Wind turbine noise: an overview of acoustical performance and effects on residents

Frits van den Berg

GGD AMSTERDAM Public Health Service, Environmental Health, Amsterdam, The Netherlands

ABSTRACT

Sound from modern wind turbines is predominantly aerodynamic noise with most audible sound energy at medium and higher frequencies. Wind turbine sound is relatively annoying, probably due to acoustical characteristics, such as amplitude modulation, that increase the risk for annoyance and disturbed sleep. Other health effects, all resembling stress symptoms to at least some degree, are attributed to infrasound, but this is not supported by existing knowledge of noise or noise annoyance and the claims lack substantiation. There is certainly room for the reduction of noise and noise annoyance, perhaps at the expense of maximum energy yield.

This paper gives an overview of knowledge about wind turbine noise and its effects on neighbouring residents. It emphasizes robust knowledge, from both the (psycho) acoustics and public health arena. But also attention has been paid to relatively new knowledge and ideas such as presented at the 5th International conference on Wind Turbine Noise in August 2013.

SOUND PRODUCTION

Sound sources

An overview of wind turbine sound sources is given in a number of publications such as Wagner (1998), Van den Berg (2006), Leventhall and Bowdler (2011), and more recently Doolan et al (2012). Mechanical sound (mostly from the gear box) was a relevant source for early turbines but has been reduced and is generally not an important source.
Aerodynamical sound is the dominant source for modern turbines. The most important contributions are from inflow turbulence and trailing edge turbulence. Free turbulence, such as in the atmosphere, is a very weak and therefore irrelevant sound source. However, interaction of turbulence with a hard surface leads to high local velocity changes (the flow normal to the surface must stop at the surface) which is the basic mechanism for the sound production. There are several aerodynamic sources:

- Trailing edge turbulence is generated because the air flow at the blade surface develops into a turbulent layer as is the fate of all flowing media subject to surface friction (even for laminar inflow). The frequency with highest sound energy content depends on the thickness of the turbulent layer that in its turn depends on local flow speed, blade width and angle of attack, but is usually in the range of a few hundred Hz up to 1 kHz. TE noise has a symmetrical spectrum that decreases initially with 3 dB per octave and steeper at further frequencies. At the blade tips conditions are somewhat different due to sideways air flow, but tip noise is relatively similar to trailing edge noise and usually not distinguished as a relevant separate source.
- Inflow turbulence is generated because the blade cuts through turbulent eddies that are present in the inflowing air (wind) and has a maximum sound level at around 10 Hz, falling off with an initial 3 dB per octave up to 12 dB per octave at higher frequencies. The frequency of maximum sound level increases with tip speed and decreases with turbine height, the level depends on the turbulence strength.
- Thickness sound results from the displacement of air by a moving blade and is insignificant for sound production when the air flows smoothly around the blade. But in front of the tower there is a slightly reduced wind speed and hence a change in lift forces when a blade passes the tower. The rapid change in forces on the blade results in a sideways movement of the blade and a sound pulse in the infrasound region. Because of the finite pulse length (tower diameter/ blade speed) a series of sound pulses are generated, consisting of harmonics of the blade passing frequency with a peak at the inverse pulse length (see Van den Berg, 2006: p.34).

Inflow turbulence noise is important in the low and middle frequency range, overlapping with trailing edge noise at medium and higher frequencies. As both are highly speed dependent, noise production is highest near the fast rotating tips of the blades. The level of radiated sound also depends on the direction (with respect to the incoming flow) and on blade speed, both of which cause the typical swish that is audible near a wind turbine.

Søndergaard (2013) has shown that the spectral form of wind turbine sound emission is very much the same for all modern, upwind turbines and has not changed significantly for turbines that produce over 200 kW electric power. The actual level depends on turbine size. Close to a modern wind turbine at high speed the sound level is in the order of 55 dB(A). At larger distances sound levels are lower, though low frequencies will be attenuated less than high frequencies.

