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Noise

Session 3aNSa: Wind Turbine Noise I

3aNSa3. Criteria for wind-turbine noise immissions

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Each of the two authors has developed single, 24-hour, constant wind turbine noise criteria; the criteria are constants because wind turbine noise is basically not adjustable. Hessler develops his criteria from his knowledge of how wind turbine noise is being regulated at the local, state, and national levels, from regulations in other countries, and from his extensive experience with numerous wind turbine projects. Schomer develops his recommended criteria on the basis of existing national and international standards, notably ISO 1996-1 and ANSI/ASA S12.9 parts 4 and 5. Ultimately, Hessler comes up with a single, 24-hour A-weighted average criterion of 40 dB, and Schomer comes up with a 24-hour, A-weighted average criterion of 39 dB. These two researchers have decidedly different backgrounds, different experience, and a slight difference in orientation towards the industry. Thus, it is remarkable that these two criteria, derived in such different ways result in nearly identical 24-hour A-weighted criteria levels. Although there is essential agreement in immissions criterion, there are variables debated herein for both modeling wind turbine emissions and certifying such emissions at far-off receptors that could result in a 10 dBA difference in the actual immissions level.

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INTRODUCTION

Criteria for wind-turbine noise immissions should address all aspects of the receiving pressure level including magnitude and character. For wind-turbines this should include at least the overall A-weighted level related to annoyance, possible spectrum imbalance, infrasound/low frequency noise (LFN), tonal issues, and any other unusual character issues such as occasional "thumping." Space limitations and the current extent of scientific knowledge of this subject do not allow for a full discussion in this paper, although each aspect will be touched on. The main focus is criteria to minimize annoyance from wind-turbine immissions.

Hessler Associates, Inc. has worked on over 70 wind-turbine projects over the last decade and has published a peer-reviewed journal paper recommending a design goal of 40 dBA or less at residences coupled with a maximum legal criterion of 45 dBA, all based mostly on observations and experience.¹ Schomer and Associates, Inc. is a recognized world-wide expert in community noise and also has worked on numerous wind-turbine projects--about equally for project developers and anti-project advocacy groups. Schomer, using a wholly different approach than Hessler, recommends a design goal of 39 dBA at residences to minimize annoyance.

This paper presents measured data of a typical wind farm in the American Midwest, provided by Hessler and a discussion of those data and some data analyzed along with a discussion by Schomer of some Western data, both insofar as they pertain to aspects of immissions criteria.

The purpose of this paper is to compare and contrast the views of the two authors. Note in the sections that follow, the material of a particular author represents the views of that author, and not necessarily the views of both authors. However, the conclusions do reflect the views of both authors.

TYPICAL WIND FARM IMMISSION SPECTRA AND LEVELS – HESSLER

Figure 1 presents data from a very typical wind farm composed of (90) 1.8 MW wind-turbines dispersed over approximately 88 sq km (34 sq miles) of flat farmland with nearly 500 residences. The rotor diameter and hub height are 90 m and 80 m, respectively. The data presented are from a rigorous certification measurement survey where sound levels and spectra were measured over three periods during midday (12 pm – 2 pm), evening (6 pm – 8 pm) and night (10 pm – 12 am).

The project layout was designed by the owner using a minimum buffer distance of 381m (1250 feet) from the closest turbine to any residence. Measurements were made at four "worst case" locations that were miles apart but had both the closest and the largest number of turbines adjacent to a residence.

Measurements were performed with an off-the-shelf type 1 precision sound level meter with its frequency range extended down to the 0.4 Hz one-third octave-band, although the rated frequency response of the microphone is ± 1 dB from 5 Hz to 20,000 Hz. A separate test comparing this off-the-shelf system side-by-side to a custom designed system with a proven accuracy of ± 1 dB from 0.1 Hz to 20,000 Hz demonstrated that the off-the-shelf sound level meter system measured accurately down to the 2 Hz one-third octave-band--better than the manufacturer's published rating. Levels below 2 Hz in Figure 1 show microphone roll-off.

Measuring low-frequency sound in the presence of wind at a height of 1 to 1.5 m above grade is problematic as will be shown. The microphone was protected with a 175 mm (7 inch) diameter foam windscreen with 20 ppi porosity to minimize pseudo noise and wind-generated pulsations.

