Health Effects from Wind Turbine Low-Frequency Noise & Infrasound

Do Wind Turbines Make People Sick? That is the Issue.

George Hessler, George Hessler Associates, Inc., Haymarket, Virginia
Goeff Leventhal!, Consultant., Ashtead, Surrey, United Kingdom
Paul Schomer, Schomer and Associates, Inc., Champaign, Illinois
Bruce Walker, Channel Islands Acoustics, Camarillo, California

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Do wind turbines make people sick? That is a contentious issue in licensing wind farms. In particular, low frequency sound emissions (infrasound and "pulsed" and steady low frequency sound) from wind turbines are blamed by opponents but vigorously denied by project proponents. This leads to an impasse of testifying "experts," and regulators must decide on the basis of witness credibility for each project, leading to inconsistent findings. This article presents the opinions of four very experienced independent investigators with wind turbine acoustics over the past four decades. The latest Threshold-of-Hearing research down to 2 Hz is compared to today's modern wind turbine emissions. It is jointly concluded that infrasound (0-20 Hz) can almost be ruled out, subject to completion of recommended practical research, and that no new low frequency limit is required, provided adequate "A"- weighted levels are mandated.

Claims of adverse health effects are made by individuals and organized community groups at some operating wind turbine sites located around the world. Adverse publicity is intense at about a dozen operating sites in the United States, the United Kingdom, Canada, Scandinavia and Australia. Health effects attributed to wind turbines include symptoms similar to those of motion sickness, such as, dizziness, nausea, vomiting and a general feeling of discomfort or not feeling well. Sea sickness (a form of motion sickness) is well understood as a disturbance of the inner ear, and the cause is both obvious and indisputable. Motion sickness is more subtle and is caused by the brain receiving conflicting messages about what is seen by the eye as opposed to what is felt or sensed.[1] For example, air sickness can result from plane motion caused by invisible turbulence in the air. To date, no such similar connection has been found at wind turbine sites, although some residents claim they can sense when wind turbines become operational without benefit of sight or hearing.

It has now been demonstrated by multiple independent researchers that wind turbines, like any other rotating fan, emit measurable tones at the blade-passing frequency (BPF) and up to about the fifth harmonic plus broadband noise. For a typical large three-bladed wind turbine rotating at 16 RPM, the BPF and harmonic tones are at frequencies of 0.8, 1.6, 2.4, 3.2, 4 and 4.8 Hz. These very-low-frequency tones are commonly called infrasound, defined as low-frequency noise in the 0-20 Hz frequency range. A better definition used by one of the authors is "pulsed LFN," since the tones result from analysis of pulses produced by tower blade interaction. The 0-20 Hz measurements are all well below the threshold of hearing, as established by the latest research at frequencies down to about 2 Hz. But it might at least be asked: Are the pulses the invisible source of conflicting messages to the brain? Reference 1 states that messages "are delivered from your inner ear, your eyes (what you see), your skin receptors (what you feel) and muscle and joint receptors," but there is the open question of whether the low levels of pulsed LFN or infrasound from wind turbines excite any of these receptors.

Permitting authorities for new projects must evaluate adverse health effect claims presented as proven factual data by opposition forces, countered by project advocates that state no physical link to health effects has ever been demonstrated at wind turbine sites. This debate has now raged for at least a decade and is now at an impasse.

It has been the first author's privilege and pleasure to associate and collaborate with three prominent co-author scientists in the wind turbine acoustical field. All four authors do not doubt for a moment the sincerity and suffering of some residents close to wind farms and other low-frequency sources, and this is the reason all four would like to conduct, contribute or participate in some studies that would shed some light on this issue. It must also be said that it is human nature to exaggerate grievances and that some qualitative measure must be made available to compensate affected residences.

The first author has asked each co-author to independently summarize their opinions and recommendations on how the current impasse can be broken.

Current Research on the Threshold of Hearing

Research to measure the threshold of hearing at low frequencies can be summarized in one graphic (see Figure 1). The highest and lowest gray bars encompass the results of 10 studies over the listed 30-year period that is nicely shown in the Noise & Health Journal.[2] These are the min. and max. at each 1/3-octave-band frequency for any of the 10 studies. The graphic also plots ISO 226:2003(E) that covers the entire audible range from 20 Hz to 12,500 Hz (plotted to 1000 Hz). The green line comes from Project EARS funded by the

European Union [3] and represents "acceptance levels" based on the 10% percentile hearing threshold values determined in the EARS Project and is the latest research on the subject.

Figure 1. Research summary for determining threshold of hearing at low frequencies.

Figure 2. Typical wind turbine spectra and levels compared to threshold of hearing at low frequencies.

Defining the Problem

How does ILFN from a modern wind farm compare to the above summary? Figure 2 replots the contents of Figure 1, all in blue, and adds the measured spectra and overall levels at three locations from a study"' funded by Clean Wisconsin (an environmental organization) and the state of Wisconsin. This study was carried out at a wind farm located among residences in a quiet environment of residences and farmland, typical of wind farm sites in the American midwest and northeast. Response at this site has been adverse, to say the very least. The three plots are near residences reported to be abandoned due to adverse health effects. Several things may be deduced form this plot.

First, the wind farm was designed to a standard of 50 dBA at nonparticipating residences, and that level is not endorsed by any of these four authors. All of us have been at or near 40 dBA for many years. Had 40 dBA been used, there would not be a wind turbine as close as 1100 feet at R2, where a level of 48 dBA was measured. Wind turbine sound was readily detectable by the test engineers at R2, but not at R1 and R3 where levels are less than 40 dBA.

