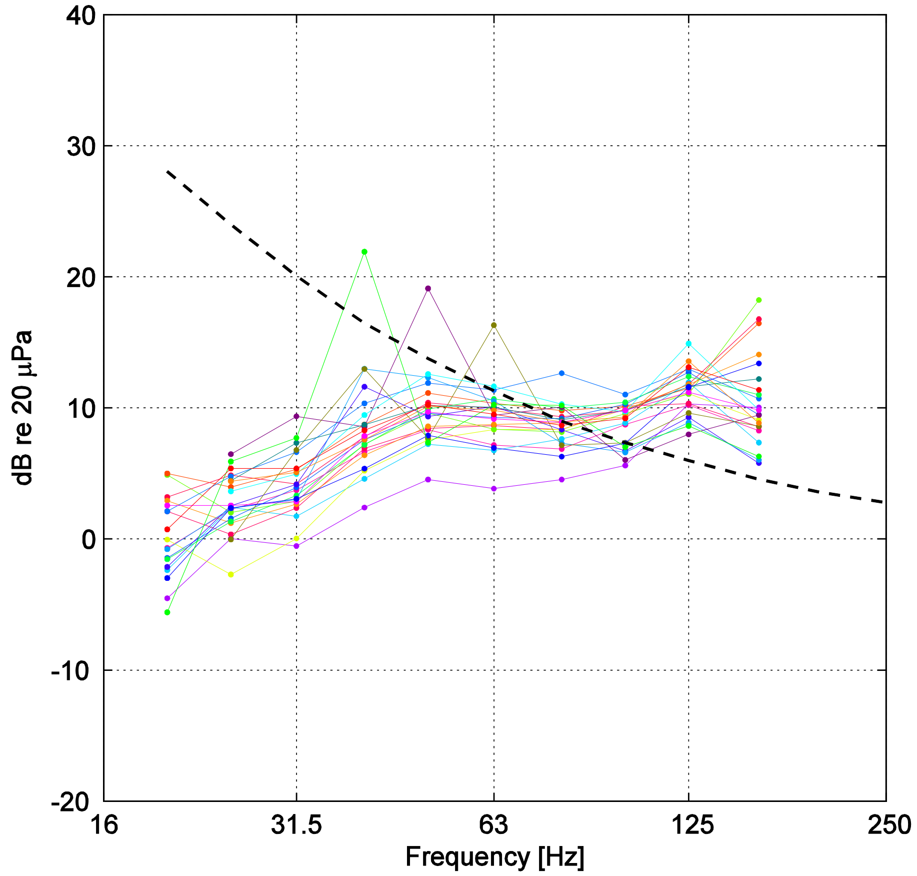

Figure 10: Indoor spectrum calculated according to the Danish regulations for the situation in Table 2, for the 23 large wind turbines, where the outdoor sound pressure level is 44 dB.

By comparing Figure 10 with Figure 9 it is seen that the Danish regulations underestimates the indoor levels at the neighbours. This is especially seen in the frequency above 63 Hz, where the differences between specific turbine/room combination and the one-third-octave-band level estimated by the regulations are up to 10-15 dB.

The major contributing factor to the underestimation is found in the sound insulation numbers used in the regulations. They are based on the work by Hoffmeyer & Jakobsen [28] who claim to use the measurement method used for low-frequency noise complaints [9]. Unfortunately, the method was not accomplished as prescribed. Only physical sound insulation was measured in the study, and no complainant was involved. Consequently, the measurement positions were not appointed, where the noise was loudest and without this important detail, it is obvious that the method fails its objective (for more details see [29]).

Although the sound insulation in the Danish regulations is based on the work by Hoffmeyer & Jakobsen, the insulation is higher than the insulation proposed by Hoffmeyer & Jakobsen. Figure 11 shows the insulation proposed by Hoffmeyer & Jakobsen, the insulation in the Danish regulations, and the 10th, 50th and 90th percentile calculated from the mean and standard deviation of the insulation measurements of the 9 rooms (assuming normal distribution). The reason that the percentiles are not calculated directly from the raw data, is that it would give more uncertainty to the single numbers because of the limited data material available.

