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Wind Turbine Noise

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A proposed theory to explain some adverse physiological effects of the infrasonic emissions at some wind farm sites

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Summary

For at least four decades there have been reports in scientific literature of people being made ill by low-frequency sound and infrasound. In the last several years there have been an increasing number of such reports with respect to wind turbines, which corresponds, obviously, to their becoming more prevalent. A

study in Shirley, WI has lead to interesting findings that include: (1) for major effects, it appears that the source must be at a very low frequency, about 0.8 Hz and below with maximum effects at about 0.2 Hz; (2) the largest, newest wind turbines are moving down in frequency into this range; (3) the symptoms of motion sickness and wind turbine acoustic emissions "sickness" are very similar; (4) and it appears that the same organs in the inner ear, the otoliths may be central to both conditions. Given that the same organs may produce the same symptoms, one explanation is that the wind turbine acoustic emissions may, in fact, induce motion sickness in those prone to this affliction. Finally, It is shown that the probability that sensitivity to motion sickness and sensitivity to wind turbine acoustic emissions are unrelated is less than 2 in 1,000,000.

1. Introduction

For at least four decades there have been reports in the scientific literature of people being made ill by low-frequency sound and infrasound. (Dawson 1982; Tesarz 1997)

Currently, these same problems are appearing in the vicinity of wind farms, and as in 1982 and earlier, nobody understands how these problems come to be; nobody understands why only a fraction of the population is affected; ***nobody understands how the sound can be below the threshold of hearing and be affecting people***.[i]

2. Data from a problem site

2.1 Observations from people affected by the installation of wind turbines

One wind farm that is experiencing these problems is in Shirley, WI. Here three families have abandoned their homes because family members who became ill after installation of the turbines could not acclimate to the problems.[ii] Because of these problems in Shirley, a study was conducted with the proposed test plan calling for the wind farm owner, Duke Energy, to cooperate fully in supplying operational data and by turning off the units for short intervals so the true ON/OFF impact of turbine emissions could be documented. Duke Energy declined this request citing the cost burden of lost generation from the eight turbines at the Shirley site.

Four acoustical consulting firms cooperated to jointly conduct this study: (1) Channel Islands Acoustics (ChIA); (2) Hessler Associates, Inc.; (3) Rand Acoustics; and (4) Schomer and Associates, Inc. This study was conducted during a three day period in December, 2012. The first task accomplished was to meet with residents having problems with the wind turbine acoustic emissions including members of the three families who had abandoned their homes. These discussions with the residents yielded the following observations:

1. At most locations where these various symptoms occurred, the wind turbines were generally not audible. That is, these problematic symptoms are devoid of noise problems and concomitant noise annoyance issues. The wind turbines could only be heard distinctly at one of the three residences examined, and they could not even be heard indoors at this one residence during high wind conditions.
2. The residents reported that at least some of them could sense when the turbines turned on and off; this was independent of hearing or seeing the turbines. This assertion by the residents is readily testable.
3. The residents reported "bad spots" in their homes but pointed out that these locations were as likely to be "bad" because of the time they spent at those locations, as because of the "acoustic" (inaudible) environment. The residents did not report large changes from one part of their residences to another.
4. The residents reported little or no change to the effects based on any directional factors. Effects were unchanged by the orientation of the rotor with respect to the house; the house could be upwind, downwind, or crosswind of the source.
5. The residents were asked if they were susceptible to motion sickness, and all of the residents who reported motion sickness like symptoms as major adverse effects associated with the wind turbines, were also sensitive to motion sickness.[ii]

Two of the major implications of these five findings are: (1) Because these residents largely report wind turbines as inaudible, it seems that suggestions some have made that these conditions are being caused by extreme annoyance can be ruled out, and (2) the lack of change with orientation of the turbine with respect to the house and the lack of change with position in the house suggest that we are dealing with very low frequencies; frequencies such that the wavelength is a large fraction of the wind-turbine diameter (i.e., about 3 Hz) or lower.