Second, the levels at all the residences in the infrasound range (0-20 Hz) are far below perceptible levels in this range. This strongly suggests the source of any message to the brain is not from wind turbine infrasound directly but may occur as audible LFN or pulsing LFN at the blade-passing frequency well inside the infrasound range.

Third, a wind turbine is not a classic LFN noise source — a source heavily weighted with LFN. Such sources typically have C-weighted levels 15 or 20 dB above A-weighted levels. Observe from the plot that C-weighted levels are both relatively low (<60 dBC) based on typical C-weighted guidelines, and the C-A differential is less than 15 dB.

To understand just how difficult this issue is, consider that the residents (husband, wife and young baby) at R2 experienced their child awakening at night screaming, but not on nights away from home. The wife was highly annoyed, and the husband had "no problem at all" with wind turbine sound. Add to this that there is a home across the street, the same distance and direction from the turbine, but the owners accept "good neighbor" payments.Could any payment be enough if suffering serious health effects?

And last, there are thousands of landowners that lease their land for wind turbines and live very close to turbines. It is hard to abandon the notion that higher levels closer to the source should produce higher levels of affected residents, but a recent large-scale, long-term measurement survey in Australia showed no correlation between complaint locations and measured levels.

It would seem one promising direction of a study could be extensive interviews of such folks exposed to high levels of wind turbine noise that could reveal common symptoms and/or the number of folks seriously affected.

Opinions and Recommendations of Geoff Leventhal!

Wind Turbine Noise and Health. Wind turbine noise spans a range from below 1 Hz up to 10 kHz or more. A one-third-octave spectrum typically drops off at between 4 dB/octave and 6 dB/ octave. Blade-passing tones are added into the falling spectrum in the range from about 1 Hz to 7 or 8 Hz and have normally disappeared from the spectrum by 10 Hz, although they may reappear at a low level at higher frequencies. (Zajam§ek, Hansen *et al.* 2016). The high correlation between wind turbine dBA and dBC, (Keith, Feder *et al.,* 2016) is explained by this generalized falling spectrum from infrasound to high frequencies, also described by Tachibana *et al.,* who found 4 dBA per octave fall-off (Tachibana, Yanob *et al.,* 2014).

Sound level at nearest residential distances of, say 500 m, may be around 60 dB at 10 Hz, while the hearing threshold is close to 100 dB at this frequency. A falling spectrum of 6 dB/octave (20 dB/decade) gives 80 dB at 1 Hz for a level of 60 dB at 10 Hz. The hearing threshold is not well known at 1 Hz but is likely to be about 130 dB, since measurements have shown a threshold of 120 dB at 2.5 Hz (Kuehler, Fedtke *et al.,* 2015)

Levels of wind turbine infrasonic blade tones are well below our normal hearing threshold, while at higher frequencies, say 30-50 Hz, the blade harmonics, if present, may approach median threshold. (Zajamgek, Hansen *et al.,* 2016).

Wind turbine sound fluctuates due to short-term variations in propagation, with typical maximum fluctuations of about 15 dB (Bray and James 2011). Wind turbine low-frequency noise normally becomes just audible to the average listener at frequencies above 40-50 Hz. Higher audible frequencies, 250-1000 Hz from aerodynamic noise may vary in level at the blade-passing frequency, giving amplitude modulation (swish) of about once per second: Frequencies in the higher kilohertz range are heavily attenuated by air absorption and are not normally a factor in wind turbine noise at residences.

Does wind turbine noise, as experienced at typical residential distances, affect health through either direct or indirect mechanisms? There is wide variation in human response to audible noise, especially to low levels of noise like that produced by wind turbines, but these low levels are not known to have direct and adverse physiological effects on the body. The term "physiological effects" must be used carefully, since any response to a stimulus is a physiological effect. The great majority of these responses are harmless, beneficial or essential to our proper functioning.

Figure 3. Response process (left) and range of responses (right).

Figure 3 shows a simplified diagram of the hearing process, leading to perception and response to a noise (Leventhall 1998). Input noise is detected, stimulating perception via the auditory cortex. Response, the reaction to perception, is very variable, as in Figure 1, depending on many personal and situational factors and conditioned by both previous experiences and current expectations. Response to the same noise from within a large group might range from passive acceptance (I can hear it, but it does not bother me) to aggressive resentment (I can't stand this noise — it's ruining my life).

Daytime disturbance by noise leads to irritation and aversion, while sleep disturbance may be an additional night effect, although investigations have shown similar numbers of poor sleepers and good sleepers both close to and remote from wind turbines (Nissenbaum, Aramini *et al.* 2012) (Jalali, Nezhad-Ahmadi *at al.* 2016) (Michaud, Feder *at al.,* 2016). Cognitive behavioral therapy reduces disturbance from noise through a process of desensitization and can improve sleep and quality of life (Leventhall, Robertson *et al.,* 2012).

The main effect of low levels of unwanted audible sound is creation of hostile reactions and negative thoughts, leading to stress and to the adverse health effects that might follow. Stress has different intensities, ranging from cataclysmic events (war and earthquakes), to acute personal stress (bereavement), and to chronic low level stress (long-term illness or persistent personal problems) (Benton and Leventhall, 1994). Stress from wind turbines, if it arises, is normally low level but, in a very small number of people, it may become intense and overpowering so that opposition to wind turbines is the dominating emotion in their lives. Unfortunately, concentrating attention on an unwanted noise aggravates any problems. Anticipatory stress also occurs following approval of a wind farm, although it has not yet been built, and a few anxious residents may experience similar symptoms to those that they believe to be associated with an active wind farm (Mroczek, Banas *at al.,* 2015).