Sound spectra

Figure 1 gives a plot of a sequence of 1 second sound samples, totalling 2 minutes, from the Rhede wind farm (similar to figure 5.1 in Van den Berg, 2006). At high frequencies (> ≈ 600 Hz) we see increasing levels peaking at 1 kHz and then dropping to background values due to trailing edge sound (and spikes due to birds > 2 kHz). At lower frequencies this overlaps with inflow turbulence sound which, at very low frequencies (< 10 Hz), again overlaps with thickness (infra)sound. However, this low frequency range may also include infrasound due to wind and possibly other sources. As for all unweighted wind turbine sound spectra the physical sound level is highest at infrasound frequencies and more or less monotonously decreases to background levels at a few kHz. With little atmospheric turbulence (in a stable atmosphere) inflow turbulence sound levels may be lower and traling edge sound may show up as a local maximum or 'hump' in the spectrum.

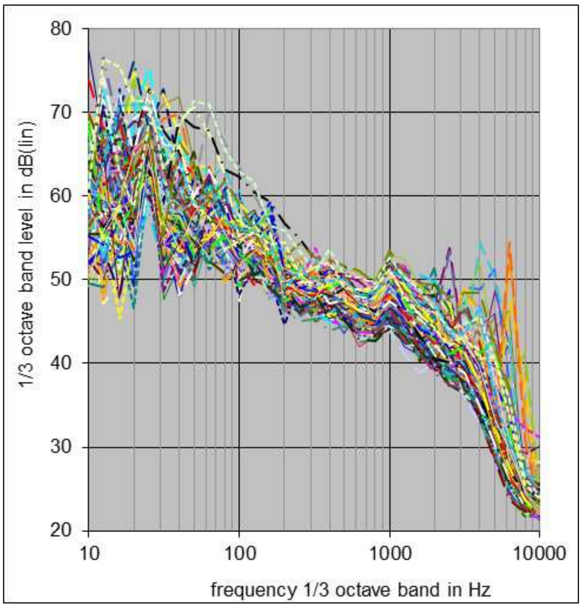

Figure 1. 2 minutes of 1 second spectra of wind turbine sound at a reciever position

We must take human hearing capabilities into account when assessing the relevance of (spectra of) wind turbine sound for its effect on people. Human hearing is relatively insensitive at low frequencies which thus compensates for the physically higher levels at these frequencies. To this end it is usual to apply A-weighting to a sound. A-weighting is sometimes discarded because it allegedly underestimates the effect of low frequency sound on people. For wind turbine noise at residences such objections to A-weighting are not convincing. A-weighting mimics the frequency dependency of human hearing at a loudness corresponding to the level of a tone at 1000 Hz of 40 dB. Such a low to moderate loudness is comparable with night time limits in many countries and therefore it is also in agreement with actual sound levels at many residences near wind farms. Therefore, A-weighting should be a (near) correct estimate of the loudness of a sound. A-weighting is indeed less correct at lower loudness levels; application of A-weighting to low levels (roughly < 30 dB(A)) may allow for more low frequency sound, though of course levels are already low there and will comply with limits. Infrasound will be discussed further in the section 'Other health effects and Quality of Life' below..

In figure 2 immission spectra are plotted at 300 m and 1500 m from an 'average' wind turbine, with maximum and minimum immission levels according to the maximum and minimum emission levels in modern wind turbines. The spectra are A-weighted to show levels that are relevant to human perception. It is often assumed that wind turbines are not directive sources, also because the directivity does not lead to large differences. When the sound is propagated into a dwelling, the construction will attenuate the higher frequencies better than the lower frequencies. As a result, indoor levels will be lower than in figure 2, but the spectrum will also be skewed towards lower frequencies, resulting in a lower pitched indoor sound. Thus, for indoor perception inflow turbulence sound may be an important component.

