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Low-frequency noise from large wind turbines

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As wind turbines get larger, worries have emerged that the turbine noise would move down in frequency and that the low-frequency noise would cause annoyance for the neighbors. The noise emission from 48 wind turbines with nominal electric power up to 3.6 MW is analyzed and discussed. The relative amount of low-frequency noise is higher for large turbines (2.3–3.6 MW) than for small turbines ($\leq$ 2 MW), and the difference is statistically significant. The difference can also be expressed as a downward shift of the spectrum of approximately one-third of an octave. A further shift of similar size is suggested for future turbines in the 10-MW range. Due to the air absorption, the higher low-frequency content becomes even more pronounced, when sound pressure levels in relevant neighbor 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 neighbors.
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I. INTRODUCTION

Wind turbines get larger and larger, and worries have 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 neighbors. 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.

A. Low-frequency sound and infrasound

A few introductory words about low-frequency sound and infrasound are appropriate. For a more comprehensive review of human hearing at low and infrasonic frequencies, see, e.g., Ref. 1.

It is usually understood that the lower limit of the human hearing is around 20 Hz, and the terms *infrasound* and *infrasonic* are used with frequencies below this frequency. The frequency range 20–200 Hz denotes the *low-frequency* range (sometimes with a slightly different upper limit).

However, as a surprise to many people, the hearing does not stop at 20 Hz. If the level is sufficiently high, humans can hear infrasound at least down to 1 or 2 Hz. The sound is perceived through the ears, but the subjective quality differs from that of sound at higher frequencies. Below 20 Hz, the tonal sensation disappears, the sound becomes discontinuous in character, and a sensation of pressure at the eardrums occurs. At a few hertz, the sensation turns into discontinuous separate puffs, and it is possible to follow and count the single cycles of a tone.

At low and particularly infrasonic frequencies, the loudness increases more steeply above the hearing threshold than at higher frequencies,[2–5] and a sound moderately above threshold may be perceived not only loud but also annoying.[6–9] Since there is a natural spread in hearing thresholds, a sound that is inaudible or soft to some people may be loud and annoying to others. Low-frequency noise above the hearing threshold may also affect task performance[10] and cause sleep disturbances.[11] There is no reliable evidence of physiological or psychological effects from infrasound or low-frequency sound below the hearing threshold (see, e.g., Ref. 12).

Infrasound is measured with the G-weighting curve,[13] which covers the frequency range 1–20 Hz. At the normal hearing threshold for pure tones,[2,8,14–17] the G-weighted level is in the order of 95–100 dB. G-weighted sound pressure levels below 90 dB[13] or 85 dB[18] are normally not considered to be detectable by humans.

B. Previous studies

Many studies deal theoretically with generating mechanisms of low-frequency noise in wind turbines, whereas original information on low-frequency noise from complete wind turbines is more limited. In the following, only horizontal-axis turbines are considered.

Hubbard and Shepherd[19,20] reviewed the literature on wind turbine noise especially emphasizing studies carried out at NASA for more than two decades and comprising turbines up to 4.2 MW. It was observed and explained by numerical models that harmonics of the blade-passage frequency arise from differences in the inflow wind velocity across the rotor area and, for turbines with the rotor downwind of the tower, from impulses created by the passage of the blades through the wake of the tower. In particular, the

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latter mechanism is responsible for high levels of discrete-frequency noise in the infrasonic and low-frequency region for downwind turbines. Also "broadband" (stochastic or continuous-spectrum) noise is generated at low and infrasonic frequencies due to turbulence in the inflow. Inflow turbulence is the main reason for broadband noise below some hundred hertz. Propagation of sound from the turbines was also studied, and it was observed and explained by atmospheric refraction that downwind propagation of low frequencies (exemplified with 8–16 Hz) was cylindrical from a certain distance rather than spherical as normally assumed in noise prediction. This means that the level decreases by 3 dB per doubling of distance rather than 6 dB. Room resonances and low sound insulation of houses at low frequencies were used to explain that wind turbine noise is sometimes perceived more readily indoors than outdoors. The infrasonic part of the spectrum was below the normal hearing threshold in all investigated cases of complaints, but it was said to cause perceptible vibrations and rattling of windows and wall-mounted objects, which contributed to negative reactions to wind turbine noise. Using some of the same turbines as examples, Guidati *et al*.[21] showed that the interaction of the blades with the tower also creates impulsive infrasonic and low-frequency noise for upwind turbines, however, considerably less than for downwind turbines.

Legerton *et al*.[22] measured noise from two 450 kW turbines at a distance of 100 m. The levels reported for the one-third-octave bands up to 20 Hz are much below the normal hearing threshold for pure tones, while the levels in the 31.5-Hz band are just below the threshold.

Betke *et al*.[23] and Betke and Remmers[24] presented a technique to reduce wind noise in measurements of low-frequency noise from wind turbines. They used two microphones mounted in the ground with a distance of 10 m and a cross-correlation technique. At a distance of 200 m from a 500 kW wind turbine, the frequency spectrum seemed to be continuous when calculated with a very fine frequency resolution, however, with peaks at the blade-passage frequency and its harmonic. The G-weighted sound pressure level at this distance was 63.9 dB.

Jakobsen[25] reviewed data from the studies mentioned in the previous three paragraphs and sought further information in original measurement reports and by contact to the authors. He estimated the G-weighted levels for ten turbines in the range 50 kW–4.2 MW and found that levels from upwind turbines were around 70 dB or lower at a distance of 100 m, whereas levels from downwind turbines were about 10–30 dB higher. It was concluded that, even close to upwind turbines, indoors as well as outdoors, the G-weighted level would be below the limit of 85 dB given in the Danish guidelines for low-frequency and infrasonic noise[18] (summarized in English by Jakobsen[26]). For downwind turbines, this limit might be exceeded at distances up to several hundred meters. On the other hand, levels of infrasound even from downwind turbines were too low to explain complaints reported in the original studies at distances up to 2 km. In an attempt to find an alternative explanation, Jakobsen estimated the indoor A-weighted levels for the 10–160 Hz frequency range, a measure used by the Danish guidelines for the low-frequency range. The recommended evening/night limit of 20 dB for dwellings was exceeded in all cases but one. On the other hand, in those cases, normal outdoor A-weighted levels were also high enough to explain the complaints (47–61 dB), so it is not possible to tell, if the complaints were caused by the normal noise or the low-frequency noise. (Jakobsen erroneously referred to the Danish evening/night limit as 25 dB.)

Van den Berg[27] noted that the blade passage in front of the turbine tower gives rise to noise in the infrasonic range, but more important, to modulation of noise at higher frequencies perceived as swishing. In a stable atmosphere, which often exists at night, the difference in wind speed between top and bottom of the rotor is much higher than at other times, and this increases the modulation and changes the swishes to "clapping, beating, or thumping." For a wind farm with 17 turbines of each 2 MW, this was heard clearly at distances at least up to 1 km. Measurements were made at night, 100 m from each of two of the turbines as well as 750 m from the nearest row of ten turbines. One-third-octave-band levels up to 20 Hz were much below the normal hearing threshold, even for the closest measurements. Levels were above the normal hearing threshold [ISO 389-7 (Ref. 28)] from 31.5 to 40 Hz and up, even at 750 m.

Pedersen and Møller[29] analyzed indoor low-frequency and infrasonic noise in four houses near one or more wind turbines (0.6–2.75 MW) with distances to the closest turbine of 90–525 m. There were no audible harmonics of the blade-passage frequency, but audible components existed in the low-frequency range, in several cases with some amount of tonal character. G-weighted levels were 65 dB or lower, i.e., much below the normal hearing threshold, and it was concluded that infrasound would not give rise to nuisances. A-weighted levels for the 10–160 Hz frequency range were around or below the Danish evening/night limit for dwellings of 20 dB.[18] The highest levels observed were with a low wind speed (6.6 m/s) but closer to a turbine than people would normally live (90 m) or further away (325 m) in the only measurement that was made at a higher wind speed (9.4 m/s). The measurements were made according to the method in the Danish guidelines, however, without a complainant to appoint measurement positions, where the noise was loudest, which is important in the method.[18] Measurements were not in general corrected for background noise, but substantial effort was undertaken to analyze only periods without disturbances. Additional measurements in two of the houses suggested that people might be exposed to higher levels at other places in the room than measured with the official method. The study was inconclusive regarding the low-frequency noise and was part of the motivation for the present project.

The Hayes Mckenzie Partnership Ltd. consultancy[30] measured infrasound at a distance of 360 m downwind from a wind farm with twelve 1.65 MW turbines. With wind speeds up to 20 m/s, G-weighted levels were up to 80 dB. In another part of the study, low-frequency noise was measured in three houses, where the inhabitants had complained of low-frequency noise from wind farms with 3–16 turbines. Turbine size and distance to the wind farm were only reported for one of the cases (three 1.3 MW turbines, distance 1030 m). It was concluded that, for the 10–160 Hz range, levels are below the criteria proposed by Moorhouse *et al*.[31,32] for the UK Department for Environment, Food, and Rural Affairs (DEFRA), as well as the Danish 20-dB criterion.[18] Nevertheless, the data show that both limits were indeed exceeded in two of the three houses. In one house, this happened occasionally until the microphone was moved to another position in the room. It was argued that, in the first position, the microphone picked up sound from a nearby stream rather than from the turbines. The present authors are skeptical about the idea that moving of the microphone within the same room would reduce low-frequency sound and infrasound from the stream but not from the wind turbines. Both the UK and the Danish guidelines specify the noise to be measured, where it is loudest, and it is not possible to verify from the data, whether the sound in the first position (or both positions) was dominated by sound from the stream. In the second house, complaints were only reported two times during the measurement period, and both the UK and the Danish limits were exceeded at one of these occasions. A window was open at both occasions, and it was said that both sets of guidelines require windows to be closed during measurements. This is not correct, though. The UK documents do not have instructions on window settings during measurements but require extensive questioning of the annoyed person about conditions during annoyance, and it is logical to assume that measurements should be carried out under the same conditions. The Danish guidelines note specifically that measurements should be made with open windows, if the complainant finds that the noise is louder in this condition.

Jakobsen[33] used the apparent sound power (mainly at 8 m/s) from ten turbines in the 850 kW–3 MW range to calculate sound pressure levels at distances of 200–800 m. Outdoor and indoor A-weighted levels for the 10–160 Hz frequency range were derived; the indoor levels were derived by means of sound insulation data used in the Danish regulation for low-frequency noise from high-speed ferries.[34] It was concluded that indoor A-weighted levels for the 10–160 Hz range would not exceed the Danish 20-dB evening/night limit,[18] unless the outdoor A-weighted level for the full frequency range exceeds 45 dB. However, this is not what the data show. With an outdoor level just below 45 dB, indoor levels are above 20 dB in approximately half of the calculated cases. It was argued that insulation measurements of town houses (unpublished data) had shown better sound insulation than the buildings used in the background material for the regulation of noise from high-speed ferries.[35]

Lee *et al*.[36] and Jung *et al*.[37] measured noise from two upwind turbines of respectively 660 kW and 1.5 MW. The A-weighted noise increased with wind speed for the 1.5 MW turbine, whereas it was fairly constant over most of the operating range for the 660 kW turbine. The two turbines were respectively stall and pitch controlled, and the lack of increase in A-weighted noise at higher wind speeds was said to be typical for pitch-controlled turbines and to be one reason for favoring this type of control with large turbines. The infrasonic frequency range was dominated by the blade-passage frequency and its harmonics, and the level increased with increasing wind speed for both turbines. Worries were expressed that infrasound and low-frequency noise would become a problem with modern turbines, where the pitch control limits the A-weighted noise but not the low-frequency and infrasonic noise. It was concluded that the low-frequency part of the noise from both turbines is audible for an average person and would probably lead to complaints, and that the infrasonic part might cause complaints due to rattling noise, e.g., from windows. The distance to the turbines for this conclusion was not reported, but it can be derived from other data in the article that it must have been quite close, in the order of 70–100 m.

Gastmeier and Howe[38] measured the indoor noise at a distance of 325 m from the closest of several 1.8 MW turbines. The wind speed was 5 m/s. The level was said to be at least 30 dB below the normal hearing threshold (from Watanabe and Møller[17]) at all frequencies below 20 Hz. The figure in the article erroneously compared narrow-band levels with pure-tone hearing thresholds, but the present authors estimate that there is nevertheless a fair margin up to the threshold.

