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REPRINTED FROM

WIND ENGINEERING

VOLUME 37, NO. 1, 2013

MULTI-SCIENCE PUBLISHING COMPANY
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A Review of Wind Turbine Noise Perception, Annoyance and Low Frequency Emission

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Received October 9, 2012; Revised December 10, 2012; Accepted December 10, 2012

ABSTRACT
Current literature concerning the perception, annoyance and emission of low-frequency noise from wind turbines are reviewed. Wind turbine noise has been shown to be annoying to people with annoyance related to noise load. Other factors, such as those related to visual, economic and psychological effects, were also shown to affect a person's annoyance of wind turbine noise. Published infrasound (noise at frequencies less than 20 Hz) measurements show that levels at typical residential set-back distances are too low to be directly audible, but may be perceived via window rattling. On the other hand, low-frequency noise levels, in the frequency range of 20–200 Hz may exceed audibility thresholds and it is postulated they may be correlated with annoyance. A review of general low-frequency noise annoyance studies is presented and highlights the similarities of many wind turbine noise complaints with those due to low-frequency noise. The paper concludes with a suggestion to develop a new methodology that can simultaneously acquire annoyance and noise data at the time a person believes they are annoyed by wind turbine noise.

1. INTRODUCTION
Wind turbines are now a well-established part of a modern society's electrical generation network. On the whole, they are considered a positive benefit to society [1]; however, opinions of those in the communities nearby wind farms are often negative and at odds with the national outlook [2].

Recently, the Australian government has conducted a Senate inquiry into the social and economic impact of rural wind farms [3]. The final report documents many claims from residents, community groups, acoustic consultants and the wind energy industry. After considering the submissions, the Senate committee made the following recommendation relating to low-frequency noise (i.e. noise in the frequency range of 20–200 Hz):

> The Committee considers that the noise standards adopted by the states and territories for the planning and operation of rural wind farms should include appropriate measures to calculate the impact of low-frequency noise and vibrations indoors at impacted dwellings.

Hence it has been officially recognised, in Australia at least, that the "impact" of low-frequency noise from wind farms on dwellings needs to be assessed. Further, Health Canada are proposing to investigate the relationship between noise (including low-frequency noise) and health [4]. However, it is not clear what an acceptable level of impact is. Annoyance by low-frequency noise occurs usually at low levels, often in the range of a person's hearing threshold and can vary significantly between individuals [5]. Therefore it is important to understand the levels of low-frequency noise inside people's homes to determine how it is related personal annoyance. Unfortunately, there is very little information currently available to make an assessment concerning the relationship between low-frequency noise and annoyance.

The aim of this paper is to review studies that have previously examined human perception and annoyance by wind turbines and studies that report wind turbine low-frequency noise emission. Additionally, human annoyance due to low-frequency noise in general is reviewed. The paper concludes with a brief discussion of the limitations of previous work and a suggestion of how to extend the current level of knowledge in this area.

2. WIND TURBINE NOISE PERCEPTION AND ANNOYANCE

Janssen et al. [6] derive exposure-response relationships due to wind turbines for both indoor and outdoor receiver locations. Compared with other environmental noise sources (road, rail and aircraft noise), annoyance due to wind turbines was found at lower exposure levels. This supports earlier studies [7, 8, 9] who also found that annoyance due to wind turbine noise is related to negative attitudes towards wind turbines and a person's noise sensitivity. Annoyance may be enhanced by wind turbine visibility [10, 11] and sound quality issues [7, 8] such as amplitude modulation, intermittency, and the presence of the wind turbine noise at night. Interestingly, the effect of urbanisation and terrain was found to affect perception and annoyance [9], with annoyance associated with negative emotions and lowered sleep quality. A psycho-acoustic study of recorded wind turbine noise [12] found that while "lapping" and "swishing" noises were most annoying, none of the normal psycho-acoustic parameters could explain why this was the case. It should be noted that people who benefited economically from wind turbines were excluded from these studies as they consistently showed a lower level of annoyance than other people.