Reaction to noise, especially low-level noise, is largely conditioned by attitudes to the noise and its source. Noise level contributes only about 20-30% of the total annoyance from noise (Job, 1988), while feelings, fear and opinions shape many of our responses, influencing tolerance levels. Negative emotions give an additional impact to an unwanted stimulus. The attitudes of nearby residents toward wind turbines is a major factor in the effects that turbines may have on their health (Rubin, Burns *et al.,* 2014). It has been shown that sham exposures to infrasound, (Crichton, Dodd *et al.,* 2014) or to sham electric fields (Witthoft and Rubin, 2013) produce symptoms in those who have been primed to expect an effect from exposure. The human being is clearly very complex in its reactions to physical and psychological stimuli.

Infrasound has a special place in discussions of the health effects of wind turbines, with many claims centered on direct pathological interactions, initially fostered by media scare stories originating in the 1960s and still continuing (Leventhall, 2013a).

In his 1974 popular science book *Supernature,* Lyall Watson described infrasound as causing deaths ("fell down dead on the spot"), while focused infrasound "can knock a building down as effectively as a major earthquake." This is unfounded, but an aura of mystery and danger persists around infrasound deep in the minds of many people, where it waits for a trigger to bring it to the surface. A recent trigger, heavily manipulated by objectors and media, has been wind turbines (Deignan, Harvey *et al.,* 2013).

A concept from psychology is the "truth effect," which explains how we can develop belief in false statements through their repetition by others (Henkel and Mattson, 2011).

- We believe statements that are repeated, especially by different sources.
- The path to our belief is made easier by each previous repetition.

Advertising and political propaganda are clear examples of the operation of the truth effect, which is also known as "illusory truth."

We all also have our preferred beliefs. When there is a choice, we tend to believe what we wish to believe. We feel comfortable when our existing beliefs are confirmed, and if we have become antagonistic to wind turbines we readily absorb negative statements about them.

Some objectors to wind turbines further their cause by generating anxiety on effects on health, particularly from infrasound and low-frequency noise, in populations close to proposed wind farms. Persistent repetition that infrasound from wind turbines will cause illness develops stressful concerns in residents, but repetition is neither evidence nor proof. However, a nocebo effect may occur, by which expectation of an outcome may lead to realization of that outcome (Chapman, Joshi *at al.,* 2014).

There are a large number of coordinated objector groups working internationally. A web page (https://quixoteslaststand.com/) gives links to more than 2000 groups that share information on wind turbines, while some make unsubstantiated, anecdotal claims about their effects. However, there is no doubt that when stress is persistent it may result in somatic effects in a small number of people who have a low-coping capacity, although the ability to cope can be enhanced (Leventhall , Robertson *et al.,* 2012).

In considering infrasound and other sound from wind turbines, it is necessary to take a very analytical, critical, unemotional view of the topic and to remain free of the influence of incorrect, but frequently repeated, statements.

There is no evidence that inaudible infrasound from wind turbines affects health, but there are indications from exposure tests that it does not (Tonin, Brett *at al.,* 2016). Inaudible infrasound has not been shown to affect those exposed, but just audible infrasound has a sleep-inducing effect (Landstrom, Lundstrom *et al.,* 1983).

Comparisons have been made of levels of infrasound from wind turbines at dwellings with the levels of infrasound that occur from man-made sources in urban and industrial areas and also levels that occur naturally in coastal and other regions. The infrasound exposure levels are similar (Turnbull, Turner *et al.,* 2012).

There is a persistent microbarom frequency of about 0.2 Hz caused by interacting sea waves, which goes to high levels during storms, propagating long distances over land. Microbarom six-hour averages have been measured in the region of 60-70 dB, while power spectral densities as high as 120 dB at 0.2 Hz have been observed (Shams, Zuckerwar *et al.,* 2013). We are not affected by this infrasound, which is at higher sound pressure levels than wind turbine infrasound at 0.2 Hz.

Investigations to find a link between infrasound from wind turbines and adverse physiological effects include work by Salt, who used high-level 5-Hz infrasound to bias the hearing of guinea pigs and noted that the outer hair cells (OHC) responded to this stimulus. The response threshold was lower than the hearing threshold, which is determined by the inner hair cells. Salt used the single measurement as a point on an OHC threshold curve and deduced an OHC threshold for humans by considering the low-frequency mechanics of the ear and comparison of human sensitivity with guinea pig hearing sensitivity. The human OHC threshold was determined as 100 dB at 1.0 Hz, falling by 40 dB/decade, so that it meets the inner-hair-cell threshold at about 100 Hz (Salt and Hullar, 2010). They conclude: "The fact that some inner ear components (such as the OHC) may respond to infrasound at the frequencies and levels generated by wind turbines does not necessarily mean that they will be perceived or disturb function in any way. On the contrary though, if infrasound is affecting cells and structures at levels that cannot be heard, this leads to the possibility that wind turbine noise could be influencing function or causing unfamiliar sensations."

Wind turbine emissions are generally below the OHC threshold so that, under these circumstances, the threshold is not relevant to wind turbine infrasound. The effects of stimulation of the OHCs remain unknown. The OHCs are the main component of the cochlear amplifier and are continuously active, being the source of otoacoustic emissions (Ashmore, Avon *et al.,* 2010). But wind farms at which nausea and similar effects are reported, may have a spectrum that is entirely below the Salt OHC threshold, so that it is not exceedance of this threshold that is the cause of distress.

Salt's further publications, seeking to support the adverse effects of infrasound, use examples in which the frequencies and levels are higher than those from wind turbines (Salt and Lichtenhan, 2014). As pointed out by Dobie, Salt and Lichtenhan, quote effects resulting from 30 Hz at 100 dB and 120 dB and from 50 Hz at 85-95 dB (Dobie, 2014). These low-frequency pure tones are not directly relevant to wind turbine noise, which does not contain such high-level tones. Salt's connection of his work to wind turbine infrasound is not yet convincing.