Ramakrishnan[39] measured noise close to a single 660-kW turbine and close to a single turbine in a wind farm with more than 50 turbines of each 1.5 MW. G-weighted levels were around 70 dB in both cases.

Harrison[40] noted that since inflow turbulence is essential for low-frequency noise emission, more focus should be on control of turbulence during measurements and predictions. A specific issue is that turbulence is increased in the wake of wind turbines, and this is not taken into account during measurements of noise emission, which are made with single turbines. Barthelmie *et al*.[41] showed that turbulence is markedly increased at distances up to at least four times the rotor diameter. Wake turbulence may thus be important for the emission of low-frequency noise from wind parks.

1. Summary of previous studies

The above studies have used a variety of methods, and most data cannot be compared directly. None of the studies investigated systematically the development of low-frequency and infrasonic noise with turbine size. Some of the studies lack basic information such as information on the turbine(s), measurement distance, direction and height, wind speed, analysis bandwidth, background noise, sound insulation when indoor measurements were made, etc. Nevertheless, it seems possible to make some conclusions.

The passage of the blades through areas of varying wind speed and density modulates the sound at higher frequencies with the blade-passage frequency but also creates infrasonic and low-frequency components. The differences in wind speed and density stem from the varying height above ground, atmospheric turbulence, and the presence of the turbine tower. Noise from the turbine mechanics may also play a role. The modulation of sound at higher frequencies may, due to the low modulation frequency, erroneously be interpreted as infrasound.

For upwind turbines, the level of infrasound is much below the normal hearing threshold, even close to the turbine. On downwind turbines, the passage of the blades through the wake of the tower generates infrasound that may exceed the normal hearing threshold close to the turbine and possibly cause rattling of, e.g., windows even in relevant neighbor distances. Most modern turbines, but not all, are upwind turbines.

For the low-frequency range, results are less conclusive. Indications diverge between studies, and it is not possible from the above to conclude, to which extent low-frequency noise from wind turbines is responsible for nuisances. The answer likely depends on turbine, distance, atmospheric conditions, being indoors or outdoors, etc.

At this place, it is appropriate to mention that, in addition to original studies, a substantial amount of summaries, reviews, white books, information folders, web pages, etc. exist on low-frequency noise and infrasound from wind turbines. Many of these have been made by organizations working keenly against or in favor of wind turbines, and unfortunately, many expositions are of doubtful quality. At some places, a variety of effects and symptoms are reported to be due to infrasound or low-frequency sound without any evidence of the causal relationship. Infrasound and low-frequency sound are often not properly distinguished, and, as a peculiar consequence, low-frequency noise is frequently rejected as the cause of nuisances, just because infrasound can be discarded (usually rightfully as seen in the above). Infrasound is (still) often claimed inaudible, and sometimes even low-frequency noise, or it is reported that both can only be heard by especially sensitive people—which is all wrong. Weighting curves are misunderstood or (mis)used to give the impression of dramatically high or negligibly low levels. Sometimes, political utterances (from both sides) are disguised as scientific contributions.

C. Outline of study

The present project was carried out in cooperation with Delta, a consultancy and official acoustics laboratory for the Danish environmental protection agency. Noise from four large turbines was measured, noise data for 44 other small and large turbines were aggregated, and low-frequency sound insulation to exterior sound was measured for ten rooms in normal living houses. Measurements and data aggregation were carried out by Delta.[42–45] In this article, the data from the project are used to examine the connection between emitted sound power and turbine size. Source spectra are analyzed and discussed, and, in particular, the hypothesis that the spectrum moves toward lower frequencies for increasing turbine size is investigated. Outdoor and indoor spectra at relevant neighbor distances are analyzed and discussed.

II. METHODS

A. Wind turbines

Forty-eight wind turbines were included in the project. Four prototype turbines with nominal electric power above 2 MW were measured by Delta as part of the project (turbines 1–4), while data for seven other turbines above 2 MW were taken from measurements made by Delta outside the project (turbines 5–11).[42,43] Data for 37 turbines with nominal power at or below 2 MW were taken from previous measurements made by Delta.[44] Among the small turbines, a few physical turbines appear more than once, representing the turbine measured at different occasions. All turbines were three-bladed with the rotor placed at the upwind side of the tower.

B. Emitted sound power

The sound power emitted from the turbines was measured in accordance with IEC 61400–11.[46] 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 center that would radiate the same sound in the direction, where the measurement is made. The result is denoted as 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.[18]

Data were obtained for all turbines in the downwind 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 are made for this. Turbines 1–4 were also measured at various other wind speeds. For evaluation of the content of pure tones, tonal audibility, ΔL_{ta}, was determined for turbines 1–4, and to get some insight into a possible directional pattern of the sound radiation, turbines 1–3 were measured at $\pm 60^{\circ}$ to the sides of the reference direction and in the upwind direction, still at the ground. All turbines were measured in the required frequency range of 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.

C. Outdoor sound pressure levels at neighbors

Free-field sound pressure levels, L_{p}, for downwind neighbor positions were calculated according to the method given by ISO 9613–2,[47] except that one-third-octave bands were used instead of octave bands.

The direction to neighbors 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, $L_{\mathrm{W}} + D_{\mathrm{C}}$, 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[48] 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 as d and the attenuation constant is α

$$L_p = L_{WA} - 20\ \text{dB} \cdot \log_{10}\left(\frac{d}{1\ \text{m}}\right) - 11\ \text{dB} - \alpha \cdot d + 1.5\ \text{dB}. \quad (1)$$

This calculation corresponds to the one used in the Danish regulation of noise for wind turbines.[49]

D. 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.[45]

The house was exposed to sound from a loudspeaker placed on the ground and directed toward the facade of the house at a horizontal angle of incidence around 45° at the center 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,[50] 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., Refs. 51–53). To fulfill this, *indoor sound pressure levels* were obtained as the power average of measurements in four arbitrary three-dimensional (3D) 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*.[53] 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,[54] 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 3–4 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.

Additional indoor measurements were made in an attempt to use a method given by the Danish guidelines for low-frequency noise.[18] The method specifies two measurements in areas of the room, where persons would be exposed to sound during normal use of the room (with certain geometrical restrictions) and one measurement near a room corner (0.5–1.0 m from the walls, 1.0–1.5 m above the floor). Measurements were carried out in positions complying with this. However, the method is meant for use in cases of noise complaints, and the two non-corner positions should be positions, where the complainant perceives the noise as being loudest. Without a complainant and without the actual annoying noise, it was not possible to fulfill this. Therefore, even when the geometrical conditions of the method were fulfilled, the measurements did not comply with the method as a whole, and the results are not reported. It must be concluded that the method is unsuitable for measurements of sound insulation, unless some kind of search for maximum level is added to the procedure.

E. Indoor sound pressure levels at neighbors

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.

F. Statistical methods

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

III. RESULTS AND DISCUSSIONS

Three turbines, one at 1650 kW and two at 2.3 MW, were added to the material at a late stage, and one-third-octave data are not available for these, thus only L_{WA} and L_{WALF} are reported. Twenty-hertz high-pass filters had unfortunately been inserted during some of the measurements (reference, left, and right directions for turbine 1 and reference direction for turbine 3), so, before data processing, the effect of these filters was counteracted by subtracting the filter response from the measured levels in the affected frequency range. High-frequency electrical noise from the frequency converter affected some of the measurements at frequencies above 5 kHz, and data for turbines 1–4 are thus not reported at these frequencies. Some inconsistencies exist in the data given by Delta in different reports, tables, and figures. The results in the present article are based on the least processed data reported, which with few exceptions means emitted sound power levels in one-third-octave bands.

A. Emitted sound power

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 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.

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 ($t = 3.94$, d.f. $= 90.0$, one-sided $p < 0.001$). 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 ($t = 1.82$, d.f. $= 79.8$, one-sided $p = 0.036$).

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 ($t = 5.42$, d.f. $= 46$, one-sided $p < 0.001$) as well as with the four smallest turbines removed ($t = 2.54$, d.f. $= 42$, one-sided $p = 0.007$).

It is also seen in Fig. 1 that there is some variation between turbines of the same size. As mentioned in Sec. II A, turbines of the same size may be of the same or different make and model, or, for a few turbines below 2 MW, the same physical turbine measured at different occasions.

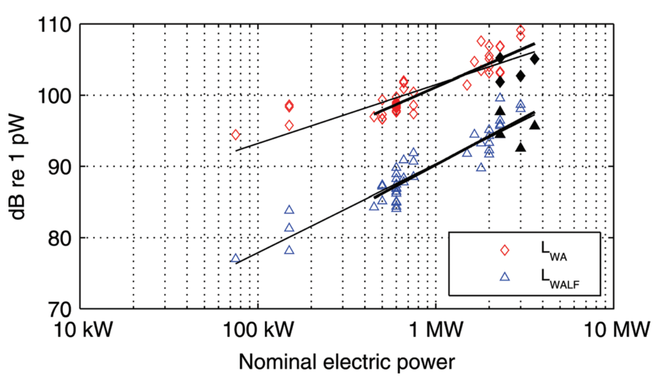

FIG. 1. (Color online) Apparent sound power levels (L_{WA} and L_{WALF}) in the reference direction as a function of turbine size. Wind speed is 8 m/s. Regression lines: all turbines included (thin lines), four turbines below 450 kW excluded (bold lines). Black-filled marks are for turbines 1–4.

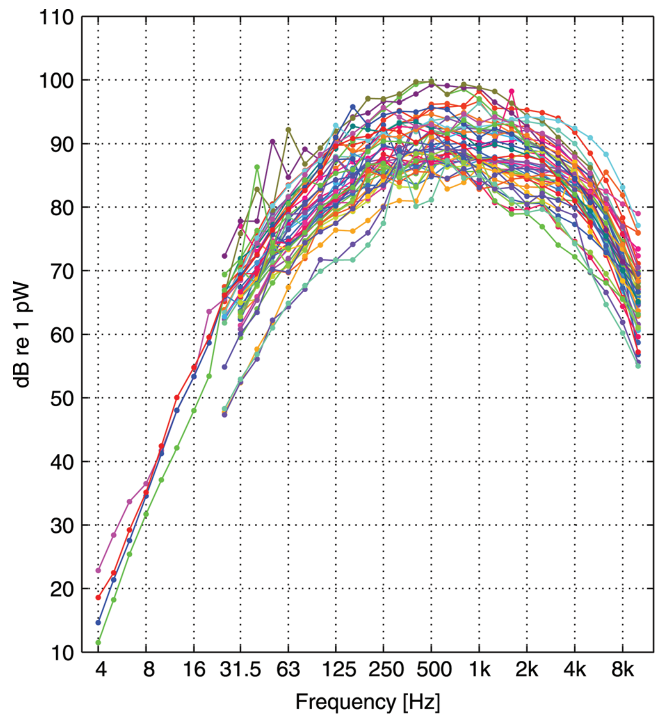

FIG. 2. A-weighted apparent sound power levels in one-third-octave bands. Forty-five turbines with nominal electric power 75 kW–3.6 MW.

2. One-third-octave-band spectra

Apparent sound power levels for one-third-octave bands are shown in Fig. 2.

Regarding the infrasonic part of the spectrum, the G-weighted[13] apparent sound power levels, calculated from the levels in the one-third-octave bands up to 20 Hz, 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 center, this will only give G-weighted sound pressure levels of 69–75 dB, which is far below the normal threshold of hearing.[1] This calculation does not account for possible near-field phenomena, e.g., from a closely passing blade.