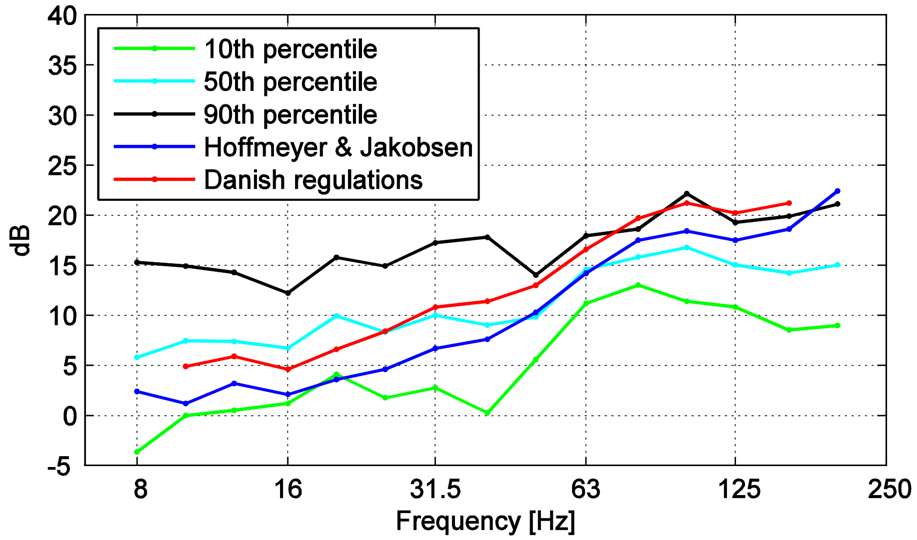

Figure 11:10th, 50th and 90th percentiles of sound insulation measurements for 9 rooms from 5 houses, Hoffmeyer & Jakobsen proposed insulation values and those used in the new Danish regulations (see Table 1).

It can be seen that the insulation of the Danish regulations lies around the 50th percentile for frequencies up to 31.5 Hz, while it is around the 90th percentile for 50 Hz and above. This means that it can be expected that 90 percent of houses have a worse sound insulation than what is used for the Danish regulations in the frequency range, where the low-frequency noise from large wind turbines is most dominating and most audible.

Another difference between the indoor levels in Figure 9 and Figure 10 is the ground reflection. In the calculations of sound pressure levels at the neighbours in Figure 9, the ground reflection is accounted for by adding 1.5 dB to the direct sound. As mentioned in Section 2.3, the 1.5-dB value is used by Danish regulations for the total noise. Swedish guidelines add 3 dB to the direct sound (for distances up to 1000 m) [30], a value that also follows from ISO 9613-2 [10] for the 31.5 and 63 Hz octave frequencies, irrespective of the ground surface. During measurements of sound emission from the turbines [8], it is assumed that the ground reflection adds as much as 6 dB to the direct sound. Certainly, a reflecting board is used during measurements, but this has only little effect at low frequencies, where the assumed 6-dB reflection is due mainly to the ground itself.

On this background, it is reasonable to suspect that the addition of 1.5 dB for the ground reflection is too low at low frequencies, and that higher values up to a theoretical maximum of 6 dB would be more appropriate. Thus, the procedure used to calculate outdoor sound pressure levels at the neighbours described in section 2.3 is likely to underestimate the low-frequency sound.

Therefore, it seems reasonable that the low-frequency part of the new Danish regulations uses a ground reflection of 6 dB at the lowest frequencies. However, at the higher range of the low frequencies the ground reflection is gradually reduced all the way down to 0 dB at 160 Hz (see ΔL_g (land) in Table 1). This dip at 160 Hz occurs because the ground reflection is based on calculations with the Nord 2000 method, for a specific receiver height of 2 m. However, in reality the whole facade of a house is exposed – not just a single point. In reality, there will be a ground reflection of approx. 6 dB near the ground, which is possibly getting lower at higher points on the facade due to destructive interference with the direct sound (depending on wavelength, geometrical and atmospheric conditions). Thus, the part of the facade from 0-2 m is exposed to a higher ground reflection than what is used in the regulations, and as a result, the regulations underestimate the overall effect of the ground reflection for the higher range of low frequencies – especially at 160 Hz.