Bakker et al. [13] investigated the relationship between exposure to the sound of wind turbines and annoyance, self-reported sleep disturbance and psychological distress of people who live nearby wind farms. The mode of study was via questionnaire and calculated sound pressure level (dB(A)) inside and outside homes. The study showed that people who lived near wind farms are at risk of being annoyed by the noise and this may lead to sleep disturbance and psychological distress. Similar conclusions were drawn by Pedersen and Waye [14] who argue that annoyance caused by wind turbine noise affects restoration, that is the "degree to which an environment can aid recovery from mental fatigue and restoration of attentional capabilities". The deterioration of restoration quality and annoyance was also found to be correlated with the characteristic of the noise, which was described as either "swishing, whistling, resounding and pulsating/throbbing". It was also suggested that the inability to disregard the moving visual and audible intrusion of the turbines was a factor contributing towards a reduction in the restorative quality of a person's home.

Psychological and policy studies provide some insight into why some people find wind turbines annoying (or are *disturbed* by them) and some are not. Pedersen et al. [15] find that those who perceive wind turbines as intruding upon their territory or homes (as noise, flicker or visual intrusion) will be more annoyed than those who are not. Intrusion was linked with a feeling of lack of control and injustice. Wolsink [16] suggested that the nature of the planning process strongly influences negative reaction and opposition to wind farm development. A "top-down" process was found to be an ineffective way to obtain support for a wind energy project and more consultative methods are needed to ensure wind energy projects are successful. In their examination of why local communities oppose wind farm developments, Devine-Wright [17] suggested that more concentration on how the project is developed rather than the technical aspects may greatly influence the acceptance of a wind farm by a local community. The same conclusions were drawn by Bowdler [18], who also argue that non-acoustic factors moderate a person's perception and annoyance to wind turbine noise and feelings of *unfairness* relating to the development process influence these moderating factors. The role of personal moderating factors is also made clear by Shepherd et al. [19] who show that health-related quality of life is diminished for people that live within 2 km of wind turbines. The degree to which these factors affect noise sensitivity is unknown but should be studied as part of future research.

3. WIND TURBINES AND LOW FREQUENCY NOISE EMISSION

The sources of low frequency noise from wind turbines were first identified in the 1980's and some of these studies are summarised by Hubbard et al. [20]. Downwind machines are shown to be the highest emitters of low-frequency noise, due to the interaction of the blades with the tower wake. Modern upwind machines avoid this interaction by placing the rotor disk upwind of the tower. However, low-frequency noise can still be generated via aerodynamic loading of the blades, known as *loading* noise [21]. Loading noise from a wind turbine is mainly due to unsteady aerodynamic loading of the blades as they rotate [20]. Unsteady loading is due to either mean shear in the atmospheric boundary layer or from unsteadiness due to turbulent gusts. Loading noise may be increased if they are placed on ridges or hill tops where the flow approaching the turbines has high mean shear and turbulent kinetic energy due to strong adverse pressure gradients induced by the upwind terrain.

While blade-tower interaction on downwind turbines has been identified as a strong source of low-frequency noise, it has been recently suggested [22] that blade-tower interaction (or BTI) noise may be possible for upwind wind turbines as well. As the wind approaches the tower, the upwind streamlines develop curvature to accommodate flow over its surface. The rotor blades pass through these curved stream line, creating a short-lived angle-of-attack change, thus creating unsteady lift at low-frequency. While possible, this mechanism has not been experimentally verified and the extent to which it influences the overall sound field is yet to be quantified.

Shepherd and Hubbard [23] illustrate the effects of atmospheric propagation and the interaction of low-frequency noise with buildings. The atmosphere has the ability to attenuate the high-frequency noise components whilst leaving the low-frequency components relatively unaffected over large distances [24]. Further, the atmospheric boundary layer created velocity gradients that can refract sound differently in the upwind and downwind directions, resulting in a -3 dB per doubling of distance instead of -6 dB expected for spherical spreading. Hence low-frequency noise components from wind farms may appear at levels higher than predicted using spherical spreading rate models.

Further, Shepherd and Hubbard [23] show how low-frequency sound interacts with buildings. Specifically, the outside-to-inside noise reduction was shown to reduce as frequency decreases (following the mass law, see [25]), with a minimum at about 10 Hz, below which, stiffness dominates the response of the structure and the noise reduction increases again. Therefore, low-frequency noise (10–200 Hz) from a wind turbine will not be reduced by a building's structure to the same extent as noise in the higher frequency bands. Additionally, resonant acoustic modes can be excited in buildings by low-frequency noise exposure, thus explaining why low-frequency noise is sometimes measured at a higher level inside a building than outside.