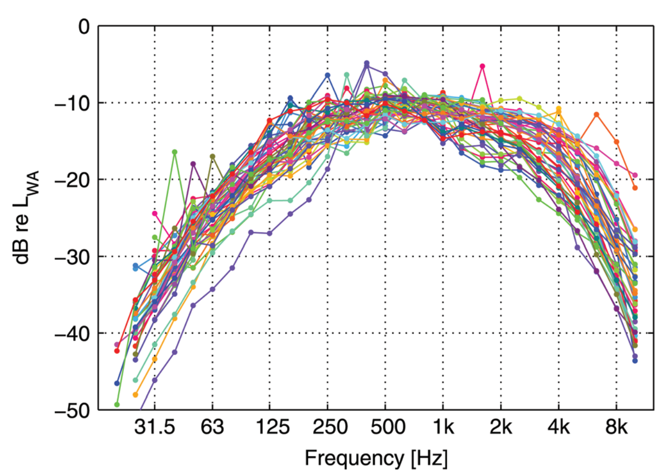

FIG. 3. Normalized A-weighted apparent sound power levels in one-third-octave bands. Forty-five turbines with nominal electric power 75 kW–3.6 MW. (Normalized meaning that L_{WA} for the individual turbine has been subtracted from all one-third-octave-band levels.)

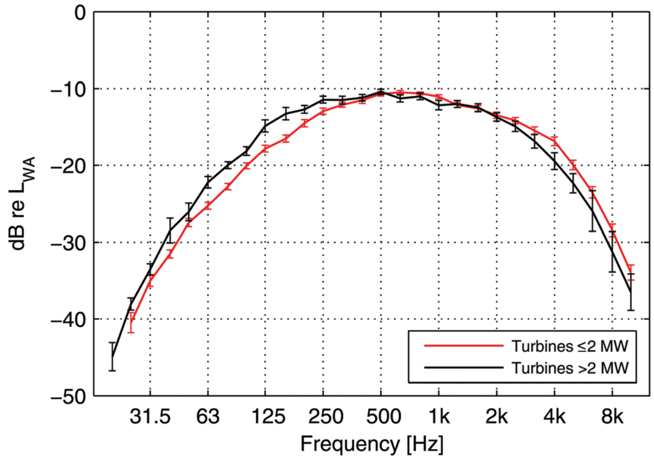

FIG. 4. (Color online) Normalized A-weighted apparent sound power levels in one-third-octave bands, means of two groups of turbines: ≤ 2 MW and > 2 MW. Error bars indicate ± 1 standard error of mean.

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 sound power level, L_{WA}. The result is shown in Fig. 3.

A possible difference in spectrum between small and large turbines is 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.

The spectrum of the large turbines lies 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 and at 4 kHz [$t = (3.49, 4.52, 2.81, 3.27, 3.49, 2.63, 2.52, -2.10)$, d.f. $= (14.3, 22.1, 17.0, 13.5, 13.6, 23.8, 22.6, 12.5)$, one-sided $p = (0.002, <0.001, 0.006, 0.003, 0.002, 0.007, 0.010, 0.028)$]. If the four smallest turbines are discarded, the difference is significant at the same frequencies plus 5 kHz [$t = (2.94, 4.09, 2.22, 2.76, 2.97, 1.93, 1.83, -2.07, -1.93)$, d.f. $= (11.7, 18.0, 14.5, 11.1, 11.6, 18.7, 20.1, 12.9, 11.7)$, one-sided $p = (0.006, <0.001, 0.022, 0.009, 0.006, 0.035, 0.041, 0.030, 0.039)$].

The significant differences between small and large turbines are at moderate 1.5–3.2 dB, but as mentioned in the introduction (Sec. I A), at low frequencies, even small differences may affect human perception of the sound. In addition, if low frequencies have a notable impact on requirements of distance to the neighbors, 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 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.*[55]).

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 (see introductory remarks of Sec. III). If turbine 6 is disregarded at these frequencies, the large turbines lie at or below the mean of small turbines in virtually every one-third-octave band above 2 kHz. The difference between means of the two groups is then significant for all one-third-octave bands in the 2.5–10 kHz range [$t = (-1.83, -2.49, -3.47, -3.18, -2.42, -2.76, -2.64)$, d.f. $= (15.2, 15.6, 14.5, 14.8, 4.1, 4.6, 6.3)$, one-sided $p = (0.044, 0.012, 0.002, 0.003, 0.036, 0.022, 0.018)$].

3. Tonality

The tone analyses show that tones generally vary in level and frequency with wind speed. Figure 6 shows tonal audibility for the most prominent tones of turbines 1–4.

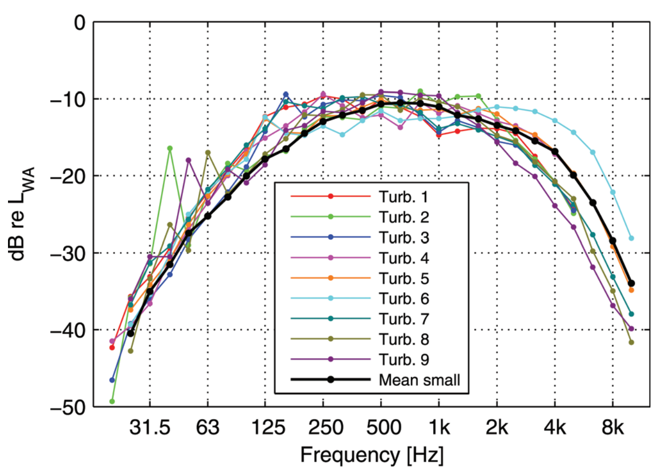

FIG. 5. Normalized A-weighted apparent sound power levels in one-third-octave bands, mean of 36 turbines ≤ 2 MW (bold line) and 9 individual turbines > 2 MW.

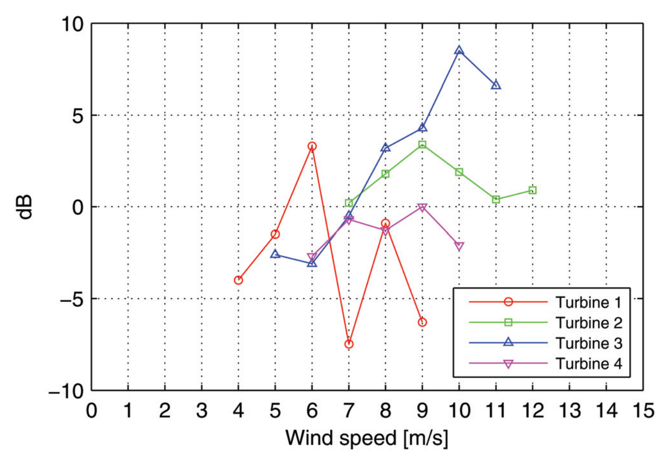

FIG. 6. (Color online) Tonal audibility, ΔL_{ta}, as a function of wind speed for turbines 1–4, reference direction (turbine color code as in Fig. 5).

Values are below 3–4 dB, except for turbine 3 at high wind speeds. For turbines 1 and 3, the data apply to a tone that varies with wind speed around 110–145 Hz, approximately the same frequency range for both turbines. For turbine 2, the data apply to a tone with a nearly constant frequency around 40 Hz. Turbine 4 has several tones at higher frequencies, and those in the frequency range 800–1400 Hz alternately dominate, depending on wind speed. One-third-octave-band peaks can be identified in Fig. 5 for the two turbines with tonality above 0 dB at 8 m/s (turbine 2, 40 Hz; turbine 3, 160 Hz).

ISO 1996–2 (Ref. 56) specifies a tone penalty to be used, when the tonal audibility exceeds 4 dB. National criteria for tone penalty may vary, e.g., Danish regulation requires that the tonal audibility exceeds 6.5 dB, before a penalty is given.[57]

Only one turbine exceeds the 4 dB limit and only at high wind speeds, where noise regulation may not apply. It is quite surprising that not even the most distinct tone in the one-third-octave-band spectra, the 40-Hz tone of turbine 2, results in a tone penalty. This is most likely an effect of the critical band used for tone assessment being very wide at low frequencies. It is outside the scope of the present article to evaluate if the tones will be perceived as being tonal despite the lack of tone penalty.

4. *Directivity*

Figure 7 shows the directivity of the three turbines measured.

The data differ somewhat between turbines, and it is difficult to find a general pattern. Both higher and lower levels are seen in other directions than the reference. At the lowest frequencies, a low directivity would be expected, but this is not seen in the data. A measured directivity may reflect a true directivity, but if the main noise source is at one side in the rotor plane, e.g., at the down going blade as shown by Oerlemans and Schepers[58] and Oerlemans *et al*.[59] the measurement in this side is closer to the source, and a false indication of directivity may result.

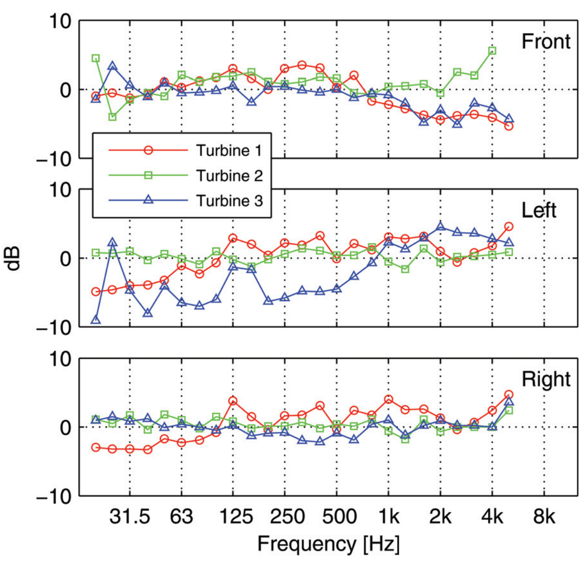

FIG. 7. (Color online) Directivity of turbines 1–3. Wind speed is 8 m/s except for turbine 2, front, which was measured at 10 m/s (and compared to reference direction at 10 m/s). Data missing for turbine 2 front at 5 kHz due to electric noise in the measurement (turbine color code as in Fig. 5).

A possibly source of error for the directivity data is that the measurements for the various directions do not always refer to the same period. Each of the other directions was in fact measured together with the reference direction, but they were not all measured at the same time. Only one data set exists for the reference direction, and thus this cannot apply to all directions. At low frequencies, poor signal-to-noise ratio may be responsible for large uncertainty.

The direction from the turbine to neighbors is typically more horizontal than the direction to the measurement positions. In particular, if sound is radiated from synchronous vibrations in blades and/or tower, chances are that the radiation will be more perpendicular to the rotor plane and/or the tower, i.e., close to the horizontal plane. More knowledge is called for on this issue.

5. *Effect of wind speed*

Figure 8 shows L_{WA} as a function of wind speed for the four turbines, where data is available.

The noise increases with wind speed but levels out or even decreases above 7–8 m/s. The four turbines are all pitch-controlled, and the observation is in line with the reports by, e.g., Lee *et al*.[36] and Jung *et al*.[37] for pitch-controlled turbines.

B. Outdoor sound pressure levels at neighbors

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[60] have shown that around this sound pressure level, the percentage of highly annoyed persons increases above 5%, and the percentage of annoyed persons increases above 10% (Pedersen *et al*.[61]). Pedersen and Nielsen[62] recommended a minimum distance to neighbors 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.[63] Thus, 35 dB seems as a very reasonable limit for wind turbine noise. It is also the limit that

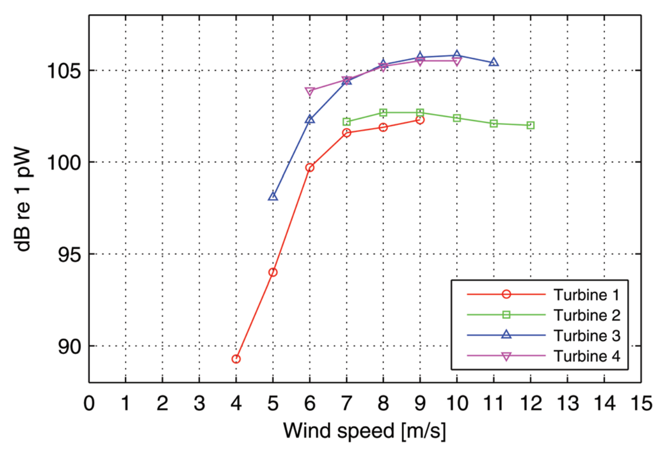

FIG. 8. (Color online) A-weighted apparent sound power level, L_{WA}, as a function of wind speed for turbines 1–4 (turbine color code as in Fig. 5).

TABLE I. Key figures at the distances from a single turbine, where the total A-weighted sound pressure level is 35 dB. Distances are given as slant distance to rotor center, which, for actual turbine heights, is close to horizontal distance.