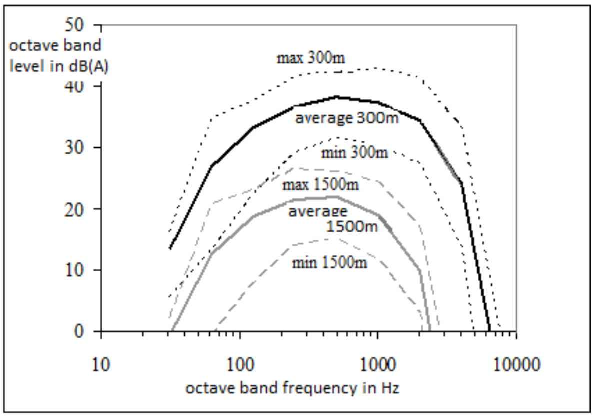

Figure 2. maximum, average and minimum immission sound levels due to a wind turbine at two distances

Influence of wind on sound production

Sound production is primarily determined by the wind speed at hub height. At a certain hub height wind speed, the vertical wind speed gradient does have effect on the electric power output (see, e.g., Wharton and Lundquist 2011) and it may have a small effect on sound power level, but its effect on the sound character is more prominent. When the gradient is strong, the blades pass through layers of air with significantly different wind velocities causing changes in the direction of the incoming flow relative to the blade. As a result the thickness of the turbulent trailing edge layer varies periodically leading to periodical changes in the emitted sound and its spectral composition. The resulting amplitude modulation (AM) causes changes in sound level at the rhythm of the rotating blades, as has been demonstrated by several researchers (e.g. Van den Berg 2006, DiNapoli 2012, Stigwood 2013). AM may be terrain dependent: over complex terrain the wind gradient may be rather different from the wind gradient over flat terrain. Even so, with turbines on a ridge and residents in a valley, a high contrast between wind turbine and background sound may exist (Van den Berg, 2007), similar to atmospheric stability effects over flat ground.

The vertical wind speed gradient is highly correlated to atmospheric turbulence strengthth: a stronger gradient implies less turbulence. It is not clear how this influences the electric power output, though one would expect less power with more turbulence as the angle of attack of the blades will have more variation. It does have effect on sound power: less turbulence and air flowing in at a more constant angle, implies less noise production. Inflow turbulence can be viewed as eddies at length scales ranging from a millimetre to several hundred meters. Large scale turbulence will cause variations in local wind speed. Figure 3 shows the variations in wind as a spectral plot: there is a high variability at time scales of seconds up to several minutes, and very little variation (the 'spectral gap') at time scales of 5 minutes to 1 hour. Then there are peaks at the scale of a day (diurnal variation), week (passage of weather systems) and year (seasonal varition). The high variability at the scale of minutes causes variations in sound production that are essentially chaotic and thus irregular. The low variability in te spectral gap is the reason to do background measurements over periods of at least 5 minutes so as to average over short scale variations.

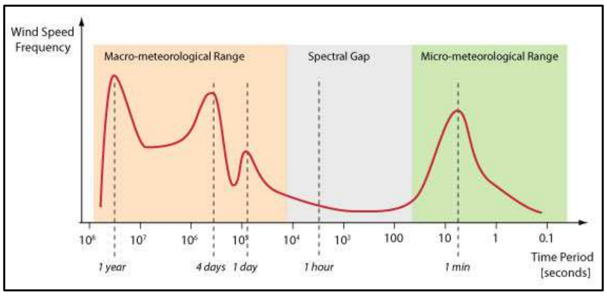

Figure 3. distribution of wind speed over time

Sound character

Although some people worry that low frequency sound or infrasound may be the cause for serious effects, the sound produced by wind turbines is not essentially different from the sound produced by the air flow around an aircraft or a fast riding car. Jet engines from large aircraft produce higher levels of low frequency and infrasound. Bolin et al (2011) have shown that wind turbine sound contains less low frequency sound compared to road traffic sound at levels considerd normal and acceptable. Of course this does not mean the sound can have no effects: it can be perceived as unwanted and uncomfortable noise, but the resulting effects are known from other noise sources.