Jakobsen [26] reviewed a series of noise measurements from wind turbines that included data in the infrasonic frequency bands. He concluded that for upwind "contemporary" wind turbines, the infrasound level would be 70 dB(G) at 100 m. Based on this review, Jakobsen concludes that infrasound emission is well below environmental noise limits for infrasound (85 dB(G) for Denmark) for modern wind turbines. However, an examination of inside A-weighted levels in the low-frequency range shows that noise guidelines for dwellings were exceeded thus suggesting that low-frequency noise is a possible reason for some of the noise complaints about wind farms. Similarly, Van Den Berg [27] concludes that infrasound from wind turbines should not be audible and measurements show significant levels of low-frequency noise. Turnbull et al. [28] summarises infrasound measurements from Australian wind farms and also find that levels of infrasound were too low to be audible; however, no data is presented above 20 Hz, thus no conclusions can be drawn regarding low-frequency noise levels.

Jung et al. [29] measured noise from two wind turbines (1.5 MW and 660 kW) and assess noise levels down to infrasonic frequencies. They conclude that pitch regulated machines are superior to stall regulated machines for noise control. Further, they show that infrasound levels are too low to be audible but low-frequency noise is above perception thresholds and would likely lead to complaints. Interestingly, while infrasound levels were below perception thresholds, they were found to be high enough to cause window rattle which may also cause significant levels of complaint.

Møller and Pedersen [30] performed a comprehensive review and analysis of low-frequency noise emission from wind turbines, including reviews of work in Danish not included here. Møller and Pedersen [30] concluded that as wind turbines increase in size, the proportion of sound in the low-frequency bands (63–250 Hz in this study) will increase. While infrasound emission was found to exist, the levels below 20 Hz were concluded to be below the human hearing threshold. However, it was found that a substantial part of the noise is in the low-frequency range and there is a risk that residents living close to wind turbines will be annoyed by low-frequency noise. Interestingly, Møller and Pedersen [30] concludes that low-frequency tones emitted from the turbines may not be penalised under noise standards as they are not very distinct in one-third octave bands. They also show that because the proportion of low-frequency noise content increases non-linearly with turbine power, then a greater area around a wind turbine or wind farm will be affected by low-frequency noise.

4. GENERAL LOW-FREQUENCY NOISE ANNOYANCE

Annoyance due to low-frequency noise in general has been observed and studied for at least 40 years. An early and seminal work by Vasudevan and Gordon [31] studied the noise spectrum in two people's homes who reported annoyance by low-frequency noise from an unidentified source and also further investigated annoyance with laboratory listening tests. They concluded that annoyance due to low-frequency noise was real (i.e. not imagined) and always occurred indoors. The levels were low as well as being at or below the perception threshold. The noise was perceived by the test subjects as "low-frequency throbbing". Interestingly, they conclude that annoyance was most likely caused by noise with a smooth, broadband spectrum, although it was described as "unbalanced", that is, having a predominance of low-frequency content. Vasudevan and Gordon [31] speculate that it is the unbalanced nature of the noise spectrum that is most significant. This can be exacerbated by atmospheric attenuation, low background noise levels, the transmission loss of a home's structure acting as a kind of low-pass filter and age-related hearing loss that reduces the sensitivity of a person to mid-to-high frequency sound.

In his comprehensive review, Broner [32] provides a summary of many test cases from the 1960's and 1970's concerning low-frequency noise and infrasound exposure. He found that infrasound may have an effect on people but only at high levels that would be found only in extreme circumstances.

Persson and Rylander [33] presents noise complaint survey results from local environmental health authorities in Sweden. They conclude that the majority of noise complaints are the result of low-frequency noise and the number of complaints increase over time. The dB(A) scale was also found to be inadequate as an indicator of low-frequency noise annoyance. Also, noise complaints were reported in this study even though the noise levels expressed in dB(A) were low.

Many of the conclusions drawn in the above and most other available studies are confirmed and summarised in the review by Berglund et al. [34]. Further, Berglund et al. [34] point out that socioacoustic survey results show that there is higher annoyance for sources that have a greater low-frequency noise content. Higher annoyance may also be reported due to the coupling of building structures with low-frequency noise to produce window rattle and other vibration.