	Turbine									
	1	2	3	4	5	6	7	8	9	Mean small
Distance (m)	629	647	879	822	679	758	713	1227	1144	453
L_{pA} (dB)	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
L_{pALF} (dB)	28.8	26.7	28.9	27.6	28.0	29.1	28.8	27.0	27.0	24.8
L_{pALF}–L_{pA} (dB)	−6.2	−8.3	−6.1	−7.4	−7.0	−5.9	−6.2	−8.0	−8.0	−10.2
L_{pG} (dB)	59.1	54.5	55.0	58.0						

applies in Denmark in open residential areas (night) and recreational areas (evening, night, and weekend) for industrial noise[64] (but not for wind turbine noise[49]).

Table I shows the distances for the individual turbines as well as various key figures at the 35-dB distances.

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 over 600 m to more than 1200 m.

The one-third-octave-band spectra at the same distances are shown in Fig. 9.

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 Fig. 5).

It is important to note that, for several turbines, the highest level for a one-third-octave-band is at 250 Hz or lower, even when A-weighted levels are regarded (Fig. 9). It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbors and that the low-frequency sound must be treated seriously in the assessment of noise from large turbines.

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 regulation allows 44 dB.[49] For visual reasons, the Danish regulation has a setback distance for dwellings of four times the total

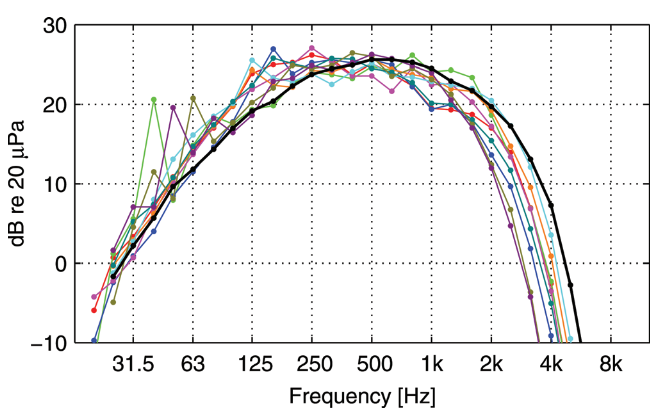

FIG. 9. A-weighted one-third-octave-band sound pressure levels at the distance from a single turbine, where the total A-weighted sound pressure level is 35 dB (see Table I and turbine color code as in Fig. 5).

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 there are several turbines together in wind farms. Table II lists distances to small wind farms, where the A-weighted sound pressure level is 44 dB, as well as various key figures at those distances.

C. Sound insulation

During the measurements, there were severe problems with background noise at the three lowest frequencies. Eighteen measurements with a signal-to-noise ratio below 1.3 dB were discarded. Consequently, seven room/frequency combinations had to be derived from measurements in only two or three 3D corners. Two room/frequency combinations with measurements from only one 3D corner were not calculated. Figure 10 shows the sound insulation for the ten rooms.

For the frequencies 63–200 Hz, with few exceptions, the rooms have 10–20 dB sound insulation. Toward lower frequencies, the insulation decreases, while the variation between rooms becomes larger. Some rooms show very little or even negative insulation at certain frequencies. A single room has unusually high insulation in the 16–31.5 Hz range. This room was a small room used for storage of furniture and other goods. The room is thus not considered a typical living room, and its data are discarded in further calculations.

Be aware that, for each one-third-octave band, the indoor level refers to the maximum level that people would normally be exposed to in the room (Sec. II D). Thus, in particular, for the higher end of the frequency range, the insulation data are lower than traditional insulation data employed for technical purposes, where room average levels are typically used.

1. Shortcomings of insulation measurements

A shortcoming with the measurement method used is that the exposure is focused at the facade of the house. In the situation of the house being exposed to noise from wind turbines, the whole house, including the roof and, at low frequencies, also the back of the house, will be exposed to nearly the same sound. In the measurement situation, these other surfaces receive much less sound due to loudspeaker directivity, higher distance to the loudspeaker, shadowing, etc.

TABLE II. Key figures at the distances where the total A-weighted sound pressure level is 44 dB. Wind farm with two rows of each six identical turbines, 300 m distance between turbines in both directions (200 m for small turbines). Observer point centered at long side. Distances are given as slant distance to closest turbine.

	Turbine									
	1	2	3	4	5	6	7	8	9	Mean small
Distance (m)	530	546	831	759	585	679	631	1241	1142	393
L_{pA} (dB)	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0
L_{pALF} (dB)	37.9	35.9	38.1	36.8	37.2	38.3	38.0	36.3	36.3	33.9
$L_{pALF}-L_{pA}$ (dB)	−6.1	−8.1	−5.9	−7.2	−6.8	−5.7	−6.0	−7.7	−7.7	−10.1
L_{pG} (dB)	68.4	63.9	64.6	67.4						

A further problem is that the outdoor free-field sound pressure level is calculated by simply subtracting 6 dB from the measured level at the facade. This assumes that the facade is large enough to be totally reflecting at all frequencies, an assumption which hardly holds at the lowest frequencies. A better solution might have been to measure the free-field level from the loudspeaker at a place without reflecting surfaces (other than the ground), and have used this value in the calculation.

The problems with background noise might have been overcome by using a modern technique that utilizes the correlation between the outdoor and indoor signals, e.g., the maximum-length-sequence (MLS) technique. Alternatively, it might have been possible to increase the signal level by measuring one one-third-octave band at a time rather than the whole low-frequency range simultaneously.

D. Indoor sound pressure levels at neighbors

Figure 11 shows indoor one-third-octave-band levels for all 81 combinations of 9 turbines and 9 rooms at the distance with a total A-weighted outdoor sound pressure level of 35 dB. Be aware that the indoor levels estimate the maximum level that people would normally be exposed to in the room and not the average level of the room (Sec. II D).

Large differences are seen between turbine/room combinations. Most of the variance is attributed to differences in the room sound insulation, except at 63 and 80 Hz, where both room and turbine contribute equally. Values in the upper end of the range at 40 Hz are due to high emission from a single turbine, whereas high values at 200 Hz are due to low sound insulation of a single room.

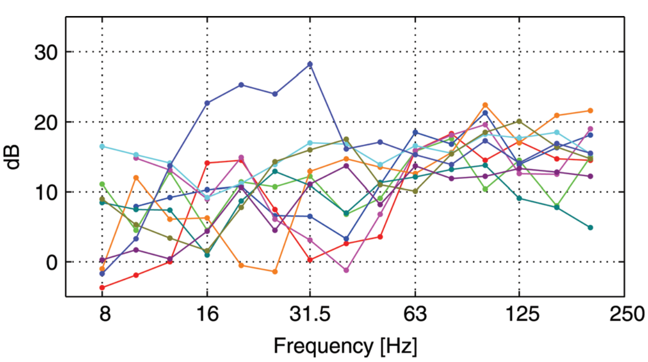

FIG. 10. Sound insulation measured for ten rooms.

It is seen from the inserted hearing threshold (dashed line), that the low-frequency sound will be audible in many turbine/room combinations, mainly at the highest of the low frequencies. The sound will not be very loud, but as mentioned in the introduction, low-frequency sound can be annoying only slightly above the hearing threshold (Sec. I A), and some people may be annoyed by the sound.

Figure 12 shows indoor levels for the situations from Table II where the A-weighted outdoor sound pressure level from a wind farm is 44 dB.

Here, there will be audible sound somewhere in all rooms and with all turbines. In more than half of the cases (48 out of 81), the normal hearing threshold is exceeded by more than 15 dB in one or more one-third-octave bands, and there is a risk that a substantial part of the residents will be annoyed by the sound.

For continuous noise, to avoid sleep disturbance, WHO recommends an indoor limit of 30 dB for the A-weighted sound pressure level,[65] but also notes that, if the noise includes a large proportion of low-frequency noise, "*a still*

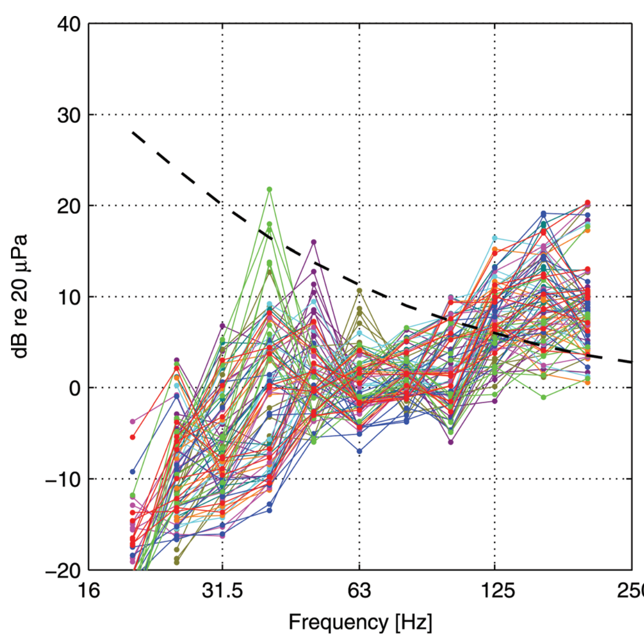

FIG. 11. Indoor A-weighted one-third-octave-band sound pressure levels at the distance from a single turbine, where the total A-weighted outdoor sound pressure level is 35 dB (see Table I); 81 turbine/room combinations. Dashed line is hearing threshold according to ISO 389–7 (Ref. 28) (colors indicate the turbine, color code as in Fig. 5).

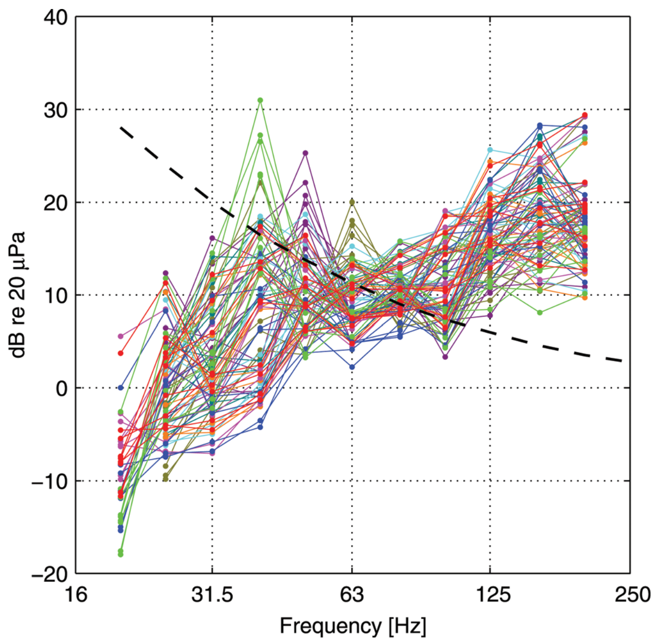

FIG. 12. Indoor A-weighted one-third-octave-band sound pressure levels at the distance from wind farms, where the total A-weighted outdoor sound pressure level is 44 dB (see Table II); 81 turbine/room combinations. Dashed line is hearing threshold according to ISO 389–7 (Ref. 28) (colors indicate the turbine, color code as in Fig. 5).

lower guideline value is recommended, because low-frequency noise …. can disturb rest and sleep even at low sound pressure levels." How much lower is not stated, but unless the level above 200 Hz is exceptionally low, the total A-weighted sound pressure level will obviously exceed, e.g., 25 dB in many of the cases in Fig. 12.

1. Danish indoor limit

The Danish indoor evening/night limit for L_{pALF} in dwellings of 20 dB (Ref. 18) does not apply to measurements in single positions but to levels measured by the method mentioned in Sec. II D. The method uses the power average of measurements in three positions: one position near a corner of the room and two positions where the complainant perceives the noise as being loudest. Assuming that the complainant appoints such positions adequately, the result of the entire method—the power average with a corner position—will still be a level close to the maximum.

It is not possible to find the maximum L_{pALF} by simply adding the one-third-octave-band levels from Fig. 11 or Fig. 12, since the various one-third-octave bands may have their maximum in different areas of the room. However, 40 of the 81 turbine/room combinations of Fig. 12 exceed an A-weighted level of 20 dB for at least one one-third-octave band in the 10–160 Hz frequency range, and it is reasonable to believe that the total for that frequency range, L_{pALF}, will exceed 20 dB for even more combinations.