The owner was quite cooperative, and measurements were made for 10-minute periods with all turbines operating followed by the same measurements with all contributing turbines shut down to obtain ON/OFF measurements. The plotted data are the arithmetic average of the median spectra and L50 during the twelve ON and twelve OFF 10-minute periods. Three measurement periods at each of four residences yielded twelve ON/OFF results.

Wind conditions varied, but the average wind speed at the 80 m hub height was 9 m/s (7.5 to 11.6 m/s range), and at the 1 m microphone height, the average wind speed was 2.9 m/s (1.7 to 4.4 m/s range).

The measured A-weighted levels shown on Figure 1 are 43.6 and 39.3 dBA, ON and OFF, respectively. Applying the standard background correction calculation yields an average noise immission from the turbines of 42 dBA.

Community Response to this Wind Farm

The community response to the example wind farm noise that encompasses 489 non-participating residences and 42 participating residences (residents leasing land for wind turbine installation) can be described as minimal adverse response with no claims of health issues. To our knowledge, there are continued complaints from two residences that opposed the project from the beginning, but no other complaints in four years of operation (2009 through 2012). It is not known how many residents, if any, would give a negative response in an area-wide survey or questionnaire, but we can certainly conclude that the percentage of highly annoyed residents is not large.

ANALYSIS AND CONCLUSIONS FROM DATA – HESSLER

A-weighted Criteria

The resulting community response to this wind farm and many others like it leads us to reaffirm our 40 dBA design goal and 45 dBA criteria recommendations given in Hessler and Hessler (2011). When developers are able to lay out the project with our modeling assistance, i.e. space permitting, experience at every such site is no adverse response. When space is more restrictive, a number of residents will experience higher levels than 40 dBA, but none higher than 45 dBA. Since criteria must be met, contingency or safety factors are often applied with the result that the actual immissions level falls between 40 and 45 dBA. The example data set above had an average of 42 dBA at the closest turbine to receptor locations. Hessler believes this is exactly the result desired—a reasonable balance between protecting the acoustic environment weighed against an environmentally friendly source of power generation.

We should point out that the example community is made up of quiet, rural farmland, and when winds are calm and still (i.e., when there is no wind at ear height and no visible movement or audibility of high elevation tree leaf and branch coverage) the residual LA90 drops to the low twenties usually in the early morning hours. Some anti-project consultants continue to erroneously assert that a 40-45 dBA sound imposed upon such an environment (a 20-25 dBA increase) creates a huge impact. As the following shows, this is not the case. It is recognized that wind shear and topography effects reduce ground level wind speed below hub height speed, but those factors never reduce wind speed to calm and still conditions.

Schomer has analyzed data for long-term measurements with repeated samples with turbines on and off over the past seven months. These data show that the *largest* difference in sound level between these two conditions is about 10 to 15 dB in a very quiet rural setting. This difference occurs mainly during the night and mainly during the summer and during these times the ground winds frequently have been observed to be less than 0.5 m/s. Although, winds at microphone height were less than 0.5 m/s, wind at hub height was sufficient for near or full power and yet the 10 to 15 dBA difference was maintained. For the example site, Figure 1, the largest delta between the twelve on and off measurements was 9 dBA.

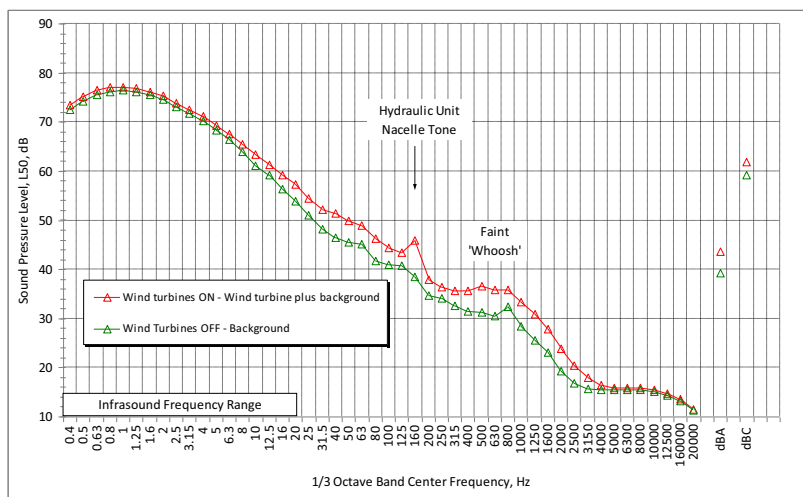


FIGURE 1. ON/OFF sound level spectra and overall levels averaged over three measurement periods each at four locations (12 ON/OFF data sets) at a typical American Midwest wind farm.