This is less so for the changes in wind turbine sound over time. Wind turbine sound has temporal variations that are not often present near residences for a long time. The most important feature is its rhythmic variation at the blade passing frequency or the Amplitude Modulation (AM) of the sound level. An explanation for the typical swish that is audible close to a turbine has been given by Oerlemans (2011). Because of the forward directivity of trailing edge sound and the Doppler amplifications forward of the moving blade there is a high level when the blade tip is moving towards an observer and a lower level when it moves away. One can also hear a Doppler shift in frequency when a blade tip approaches. This was found from measurements close to a turbine, but the explanation does not hold for an observer at a distance downwind from a turbine. When the blades move in a plane normal to the observer there is no blade moving towards the observer. In that case the change in wind speed gradient, discussed in the section above, can explain a rhythmic beating that is most pronounced when there is a strong wind gradient such as occurs when the temperature of the ground surface drops (Van den Berg, 2006). In long term measurements Öhlund and Larsson (2013) found that at 1 km from the closest (and most central) of 12 turbines AM occurred predominantly during a temperature inversion (positive temperature gradient, i.e. stable atmosphere) and more often downwind from the turbines. At 400 m from another farm, of only two turbines, AM also occurred most often downwind from one, but perhaps also more sideways from the second turbine. Stigwood et al. (2013) comclude that AM is found in all wind conditions, but is most easy to detect in evening, night time and early morning periods when there is low cloud cover / high wind shear.

A second important feature may be that –on the average- wind turbine sound does not subside at night. In fact, it may be somewhat louder and attract more attention because of the AM that is reported to occur more often at night (van den Berg 2006, Stigwood 2013).

Propagation of sound

There are no clear indications that noise propagation models that are commonly used for point sources are not valid for wind turbines, except perhaps for upwind propagation over a large body of water. Of course, noise propagation models are always a compromise between accuracy and practical aspects, and they usually average over different terrain and weather situations. Because wind turbines are elevated sources, the sound shadow is at larger distances then it is for a low source (such as traffic). Because of this a road level with the ground may not be heard at moderate distances upwind, but a turbine may still be audible at large distances upwind (Van den Berg, 2009).

EFFECTS ON RESIDENTS

Effects that are related to wind turbines are visual and aural impact, accidents and impacts in the construction phase. Though these are all distinctly different causes, for residents they may be connected because of multimodal interaction and because worry or annoyance from one factor may influence the effect of another factor. Impacts usually are assessed separately (effect of noise, impact on landscape, etc.), but can also be assessed in an integrative way by investigating the effect on the quality of life.

The effects that noise can have on people have been investigated for a number of sources and this has led to a reasonable understanding of the impact of noise on people. The effects most studied are annoyance and sleep disturbance as these occur at relatively low noise levels and thus are most prevalent. This is also true for wind turbine noise.

Audibility

As has been illustrated above, at some distance from the rotor most audible sound energy from wind turbines is in the medium and higher frequency range, less at low frequencies and nothing at infrasound frequencies. This has been supported by a recent Japanese research project, showing that infrasound and low frequency components just above infrasound frequencies do not contribute to the perception of wind turbine and A-weighting gives the best correlation with perception (Yokoyama et al, 2013).

A substantial proportion of residents notice wind turbine sound in- and outdoors at (outdoor) levels of 35 dB(A) (Pedersen et al, 2007; Pawlaczyk-Luszczynska et al, 2012). In principle sound at any level, if audible, can lead to annoyance and further effect. According to the World Health Organization (WHO, 2009) indirect effects of noise start with noise-induced disturbances of activities such as communication or sleep. For such effects moderate and high level exposures have similar health otcomes. Thus the degree of (e.g.) annoyance does not depend on the noise level (although the level does influence the percentage of people that are annoyed). The WHO (2009) also states that objective noise ecposure (sound level) and subjectively perceived exposure (annoyance) can act independently as exposure variables when analyzing the relationship between noise and health.

Annoyance

Combining Swedish and Dutch survey results, Janssen et al (20011a) have shown that wind turbines are relatively annoying sound sources when compared to other noise sources. The relation between the dose (average day-evening-night sound level Lden) and effect (percentage of residents seriously annoyed) is plotted in figure 4. For wind turbine sound comparable results for annoyance were found in a more recent Polish study (Pawlaczyk-Luszczynska et al, 2012). The curves for road traffic, trains and industry are those from Miedema and Vos (1998, 2004). The curve for aircraft is an updated curve based on studies that showed that since the 90's aircraft noise are perceived as more annoying than the Miedema curve, based on earlier surveys, predicted (Janssen, 2011). The curve shown is now used in Dutch aircraft noise policy; it is –perhaps accidentally- almost an extension of the wind turbine noise curve. Also plotted in figure 4 are limits for the preferred and maximum allowable noise levels according to the Dutch Noise Act. This shows that the single limit for wind turbine noise leads to a somewhat higher percentage compared to the preferred limit for road traffic, trains and industry, but lower when compared to the maximum limit. For aircraft noise, limits are substantially higher.