It should be mentioned that wind turbines have been exempt from the general Danish guidelines for low-frequency sound since 2006, when the regulation for wind turbines was updated.[49] The argument was that indoor L_{pALF} will not exceed 20 dB, if the normal outdoor limits are complied with.[66] This may be true for smaller turbines, but as seen, the indoor level may easily exceed 20 dB with large turbines above 2 MW.

IV. GENERAL DISCUSSIONS

A. Noise versus turbine size

The data material gives a useful overview of the sound power emitted from wind turbines of different sizes, and, with caution, it may be possible to use the data to estimate the apparent sound power level of future, larger turbines. Figure 13 repeats the data for L_{WA} from Fig. 1, now with an extrapolation toward higher nominal electric power, and data for the regression line inserted.

The regression line in Fig. 13 corresponds to the following connection between the apparent sound power, P_A, and the nominal electric power, P_E:

$$P_A = constant_1 \cdot (P_E/1\text{MW})^{slope/10\text{dB}} \tag{2}$$

where *slope* is the slope of the regression line, and $constant_1$ can be derived from the last term of the regression line. Since the slope is 11.0 dB, the exponent is 1.10, meaning that the apparent sound power increases more than proportionally to the nominal electric power. Thus, to the extent that turbines follow the trend of the regression line, a turbine of double size emits more than the double sound power.

The area A of the circle, within which a certain noise limit is exceeded, is of particular interest. The radius of the circle can be found by solving Eq. (1) with respect to d, and, if omitting the atmospheric absorption, which mainly has effect at high frequencies and at long distances, it is found that the area is proportional to the apparent sound power. After insertion of Eq. (2), it follows that

$$\begin{aligned} A &= constant_2 \cdot P_A \\ &= constant_2 \cdot constant_1 \cdot \left(\frac{P_E}{1\text{MW}}\right)^{slope/10\text{dB}} \end{aligned} \tag{3}$$

where $constant_2$ depends on the noise limit.

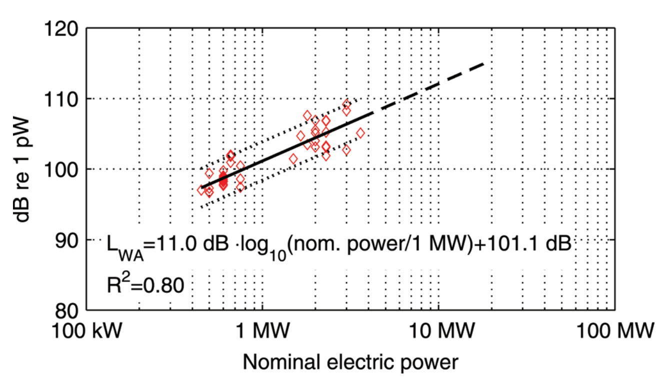

FIG. 13. (Color online) Apparent sound power level (L_{WA}) as a function of turbine size, four turbines below 450 kW excluded, wind speed 8 m/s. Linear regression line, standard error of estimates (s.e.e.) 1.64 dB. Extrapolation dashed, 90 % confidence intervals (dotted) based on s.e.e.

Thus, at the regression line, the noise-occupied area increases more than proportionally to the nominal electric power. This is a remarkable result, when considering today's development with constantly increasing turbine sizes and even, at least in Denmark, replacing many small turbines with few larger turbines. From a noise pollution point of view, this seems as a step back. If the installed nominal electric power is the same, large turbines affect a larger area with noise than small turbines do.

It must be added that the slope of the regression line is not significantly higher than 10 dB [90% confidence interval 9.53–12.40, $p(slope \leq 10\ \text{dB}) = 0.133$]. With a slope of 10 dB, the noise-occupied area is the same for small and large turbines for the same installed nominal electric power.

B. Variation between turbines

The data in Fig. 13 are based on measurements on single turbines. In order to account for variations between different samples of the same model, somewhat higher apparent sound power levels should be used in project planning. According to IEC TS 61400-14,[67] manufacturers should declare values that are 1.645 times the standard deviation between turbines higher than the mean of turbines of the given model. This value corresponds to the upper limit of a 90% confidence interval, meaning that the probability is 5% that a random sample turbine of the actual model emits more noise than reflected by the declared value.

The size of this safety margin thus depends on the variation between turbines of the actual model. The standard deviations in Fig. 13 for turbines of the same size and make range from 1.6 to 3.5 dB, when disregarding turbine sizes that comprise repeated measurements on one or more turbines. Since the standard deviation must be multiplied by 1.645, the margin will typically be several decibels.

Broneske[68] pointed out that manufacturers often declare values that do not have the safety margin specified in IEC TS 61400-14. It is also the present authors' impression that minimum distances to dwellings are often calculated from noise data that lack an appropriate safety margin. Using data without safety margin, such as mean values for a given turbine model, measurements from a single turbine, or "best guess" for future turbines, gives in principle a probability of 50% that the actual erected turbine(s) will emit more noise than assumed, and that noise limits will be exceeded, if the project is planned to the limit.

It is noted that small changes in apparent sound power level may result in sizeable changes in distance requirements. As an example, for a single turbine, 3 dB higher apparent sound power level results in a 41% higher distance requirement.

C. Data from project WINDFARMperception

A study of visual and acoustic impact of wind turbines on residents was carried out by van den Berg *et al.*[69] As part of the study (known as project WINDFARMperception), measured spectra of apparent sound power from wind turbines were collected. Sound power levels at 8 m/s for 28 turbines with nominal electric power in the 80 kW–3 MW range were selected for calculations of sound pressure levels at the neighbors. Only four turbines are above 2 MW, but if three 2-MW turbines are included in the group of large turbines, it is possible to make a relevant comparison of large and small turbines. Figure 14 shows means of turbines < 2 MW and ≥ 2 MW.

Also with these data, the low-frequency part is clearly higher for large turbines than for small. The level differences at 63 and 125 Hz are statistically significant [$t = (2.70, -2.39)$, d.f. $= (12.8, 16.9)$, one-sided $p = (0.009, 0.015)$].

The differences (3.6 and 2.2 dB) are in the same order of magnitude as the differences in the present investigation (compare with Fig. 4).

A comparison with data of the present investigation converted to octave bands shows very similar values in the two investigations, see Fig. 15. Data from the two investigations for the same power group are not significantly different at any frequency. (There is no overlap in original data.)

D. Tonal components

Søndergaard and Madsen[70] conclude (1) that the "*frequency spectra of the aerodynamic noise from the rotor blades of the largest wind turbines does not deviate significantly from the spectra for smaller wind turbines. This means that for the aerodynamic noise the low frequency range is not more prominent for large turbines than for small turbines*," (2) that the observed "*slightly higher …. relative amount of low frequency noise …. is mainly caused by gear tones at frequencies below 200 Hz*," and (3) that this "*is not unusual for prototypes and usually the fully developed commercial wind turbines are improved on the noise emission, especially concerning audible tones in the noise*."

However, these conclusions are not substantiated by adequate statistics or other data analyses. The separation of aerodynamic noise and gear noise referred to is not explained, and data are not given. Regarding the development of noise from prototypes to commercial turbines, no

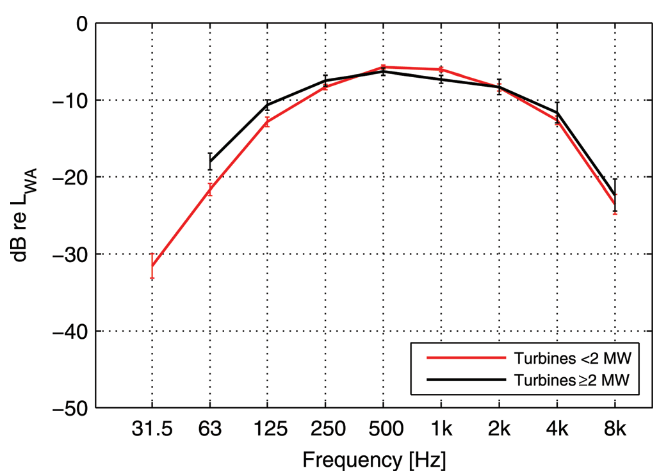

FIG. 14. (Color online) Normalized A-weighted apparent sound power levels in octave bands, means for two groups of turbines: < 2 and ≥ 2 MW. Data from van den Berg *et al.*,[69] Appendix D. Error bars indicate ± 1 standard error of mean. (None of the large turbines was measured in the 31.5-Hz octave band).

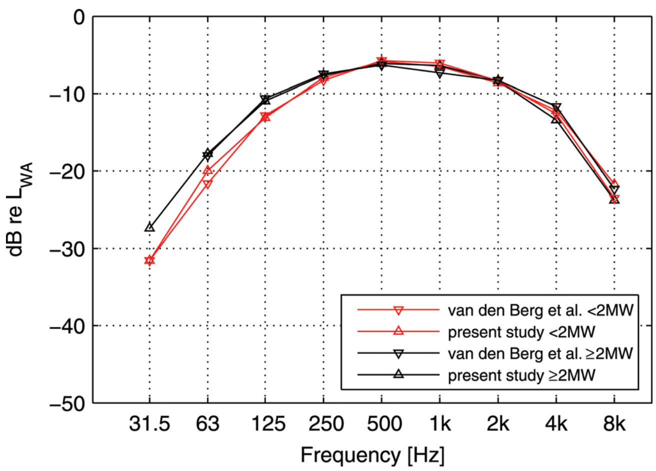

FIG. 15. (Color online) Normalized A-weighted apparent sound power levels in octave bands, means for two groups of turbines: < 2 and ≥ 2 MW and from two investigations: van den Berg *et al*. (Ref. 69), Appendix D and present investigation (converted to octave bands).

data or references are given. If the turbines of the present project are considered, it is unclear, whether turbines 5–11 are prototypes or not, since the turbines are anonymous, and the informations diverge between reports. The original report[43] only specifies turbines 1–4 as prototypes, but a summarizing report[70] refers to all the turbines above 2 MW as prototypes. If turbines 5–11 are indeed prototypes, this means that the third conclusion is made without data for large commercial turbines. If, on the other hand, turbines 5–11 are commercial turbines, it is worth noting that some of these also have obvious one-third-octave-band peaks (Fig. 5), and that their noise emissions (L_{WA} or L_{WALF}) are not lower than those of turbines 1–4, perhaps on the contrary (Fig. 1).

Regarding reduction of tonal noise, Søndergaard and Madsen refer to the tone penalty as a means to guarantee that the tones are actually reduced, before the turbines are put on the market, and they use expressions like "*the necessary tone reduction*"[70] and "*… reduced to a level where there is no penalty according to Danish rules….*"[43,70] They have evidently ignored that the results of their tone analyses will not release a tone penalty to any of the turbines (Sec. III A 3).

A closer look at the data reveals that, even when some of the one-third-octave-band peaks at low frequencies are very distinct, the peaks are not in general responsible for the difference between small and large turbines. Figure 16 shows an imagined situation, where all peaks below 200 Hz have been removed from the large turbines by replacing the level at the peaks with levels obtained by linear interpolation between the levels in the two adjacent one-third-octave bands. One to three peaks have been removed for each turbine, except for turbine 4, which does not have peaks in this frequency range. Only removal of the 40-Hz peak of turbine 2 affects the mean of the large turbines by more than 1.0 dB.

Generally, the large turbines are still above the mean of the small turbines in the low-frequency range. The difference between the means of large (> 2 MW) and small turbines (≤ 2 MW) is still significant in the same one-third-octave bands as they were with the peaks [63–160 Hz (unchanged above 160 Hz): $t = (3.03, 3.59, 2.81, 2.83, 3.18)$, d.f. = (22.4, 23.6, 17.0, 19.2, 18.9), one-sided $p = (0.003, <0.001, 0.006, 0.005, 0.003)$].

The striking similarity with the spectra from van den Berg *et al*.[69] (Fig. 15) supports that the spectra for the large turbines from the present project, including the tones, are representative for wind turbines of such size.