Tonal Character

The data in Figure 1 clearly shows a tone (unusual for wind turbine sites) in the 160 Hz band, and this tone is audible at the four measurement locations; more prominently at one than at the others. Our work over many years has given very good results using the definition of a “pure tone” as defined and calculated by the U.S. EPA method² to determine prominence by the increase between the tonal one-third octave-band compared to the average of the two adjacent one-third octave-bands. This simple method allows the presence of faint to moderate tones, but if prominence is exceeded, then the tone must be addressed and rectified. We recommend this expedient 1/3 octave band method for assessing tones in wind turbine emissions.

Infrasound and the LFN Issue

The ON/OFF measurements in Figure 1 show virtually no change in measured spectra at very low frequencies when measured using conventional techniques. Figure 2 contains the same data overlaid with measured spectra of estimated pseudo noise in various wind-speed bins. These estimates were collected in a quiet environment in the Mojave Desert with few man-made acoustic sources but at a site with lots of wind. The site is shown in Figure 3 where different windscreens have been tested as part of a volunteer ASA effort in support of a new standard.³

Clearly, at the sample site used for measuring the data shown in Figure 1, the very low frequency data, measured both with turbines ON and OFF, are influenced by microphone pseudo noise for the 175 mm windscreen above grade, and these data do *not* represent infrasound or LFN from the wind turbines. What we can deduce from the example site measurements is that whatever low-frequency noise there is that is attributable to the project, is very low in magnitude. The measured data, even with pseudo noise effects, are similar to what one finds in a remote desert specifically chosen to have no man-made sources, and certainly no infrasound.

Figure 4 below shows narrow band spectral measurements at three locations near a residence at a different wind turbine site. These measurements were made at a later date than the wind farm measurements described above, and these measurements use a better microphone wind screening system by placing the microphone on a ground plane covered with a hemispherical wind screen covered in turn with a turbulence screen. The blue and green lines in Figure 4 show the results for two measurement positions outside the residence. The difference between these two is their exposure to wind. The position represented by the blue line was exposed to moderately high wind whereas the position represented by the green line was sheltered from the wind. The smooth blue line exhibits the effects of wind even though these data were measured using the better microphone wind screening system. Note that the real outside tonal infrasonic wind turbine data, shown as a green curve, are 10 dB *below* the wind influenced measurement. The green line shows the wind-turbine blade passage frequency of at 0.7 Hz and harmonics at 1.4, 2.1, 2.8, 3.5 and 4.2 Hz, clearly identifying the source to be from the nearby wind turbines. Note that the very low frequency infrasound passes unimpeded through the house facade.

This discussion illustrates the difficulty of measuring wind turbine emissions or immissions in the presence of wind.

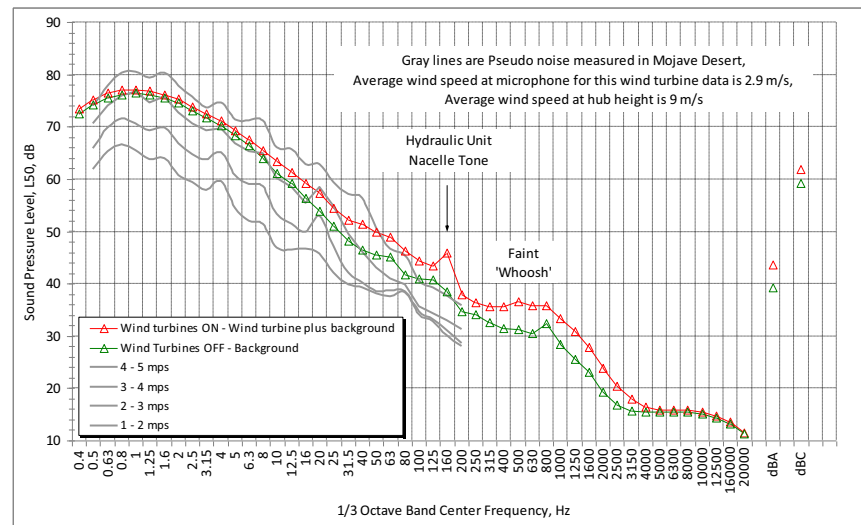


FIGURE 2. ON/OFF sound level spectra and overall levels compared to measured pseudo noise for 175 mm (7 in) wind screen.