It should be mentioned that there are about 120 residences within about 5000 ft of the closest turbine, which suggests that there are about 275 residents. Of these 275 residents, 50 have described adverse effects that they have experienced after the introduction of the wind turbines. The most common complaints are feelings of pressure and pulsations in the ears. A sub-subset of 2 of the 5 people exhibiting motion sickness symptoms fit the following search criteria: about one half or more of their symptoms must be motion sickness symptoms, the overall symptoms must be severe enough that the people abandon their homes (or equivalent), the motion sickness symptoms must include nausea, and the motion sickness symptoms must play a prominent role in the subjects overall response to wind turbine noise. Only 2 of the 50 residents reporting any type of symptom meet these rather selective criteria. .[iii] It is not known how many of the 120 residences are "participating," but most agreements for participating residences include some form of confidentiality and non-complaint clauses.[iv]

2.2 Physical Measurements

Figure 1 is an aerial photo of the Shirley wind farm. This figure shows the positions of five of the eight wind turbines that make up this site, Nordex N-100s, and the position of the three abandoned residences. Primary measurements were made at residences 1, 2, and 3 on consecutive days. Each of the four consulting firms contributed to the overall study.

Figure 1: Aerial photograph of the site showing the 3 residences, and the 5 closest wind turbines

Bruce Walker of Channel Island Acoustics employed a custom designed multi-channel data acquisition system to measure sound pressure in the time domain at a sampling rate of 4,000/second where all signals are collected under the same clock. The system is calibrated to be accurate from 0.1 Hz thru 10,000 Hz.

At each residence, a multi-channel recorder was connected to an outside wind-speed anemometer and a microphone mounted on a ground plane covered with a 3 inch hemispherical wind screen that in turn was covered with an 18 inch diameter and 2 inch thick foam hemispherical dome (foam dome). Other channels of the recorder were connected to microphones inside each residence that were situated in various rooms including basements, living or great rooms, office/study, kitchens and bedrooms. The objective of this layout was to gather sufficient data for applying advanced signal processing techniques.

Robert Rand of Rand Acoustics observed measurements and documented neighbor reports and physiological effects including nausea, dizziness and headache.

Paul Schomer of Schomer and Associates, Inc. observed all measurements. Among other things the following observations are made based on the results of the physical measurements. In particular, these observations are based upon the coherence calculations by Bruce Walker. He produced both amplitude, frequency and coherence plots and 10-minute coherence charts showing only amplitude and frequency. While both types of plots show the same thing, this analysis concentrates on the latter, 10-minute coherence charts, because the amplitude, frequency and coherence plots have only a 30 dB dynamic range. Figures 2 shows the coherence between the outdoor ground plane microphone and 4 indoor spaces at Residence 2: the living room, the master bedroom, behind the kitchen, and in the basement. The data collected at Residence 2 were measured with only 58% of turbine power, although the wind conditions were optimal for turbine operation, and the power was much less than 58% during the measurement periods at R1 and R3.

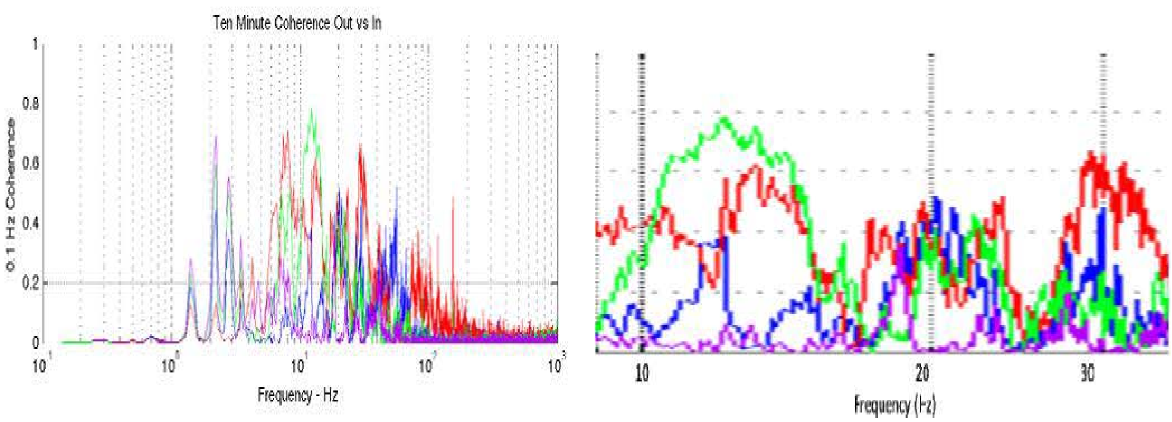

Figure 2a,b: R2-5T212420--coherence with outdoor-ground plane microphone; Living Room-Blue, Master Bed Room- Red, Behind Kitchen- Green, Basement-Purple, b is an expanded view from 9 Hz to 35 Hz

