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Infrasound and low frequency noise from wind turbines: exposure and health effects

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Abstract
Wind turbines emit low frequency noise (LFN) and large turbines generally generate more LFN than small turbines. The dominant source of LFN is the interaction between incoming turbulence and the blades. Measurements suggest that indoor levels of LFN in dwellings typically are within recommended guideline values, provided that the outdoor level does not exceed corresponding guidelines for facade exposure. Three cross-sectional questionnaire studies show that annoyance from wind turbine noise is related to the immission level, but several explanations other than low frequency noise are probable. A statistically significant association between noise levels and self-reported sleep disturbance was found in two of the three studies. It has been suggested that LFN from wind turbines causes other, and more serious, health problems, but empirical support for these claims is lacking.

Keywords: wind turbine noise, infrasound, low frequency noise

1. Introduction

Wind power is a renewable source of energy that has seen a dramatic increase in installed capacity the last decade. The growth has not only been in the number of wind turbines but also in their size, from average capacities of 100 kW in the 1990s to 2 MW turbines at present date. Presently, hub heights are around 100 m with rotor blades around 50 m and 10 MW prototypes taller than 200 m have been developed.

The growing turbine sizes have raised fears that the sound characteristics will shift to lower frequencies (Møller and Pedersen 2011). This should be taken seriously, because sounds with prominent infrasound (1–20 Hz) and low frequency (20–200 Hz) components may affect human health and well-being to a larger extent than sounds without such components. For example, loudness and annoyance of infrasound and low frequency noise (LFN) increases more rapidly with increasing sound pressure level than sounds of higher frequencies (e.g., Møller and Pedersen 2004, Leventhall 2004). Thus, once the sound pressure passes the absolute threshold of detection (given in figure 1), only a small further increase is needed to make the sound loud and annoying. Prolonged exposure to audible low frequency sounds may cause fatigue, headache, impaired concentration, sleep disturbance and physiological stress, as indicated by increased levels of saliva cortisol (e.g., Berglund *et al* 1996, Bengtsson *et al* 2004, Pedersen and Persson Waye 2004). Similar effects may occur after exposure to infrasound, provided that the levels are high enough to exceed the absolute threshold of detection (e.g., Landström 1995).

This article reviews the present knowledge of infrasound and LFN exposure from wind turbines and related disturbances or ill-health of residents living near wind turbines. In this article, LFN is defined as sounds with frequencies between 20 and 200 Hz and infrasound is defined as sound with frequencies between 1 and 20 Hz. The literature review was

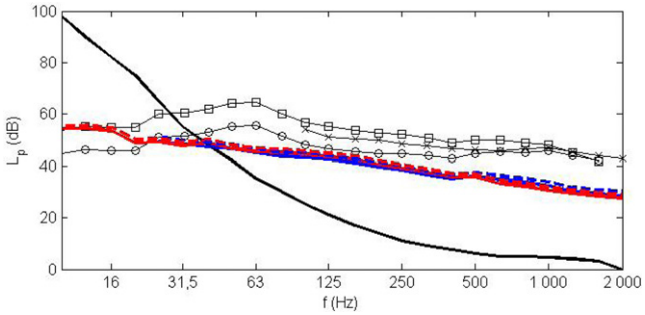

Figure 1. 1/3 octave sound power level spectra from old turbines <2 MW (-/– – –) and new ⩾2 MW (-/– – –), recalculated from Madsen and Pedersen (2010) to an average level of 40 dB (L_{Aeq}) at 500 m distance (solid) and 1000 m distance (dashed). For comparison, ISO717-1 (ISO 717-1 1996a) spectra for road traffic noise (-x-), measured road traffic noise 10 m distance (-o-) (light traffic) and recalculated at 500 m (-□-) are shown at 55 dB (L_{Aeq}), as well as the absolute detection threshold (-) (Watanabe and Møller 1990).

conducted over a six month period ending in April 2011. Literature was searched in the databases PubMed, PsycInfo and Science Citation Index. In addition, proceedings of the conferences Inter-Noise and Wind Turbine Noise were searched. Grey literature was searched through reference lists of published articles and using internet search engines (Google, Google Scholar). Finally, personal contacts were taken with researchers and noise consultants working with wind turbine noise.