FIGURE 3. Comparative windscreen test setup in the Mojave Desert.

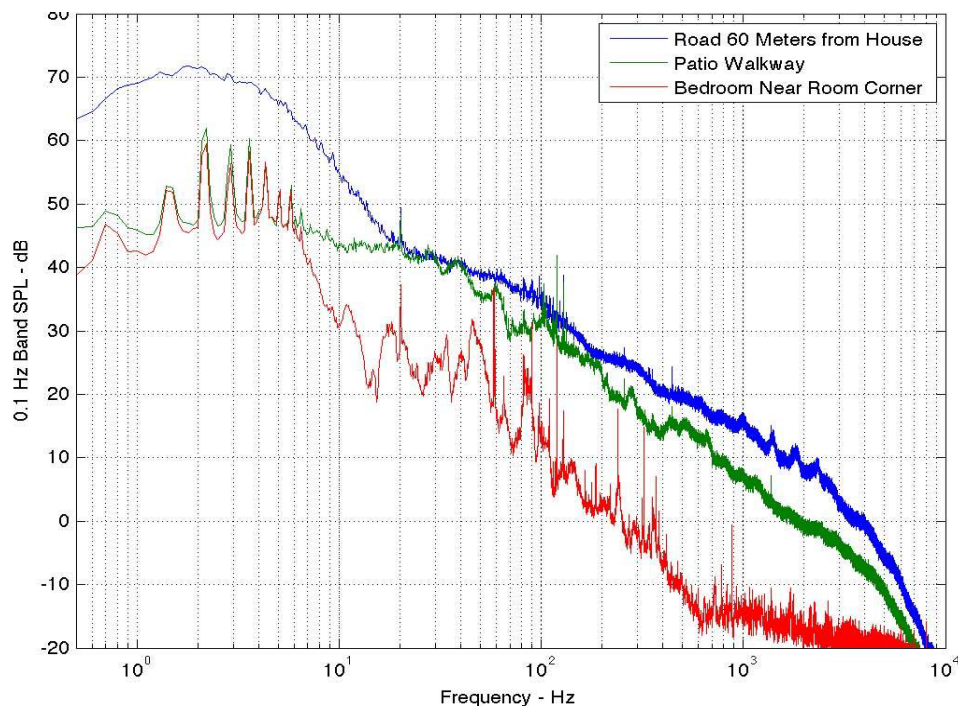


FIGURE 4. Measurement using advanced signal processing and ground plane microphones at three locations near a wind farm.

While the above and similar recently completed careful testing shows that infrasound from wind farms is present and detectable with proper instrumentation, the magnitude is extremely low. For both sample sites, we have shown that infrasound levels are lower than one can measure in the remote Mojave Desert, so it is hard to make a case for any adverse effects from this low-level noise. This result reaffirms our conclusions given 2 years ago at the Rome Wind Turbine Noise Conference.⁴ Conversely, the infrasound is tonal in nature, and that may have some influence on its potential effects on residents. The cadre of anti-project consultants claim catastrophic health effects due to infrasound and LFN but with little scientific support. Objective researchers have not established a well-defined causal relationship between turbine emissions and adverse subjective effects.

We can only conclude at this point in time (January 2013) that much more investigative study is required before the need for any low-frequency criteria, is established, and before any regulation on projects should be developed. Moreover, if any such regulations are developed, they will also need to surmount the difficulty of accurately measuring LFN outdoors as discussed above.

ANALYSIS AND CONCLUSIONS FROM DATA – SCHOMER

General

Schomer and Associates believes that three separate criterion are required to properly address the acoustic impact of wind farms: (1) the A-weighted day-night average sound level (DNL) to assess annoyance, (2) the WHO criterion to assess sleep disturbance, and (3) a methodology to assess adverse physiological effects.