Over the past 45 years, popular culture has attributed a number of unpleasant, even fatal, effects to infrasound, but none has been sustained by evidence. Concerns on inaudible infrasound from current designs of wind turbines commenced 10-15 years ago, linked to objections to the growth of wind farms, and have accelerated over the past 5-10 years. It is inevitable that, in the absence of good supporting evidence, these speculative claims will become discredited over the next 5-10 years.

At the present time, conclusions are:

- Audible wind turbine noise acts through annoyance and stress, which may lead to poor sleep quality, especially in hostile people. Hostility is heightened by the actions of objector groups. There is no known direct effect on health from the low levels of audible wind turbine noise. However, stress may develop from an individual's reaction to the turbines.
- There is no established evidence that the inaudible infrasound from wind turbines affects health, but there are indications that it does not.

Opinions and Recommendations of Paul Schomer

Currently, I think this group of four find ourselves in the following situation: We all agree that sound flowing through the cochlea is not the source of problems below the threshold of hearing. That statement leaves two of what I will call technical possibilities. One possibility is that there are pathways other than through the cochlea for the infrasound to get to the brain. A second possibility is that to date we have missed something in the audible sound range that is the source of problems or that both of these situations exist.

Are There Noncochlear Paths for Infrasound to Reach the Brain? The following is a relatively simple study that could test whether individuals who claim they can detect the turning on and off of turbines can actually do this without visual or audible clues. There are at least a few small groups in the United States, Australia, and Canada that claim to have this ability. The results could be that none of these people could detect the turning on and off, or it could be the reverse and everyone would be able to detect the turning on or turning off. It is likely that the result will be somewhere in between.

In Shirley, Wisconsin, there are residents who say they have this ability. This study could be readily performed in Shirley; however, it requires the cooperation of the energy company.

Suggested Test 1

Consider the two houses in Shirley where there is no audible sound; the R-1 house and the R-3 house. The residents of the houses, and others, who would be subjects, would arrive at the house with the wind turbines off. The test itself would likely take 0.5 to 2.5 hours to perform.

Sometime during the first 2 hours, the wind turbines(s) that had been designated by the residents as the turbines they could detect, might or might not be turned on. It would be the residents' task to sense this "turn on" within some reasonable time designated by the residents — say 10 or 30 minutes. Correct responses, "hits," would be correctly sensing the turbines being turned on, or sensing no change if they were not turned on. Incorrect responses, "misses," would be failure to sense a turn on when the turbines were turned on, or "false alarms" would be sensing a turn on when the turbines were not turned on. Similar tests could not necessarily be done starting with the turbines initially on because the subjects, when sensitized, find it more difficult to sense a turn off. More information about this test can be found in Schomer *et al.,* 2015.

Possible Overlooked Audible Path. This pathway is predicated on several key facts described below. The main hypothesis is that the electric power being generated changes the acoustic signal without changing the A-weighted level. If the electric power correlates better than A-weighted level to subject response, then this would indicate that the electric power being generated controls some aspect of the sound that the subjects are sensing. This is important for two reasons:

- The subjects are incapable of having detailed knowledge of the electric power.
- If this is all true, it is something that is potentially correctable.

Facts:

Discussion with Geoff Leventhall. At one point when I suggested to Leventhall that 30 and 40 years ago, the reported effects were very similar to today's reported effects and that we had much the same problem, he remarked that the sound at that time period was low-frequency audible sound at around 40-50 Hz. The problems with infrasound and low-frequency noise that occurred 30 and 40 years ago is that they produce the same symptoms as today, but were for frequencies in the 40-50 Hz range — not infrasound.

Steven Cooper. Cooper finds and reports in his Cape Bridge Water Study that the subject's response correlated better to the electric power being generated, to turbine operations hovering around cut in speed, and to large changes in the electric power being generated rather than to the acoustic signal.

Bruce Walker. "I did a lot of work with Hansen's cleanest data set. When the extremely narrow band spectrum was plotted on a linear frequency scale, it conformed pretty well to sin(x)/x envelope with lobes at ZF, 30 and 45 Hz (more or less) and lines every blade-passing frequency. The lines in the 45 Hz lobe would combine into a wave packet that exceeded the audible threshold briefly once every blade pass. Walker added, "One thing I've observed with modern 100-meter rotors is that when producing power, the blades deflect axially to pass pretty close to the tower near the tip, into a region where the upstream flow deficit could be significant, though not separated as in downwind designs. Overly aggressive pitch programming could cause periodic brief stalls that might produce the requisite steep edge on the pulses."

Discussions at the ASA meeting in Salt Lake City. Discussions at the meeting made it clear that the frequency may not be limited to 45 Hz but may be based on the manufacturer and the specifics of the blades. It was also suggested that these frequencies might interact with chest cavity resonances. Rainford and Gradwell (2012) find, using their procedure outlined in Rainford (2006) that the typical chest cavity has a resonance at about 50 Hz. This does not seem to be a factor, since Leventhall reports that below 80 dBA, at 50 Hz there is no chest cavity response.

George Hessler. The measurements at Shirely show a relatively constant noise being generated during the day and time of the R2 measurements. However, the measured acoustic level was 1.5 dB below the expected level for full power with a Nordex N-100/2500 wind turbine, the turbine used at Shirley. Nordex literature reports that the acoustic output of the N-100/2500 is a constant for wind speeds measured at a height of 10 meters. At a wind speed of 4 m/s, the Nordex sound level is down about 1.0 dB from the maximum. Wind turbine noise vs. wind speed plots are unusual. As the wind speed increases from 0, it reaches a speed where the rotors of the turbine can start to turn. From this point, the noise from the turbine begins and goes up rather rapidly with increasing wind speed until it reaches a transition plateau where the sound level no longer increases with wind speed. However, the power generated by a wind turbine goes up much more gradually in power as a function of wind speed and only reaches its maximum several meters per second above the acoustic limit. The result is that for a very small change in sound level generated by the wind turbine, there can be a very large change in the electric power generated. This is true for the Nordex N-100/2500. Table 1 is compiled from Nordex literature and gives the relationship shown between acoustic power emitted and electrical power generated as a function of wind speed.