2. Sound production and exposure

2.1. Generation mechanisms

Sounds generated by wind turbines are usually divided into mechanical sounds radiating from the machinery in the hub and aerodynamical sounds generated by the blades interacting with the air. Mechanical noise emitted from the rotating machinery is often of periodic and tonal character. These sounds are of less importance in modern wind turbines because of improved sound insulation of the hub (van den Berg 2005, Oerlemans *et al* 2007). Aerodynamic sources at the blades are therefore the dominating sound source from modern wind turbines. Laminar flow around the blade generates very little sound while turbulent flow will inherently produce sound (Wagner *et al* 1996). Three different generation mechanisms have been suggested by van den Berg (2005), here discussed in order of increasing frequency ranges. The first source is the periodic blade–tower interaction, which generates noise that contributes to the spectra at blade passing frequency and its harmonics from around 1 to about 30 Hz. Sounds from this source are typically far below the average absolute threshold of detection (cf figure 1). The second source originates from the in-flow turbulence which is the main sound source in frequencies from around 10 Hz up to a few hundreds of hertz (van den Berg 2005). A model for this source by Madsen (2008) has been experimentally verified and shows satisfying results from 10 to 50 Hz. The third source is the trailing edge noise, which has its peak frequency between 500 and 1000 Hz, that is, above the region of LFN.

2.2. Outdoor noise exposure

Several countries have guidelines for wind turbine noise at the facade of dwellings. As an example, the Swedish value is an A-weighted sound level of 40 dB (L_{Aeq}) and the Danish guideline value is 44 dB (L_{Aeq}), both at wind direction from the turbine towards the immission point at wind speeds of 8 m s^{-1} on 10 m height. In comparison, guideline values for road traffic noise, the main source of noise annoyance in many countries (e.g., EEA 2009), are higher. A compilation of guideline values in 14 European countries showed that the average value was 58 dB L_{DEN} outdoor at the facade of dwellings (EEA 2010), which corresponds to about 55 dB $L_{Aeq,24h}$.

A comprehensive Danish study of 33 old and 14 new turbines found an average increase of low frequency noise per installed power of around 1 dB for new turbines compared to older turbines (Madsen and Pedersen 2010). However, the variations between different turbines are large and an individual small old turbine may thus emit more LFN per installed power than a new turbine. This conclusion is disputed by Møller and Pedersen (2011), who show a significant shift towards lower frequencies for newer turbines.

Spectra of sound pressure levels from wind turbines, road traffic noise and the absolute detection thresholds are shown in figure 1. Sound propagation to representative distances from noise sources was calculated according to ISO9613 (ISO 1996b). To compare representative exposure levels, each source was normalized to levels corresponding to typical planning guideline values, 40 dB L_{Aeq} for wind turbine noise and 55 dB $L_{Aeq,24h}$ for road traffic noise. Compared to road traffic noise, the permitted noise from wind turbines is lower for all frequencies above 20 Hz, which indicates that LFN from wind turbines does not generate more LFN than road traffic noise at levels often found in urban residential areas (cf EEA 2009).

Two articles (Jung and Cheung 2008 and Sugimoto *et al* 2008) have been cited as arguments that wind turbines generate high levels of infrasound and LFN (Salt and Hullar 2010). However, the measurements reported in those articles were made in close proximity to wind turbines and are uncharacteristic of exposure in residential buildings. Jung and Cheung (2008) measured at 10 and 98 m from a 1.5 MW turbine with levels exceeding 80 dB in the frequency range 1–10 Hz. Sugimoto *et al* (2008) report levels of up to 80 dB in the frequency range 1–20 Hz inside a small shed 20 m from the wind turbine.

2.3. Indoor noise exposure

Lower frequencies are commonly less attenuated by buildings than higher frequencies. In combination with standing wave patterns in rooms this could potentially create high levels of infrasound and LFN indoors. However, conclusions from several studies indicate that indoor LFN from wind turbines typically complies with national guidelines (Lindkvist and Almgren 2010, Madsen and Pedersen 2010, O'Neal *et al* 2011, Department of Trade and Industry 2006). O'Neal *et al* (2011) compared indoor and outdoor LFN and infrasound at two wind farms (30 turbines × 1.5 MW and 15 turbines × 2.3 MW). They

concluded that the measured levels at both sites complied with several different national guidelines for LFN and infrasound at 305 m distance or more from the wind turbines. This does not, of course, exclude that a sizeable LFN component may occur in rare cases. As a rule of thumb, it has been proposed that further investigations should be conducted if the measured difference between C-weighted and A-weighted sound pressure level of the outdoor exposure is greater than 15 dB (Lindkvist and Almgren 2010; see e.g., Lundquist *et al* 2000 for dBC–dBA as an indicator of low frequency noise).