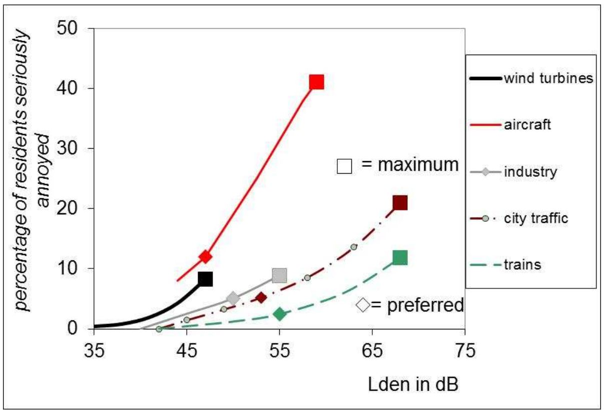

Figure 4. serious annoyance vs. sound level for different noise sources; markers show preferred level (diamonds) in the Netherlands and maximum allowable level (squares)

Research into wind turbine noise has shown that wind turbine noise may be relatively annoying because of physical characteristics (van den Berg, 2006; Pedersen et al, 2007; Bolin, 2012; Gabriel, 2013; Stigwood et al 2013). Most prominent is a swishing or thumping character of the sound. Also, the unpredictability of the sound and better audibility at night may contribute to the annoyance. However, those who are economically involved hardly or not report annoyance. This is discussed in the section 'Non-acoustical factors' below.

Sleep disturbance

Studies by Bakker et al (2012), Shepherd et al (2011) and Nissenbaum, Aramini and Hanning (2011) show a significant relation between self reported sleep disturbance or sleep quality and noise from or distance to a wind turbine or wind farm. In one of three studies (two in Sweden, one in the Netherlands) Pedersen (2012) did not find such a relation. Based onn the Dutch study, Bakker et al (2012) found there is no direct relationship between the self-reported frequency of being disturbed in sleep by noise (from any source) and annoyance from wind turbine noise when being indoors, as found in the Dutch study. The thin bars are the standard deviations illustrating there is a high variability of annoyance for each sleep disturbance frequency.

Though it has been shown that noise and/or noise annoyance from wind turbines are associated to sleep disturbance or sleep quality, little data is available to quantify this effect. Shepherd et al (2011) have shown that sleep is affected when comparing respondents living within 2 km and further than 8 km from one windfarm. Nissenbaum, Aramini and Hanning (2011) have shown the same when comparing respondents that live whithin 400 m or further from one of two wind farms, though from their results in fact the effect appears to occur whithin 1000 m or at hourly averaged noise levels above 41 dB(A). In a Dutch report Janssen et al (2008) gave a relation between the frequency of being disturbed in sleep and noise level. They showed there was a relation between wind turbine sound level and self reported disturbed sleep (being disturbed at least once a month), though this relation was not significant when taking personal characteristics (age, noise sensitivity, economical benefits) into account. The influence of age and noise sensitivity were similar as found with other noise sources: less annoyance for younger and older adults and for those not sensitive. Economical benefits had a clear reducing effect on sleep disturbance, similar to the influence on noise annoyance.

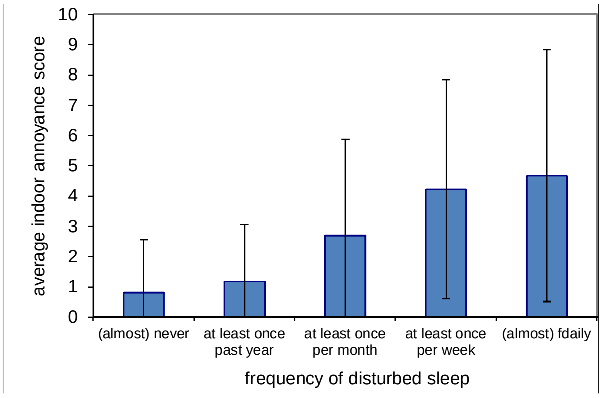

Figure 5. average score for annoyance from wind turbine sound vs. self reported frequency of sleep disturbed by (any) sound