Geoff Leventhall. Leventhall reports that the highest reaction to low-frequency sound occurs in the 40 to 50 Hz range. However, his data (Figure 4) show almost equal responses in the 30 to 40 Hz range and the 70-80 and 80-90 Hz ranges.

Shirley Report. The Shirley report shows levels of 25-30 dB in the 40-50 Hz range, and it shows room resonances and possibly some wall resonances. Room resonances are in the 35-100 Hz range. Wall resonances are typically in the 10-30 Hz range.

Table 1. Electric power (kW) and acoustic A-weighted power level (dB)
both as functions of WS (m/s).

Figure 4. Unacceptability ratings for group of "specials" to noise stimuli.

Threshold of Hearing. The pulses, roughly one per second, that result from the blades passing the support tower, appear to have about a 10% duty cycle and would drop the threshold of audibility by about 8 to 10 dB. Figure 1 shows threshold of audibility based on several sources along with the lowest and highest levels of audibility at a given frequency. These levels are for continuous sinusoidal signals. With a 10% duty cycle, the thresholds go down by about 9 dB. For the most sensitive subjects, this indicates a threshold of hearing of about 31 dB at 50 Hz to 35 dB at 40 Hz.

Bruce Walker. Bruce Walker's findings that the tone at 45 Hz was above the threshold of hearing stands in support of the theory that low-frequency audible sound exists in the vicinity of wind turbines and could be the source of problems. There is a possibility that these offensive signals can only be found using narrow-band analysis as Walker used. Constant bandwidth filters may be too broad.

Steven Cooper. It is somewhat amazing that Cooper's findings fit this situation so well. He found that the peoples' responses correlated to large changes in electric power, turbine operations hovering around a cut in speed, and the absolute level of the electric power being generated better than to the acoustic level. Table 1 supports Cooper's findings. The electric power changes gradually until full power is reached; the acoustic signature rises quickly and then becomes a constant. Please note that the subjects could know when the turbine was on or off, but the data in Table 1 clearly shows that there is no way to know what percent of the maximum electric power is being generated from any data available to the subjects. So the fact that the subjects' responses correlated with the electric power, which is something the subjects could have no way of knowing, lends strong support to Cooper's findings. The acoustic data during "large" transitions in percent of full electric power should be analyzed, since it could be a potential source of problems.

The Energy Company. Clearly, it would be nice to have trustworthy confirmation of this analysis. To date, the power company at Shirley has not given any clear data on the actual power generated (or any other physical parameters, such as blade rpm, wind speed, or direction) for any time during our measurements. So we are limited to the indirect analysis of estimating a large change on the basis of a 1 dB acoustic change.

This all suggests that the Shirley signals would be slightly too low to trigger this chain of reactions. There are at least two possibilities. One possibility is that there are other undiscovered mechanisms and pathways. Another possibility is that the acoustic level is higher than we measured, because we measured on a quieter day. We do not know, because we do not have the physical parameters. Bruce Walker suggests that sufficiently high levels exist at some wind farms. Hessler's relatively constant measured data suggests we are not at a low power. So it seems this is another conundrum, but again this is a needless problem that the power company could sort out.

Analysis and Hypothesis Development

Point 1: Suggests looking for something in the 40-50 Hz range as our possible "culprit."

Point 2: Suggests that the electric power being generated is a very important parameter to a person's response. As Table 1 shows, the acoustic output is more or less constant over a wide range of wind speeds, but the electrical power being generated is changing with wind speed. It is true that the subjects in Cooper's study could have known when the sound, hence the wind farms, were turning on and off, but they would have no way of knowing the electric power from the acoustical signal. This lends strong support to Cooper's results.

Point 3: Suggests that there is a source of low-frequency audible sound that is produced each time a blade passes the support tower (or the low point of each blade during each revolution). The wind turbine blades flex so that the blade tips come closer to the support tower (the flex increases) as the electric power being generated increases. The reverse occurs as the power being generated decreases; the flex decreases and the minimum distance between the support pole and the blade tip increases. So, this particular sound increases and decreases in step with changes in the electric power being generated.

The physical mechanism that is at work here is the same as a stick or pole placed in a river. The pole represents an object that can disrupt the regular flow. There is a big wake downstream as everybody knows, but if one examines the situation a little more closely, you realize that there has to be pressure reflected upstream off this pole in the river, and that causes some disturbance upstream. The closer one is to the pole, the stronger the upstream reflection effect is. Much the same is happening with the wind turbine. As the blade gets closer to the support tower, it gets into more of this upstream disturbance.

In summary, there is a sound source that produces low-frequency pulses at the blade passage frequency, and the sound level of the source goes up and down in accordance with the amount of electric power being generated. The facts in this analysis indicate that this should be studied further, since this may be an important factor in the community response — both annoyance and other physiological effects. Moreover, the fact that this *sound* source can be controlled by the operator, to some degree, gives some promise to our ability to mitigate or eliminate this problem.

The hypothesis is that there is a frequency that will be characteristic of a specific blade and manufacturer that based on the discussion at ASA appears to be in the 25-60 Hz range. This tone modulated at 1 Hz causes a reaction in at least some people. This potential phenomenon should be able to be tested in a variety of ways, most of them quickly and inexpensively.