The total correction to the (outdoor) direct sound from the wind turbine for both the Danish regulations and the 10th percentile sound insulation from Figure 11 using different values for the ground reflection is shown in Figure 12.

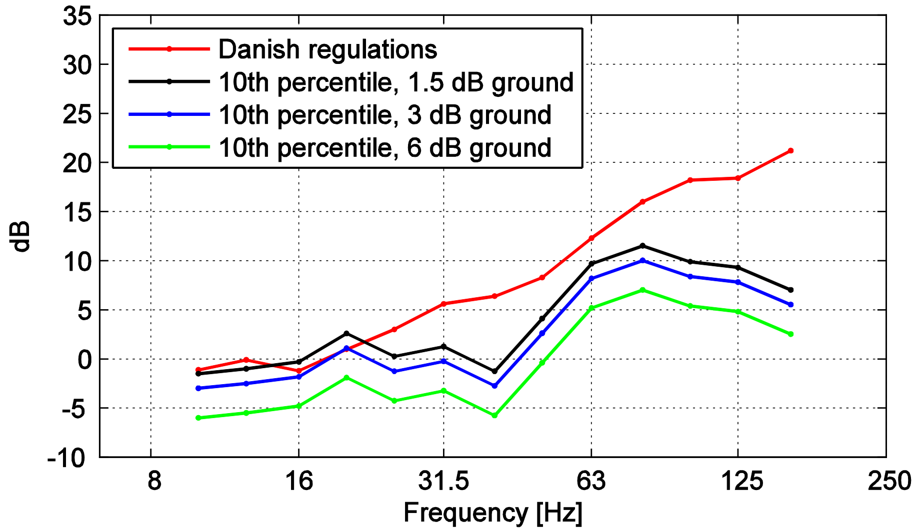

Figure 12: Comparison between the total correction to the direct sound from the wind turbine for the Danish regulations and a 10th percentile of the highest levels found indoor with different constant ground reflection values.

It is seen that the largest difference in total correction is at the 160 Hz one-third-octave band, which is also where the lowest ground reflection is used. From the spectrum of large wind turbines in Figure 5 it is seen that several turbines have spectral peaks in the 160 Hz band, and as a consequence this is the frequency band, where the new Danish regulations most severely underestimate the problems with low-frequency noise from large wind turbines.

3.6 Windows

The measurements of sound insulation were made with closed windows. However, in large parts of the world, many people prefer to sleep with the windows at least slightly open, and WHO recommends that noise limits should permit this [31], 32]. In Denmark, indoor measurements of low-frequency noise are usually made with closed windows, but if the complainant finds the noise as being louder with open windows, measurements should also be made for this situation [9]. It would therefore have been appropriate to measure the insulation also with slightly open windows and to estimate the resulting indoor sound pressure levels accordingly.

4 Conclusions

The results strengthen the conclusions from the first study [1], by including a larger data material. The hypothesis that the spectrum of wind-turbine noise moves down in frequency with increasing turbine size is confirmed. The relative amount of emitted low-frequency noise is higher for large turbines (2.3-3.6 MW) than for small turbines (≤ 2 MW). The difference is statistically significant for one-third-octave bands in the frequency range 63-250 Hz.

When outdoor sound pressure levels in relevant neighbour distances are considered, the higher low-frequency content becomes even more pronounced. This is due to the air absorption, which reduces the higher frequencies a lot more than the lower frequencies. Even when A-weighted levels are observed, a substantial part of the noise is at low frequencies, and for several of the investigated large turbines, the highest one-third-octave-band level is at or below 250 Hz. It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbours.

The turbines do emit infrasound (sound below 20 Hz), but levels are low, when human sensitivity to these frequencies is accounted for. Even close to the turbines, the sound pressure level is much below the normal hearing threshold, and infrasound is thus not considered a problem with turbines of the investigated size and construction.

The new Danish regulations on noise from wind turbines underestimate the indoor levels of low-frequency noise, mainly due to the use of too large sound insulation numbers for frequencies above 63 Hz. The new Danish regulations are therefore inadequate to protect the nearest neighbours from annoying low-frequency noise.

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