Other health effects and quality of life

Several other health effects have been investigated in wind turbine noise studies, such as distress and adverse mental health effects. From the two Swedish and one Dutch survey studies Pedersen found no evidence that, apart from annoyance and sleep disturbance, other health symptoms were consistently related to wind turbine noise. Cardiovascular disease, impaired hearing, headache, undue tiredness, feeling tense and stressed or irritable were not significantly associated with wind turbine noise levels. Significant positive associations were found for tinnitus and diabetes, but each in only one of the three studies. For some of these symptoms a significant association was found with *annoyance* from wind turbine noise: headache was significantly associated to annoyance when being outdoors in one study, undue tiredness in two studies, feeling tense and stressed or feeling irritable (as well as sleep interruption) was significantly associated to annoyance outdoors in all three studies. Some of these associations were not significant when related to annoyance indoors. From the Dutch study Bakker et al (2012) found that living in the vicinity of wind turbines increased the risk of being annoyed by the noise, which in turn could lead to psychological distress (and to sleep disturbance). There was no significant relation between wind turbine noise level and psychological stress. They concluded that residents who do not hear the sound or do not feel disturbed, are not adversely affected.

Shepherd et al (2011) used a Health Related Quality of Life questionnaire for a masked survey comparing residents in a community within 2 km from a wind farm or with a control group at least 8 km to a wind farm and matched for area type (rural) and geographic, demographic and socio-economic characteristics. The overall HRQoL score was significantly lower in the 'turbine group' compared to the control group, due to lower scores on the physical and environmental domains of HRQoL; there were no significant differences in the psychological and social domains. Nissenbaum, Aramini and Hanning (2011) used the (Short Form) SF-36 survey questions to assess different components of quality of life; their survey was not masked (it was clear that it addressed adverse health effects) and included a relatively small number of participants (79). Somewhat in contrast to Shepherd et al (2012) they found that there was a significant difference in the Mental Component Score (MCS), but not in the Phsyical component Score (PSC), when comparing participants within and further than 1400 m from a wind farm ('near' and 'far' group). Some participants in the near group reported to have been diagnosed with depression or anxiety, and some reported psychotropic medications had been prescribed, both since the turbines were operational and compared with none and a few, respectively, in the far group.

New ideas have been forwarded to explain the reaction of (some) residents: people may get sick from wind turbines (Wind Turbine Syndrome, Vibro-Acoustic Disease) or may be affected otherwise by inaudible infrasound. Pierpont (2009) published a non-peer reviewed study of selected people living near wind turbines and proposed a new illness (Wind Turbine Syndrome) to explain a combination of symptoms. These symptoms also occur when persons are put under stress. A number of medically acknowledged psychological disorders that are related to stress (were disorder is a medical term referring to a disturbance of a 'normal', healthy state, either caused by internal or external triggers) may explain the reaction to the presence of wind turbines without postulating a new syndrome (Van den Berg, 2011).

Earlier, Alves-Pereira and Castelo Branco (2007) suggested that the sound of a wind turbine can cause Vibro-Acoustic Disease (VAD), identified by a thickening of the mitral valve (one of the valves in the heart) and the pericardium (a sac containing the heart). Earlier research findings related VAD to high sound levels over long periods of time. Despite this, in an investigation concerning a family living near two wind turbines Alves-Pereira and Castelo Branco concluded that VAD occurred and was caused by low frequency sound, even thoug there were no indications for physiological effects and the measured noise levels were substantially lower than levels at which VAD was thought to occur. Even if the same sound energy at the measured levels would be presented at the most sensitive audible frequencies, it would not cause hearing damage, although the ear is the most sensitive organ. As far as I know this suggestion has not been followed up, possibly because it was an urealistic speculation.