Suggested Test 1

Diary Test. Using a diary study, one could ask respondents to keep the following information:

- When they are at home and awake.
- The times when they feel a sensation caused by the wind turbines.
- If so, how strong is the sensation?

This information could be related with electric power generated and other physical parameters.

Suggested Test 2

Response Comparison. There are certainly some data that can be examined that were gathered in conjunction with peoples' responses. Hopefully, the Cooper data will show if specific tones in this region are present, how strong they are, and how they compare with the peoples' responses.

General Tests

The two following tests are more general and would aid in understanding the phenomenon we are dealing with.

Direct Human Testing. Direct human testing could be done in laboratory and field settings but, as has been testified to, there may be a period of time for the symptoms to incubate. A good start on this is underway at the University of Minnesota.

Direct Animal Testing. A cat or guinea pig's ear could be used to test for reaction to wind turbine noise. Monitoring could be done on the nerve that emanates from the otolith and from the nerves emanating from the cochlea as a function of wind turbine sound amplitude both above and below the threshold of hearing.

Opinions and Recommendations of Bruce Walker

Modern large wind turbines produce pressure fluctuations as the result of a variety of mechanisms. The time scales of these fluctuations range from minutes to milliseconds (conversely the frequency scales range from millihertz to kilohertz). Two aspects of wind turbine noise that have received significant attention over the past decade are amplitude-modulated broadband noise and quasi-periodic "thumps" generated by interaction between rotor blades and support towers. The focus of this review is the latter, which is most commonly identified as wind turbine infrasound (WTIS). In modern turbines, the time scale of this disturbance is on the order 1 second. However, the details of the individual disturbance events appear to hold the key to whether or not WTIS results in human response.

Modeling

There has been a temptation to model WTIS using the same techniques as for modeling audible sound: summation of spectral sound pressure squared from multiple point sources. At Wind Turbine Noise 2011,[5] the modeling issue was addressed by observation that the waveforms of WTIS were likely to be deterministic and therefore add coherently, so that the more correct modeling would be summation of time-domain sound pressures and subsequent computation of peak and average sound pressure levels.

For multiple turbine installations, this would produce a wide range of potential outcomes, depending on the relative synchronization of the turbines. Figure 5 shows a hypothetical result for five turbines turning at random speeds over a narrow range. For a few minutes over a six-hour simulation period, peak levels over 10 dB above the SPL predicted from pressure-squared summing were encountered. Receptors exposed to this momentary period of enhanced pulsation levels could be highly annoyed or awakened by it, while enforcement personnel might measure for hours and never witness it.

Figure 5. (a) Computed variations in SPL from a five-turbine array with unequal rotation rates relative to incoherent result; (b) expansion of largest peak.

Measurement

There has been a temptation to measure WTIS using the same techniques as for measuring audible sound: time-averaged weighted levels and power spectra. Typical field measurement results are similar to those shown in Figure 6 acquired a few hundred meters from a 2-3 MW range turbine. Spectral peaks are seen at several multiples of the 0.75-Hz blade-passing frequency. The sound pressure levels at each of these peaks is far below the generally accepted sensation threshold.

However, the putative blade/tower interaction genesis of the WTIS would suggest that the actual acoustic signal would be a sequence of relatively narrow pulses. Further, the unsteadiness of rotation speed would cause higher harmonic content of the signal to migrate among conventional PSD analysis bins and appear as broadband noise.

Figure 6. Example of field measurement data.

Figure 7. Example ensemble average waveform and time derivative with wind direction 140° re mic orientation.

Figure 8. Example ensemble average waveform and time derivative with wind direction 60° re mic orientation.

Figure 9. Shaft-order spectrum for wave shown in Figure 8.

Figure 10. Loudspeakers for WTIS synthesis in 43 m^3 *test room.*

At Low Frequency Noise 2012,[8] Wind Turbine Noise 2013[7] and ASA 2014,[8] methods were described for capturing the wave form emitted by large wind turbines by synchronous sampling and ensemble averaging several-minute recorded samples from a three- and four-microphone array. These measurements confirmed that the emitted infrasound was confined to less than 10% of the blade-pass period, as shown in Figure *7* . One set of measurements suggested that the phase of the BPF signal component depended on azimuth, as shown in Figure 8. The algorithms used to simulate synchronous sampling left too much residual jitter to retain time resolution better than approximately 50 ms.

Synthesis

An electro-acoustic system was assembled starting in 2012 to synthesize periodic signals with fundamental frequency 0.8 Hz and up to 65 harmonics in a residential bedroom. A photo of the system is shown in Figure 10, and a schematic of the test facility is shown in Figure 11. Three 18-inch "woofers" are driven by a DC-coupled, 300-

watt amplifier, excited by Fourier-synthesized waves from 16-bit, D-to-A converters. A second loudspeaker can provide synchronized amplitude-modulated, Dopplerized, audible sound if desired. An infrasound microphone is suspended above the evaluator's head. The system was described in detail at Wind Turbine Noise, 2015.[9]

Spectra corresponding to variations on that shown in Figure 12 were presented to a variety of volunteers at levels extending to approximately 15 dB above those reported from field measurements. Harmonic phases were adjusted to maximize or minimize signal crest factor and signal peak slope. If the upper limit of spectral content was 20 Hz or below, no evaluator reported any sensation. With the upper limit extended to 32 Hz and the level above 20 Hz spectrally uniform, one evaluator reported significant unease after a few minutes exposure. Subsequently, this evaluator reported unease when exposed only to amplitude-modulated audible sound.