E. Ground reflection

In the calculations of sound pressure levels at the neighbors, the ground reflection is accounted for by adding 1.5 dB to the direct sound. As mentioned in Sec. IIC, the 1.5-dB value is used by Danish regulation.[49] Swedish guidelines add 3 dB to the direct sound (for distances up to 1000 m),[71] a value that also follows from ISO 9613–2 (Ref. 47) for the lowest octave-frequency band mentioned, 63 Hz, irrespective of the ground surface. During measurements of sound emission from the turbines,[46] it is assumed that the ground reflection adds as much as 6 dB to the direct sound. Certainly, a reflecting board is used under the microphone, but the board has only little effect at low frequencies, where the assumed 6-dB reflection is due mainly to the ground itself.

Possible destructive interference between the direct sound and the ground reflection due to elevation of the receiver above ground will have little impact at low frequencies. For example, for a source height of 75 m, a horizontal distance of 800 m, and a receiver height of 1.5 m, the delay between the direct sound and the ground reflection will only be 0.8 ms, which corresponds to a first dip in the sound transmission at 625 Hz.

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 neighbors is likely to underestimate the low-frequency sound.

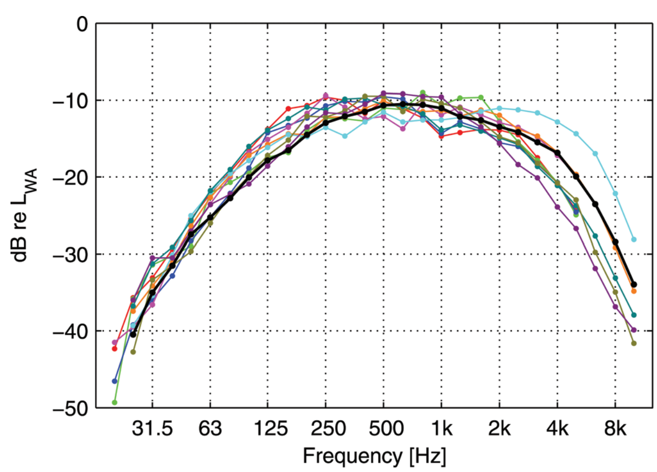

FIG. 16. Normalized A-weighted apparent sound power levels in one-third-octave bands, individual turbines > 2 MW and mean of 36 turbines ≤ 2 MW. Peaks in one-third-octave bands below 200 Hz have been removed from the large turbines by replacing the levels at the peaks by levels obtained by linear interpolation between the levels at the two adjacent one-third-octave-band frequencies (turbine color code as in Fig. 5).

F. 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.[65,72] In Denmark, indoor measurements of low-frequency noise are usually made with closed windows, but if the complainant finds that the noise is louder with open windows, measurements should also be made for this situation.[18] Therefore, it would have been appropriate to measure the insulation also with slightly open windows and to estimate the resulting indoor sound pressure levels accordingly.

G. Estimated sound power spectra for even larger turbines

In Sec. III A 2, the spectral difference between small and large turbines was seen in terms of differences in the normalized apparent sound power levels for certain one-third-octave bands. As an alternative way, Fig. 17 shows the mean normalized spectra of large and small turbines, but with the data for small turbines shifted one third of an octave down in frequency.

The two curves are very close in the main frequency range, meaning that the spectrum has maintained its shape but shifted about one third of an octave down in frequency from the small to the large turbines (compare with Fig. 4). Differences at the lowest frequencies may be real or be the result of uncertainty due to high background noise at these frequencies, a matter that is not fully expounded in the data material.

For the reader who might think that a shift of a single third octave is very modest, it is worth noting that it is the same as the musical interval of a major third, nearly the difference between two adjacent strings on a guitar.

The logarithmic means of the nominal electric power of the small and large turbines are around 650 kW and 2.6 MW, respectively, thus the downward spectral shift of approximately one third of an octave relates to an upward shift of the nominal electric power by a factor in the order of 4. It would thus be appropriate to suggest a further downward spectral shift of the same amount for future turbines in the 10-MW range.

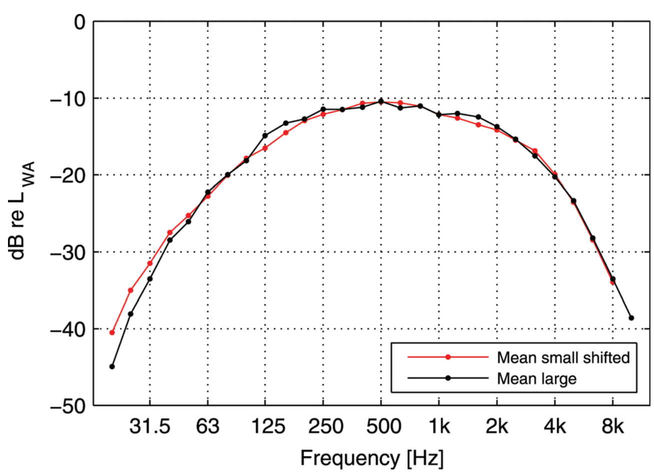

FIG. 17. (Color online) Normalized apparent sound power levels in one-third-octave bands. Mean of two groups of turbines: ≤ 2 and > 2 MW, group of turbines ≤ 2 MW shifted one third of an octave down in frequency. (Turbine 6 disregarded above 2 kHz, see Sec. III A 2.)

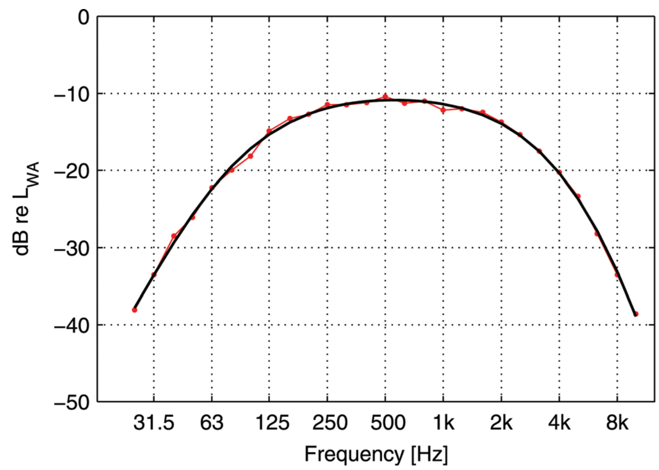

FIG. 18. (Color online) Sixth-order polynomial regression (bold line) for mean of normalized apparent sound power levels (dots and thin line) for the turbines > 2 MW (Turbine 6 disregarded above 2 kHz, see Sec. III A 2.)

As a supplement to the linear regression and the extrapolation for L_{WA} in Fig. 13, estimated spectra have been constructed for turbines around 2.5, 5, and 10 MW for possible (and cautious) use in future projects. Figure 18 shows a sixth-order polynomial regression of the relative spectrum for the turbines of the present project above 2 MW.

Table III gives relative one-third-octave-band levels for 2.5 MW turbines from the regression and, for 5 and 10 MW turbines, data shifted one sixth and one third of an octave, respectively, down in frequency. In addition, the table gives estimated absolute levels based on the linear regression of L_{WA} in Fig. 13. Note that the estimates are based on means of turbines and that they do not include a safety margin as mentioned in Sec. IV B.

The table values for the absolute level in one-third-octave bands are shown in Fig. 19.

H. Atmospheric conditions

All previous calculations assume spherical sound propagation, i.e., a 6 dB reduction of sound pressure level per doubling of distance. During certain atmospheric conditions, e.g., with temperature inversion or low-level jets, there may be a sound reflecting layer in a certain height, and thus the propagation beyond a certain distance is more like cylindrical propagation, which only gives 3 dB reduction per doubling of distance. This was observed for low frequencies, e.g., by Hubbard and Shepherd[19] and explained, e.g., by Zorumski and Willshire[73] and Johansson.[74] Above sea, Swedish guidelines generally assume cylindrical propagation beyond a distance of 200 m,[71] a distance supported by data by Bolin *et al.*,[75] who showed reflection in a height in the order of 100–200 m.

With cylindrical propagation beyond 200 m, the following equation applies (for distances above 200 m):

TABLE III. Estimated relative and absolute A-weighted sound power levels for turbines around 2.5, 5, and 10 MW based on sixth-order polynomial approximation of mean relative spectrum for turbines above 2 MW from Fig. 18 and L_{WA} from linear regression of Fig. 13. Relative levels moved, respectively, 1/6 and 1/3 of an octave down for 5 and 10 MW turbines. Approximation adjusted by +0.38 dB to achieve a total relative spectrum of 0 dB, which the mean of relative data (and its approximation) does not necessarily sum up to. Note that the estimates are based on means of turbines and that they do not include a safety margin as mentioned in Sec. IV B.

	Relative to L_{WA}						Absolute					
Frequency (Hz)	1/3-octave-band levels			Octave-band levels			1/3-octave-band levels			Octave-band levels		
	2.5 MW	5 MW	10 MW	2.5 MW	5 MW	10 MW	2.5 MW	5 MW	10 MW	2.5 MW	5 MW	10 MW
25	−37.4	−35.3	−33.2				68.1	73.5	78.9			
31.5	−33.2	−31.1	−29.0	−27.2	−25.2	−23.3	72.3	77.7	83.1	78.3	83.6	88.8
40	−29.0	−27.0	−25.3				76.5	81.8	86.8			
50	−25.3	−23.6	−22.0				80.2	85.2	90.1			
63	−22.0	−20.5	−19.1	−16.7	−15.3	−14.0	83.5	88.3	93.0	88.8	93.5	98.1
80	−19.1	−17.9	−16.8				86.4	91.0	95.3			
100	−16.8	−15.8	−15.0				88.7	93.0	97.1			
125	−15.0	−14.2	−13.4	−10.0	−9.3	−8.6	90.5	94.6	98.7	95.5	99.5	103.5
160	−13.4	−12.8	−12.3				92.1	96.0	99.8			
200	−12.3	−11.9	−11.5				93.2	96.9	100.6			
250	−11.5	−11.2	−11.0	−6.8	−6.5	−6.3	94.0	97.6	101.1	98.7	102.3	105.8
315	−11.0	−10.8	−10.6				94.5	98.0	101.5			
400	−10.7	−10.6	−10.5				94.9	98.2	101.6			
500	−10.5	−10.5	−10.5	−5.8	−5.8	−5.8	95.0	98.3	101.6	99.7	103.0	106.3
630	−10.5	−10.6	−10.7				95.0	98.2	101.4			
800	−10.7	−10.8	−11.0				94.8	98.0	101.1			
1000	−11.0	−11.3	−11.5	−6.3	−6.5	−6.8	94.5	97.5	100.6	99.2	102.3	105.3
1250	−11.5	−11.9	−12.4				94.0	96.9	99.7			
1600	−12.4	−12.9	−13.5				93.1	95.9	98.6			
2000	−13.5	−14.3	−15.1	−8.8	−9.5	−10.2	92.0	94.5	97.0	96.7	99.3	101.9
2500	−15.1	−16.0	−17.2				90.4	92.8	94.9			
3150	−17.2	−18.4	−20.0				88.3	90.4	92.1			
4000	−20.0	−21.6	−23.3	−14.7	−16.1	−17.8	85.5	87.2	88.8	90.8	92.7	94.3
5000	−23.3	−25.3	−27.5				82.2	83.5	84.6			
6300	−27.5	−29.9	−32.8				78.0	78.9	79.3			
8000	−32.8	−35.6	−38.5	−26.1	−28.7	−31.5	72.7	73.2	73.6	79.4	80.1	80.6
10 000	−38.5	−41.9	−45.2				67.0	66.9	66.9			
L_{WA}							105.5	108.8	112.1	105.5	108.8	112.1

$$L_p = L_{WA} - 20\ \text{dB} \cdot \log_{10}\left(\frac{200\ \text{m}}{1\text{m}}\right) - 10\ \text{dB} \cdot \log_{10}\left(\frac{d}{200\ \text{m}}\right) - 11\ \text{dB} - \alpha \cdot d + 1.5\ \text{dB}. \quad (4)$$

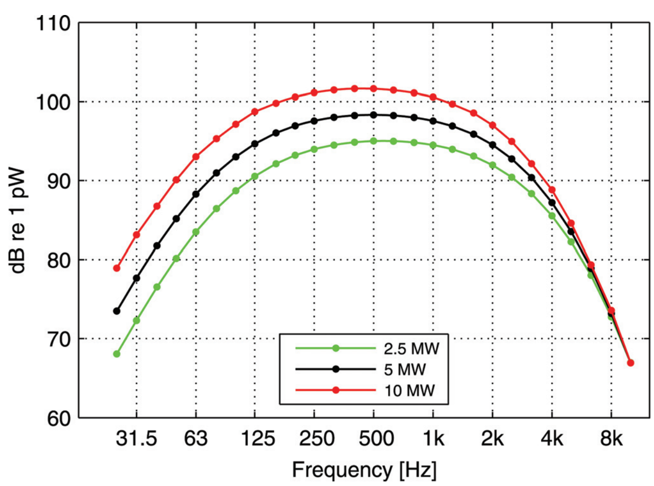

FIG. 19. (Color online) Estimated A-weighted sound power levels in one-third-octave bands for turbines around 2.5, 5, and 10 MW. Values and assumptions are taken from Table III.