Salt and Kaltenbach (2011) proposed that in human hearing the presence of high frequency sound may inhibit the perception of infrasound as they had found in animal experiments. And therefore the absence of high frequency sounds can lead to the perception of infrasound otherwise inaudible. To conclude that this leads to adverse effects from wind turbines is taken the experimental results further than warranted. It first must be shown that this phenomenon also occurs in humans, that it has an effect in humans, and that this is an adverse effect. As yet there has been no indication that this was relevant for the many cases where high levels of infrasound from whatever sound occurred, or when people reported disturbing low frequency hums. Farboud, Crunkhorn and Trinidade (2013) state that until the physiological effects of infrasound and low frequency noise from wind turbines are fully understood, it is impossible to state that they cause any of the symptoms related to wind turbine noise exposure. They also remark that the fact that the ear may respond to low frequency noise from wind turbines does not necessarily mean that such noise will be perceived or disturb function.

Another new explanation for health effects from wind turbine sound has been forwarded by Schomer et al (2013) who found symptoms (nausea) similar to those of motion sickness. Infrasound levels varying at the blade passing frequency could have an effect on people if the pressure variations act on the vestibular system (detecting head motion and posture) are comparable to accelarations in motion or seasickness. Again, as yet there has been no indication that this is relevant for cases where high levels of infrasound from whatever sound occur or for people that experience rhythmic variations in (acoustical) pressure.

Leventhall (2013) shows that infrasound from normal processes in the body would generate higher pressures in the inner ear than sound from wind turbines would. It makes sense from an evolutionary perspective that human hearing does not perceive internal infrasound because it does not carry relevant information. Van den Berg (2011) made a similar point based on low frequency pressure fluctuations from turbulence in wind. Only when loud enough, these fluctuations can be heard, as rumbling 'wind noise', but otherwise they appear not to affect people.

To conclude: the data available indicate an interaction of annoyance, disturbed sleep and distress, where only annoyance is directly associated with the noise level. New explanations for 'sickness'related to wind turbine noise have been forwarded, based on the supposedly adverse effects of inaudible infrasound, but as yet there is little to substantiate these ideas. They are not supported by experience with effects of noise on human health. This does not mean they are wrong, but it is reasonable to ask why these phenomena are not manifest in situations with similar or higher exposure conditions.

Non-acoustical factors

It is clear that the noise level as such is not sufficient to explain the impact of wind turbine noise, as the impact on different residents can vary over a wide range at the same noise level. As is the case with most noise sources, other factors must be considered. These are other physical factors (such as visibility, shadow flicker, safety), personal factors (such as costs and benefits, predictability, lack of control, attitude, noise sensitivity, fear/worry) and social factors (such as trust in authorities, fairness, justice, awareness of economic and social benefits, compensation). Visibility of the turbines from home increases the risk for noise annoyance. The influence of age and noise sensitivity were similar as found with other noise sources: less annoyance for younger and older adults and for those not sensitive (Janssen et al, 2012). According to the Dutch study economical benefits form the wind turbines suibstantiallty reduced annoyance (Pedersen et al, 2007), which is probably connected to the reduced annoyance levels for those having a positive attitude towards turbines in the landscape. Worry is an important element in the public debate, because it is important in the early (planning) phase, when residents often have no personal experience with living near a wind farm. Mitigation can also be addressed towards these factors.

Sociological research has shed light on the role of planning processes of wind turbine projects (e.g. Tyler 2000, Atkins 2010, Pepermans and Loots 2013). The general conclusion is that people are more willing to accept decisions when they feel that those decisions are made through descision-making procedures they view as fair. People evaluate a procedure as fair when all parties at stake have the opportunity to participate, the authorities are neutral, the motives of the authorities are trusted, and people are treated with dignity and respect in the process. Pepermans and Loots (2013) argue that geographical, political and social distances lead to a different way of framing interests and opinions for the parties involved. They also observe that with wind power energy production is visually brought back into residential areas which maybe welcome for some, but an intrusion into the landscape that others feel attached to.

NOISE MITIGATION AND MASKING

To reduce wind turbine sound at a receiver, keeping sufficient distance is the prime measure to consider. Of course reducing noise levels can be effective too. To reduce sound power levels the blade design can be improved or rotational speeds can be lowered. Speed reduction is already applied in low-noise setting of wind turbines. As is shown in figure 6 for one particular turbine, this effectively reduces broad band A-weighted levels, but does not have much influence on the lower frequency (≤ 125Hz) octave bands.