In 2014, Hansen *et* ai.,[19] obtained field measurement data that displayed periodic spectral detail that extended to above 50 Hz, as shown in Figure 13. At ASA 2014 and Wind Turbine Noise 2015, Palmer[11] showed correlations of resident response to nearby operations of turbines that depended on resident positions inside rooms. This suggested the possibility that the residents were affected by sound of frequency high enough to excite room resonances, typically 30-40 Hz and above.

The Hansen data were analyzed extensively and results presented in Wind Turbine Noise 2015.[12] All spectral lines were separated by the turbine BPF, but in some ranges, the actual frequencies were not exact multiples of BPF. The mechanism for generating such a spectrum could be brief bursts of mechanical resonance once per blade pass or the effect of multiple turbines at slightly different speeds. The spectra were forced into a harmonic series and synthesized for evaluation. Because the reported power spectra lacked phase information, all harmonics were assumed to be at zero phase simultaneously.

Figure 11. Layout of WTIS evaluation test room.

Figure 12. Generic WTIS spectrum used for initial evaluations.

Figure 13. Outdoor (a) and indoor (b) spectra of WTN measured by Hansen.

Response

Threshold, annoyance and sleep interference were informally investigated using the full Hansen spectrum, then with high-pass filtering at 20 and 30 Hz and finally with low-pass filtering at 20 Hz. In summary, high-pass filtering had no effect on any parameter, and low-pass filtering resulted in no response, even with 10 dB exaggerated levels.

The results of these informal tests were presented at Wind Turbine Noise 2015, with admonition that they represent small samples and relatively brief (10 minutes to 2 hours) exposure. It was recommended that more extensive similar investigations be undertaken.

Follow-Up

During Wind Turbine Noise 2015, and discussions with coauthors, it appeared that the Hansen spectrum could be approximated by a uniform BPF harmonic series, weighted by a sin (nf/18)/ (xf/18) shape function.

The resulting waves and spectra are shown in Figures 14-16. Figure 16 demonstrates that once each blade-pass period, the signal harmonics from the third spectrum lobe may constructively combine, producing a periodic "thud" that at levels just slightly above hearing threshold, produces an illusion of infrasound that is devoid of actual infrasonic energy. Note that near 45 Hz, the maximum SPL is 13 dB above L_{ew} so a measured spectral "hump" that appeared to be well below threshold could easily produce audible "thumps" that would be mistaken for infrasound. The time between the negative and positive peaks in the full-spectrum wave is 0.055 seconds, in which time the rotor blade tip would travel 4.6 meters at 84 mps tip speed. This seems reasonable for the approximate width of the support tower or its bow wake, supporting blade/tower interaction as a genesis mechanism.

An observation from the idealized spectrum shown in Figure 14 is that the phases of the components in the second lobe would be reversed relative to the first and third lobes. This detail was not followed in perception testing. In Figure 15, the effect of the phase reversal on the composite waveform is displayed. The crest factor and wave "sharpness" are clearly increased with the second lobe phase properly reversed. When reproduced at 10x frequency on loudspeakers, the properly phase-reversed signal is distinctly more impulsive sounding. The effect on perception at full-scale frequency is currently being explored.

Figure 14. Spectrum of sin(x)/x-weighted BPF harmonics.

Figure 15, Waveform of spectrum shown in Figure 14.

Figure 16. Wave-packet representation of third-spectrum lobe components.

Summary and Collective Recommendations

Disclaimer. The preceding sections are the sole and exclusive work of each author. There has been no attempt at editing or reaching agreement among authors.

Areas Identified for Needed Practical Research

Simulation. Walker has demonstrated that wind turbine infrasound and pulsed LFN, which may be upper harmonics of the Infrasound pulsations, can be mathematically defined, duplicated and simulated with loudspeakers for subject evaluator testing. A more formal and expanded set-up, perhaps at a university using student volunteers exposed to both low and high levels could establish the threshold of perception for both steady and pulsed LFN for the particular and unique source of environmental noise from wind turbines. Studies in this area are progressing in Australia.

Survey of Wind Turbine Projects Participating Residents. Landowners who lease their land for wind turbine installations may experience sound levels well in excess of proposed limits for normal siting practices and experience higher levels than nonparticipating neighbors. There should be an absolute wealth of information to be learned from these residents collected by a well-designed national survey. Such a survey must have the complete cooperation and possible sponsorship from the industries' national representative, AWEA (American Wind Energy Association) in America and others throughout the world. The authors would like to suggest questions to any study team.

Noise Source Reduction. The designers and suppliers of wind turbines must make a continued and concerted effort to reduce noise emissions from their turbine designs. Reductions can be accomplished by a combination of blade design and operational software. A universal design goal based on measurable established standards (IEC-61400) for sound power level would encourage these efforts.

Perception Testing. Schomer suggests pathways that could support some test findings in America and Australia that suggest from statistical correlation that some residents could perceive wind turbine operation and/or operational changes without benefit of sight or audibility. A detailed discussion is offered on practical perception testing that could discover something unknown to us at this time and is highly recommended for implementation.

Discussion and Collective Conclusion

None of these opinions and recommendations answers the posed question: does ILFN from wind turbines make people sick? It is abundantly obvious that intense adverse response occurs at certain sites. Realistically, it is not even possible to answer the posed question to all parties' satisfaction with practical research. For examples, a direct link to adverse health effects from yesterday's tobacco and today's excess sugar can be denied forever, because any research that could actually prove a link to all parties would take longer than forever and would be totally impractical. The wind farm industry must accept that there are enough worldwide sites that emit excessive wind turbine noise resulting in severe adverse community response to adopt and adhere to a reasonable sound level limit policy. Likewise, wind farm opponents must accept reasonable sound limits or buffer distance to the nearest turbine —not pie-in-the-sky limits to destroy the industry.