It is inferred from the residents' observations that the important effects result from very low frequency infrasound of about 3 Hz or lower. We can test this assertion with the data collected at the three residences at Shirley. Only Residence 2 was tested during a time when significant power was being generated, so it is the only source of data used herein. Figures 2 shows the coherence between the outdoor ground plane microphone and the four indoor spaces listed above. All of the four spaces exhibit coherence at 0.7 Hz, 1.4 Hz, 2.1 Hz, 2.8 Hz and 3.5 Hz, and in this range there is no coherence indicated except for these five frequencies. The basement continues, with coherence exhibited at these higher harmonically related frequencies of 4.2 Hz, 4.9 Hz. 5.6 Hz, 6.3 Hz and 7 Hz. The coherence in the basement drops low from 10-18 Hz and is more or less random and low above 18 Hz.

Figure 2b shows the coherence just for the frequency range from 10 Hz to 35 Hz, and essentially this figure exhibits random patterns with no correlation from one room to the next. For example, coherence with the microphone behind the kitchen is high from 10-14 Hz and the master bedroom is high from 12-14 Hz while the other two spaces exhibit low coherence, and again the master bedroom is high from 28-35 Hz with the others being low, and the living room is high from 50-58 Hz with the other spaces low; no pattern. In contrast, all four spaces are lock step together in their coherence with the outdoor microphone below about 4 Hz.

As an analysis that is complementary to the coherence plots of Figure 2, Figure 3 shows spectral plots of data collected at Residence 2. As in the coherence plot, we see the first several harmonics of the wind-turbine blade-passage frequency, 0.7 Hz, and nothing notable above about 7 Hz. Two channels of measurement are shown on Figure 3, the outside, ground plane microphone (green), and the indoor microphone in the living room. Note that the pressures that result from the acoustic emissions of the wind turbines, when measured indoors, keep growing as the frequency goes lower, because the entire house is behaving like a closed cavity.

Residence 2, and indeed all three residences, exhibit classic wall resonances in about the 10-35 Hz range which are different for each room and exposure, so it is reasonable to suppose that the randomness in the 10-35 Hz region in the above ground rooms is the result of wall resonances. The basement, which has no common wall with the outside, generally exhibits the lowest coherence in the 10 to 35 Hz region. Thus, we conclude that the only wind turbine-related data evident in the measurements at Residence 2 are the very low frequencies ranging from the blade passage frequency of 0.7 Hz to up to about 7 Hz. This conclusion is consonant with the residents' reports that the effects were similar from one space to another but a little to somewhat improved in the basement, the effects were independent of the direction of the rotor and generally not related to audible sound.