Annoyance

The first of these, annoyance, is assessed quite well using the complete methods in ANSI/ASA S12.9 Part 4 and ISO 1996-1. Both of these standards contain and recommend the A-weighted day-night average sound level (DNL) (ISO 1996-1 also recommends day-evening-night average sound level [DENL]), and both include a 10 dB adjustment for a quiet rural setting. It is important to note that the 10 dB adjustment is not because the ambient is quieter in rural areas, but rather, it is there because of the greater expectations of peace and quiet in rural settings.^{5, 6} Thus, given the design goal of DNL = 55 dB in residential urban or suburban areas, the design goal in quiet rural areas is simply the 55 dB design goal minus the 10 dB adjustment for a DNL of 45 dB. Note that this derivation is not unique to wind farms; it would apply equally to many noise sources. A DNL of 45 dB can, of course, be realized in a variety of ways, two of which are: (1) an A-weighted level of 45 dB during daytime and a 35 dB A-weighted level during nighttime, or (2) a constant 39 dB during day and night (24 hours per day), which makes the most sense for wind farms.

A DNL of 45 dB should be viewed as a design goal much the same as is done for airports or highways.

That is, the project must be designed to meet or better the design goal everywhere, but at the same time it must be recognized that noise prediction and measurement uncertainties dictate that *sometimes* the predictions will be exceeded. The extent by which a prediction is exceeded is normally a function of the measurement duration and other factors. In my view this uncertainty should be limited to 1 to 2 dB. That is I view the design goal to be 39 dB with a very strong recommendation not to exceed the criterion of 40 dB, and an absolute recommendation not to exceed 41 dB. The design must justifiably be for 39 dB with a margin of safety.

In terms of wind-turbine sound propagation modeling, ISO 9613-2 is frequently used. The above 1dB uncertainty tolerance attached to the 39 dB goal is consistent with general noise prediction requirements in the EU, and the requirements for the proper use of ISO 9613-2. That is, a conservative, “downwind” prediction is typically required in the EU and definitely required for the proper use of ISO 9613-2. With the use of conservative predictions, the small tolerance of 1 to 2 dB should be sufficient to accommodate all but the most unusual sound propagation situations.

Sleep Disturbance

No noise metrics or criteria are known by this author by which to assess the effects of wind-turbine noise on sleep. However, from talking with and meeting with many who have testified that airport noise was awakening them revealed that typically, they awoke for natural reasons and then could not *go back to sleep* because of the noise. Also, once one spouse was awake, it was common for the other spouse to awaken. I see no reason to assume that effects differ between wind-turbines and airports or highways. That is, I do not expect a great deal of verifiable noise-induced awakenings except if and when there are concomitant health effects. So, as with other noise sources, the wind turbine noise generally should not present any sleep disturbance problems so long as the outdoor levels are lower than those recommended by WHO, i.e., maximum indoor nighttime-hour ALEQ of 30 dB. This should always permit a maximum outdoor nighttime ALEQ nearly always greater than 45 dB, but very occasionally between 40 and 45 dB.

Adverse Physiological Effects

Recently, measurements were made at a small wind farm in Shirley, Wisconsin. These measurements were made in the homes of three families who had abandoned their homes because they could not tolerate physiological results caused by the acoustic emissions of wind turbines. This same story is being played out in a seemingly random fashion around the world. Between Hessler Associates and Schomer and Associates, five wind farms are known to have reported problems similar to those at Shirley. Perhaps 1% of wind farms have reported problems like those at Shirley; the remaining 99% have not documented such problems, and the reasons that a small percentage

have these problems are not known. And within those wind farms that have these problems, only a small segment of the population is actually affected to the degree exhibited at Shirley, again on the order of perhaps 1% to 3% of households.

From the residents of Shirley we learned: (1) most residents did not hear the turbines; residents said they could sense when the turbine was on, (2) the effects did not vary with changes in the orientation of the turbines with respect to the homes, (3) the general symptoms of those affected adversely by the wind turbine emissions were virtually the same as symptoms for motion sickness, and (4) afflicted residents were prone to motion sickness.

This told us that (1) the resident had no noise annoyance because they did not hear any wind turbine noise, (2) the wavelength of the “sound” must be large—on the order of 100 m, and (3) there must be a mechanism by which this very low frequency infrasound can cause symptoms of motion sickness in people. To this end, we found a study developed by the Navy showing that linear accelerations at 0.7 Hz were moving well into the nauseogenic region, and that the frequency that induces motion sickness at the lowest acceleration is approximately 0.2 Hz.