3. Noise annoyance

Noise annoyance is measured in questionnaire studies, in which the respondents are asked to give an overall assessment of the degree of annoyance evoked by a specific noise source during an extended period of time, for example the last 12 months (e.g., ISO 2003a, 2003b). Annoyance in relation to noise levels from wind turbines has so far been investigated in three cross-sectional studies (Pedersen and Persson Waye 2004, 2007, Pedersen *et al* 2009). These studies predicted equivalent sound levels from wind turbines and thus cannot give guidance to the specific effects related to LFN. The studies are nevertheless summarized below, to illustrate the extent of annoyance that wind turbine noise may evoke at exposure levels found in residential settings, and to discuss possible explanations for these effects.

The three studies were not independent of each other as they were conducted by the same researchers and used similar questionnaires. The response rate was around 60% in the Swedish studies and 37% in the Dutch study. The low response rate in the Dutch study is worrying. However, a non-response analysis gave support for the representativity of the sample.

All three studies used the same question to measure noise annoyance 'for each one of the following inconvenience if you noticed or were disturbed by them, when you are outdoors at your house', followed by a list of potential disturbances including noise from wind turbines. Noise annoyance was reported on a five-category scale, from 'do not notice' to 'very annoyed'. Two cut-offs were used, the two highest categories for defining 'annoyed' and the highest category for defining 'very annoyed' residents.

It should be noted that the three studies also measured annoyance to wind turbine noise as experienced indoors (Janssen *et al* 2009). The proportion annoyed indoors was lower than proportion annoyed outdoors (by approximately a factor of two). Compared to industrial noise from stationary sources, the proportion annoyed indoors was found to be higher for wind turbine noise at exposure levels above 40 dB L_{Aeq}.

Figure 2 shows the results from the three studies, the two Swedish studies combined (white bars) and the Dutch study (grey bars). These analyses did not include responses from persons who profited economically from wind turbines, as those persons reported significantly lower annoyance due to noise than those without economic benefit (Pedersen *et al* 2009). The studies show a clear association between levels of wind turbine noise and percentage annoyed residents.

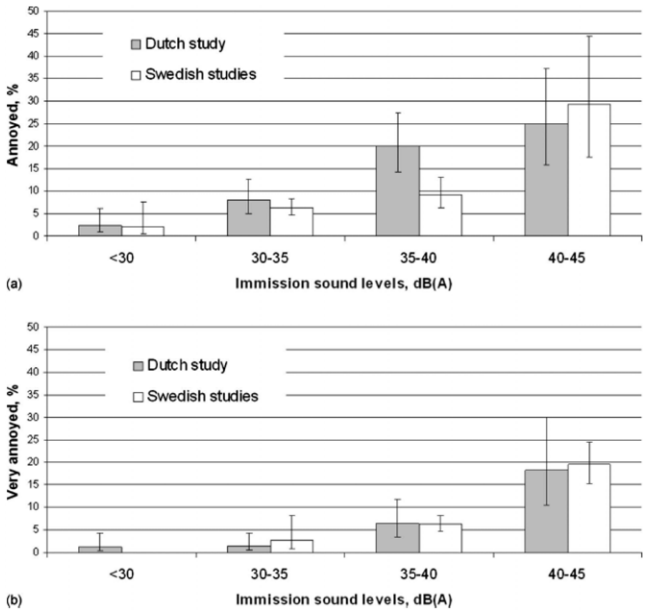

Figure 2. Proportion of respondents annoyed (a) and very highly annoyed (b) by wind turbine noise for different immission sound levels. Reprinted with permission from Pedersen E *et al* 2009 *J. Acoust. Soc. Am.* **126** 634–43. Copyright 2009, Acoustical Society of America.