Persson Waye and Rylander [35] confirm that the dB(A) scale is not appropriate for predicting annoyance of low-frequency noise. They also investigated the effects of long-term exposure to low-frequency noise at a level common for community noise complaints (in this case the sources were domestic heat-pumps). Low-frequency noise was found to interfere with concentration and persons exposed to low-frequency noise reported a higher occurrence of headaches, displayed higher levels of irritation and were unusually tired. Their results suggest that there is a link between lack of rest, due to noise and the symptoms described above.

In a series of reviews, Leventhall et al. [36] and Leventhall [5, 37] summarise many of the observations recorded during field and laboratory observations of low-frequency noise that are described above. Interestingly, Leventhall suggests that low-frequency annoyance is heavily influenced by personal and social moderating factors and not just acoustic factors. Thus a person's individual noise sensitivity, their anxiety about and attitude towards the source will affect their annoyance. Other factors such as suspicion about those who control the source, expectations concerning their environment, how they should be treated by authorities and those responsible for the noise will affect a person's annoyance to low-frequency noise. Thus a complex picture emerges that suggests that the level of annoyance is due to the coupling of an individual's physiological and psychological response with their physical and social environment. Pedersen et al. [38] provide further complexity in that 29% of complainants investigated in a low-frequency noise problem study were found to suffer tinnitus and that this was the source of their annoyance rather than physical sound.

5. DISCUSSION AND CONCLUSION

Previous studies have shown that some people who live near wind farms are annoyed by them and the degree of annoyance is related to the level of the noise exposure. It was also found that many other factors, such as visual intrusion and psychological reaction have a significant influence on a person's response to wind turbines and perhaps noise. Previous perception and annoyance studies have been performed using calculated A-weighted noise levels from wind turbines, rather than direct measurements.

Infrasound from wind turbines has been measured and was shown by many that infrasound levels at typical residential set-back distances are most likely too low to be audible; however, there is a possibility of annoyance due to window rattle caused by infrasound, yet this needs further study. Low-frequency noise levels from wind turbines may exceed audibility thresholds and thus it is possible that they are correlated with annoyance. A review of studies related to general low-frequency noise annoyance shows there are similarities with annoyance studies involving wind turbine noise.

It is well-accepted that the dB(A) scale is not a reliable indicator of low-frequency noise annoyance. Especially important is the link between personal and social moderating factors and annoyance. It conceivable that some complaints concerning wind farm noise are due to low-frequency noise and are compounded by the particular personal and social situations faced by rural communities surrounding wind farms. It is also conceivable that noise levels may comply with existing environmental noise guidelines based on the dB(A) scale yet still cause annoyance due to the uniqueness of low-frequency noise problems. However, there is very little information (level, spectral balance, temporal qualities, etc) regarding low-frequency noise in people's homes affected by wind turbines. Yet this information is essential to diagnose if there really is a problem and if there is, develop ways of fixing it.

It is clear that there are many areas of our knowledge of wind turbine noise annoyance that can be improved. A person's annoyance to wind turbine noise may change with time. As discussed, this may be due to personal moderating factors as well as the noise emission of the turbines. Noise emission will depend on weather conditions, inflow turbulence levels and the operational state of the wind farm. These conditions can vary relatively quickly with time and any measurement method must be able to capture sound and annoyance simultaneously in order to more accurately rate a person's annoyance and understand the exact character of the noise that they find annoying. Thus a new method is required that is able to acquire wind turbine noise data over a wide frequency range while simultaneously recording self-reported annoyance level. Linking this data with self-reported health and sleep information would also provide a valuable extension to the current level of knowledge in this area.

Ideally, a relationship linking wind turbine sound power, the number of turbines, the distance to an observer with low-frequency sound pressure level and annoyance is needed to assist the design and planning of wind farms. While desirable, this kind of relationship is hard to deduce as it depends on many uncertainties. These include details of the physical mechanisms creating low-frequency noise on the turbines, atmospheric propagation of low-frequency sound and the individual sensitivies of the observers. Thus more research is needed in understanding the fundamental aspects of wind turbine low-frequency noise generation, propagation and perception.

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