The turbine model used in Shirley, the Nordex N-100, is among the largest ever installed in residential areas, and has a blade passage frequency of 0.7 Hz, and a corresponding rotor frequency of 0.23 Hz. The 0.7 Hz was evident in the measurements during times when the turbines were at full power, but not when the turbines were throttled back. The 0.23 Hz was only evident part of the time.

At this point we must note that after over 4000 years of study, no one knows exactly what causes motion sickness or why some people are more affected than others. In the following, we show only that it appears to be possible that an acoustic wave at 0.5 to 0.7 Hz can generate a similar signal in the brain as the signal generated by an acceleration at 0.5 Hz. We do not expect any time soon to be able to predict who will and who will not be affected by low-frequency wind turbine emissions or the mechanism by which they occur any more than we can predict who is affected by motion sickness and who is not, and the mechanism by which people are affected by motion sickness. What we can show is that it appears quite possible for the acoustic emissions from wind turbines to produce this effect in some people. The following discussion analyzes the linear motion sensing function of the ear, and explains how the ear could respond to wind turbine emissions.

In the ear, it is the otoliths that sense horizontal and vertical acceleration of the head, so the question then becomes: “what type of transducer is an otolith and is there a way that it can sense pressure emitted by the wind turbine in addition to its measuring acceleration?” The answer to this question requires research. A theory for how this is possible is in development. So, in this paper we are giving a brief sense of the theory and analysis. Figure 5 shows the ear. We are concerned primarily with the inner ear which is shown in blue in this figure. The inner ear includes the cochlea, which provides a spectral analysis of sound in the frequency range from roughly 10 Hz to 20 kHz. The inner ear also contains the vestibular system, which provides for balance by measuring angular acceleration in three axes using the semi-circular canals (SCC), and by measuring linear acceleration along three axes. In addition to measuring linear acceleration, the otoliths measure the tilt of the head with respect to gravity.

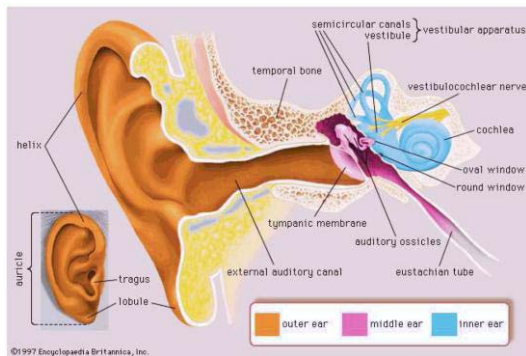


FIGURE 5. The three parts of the ear

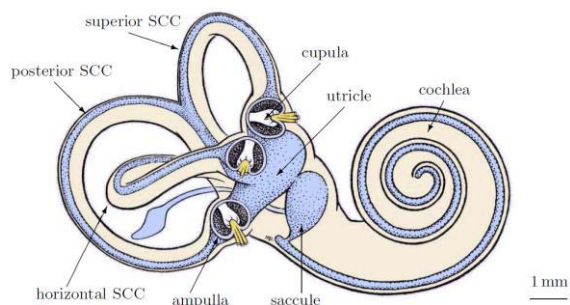


FIGURE 6. The inner ear

Figure 6 shows just the inner ear and includes the cochlea, the 3 SCCs, and the utricle and saccule, which are the two otoliths, one sensing horizontal acceleration, and one sensing vertical acceleration. These six inner ear organs open into the inner space of the inner ear termed the vestibule. The inner part of the inner ear is filled with endolymph fluid which has properties similar to water. A hard bone surrounds the inner ear and the only openings to the “outside” are two windows, the round window, which separates the air-filled middle ear from the endolymph fluid-filled inner ear by a thin membrane, and the oval window, which connects to the stapes, and also separates the inner ear from the middle ear by means of a thin membrane. Normally, the stapes bone causes motion in the endolymph fluid, and this pressure is relieved by the round window. However, at the low frequencies we are

considering here, the middle ear will not be functioning as it does in the audible range, but the slowly varying pressures at 0.7 Hz will enter the middle ear through the eustachian tube and be transferred to the endolymph fluid through the windows. Thus there is a plausible path for the infrasound pressures to reach the inner ear.