The A-weighted sound level is commonly used for assessing noise from wind farms as well as most all other large power generation facilities. Each author has been recommending the following limits for wind farm noise emissions for years: Hessler[13] — 40 dBA design goal, 45 dBA max limit; Leventhall — 40 dBA; Schomer 35-39 dBA; and Walker — 45 dBA in high ambient areas but lower in lower area ambient locales. The authors have generally found that wind farms designed to a level of 40 dBA or a bit lower at nonparticipating residential receptors have an acceptable community response. Surveys at wind farm sites for a decade have consistently shown good statistical correlation between wind farm noise level emissions and the percentage of highly annoyed residential receptors (% HA).

The question arises if an A-weighted criterion alone is adequate to protect receptors from infrasound (IS), LFN and pulsed LFN shown to be present in large wind turbines. Figure 17 plots the measured spectrum from a typical, nominal, 3-MW wind turbine plus the most commonly used overall levels. Infrasound (IS), the highest overall level, is calculated by summing the bands 1-16 Hz (0.7-22. Hz) and LFN by summing the bands 31.5-125 Hz for a frequency band of 22-177 Hz. Note that the overall C-weighted level and LFN levels are quite close together. Notice also that C-weighting filters out IS and would not be a good metric for assessing wind turbine IS but would be excellent for assessing LFN from wind turbines.

Figure 17. Typical spectrum from a *large, modern„ 3-MW wind turbine.*

Figure 18. Calculated Lp spectra as function of distance.

Figure 19. Overall levels as function of distance.

Table 2. Maximum allowable C-weighted sound level, LCeq, at residential areas to minimize infrasound noise and vibration problems.

Table 3. Criteria for assessment of LFN

Hessler[14] and Broner[15] have recommended C-weighting limits for low-frequency industrial sources based principally on extensive experience with open-cycle combustion turbines. Both have concluded independently that a level of 60 dBC is a desirable criterion to minimize adverse response from neighboring communities as shown in Table 2[14] and Table 3.[15] the C-weighted level from wind turbines will always be comfortably below 60 dBC when emitting 40 dBA or less.

Figure 18 illustrates the computed pressure spectra from 250 m (820 feet) to 64,000 m (40 miles). The calculation uses ISO-9613 algorithms for hemispherical divergence, air absorption and ground effects assuming a 100-m hub height. Note that 3 dB/doubling distance in lieu of 6 dB is used for IS beyond 1 km as measured in the recent extensive Health Canada study. The reason for doing this calculation is to determine the overall levels with distance that is shown in Figure 19.

Looking at the octave-band spectra, it is apparent that the indicator of a potential low-frequency noise problem, C-A level, should increase with distance, since the A-weighting level is reduced by excess attenuation while low frequency noise is not. The result is 11 increasing to 24 d13 if the ambient is not considered in the calculation. However, when a macro residual ambient of 25 dBA is assumed, the quantity starts at 11 dB and actually decreases to zero, as shown on Figure 19. This classic indicator of a potential low-frequency problem when C-A reaches 15 to 20 dBC will not occur when assessing LFN at wind turbine sites.

Collective Conclusions

Our analysis illustrates that a wind turbine is not a classic LFN source; that is, one with excessive low-frequency spectral content. But a wind turbine is a unique power-generating source with spectral content down to the 1-Hz octave band, emitting measurable IS in addition to LFN. Infrasound (IS, 0-20 Hz) from wind turbines can almost be ruled out as a potential mechanism for stimulating motion sickness symptoms. But to be thorough and complete, we recommend that one or two relatively simple and relatively inexpensive studies be conducted to be sure no infrasound pathways to the brain exist other than through the cochlea. Pending the results of these studies, we feel that no other IS or LFN criteria are required beyond an acceptable A-weighted level.

References

1. What You Need to Know About Seasickness or Motion Sickness, Cleveland Clinic, http://rny.clevelandclinic.org/
2. Graphic, Noise and Health, Bimonthly Interdisciplinary Journal, June 2004.
3. "A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin," Report Number 122412-1, Appendix B, PSC REF#: 178263, Dec 24, 2012.
4. Project EARS, "Assessment and Safety of Non- Audible Sound," Table 2, Communique 2015.

5. Walker, B. "Coherence Issues in Wind Turbine Noise Assessment," Fourth International Meeting on Wind Turbine Noise, Rome, Italy, April 2011.
6. Walker, B. "Time Domain Analysis of Low-Frequency Wind Turbine Noise," 15th International Meeting on Low Frequency Noise and its Control, Stratford Upon Avon, UK, May 2012.
7. Walker, B. "Infrasound Measurement, Interpretation and Misinterpretation," 5th International Meeting on Wind Turbine Noise, Denver, CO, August 2013.
8. Walker, B., Celano, J., "Measurement and Synthesis of Wind Turbine Infrasound," ASA Indianapolis, IN, 2014.
9. Walker, B., Celano J., "Progress Report on Synthesis of Wind Turbine Noise and Infrasound," 6th International Meeting on Wind Turbine Noise, Glasgow, Scotland, April 2015.
10. Hansen, K., Zajamsek, B, Hansen, C. "Identification of Low Frequency Wind Turbine Noise Using Secondary Wind Screens of Various Geometries," *NCEJ* 62(2), March-April 2014.
11. Palmer, W. "Wind Turbine Annoyance — A Clue from Acoustic Room Modes," *JASA* 136, 2204, 2014.
12. Hansen, K., Walker, B., Zajamsek, B., Hansen, C., "Perception and Annoyance of Low Frequency Noise Versus Infrasound in the Context of Wind Turbine Noise," 6th International Meeting on Wind Turbine Noise, Glasgow, Scotland, April 2015.