Among the residents with exposures in the range of 35–40 dB, the percentage annoyed by noise was about 10% in the Swedish studies and approximately 20% in the Dutch study. The percentage very annoyed by noise was around 6% in all three studies at 35–40 dB exposure. These percentages are similar to the percentages of annoyed residents due to road traffic noise, at a typical planning guideline value of 55 dB $L_{\mathrm{Aeq,24h}}$. The most comprehensive meta-analyses of such annoyance studies (Miedema and Oudshoorn 2001) predicted that at this exposure about 14% of residents would be annoyed and 5% very annoyed (calculated using the same cut-offs for defining annoyed and very annoyed as in figure 2; observe that Miedema and Oudshoorn used slightly different cut-offs for their definition of 'annoyed' and 'highly annoyed').

Overall, these comparisons suggest that guidelines for wind turbine noise in the interval 35–40 dB would correspond to the proportion of annoyed persons comparable to the proportion annoyed by road traffic noise at a typical guideline value. However, it is also clear that wind turbine noise is more annoying than road traffic noise at the same equivalent noise level. At 40 dB wind turbine noise generates a substantial proportion of annoyed residents (see figure 2) whereas the proportion annoyed by 40 dB transportation noise is negligible (Miedema and Oudshoorn 2001). There is no indication that this is linked to infrasound or LFN from wind turbines. However, there are several other plausible explanations:

(1) Wind turbines are often built in environments with low ambient noise. Studies of road traffic noise have often focused on noise annoyance among residents of large cities, where background levels are 10–15 dB higher than in rural environments.

(2) Common verbal descriptors of wind turbine noise include 'swishing', 'whistling' and 'pulsating' (e.g., Pedersen and Persson Waye 2004, Pedersen *et al* 2007). This suggests that the pulsating (amplitude modulated) trailing edge noise, with a peak frequency between 500 and 1000 Hz, is the main cause of annoyance (van den Berg 2005, Leventhall 2006). Pulsating sounds are perceived as more annoying than continuous sound with the same frequency content and average noise level (Zwicker and Fastl 1990, Kantarelis and Walker 1988), as has also been demonstrated for wind turbine noise (Seunghun *et al* 2011).

(3) The visual intrusion of wind turbines in the environment may affect the assessment of noise annoyance. This is supported by the fact that the proportion annoyed by noise among residents who can see the wind turbines is significantly higher than among residents who do not see turbines, at the same average noise exposure (Pedersen *et al* 2009).

4. Sleep disturbance

Sleep disturbance is a serious effect of noise, because good sleep is essential for physical and mental health (WHO 2009). WHO's guideline value is that the level at the facade outside the bedroom should not exceed 40 dB L_{Aeq} during the night to ensure undisturbed sleep (WHO 2009).

The cross-sectional questionnaire studies described above also measured self-reported sleep disturbance. A compilation of the studies (Pedersen 2011) found a statistically significant association between the noise level and self-reported sleep disturbance in two of the three studies. Again, these studies only reported average A-weighted sound levels ($L_{\mathrm{Aeq,24h}}$) and therefore do not allow evaluation of effects specifically related to LFN. Furthermore it is not possible to draw conclusions from self-reports regarding effects related to sleep quality, which the individuals might be unaware of.

van den Berg (2004, 2005) showed that prediction models of wind turbine noise may underestimate the actual night time exposure. The main reason is that stable atmospheric conditions, occurring during the evenings and at night, result in increased emission and immission levels of wind turbine noise which occur in combination with a decrease of the background noise levels. Thus, even if predicted levels are as low as 40 dB L_{Aeq} during night, actual levels may be higher and potentially sleep disturbing.

5. Other health effects

Various symptoms and diseases have been mentioned in discussions on wind turbines and health, often with reference to exposure to infrasound or LFN.

The book 'The Wind Turbine Syndrome' by Pierpoint (Pierpoint 2009) argues that wind turbine noise can cause a variety of serious symptoms. The study relies on interviews with 38 individuals from ten families living near wind turbines. Several of the people interviewed reported serious symptoms, including insomnia, headaches, tinnitus, dizziness, nausea, panic attacks and palpitations, which they developed after the wind turbines were erected near to their homes. According to Pierpoint, these symptoms were caused by LFN and vibrations from wind turbines affecting the body's balance system. The study has several limitations, which makes the conclusion unjustified. For example, the lack of acoustic measurements, no comparison group of people with no or low wind exposure and no investigation of the subjects prior to the wind turbines were constructed (prior health status was estimated retrospectively). In addition, the results, which are based on a very small sample, are contradicted by results from the cross-sectional studies described above, which included a total of more than 1600 people. Except for noise annoyance, and possibly self-reported sleep disturbance, no consistent associations were found between wind turbine noise exposure and symptom reporting, e.g. chronic disease, headaches, tinnitus and undue tiredness (Pedersen 2011).