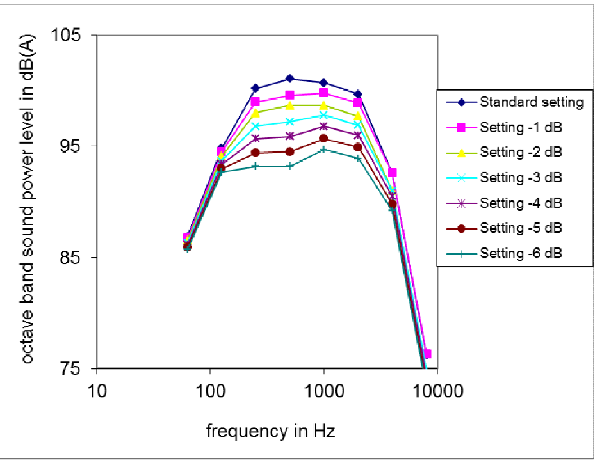

Figure 6. octave band sound power spectrum for different noise modes of a wind turbine

Reducing the level changes associated with amplitude modulation perhaps decreases the overall sound level only slightly, but it can reduce noise annoyance substantially. At least one manufacturer has developed the technique to synchronize turbines in a wind farm aimed to generate a less chaotic or more placid view of the farm. Another manufacturer applies rapid pitch variations to reduce blade load variations. Both possibilities seem to allow desynchronizing wind turbines with respect to listeners by preventing AM peaks to arrive at the same time. An 'array approach' has been proposed by Buck, Palo and Moriarty (2013) directing (incoherent) interference maxima to directions with no residents. An alternative approach is to constantly desynchronize wind turbines, so interference maxima only can occur for very short times, perhaps even making AM imperceptible (though this will depend on the wind farm lay out).

Masking wind turbine noise has been studied with natural sounds and sound from road traffic (Bolin, Nilsson and Kahn 2010; Pedersen et al 2010). This has shown that the masking potential is low because of spectral and temporal differences. Masking is most relevant at evening and night, i.e. at times that masking potential from existing sources is often lowest.

The dose-response curve for wind turbines (figure 4) has been derived from surveys where probably most respondents were exposed to sound from turbines operating without restrictions (such as low noise modes or not operational in sensitive periods). It is not clear how noise annoyance from wind turbines will change when mitigation measures are applied. It is plausible that measures reducing noise levels at evening or night time have a relevant effect in contrast to reducing noise levels in day time. Also, planning processes that are directed towards community acceptance may lead to less health effects. However, it is to be expected that even the most succesfull approaches will lead to effects for some people in the vicinity of the wind farm. This is essentially a policy issue: to what extent are negative effects (impact on landscape, effects of noise) acceptable when considering the positive effects of wind energy production (less pollutants). The health related guidelines for wind farms published by the Belgian Superior Health Council (SHC, 2013) address this issue.

CONCLUSION

Wind farms are still a relatively new phenomenon as most people have no personal experience with wind farms. Dealing with wind turbine sound has not yet become a 'standard issue' such as road traffic sound is. This holds for professionals and residents. For professionals there is as yet no generally accepted explanation for AM production or perception or a model to assess the effect of mitigation measures on annoyance. For residents acoustic information is part of the information needed in the process, but neighbours-to-be need more information on what that means to them: what do decibels mean in relation to audibility and intrusiveness? Even then they may not find it acceptable, for acoustical or other reasons. Sociological research helps to explain how planning processes may lead to diverging views and what factors are important to keep stakeholders connected or 'close'.

Wind turbine manufacturers have put great emphasis on maximizing energy yield and have been very successful in this. A small part of this can be exchanged for less noise pollution by reducing rotor speed, either at sensitive or all times. This is a simple application of "the polluter pays" principle and acknowledges the value of profit, planet *and* people. Reducing rotor speed will also lead to a reduction in AM levels, though a more sophisticated way (perhaps even with higher energy yield) may be to apply small pitch variations.

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