Table IV and Fig. 20 show key figures and sound pressure levels in one-third-octave bands, respectively, at the distances from the turbines, where the A-weighted sound pressure level has decreased to 35 dB, assuming cylindrical propagation beyond 200 m.

Much longer distances (1414–3482 m) are needed than with pure spherical propagation, and the low-frequency character of the spectrum has become even more pronounced (compare with Table I and Fig. 9). Cylindrical propagation may thus explain case stories, where rumbling of wind turbines is claimed to be audible kilometers away. A worst-case scenario combining temperature inversion with a wind park acting as a line source in a certain distance range could theoretically reduce the geometrical attenuation in that range to zero. However, more knowledge is needed about atmospheric conditions and the occurrence of various phenomena.

Also other phenomena related to the atmospheric conditions deserve some attention. It is normally assumed that the

TABLE IV. Key figures at the distances, where the total A-weighted sound pressure level is 35 dB, cylindrical propagation assumed beyond 200 m. Distances are given as slant distance to rotor center, which, for actual turbine heights, is close to horizontal distance.

	Turbine									
	1	2	3	4	5	6	7	8	9	Mean small
Distance (m)	1476	1414	2373	2100	1562	1829	1776	3482	3152	827
L_{pA} (dB)	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
L_{pALF} (dB)	29.7	28.2	30.3	29.2	29.4	30.7	30.0	29.7	29.6	25.6
L_{pALF}-L_{pA} (dB)	−5.3	−6.8	−4.7	−5.8	−5.6	−4.3	−5.0	−5.3	−5.4	−9.4
L_{pG} (dB)	60.4	56.2	57.1	60.0						

wind speed increases logarithmically with increasing height above ground, starting from zero speed at a height equal to the *roughness length* of the ground surface. Thus, knowing the roughness length, the wind speed at all heights can be determined from measurements in a single height. The wind speed in a height of 10 m is used as a reference for measurements of wind turbine noise.[46]

However, several studies have shown that actual wind-speed profiles vary a lot and often deviate substantially from the assumed logarithmical profile.[76–79] In a stable atmosphere, which often exists at night, variations with height can be much larger than assumed with high wind speed at turbine height and little wind at ground. A large variation of wind speed across the rotor area increases the modulation of the turbine noise, and the normal "swish–swish" sound turns into a more annoying, "thumping," impulsive sound as reported by, e.g., van den Berg[27,80,81] and Palmer.[82] The effect is more prominent with large wind turbines, where the difference in wind speed between rotor top and bottom can be substantial. The effect is usually not reflected in noise measurements, which are mainly carried out in the daytime, when the logarithmic profile is more common.

Another consequence of large wind speed variation with height is that the turbine may emit noise corresponding to a high wind speed—and much higher than assumed from the wind speed measured at 10 m—while it is all quiet at the ground. Thus, there is more turbine noise than expected and less wind; hence, the turbine noise will not be masked with natural wind-induced sound, as it might have been with the assumed logarithmic wind profile.

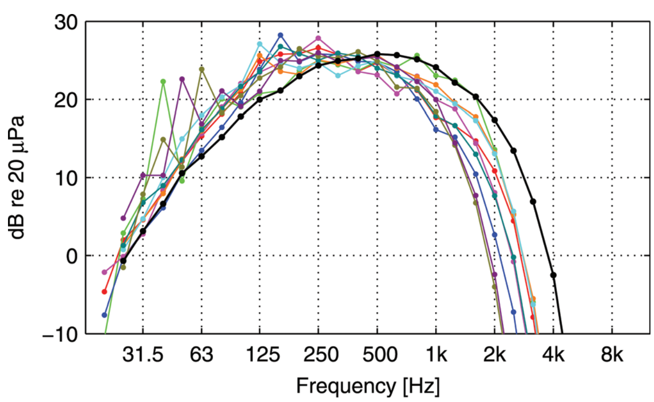

FIG. 20. A-weighted sound pressure levels in one-third-octave bands at the distances, where the total A-weighted sound pressure level is 35 dB (see Table IV). Cylindrical propagation assumed from 200 m (turbine color code as in Fig. 5).

Several authors have argued that the logarithmic wind-speed profile and the 10-m reference height are inadequate with the size of modern turbines (e.g., Refs. 77, 78, 80, 83), and a revised IEC 61400-11 will use the actual wind speed in the turbine hub height as a reference.[84] Wind profiles and statistics for the actual place can then be applied in noise prediction and regulation.

V. CONCLUSIONS

The results confirm the hypothesis that the spectrum of wind turbine noise moves down in frequency with increasing turbine size. The relative amount of emitted low-frequency noise is higher for large turbines (2.3–3.6 MW) than for small turbines ($\leq$ 2 MW). The difference is statistically significant for one-third-octave bands in the frequency range 63–250 Hz. The difference can also be expressed as a downward shift of the spectrum of approximately one third of an octave. A further shift of similar size is suggested for turbines in the 10-MW range.

When outdoor sound pressure levels in relevant neighbor 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 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 neighbors.

Indoor levels of low-frequency noise in neighbor distances vary with turbine, sound insulation of the room, and position in the room. If the noise from the investigated large turbines has an outdoor A-weighted sound pressure level of 44 dB (the maximum of the Danish regulation for wind turbines), there is a risk that a substantial part of the residents will be annoyed by low-frequency noise even indoors. The Danish evening/night limit of 20 dB for the A-weighted noise in the 10–160 Hz range, which applies to industrial noise (but not to wind turbine noise), will be exceeded somewhere in many living rooms at the neighbors that are near the 44 dB outdoor limit. Problems are much reduced with an outdoor limit of 35 dB.

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 infrasonic sound pressure level is much below the normal hearing threshold, and infrasound is thus not considered as a problem with turbines of the investigated size and construction.

The low-frequency noise from several of the investigated large turbines comprises tones, presumably from the gearbox, which result in peaks in the corresponding one-third-octave bands. The tone penalty does not guarantee that the tones are removed or reduced, since they are not sufficiently distinct to release a penalty at all. The spectral difference between large and small turbines remains statistically significant, even if the one-third-octave-band peaks are removed.

The above conclusions are based on data for turbines in the range of 2.3–3.6 MW nominal electric power. It must be anticipated that the problems with low-frequency noise will increase with even larger turbines.

The emitted A-weighted sound power increases proportionally to the nominal electric power or likely even more. Consequently, large turbines affect the same area—or possibly even larger areas—with noise, when compared to small turbines with the same total installed electric power.

There are differences of several decibels between the noise emitted from different turbines of similar size, even for turbines of the same make and model. It is therefore not feasible to make calculations down to fractions of a decibel and believe that this holds for the turbines actually set up. A safety margin must be incorporated at the planning stage in order to guarantee that the actual erected turbines will comply with noise limits. An international technical specification exists for this, but it is often not used.

Under certain atmospheric conditions, e.g., temperature inversion, the noise may be more annoying and—in particular the low-frequency part—propagate much further than usually assumed. More knowledge is needed on such phenomena and their occurrences.

ACKNOWLEDGMENTS

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[1]H. Møller and C. S. Pedersen, "Human hearing at low frequencies," Noise Health **6**(23), 37–57 (2004).
[2]L. D. Whittle, S. J. Collins, and D. W. Robinson, "The audibility of low frequency sounds," J. Sound Vib. **21**(4), 431–448 (1972).
[3]H. Møller and J. Andresen, "Loudness of pure tones at low and infrasonic frequencies," J. Low Freq. Noise Vib. **3**(2), 78–87 (1984).
[4]M. A. Bellmann, V. Mellert, C. Reckhardt, and H. Remmers, "Perception of sound and vibration at low frequencies," collected papers from the *Joint Meeting "Berlin 99" of ASA, EAA and DAGA*, Berlin, Germany (1999), Abstract in J. Acoust. Soc. Am., **105**, 1297.
[5]ISO 226 *Acoustics—Normal Equal-Loudness-Level Contours* (International Organization for Standardization, Geneva, Switzerland, 2003).
[6]J. Andresen and H. Møller, "Equal annoyance contours for infrasonic frequencies," J. Low Freq. Noise Vib. **3**(3), 1–9 (1984).
[7]H. Møller, "Annoyance of audible infrasound," J. Low Freq. Noise Vib. **6**(1), 1–17 (1987).
[8]Y. Inukai, N. Nakamura, and H. Taya, "Unpleasantness and acceptable limits of low frequency sound," J. Low Freq. Noise, Vib., Act. Control, **19**(3), 135–140 (2000).
[9]J. K. Subedi, H. Yamaguchi, Y. Matsumoto, and M. Ishiharatil, "Annoyance of low frequency tones and objective evaluation methods," J. Low Freq. Noise, Vib., Act. Control. **24**(2), 81–96 (2005).
[10]K. P. Waye, J. Bengtsson, A. Kjellberg, and S. Benton, "Low frequency noise 'pollution' interferes with performance," Noise Health. **4**(13), 33–49 (2001).
[11]K. P. Waye, A. Clow, S. Edwards, F. Hucklebridge, and R. Rylander, "Effects of nighttime low frequency noise on the cortisol response to awakening and subjective sleep quality," Life Sci. **72**, 863–875 (2003).
[12]B. Berglund and T. Lindvall (Eds.) "Community noise," Archives of the center for Sensory Research, 2 (1), Stockholm University and Karolinska Institute, 1995, prepared for the World Health Organization.
[13]ISO 7196, *Acoustics—Frequency-Weighting Characteristic for Infrasound Measurements* (International Organization for Standardization, Geneva, Switzerland, 1996).
[14]N. S. Yeowart and M. J. Evans, "Thresholds of audibility for very low-frequency pure tones," J. Acoust. Soc. Am. **55**(4), 814–818 (1974).
[15]S.Yamada, T. Kosaka, K. Bunya, and T. Amemiya, "Hearing of low frequency sound and influence on human body," in *Proceedings of Conference on Low Frequency Noise and Hearing*, Aalborg, Denmark (May 7–9, 1980), pp. 95–102.
[16]U. Landström, R. Lundström, and M. Byström, "Exposure to infrasound—Perception and changes in wakefulness," J. Low Freq. Noise Vib. **2**(1), 1–11 (1983).
[17]T. Watanabe and H. Møller, "Low frequency hearing thresholds in pressure field and in free field," J. Low Freq. Noise Vib. **9**(3), 106–115 (1990).
[18]*Lavfrekvent støj, infralyd og vibrationer i eksternt miljø (Low Frequency Noise, Infrasound and Vibrations in the External Environment)*, Orientering fra Miljøstyrelsen, nr. 9 (Danish Environmental Protection Agency, 1997).
[19]H. H. Hubbard and K. P. Shepherd, "Aeroacoustics of large wind turbines," J. Acoust. Soc. Am. **89**(6), 2495–2508 (1991).
[20]K. P. Shepherd and H. H. Hubbard, "Physical characteristics and perception of low frequency noise from wind turbines," Noise Control Eng. J. **36**(1), 5–15 (1991).
[21]G. Guidati, R. Bareiß, and S. Wagner, "An investigation of blade-tower-interaction noise (BTI) for horizontal axis wind turbines in upwind and downwind configuration. First steps towards modeling of aeroelastic effects," in *Proceedings of the 8th IEA Joint Action Symposium on Aerodynamics of Wind Turbines,* Lyngby, Denmark (1994), pp. 249–255.
[22]M. L. Legerton, D. M. J. P. Manley, J. W. Sargent, D. J. Snow, and P. Styles, "Low frequency noise & vibration levels at a modern wind farm," in *Proceedings of the 25th International Congress on Noise Control Engineering, Inter-Noise 96*, Liverpool, Turkey, pp. 459–462.
[23]K. Betke, M. Schultz-von Glahn, O. Goos, and H. Remmers, "Messung der Infraschallabstrahlung von Windkraftanlagen" (Measurement infrasound emission from wind turbines), in *Proceeding of DEWEK '96. 3rd German Wind Power Conference* Wilhelmshaven, Germany (1996), pp. 207–210.
[24]K. Betke and H. Remmers, "Messung und Bewertung von Tieffrequentem Schall," (Measurement and assessment of low-frequency sound), Fortschr. Akustik, DAGA 1998, pp. 472–473.
[25]J. Jakobsen, "Infrasound emission from wind turbines," J. Low Freq. Noise, Vib., Act. Control **24**(3), pp. 145–155 (2005).
[26]J. Jakobsen, "Danish guidelines on environmental low frequency noise, infrasound and vibration," J. Low Freq. Noise, Vib., Act. Control **20**(3), 141–148 (2001).
[27]G. P. van den Berg, "Do wind turbines produce significant low frequency sound levels," *11th Int. Meeting on Low. Frequency Noise Vib. its Control.*, Maastricht, The Netherlands (2004).
[28]ISO 398-7, *Acoustics—Reference Zero for the Calibration of Audiometric Equipment—Part 7: Reference Threshold of Hearing under Free-Field and Diffuse Field Listening Conditions* (International Organization for Standardization, Geneva, 2005).
[29]C. S. Pedersen and H. Møller, *Vurdering af lavfrekvent støj og infralyd fra decentrale el-elproducerende anlæg (Assessment of Low-Frequency Noise and Infrasound from Local Electricity-Producing Plants)* (Department of Acoustics, Aalborg University, Aalborg, Denmark, 2005).
[30]"The measurement of low frequency noise at three UK wind farms,' Hayes McKenzie Partnership, Ltd., for Department Trade Industri (DTI), Contract No. W/45/00656/00/00, URN No. 06/1412, UK, 2006.
[31]A. Moorhouse, D. Waddington, and M. Adams, "Proposed criteria for the assessment of low frequency noise disturbance," Project Rep. DEFRA NANR45, University of Salford, 2005.
[32]A. Moorhouse, D. Waddington, and M. Adams, "Procedure for the assessment of low frequency noise complaints," Project Rep. DEFRA NANR45, University of Salford, 2005.
[33]J. Jakobsen, *Lavfrekvent støj fra vindmøller*(*Low-Frequency Noise from Wind Turbines*), Memorandum (Danish Environmental Protection Agency (Miljøstyrelsen), May 31, 2006).