Alves-Pereira and Castelo Branco (2007a) have argued that infrasound and LFN from wind turbines may cause 'vibroacoustic disease' (Castelo Branco and Alves-Pereira 2004, Alves-Pereira and Castelo Branco 2007b). The authors list a variety of symptoms, including increased risk of epilepsy and cardiovascular effects such as increased risk for coronary artery surgery. The authors have reported on vibroacoustic disease for many years, but the syndrome has attracted limited attention from other researchers. The problem may only be relevant at high occupational exposures, such as aircraft maintenance (Castelo Branco and Alves-Pereira 2004), and hardly at the low dose exposures by wind turbines. Discussion of vibroacoustic disease remains at a hypothetic stage and evidence of problems related to noise from wind turbines is lacking.

Salt and Hullar (2010) hypothesized from previous research that the outer hair cells are particularly sensitive to infrasound even at levels below the threshold of perception. In their article, the last paragraph mentions that wind turbines generate high levels of infrasound, with reference to three articles, two of which are not relevant to exposure in residential environments (Jung and Cheung 2008, and Sugimoto *et al* 2008). No references were made to published compilations of knowledge that indicates that the infrasound to which humans are exposed to by wind turbines is moderate and not higher than what many people are exposed to daily, in the subway and buses or at the workplace (e.g. Leventhall 2007, Jakobsen 2005). It is therefore hard to see that Salt and Hullars' results are relevant for risk assessment of wind turbine noise in particular.

There have been no epidemiological studies of wind turbine noise and cardiovascular risk. However a number of studies in recent years have demonstrated a correlation between road traffic and aircraft noise exposure and elevated blood pressure (WHO 2011, Babisch 2008, Babisch and van Kamp 2009). There are also some studies that demonstrate a link between road traffic noise and increased risk of myocardial infarction (Babisch *et al* 2005, Selander *et al* 2009) and recently also a similar relation for aircraft noise (Huss *et al* 2010). Increased risk was observed for exposures of 55 dB L_{Aeq} equivalent level for road traffic noise and 60 dB L_{Aeq}

for aircraft noise (WHO 2000, Huss *et al* 2010), which is significantly higher than typical exposure from wind turbine noise. This speaks against a corresponding association between wind turbine noise and cardiovascular disease. On the other hand, the effects on the cardiovascular system by noise are assumed to be stress related and triggered by noise annoyance and sleep disturbance (Babisch 2002). Wind turbine noise is causing noise annoyance, and possibly also sleep disturbance, which means that one cannot completely rule out effects on the cardiovascular system after prolonged exposure to wind turbine noise, despite moderate levels of exposure.

6. Conclusions

The dominant source of wind turbine low frequency noise, LFN (20–200 Hz), is incoming turbulence interaction with the blade. Infrasound (1–20 Hz) from wind turbines is not audible at close range and even less so at distances where residents are living. There is no evidence that infrasound at these levels contributes to perceived annoyance or other health effects. LFN from modern wind turbines are audible at typical levels in residential settings, but the levels do not exceed levels from other common noise sources, such as road traffic noise. Although new and large wind turbines may generate more LFN than old and small turbines, the expected increase in LFN is small.

Wind turbine noise is associated with residential noise annoyance. It has been found that 10–20% of residents are annoyed, and about 6% are very annoyed by wind turbine noise at levels between 35 and 40 dB (L_{Aeq}, at 8 m s^{-1} wind speed at 10 m height). The main cause of annoyance seems to be the pulsating swish sound produced when the blades pass through the air. This sound has its main energy in the frequency range of 500–1000 Hz.

Except for noise annoyance, no consistent effects on health due to wind turbine noise have been reported. However, a statistically significant association between wind turbine noise and self-reported sleep disturbance was found in two studies.

It has been argued that infrasound and low frequency noise from wind turbines may cause serious health effects in the form of 'vibroacoustic disease', 'wind turbine syndrome' or harmful infrasound effects on the inner ear. However, empirical supports for these claims are lacking.

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