A model otolith is shown pictorially in Figure 7. The otoconial layer is a rather dense and reasonably hard outer layer of the otolith. It gets its density from embedded calcium carbonate crystals (otoconia). The otoconial layer creates an inertial force when accelerated owing to its mass. This force is transferred to the gel layer (cupular membrane) which then bends the hair cells causing them to transmit signals to the brain. So the fundamental measurement by the otolith is the inertial force of the otoconial layer; the otolith is measuring force. It remains to be determined exactly how pressure in the vestibule actually causes the hair cells to transmit a signal to the brain.

In summary, what is being said is that the wind-turbine acoustic wave at the very low blade passage frequency appears to have a possible pathway to the sensors in the inner ear, and that the otoliths fundamentally are sensing pressure. It is not yet clear how the pressure is transferred to otoliths so as to create shear forces in the cupular membrane. Possibly, this pathway to the inner ear and the pressure response of the otoliths can be demonstrated and validated in the laboratory by measuring signals to the brain in some surrogate animal. But the bottom line, which must be stressed, is that nobody knows what causes some people to get motion sickness, and what prevents most from getting motion sickness; likewise, we do not know why some people become sick from wind turbine emissions, and most others do not. What we do know is that in both cases, the sickness is real for those who are sensitive, and that the model presented here has potential for explaining how some are affected.

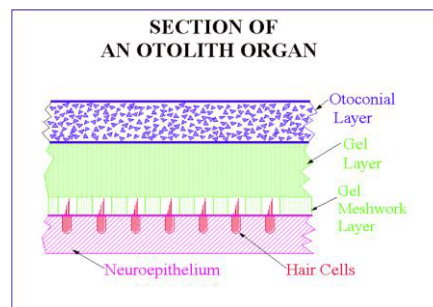


FIGURE 7. Section of a model otolith organ

CONCLUSIONS

1. The Hessler and the Schomer goals for the A-weighted wind farm levels are virtually identical at 40 and 39 dB, respectively. Hessler, based mainly on extensive observations of community response from installed wind farms, suggests 45 dBA as a criterion or legal limit, while Schomer believes the limit should be quite close to 39 dB. In conclusion, the authors agree within about 2 dB that no extensive adverse response in the form of voiced annoyance is expected at low wind turbine levels; per Hessler these levels are low forties, e.g. 42 dB, and per Schomer, these levels are very low forties, e.g. 40 dB, at the closest residences. The probability of complaints increases as the average level approaches 45 dBA.

2. The authors agree that sleep disturbance issues should not be a problem as long as the outdoor criterion is met.

3. The difference between quiet, rural A-weighted background levels and full power wind-turbine levels has been measured over seven months in a Western state and does not appear to be larger than 10 to 15dB so there is no basis for making the claim that wind-farms create a huge jump over the ambient.

4. Schomer shows that it appears possible for the acoustic emission of a wind turbine to create a sense of motion in the human brain, but this appears to be documented at about 1% or less of wind farms, and only a small percentage of households (1 to 3 %) appear to be affected. Research is clearly needed to understand why this small minority of wind farms exists, what makes them different, and what makes a small percentage of the population at these wind farms sensitive when most are not.

5. Hessler shows that it is very easy to make a completely incorrect measurement (on the high side) of infrasound unless great care is taken to protect the measuring system from pseudo noise effects.

6. Both Hessler and Schomer strongly agree and urge that research be undertaken for the explicit purpose of understanding the issues related to the very low-frequency acoustic emissions of wind turbines found to emit these very low frequencies including, but not limited to:

- (1) How are these acoustic emissions generated? Under what weather conditions? etc.

- (2) Are these emissions unique to the N-100 or are they more widespread? If widespread, then the knowledge gained on the generation of low-frequency acoustic emissions should be used as a starting point in the development of a revised IEC Standard for the measurement of wind turbine emissions.
- (3) What are the propagation characteristics of an acoustic wave in the two decades from 0.08 Hz to 8 Hz?
- (4) How does the very low-frequency sound affect people?
- (5) Why do some wind farms have health problems while most do not?
- (6) Why are some people affected while most, apparently, are not?
- (7) How can the health effects be mitigated or eliminated?
- (8) Are there feasible wind turbine design and/or layout changes that can ameliorate the situation?
- (9) Etc., etc., etc.

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