[34] *Bekendtgørelse om miljøgodkendelse af hurtigfærgeruter*(*Statutory Order on High-Speed Ferries*), Bekendtgørelse No. 821(Danish Ministry of the Environment, København, 1997).
[35] *Vurdering af lavfrekvent støj fra færger, part 2: Revideret metode til beregning af lydtrykniveauet indendørs* (*Assessment of Low-Frequency Noise from Ferries, Part 2: Revised Method for Calculating the Sound Pressure Level Indoors*), Delta Akustik & Vibration, Arbejdsrapport fra Miljøstyrelsen nr. 10, 1997.
[36] S. Lee, S.-H. Shin, C. Cheong, S.-S. Jung, and W. Cheung, "Low-frequency noise emission characterisation of upwind-type large wind turbines," in *Proceedings of the International Congress on Noise Control Engineering, Inter-Noise 2007*, Istanbul, Turkey.
[37] S. S. Jung, W.-S. Cheung, C. Cheong, and S.-H. Shin, "Experimental identification of acoustic emission characteristics of large wind turbines with emphasis on infrasound and low-frequency noise," J. Korean Phys. Soc. **53**(4), 1897–1905 (2008).
[38] W. J. Gastmeier and B. Howe, "Recent studies of infrasound from industrial sources," Can. Acoust. **36**(3), 58–59 (2008).
[39] R. Ramakrishnan, "Characteristics of wind turbine noise," Can. Acoust. **3**, 122–123 (2009).
[40] J. P. Harrison, "Inadequacy of wind turbine noise regulations and their application," Can. Acoust. **37**(3), 156–157 (2009).
[41] R. J. Barthelmie, L. Folkerts, F. T. Ormel, P. Sanderhoff, P. J. Eecen, O. Stobbe, N. M. Nielsen, "Offshore wind turbine wakes measured by sodar," J. Atmos. Ocean.ic Technol. **20**, 466–4772003.
[42] B. Søndergaard and C. Ryom, "Low frequency noise from large wind turbines—Sound power measurement method," Rep. AV 135/08, Delta, April2008.
[43] B. Søndergaard and K. D. Madsen, "Low frequency noise from large wind turbines—Results from sound power measurements," Rep. AV 136/08, Delta, revised version December2008.
[44] B. Søndergaard and K. D. Madsen, "Low frequency noise from large wind turbines—Results from previous sound power measurements," Rep. AV 137/08, Delta, May 2008.
[45] D. Hoffmeyer and B. Søndergaard, "Low frequency noise from large wind turbines—Measurements of sound insulation of facades," Rep. AV 1097/08, Delta, 2008.
[46] IEC 61400-11*Wind Turbine Generator Systems—Part 11: Acoustic Noise Measurement Techniques*, 2nd ed. (International Technical Commission, Geneva, 2002 plus Amendment 1 2006).
[47] ISO 9613-2*Acoustics—Attenuation of Sound during Propagation Outdoors—Part 2: General Method of Calculation* (International Organization for Standardization, Geneva, 1996).
[48] ISO 9613-1, *Acoustics—Attenuation of Sound during Propagation Outdoors—Part 1: Calculation of the Absorption of Sound by the Atmosphere* (International Organization for Standardization, Geneva, 1993).
[49] *Bekendtgørelse om støj fra vindmøller* (*Statutory Order on Noise from Wind Turbines*), Bekendtgørelse nr. 1518 af 14, december 2006 (Danish Ministry of the Environment, 2006).
[50] ISO 140-5, *Acoustics—Measurement of Sound Insulation in Buildings and of Building Elements—Part 5: Field Measurements of Airborne Sound Insulation of Facade Elements and Facades* (International Organization for Standardization, Geneva, 1998).
[51] J. Jakobsen, "Lavfrekvent støj, infralyd og vibrationer; Rumakustiske forhold ved lave frekvenser" (Low-frequency noise, infrasound vibrations; Room Acoust. conditions At. Low. frequencies), Rep. AV67/96, Delta Akustik & Vib., 1996.
[52] C. Simmons, "Measurement of sound pressure levels at low frequencies in rooms. Comparison of available methods and standards with respect to microphone positions," Acta. Acust. **85**(1), 88–100 (1999).
[53] S. Pedersen, H. Møller, and K. P. Waye, "Indoor measurements of noise at low frequencies—Problems and solutions," J. Low Freq. Noise, Vib., Act. Control **26**(4), 249–270 (2007).
[54] J. Brunskog and F. Jacobsen, "Measurements of low-frequency noise in rooms," Memorandum (Danish Environmental Protection Agency, 2008).
[55] S. Wagner, R. Bareiß, and G. Guidati, *Wind Turbine Noise* (Springer, Berlin, Germany).
[56] ISO 1996-2*Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 2: Determination of Environmental Noise Levels*, 2nd ed. (International Organization for Standardization, Geneva, 2007).
[57] Måling af ekstern støj fra virksomheder *(Measurement of External Industrial Noise)*, Vejledning nr. 6 (Danish Environmental Protection Agency, 1984).
[58] S. Oerlemans and G. Schepers, "Prediction of wind turbine noise and comparison to experiment," in *Proceedings of Second International Meeting on Wind Turbine Noise*, Lyon, France (2007).
[59] S. Oerlemans, M. Fisher, and T. Maeder, "Reduction of wind turbine noise using optimized airfoils and trailing-edge serrations," AIAA. J. **47**(6), 1470–1481 (2009).
[60] E. Pedersen and K. P. Waye, "Perception and annoyance due to wind turbine noise—A dose-response relationship," J. Acoust. Soc. Am. **116**(6), 3460–3470 (2004).
[61] E. Pedersen, F. van den Berg, R. Bakker, and J. Bouma, "Response to noise from modern wind frams in The Netherlands," J. Acoust. Soc. Am. **126**(2), 634–643 (2009).
[62] T. H. Pedersen and K. S. Nielsen, "Genevirkning af støj fra vindmøller," (Annoyance noise from wind turbines), Report 150, Delta Akustik & Vib., 1996.
[63] *Buller från vindkraft—Riktvärden för ljud från vindkraft (Noise from Wind Turbines—Recommended Limits For Sound From Wind Turbines)*, Naturvårdsverket (Stockholm, 2009).
[64] *Ekstern støj fra virksomheder*(*External Ind. Noise*), Vejledning nr. 5 (Danish Environmental Protection Agency, 1984).
[65] B. Berglund, T. Lindvall, and D. H. Schwela (eds.), *Guidelines for Community Noise* (World Health Organization, Geneva, Switzerland, 1999).
[66] "Høring af udkast til bekendtgørelse om støj fra vindmøller" (Hearing of draft statutory order on noise from wind turbines), Miljøstyrelsen, 30. October2006.
[67] IEC TS 61400-14, *Wind turbines—Part 14: Declaration of Apparent Sound Power Level and Tonality Values* (International Technical Commission, Geneva, 2005).
[68] S. Broneske, "Comparison of wind turbine manufacturers' noise data for use in wind farm assessments," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).
[69] F. van den Berg, E. Pedersen, J.e Bouma, and R. Bakker, "WINDFARMperception—Visual and acoustic impact of wind turbine farms on residents," Final Rep. 3., University of Groningen, University of Gothenburg, June 2008.
[70] B. Søndergaard and K. D. Madsen, "Low frequency noise from large wind turbines—Summary and conclusions on measurements and methods," Rep. AV 140/08, Delta (revised version December 2008.
[71] "Ljud från vindkraftverk" (Sound from wind turbines), Rapport 6241, Naturvårdsverket, Stockholm, Sweden, 2001.
[72] *Night Noise Guidelines for Europe* (World Health Organization, Copenhagen, Denmark, 2009).
[73] W. E. Zorumski and W. L. Willshire, "Downwind sound propagation in an atmospheric boundary layer," AIAA. J. **5**, 515–523 (1989).
[74] L. Johansson, "Sound propagation around off-shore wind turbines," in *Proceedings of 10th International Congress on Sound and Vibration*, Stockholm, Sweden (2003), pp. 1481–1487.
[75] K. Bolin, M. Boué and I. Karasalo, "Long range sound propagation over a sea surface," J. Acoust. Soc. Am. **126**(5), 2191–2197 (2009).
[76] G. P. van den Berg, "Wind gradient statistics up to 200 m altitude over flat ground," in *Proceedings of First International Meeting on Wind Turbine Noise*, Berlin, Germany (2005).
[77] P. Botha, "The use of 10 m wind speed measurements in the assessment of wind farm developments," in *Proceedings of First International Meeting on Wind Turbine Noise*, Berlin, Germany (2005).
[78] W. K. G. Palmer, "Uncloaking the nature of wind turbines—Using the science of meteoroly," in *Proceedings of Second International Meeting on Wind Turbine Noise*, Lyon, France (2007).
[79] D. Bowdler, "Wind shear and its effect on noise assessment," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).
[80] G. P. van den Berg, "Effects of the wind profile at night on wind turbine sound," J. Sound Vib. **277**, 955–970 (2004).
[81] G. P. van den Berg, "The beat is getting stronger: The effect of atmospheric stability on low frequency modulated sound of wind turbines," J. Low Freq. Noise, Vib., Act. Control **24**(1), 1–24 (2005).
[82] W. K. G. Palmer, "A new explanation for wind turbine whoosh—wind shear," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).
[83] M. Almgren, S. Schönfeld, and J. Grönlund, "Sound emission and sound propagation for wind turbines in forest terrains," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).
[84] B. Søndergaard, "The next version of the IEC 61400-11 measurement method," in *Proceedings of Third International Meeting on Wind Turbine Noise*, Aalborg, Denmark (2009).