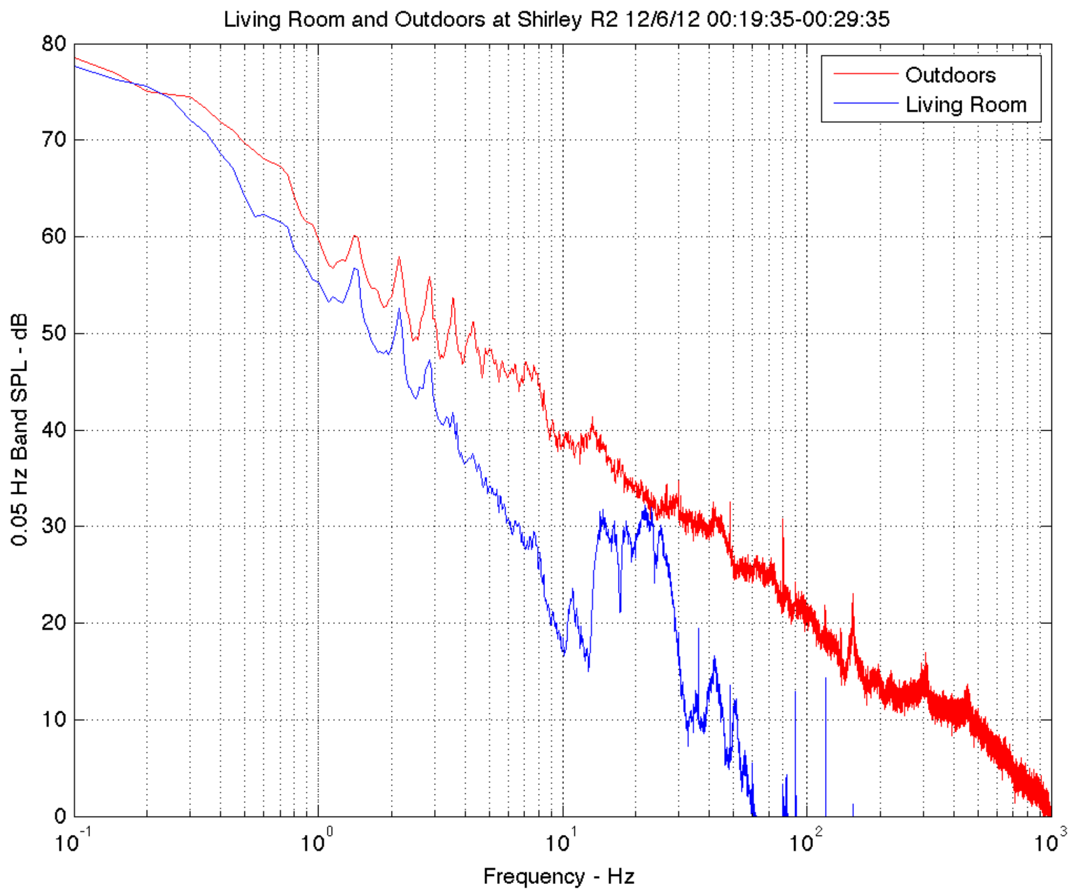

Figure 3: Spectral plot of the ground-plain outdoor microphone data and indoor data measured in the living room of Residence 2.

Figure 4 shows the sound pressure level for the first minute of the 10 minutes represented on Figure 2, above. This figure, which is sensitive to the lowest frequencies, shows that at these very low frequencies the sound pressure level in all four spaces is quite similar. The small changes from different positions in the house also suggests that the house is small compared to the wavelength so that the insides of the house are acting like a closed cavity with uniform pressure throughout being driven by very low-frequency infrasound.

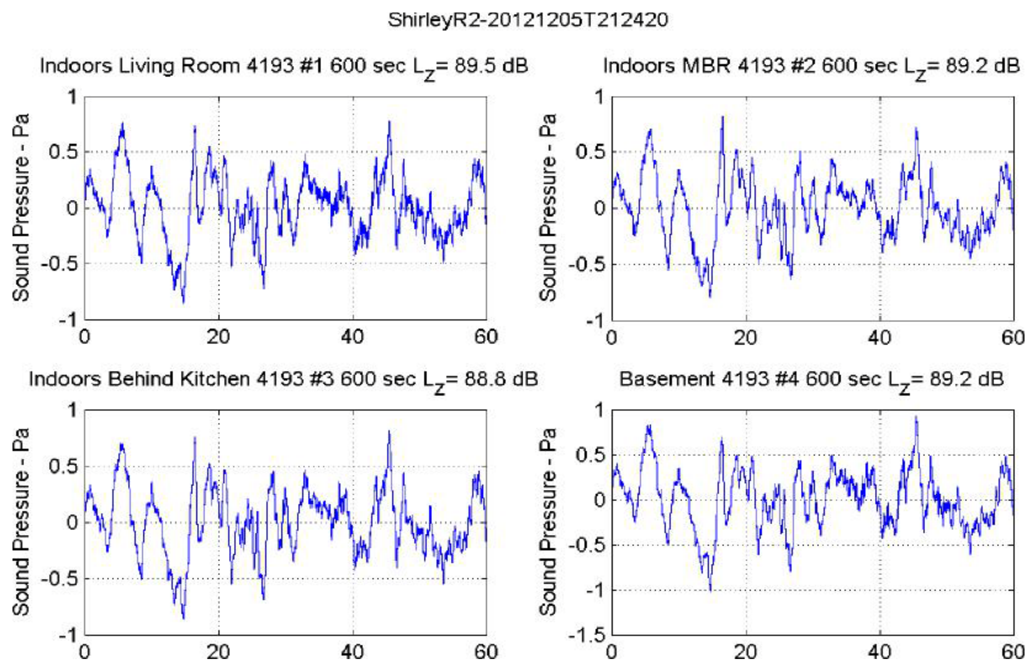

Figure 4: First of the ten minute period of 5T212420. Note that the SPL is very similar for all indoor locations.

Figure 5 is for Residence 3 which was 7000 feet from the nearest turbine, in contrast to Residence 2, which was only 1100 feet from the nearest turbine. Even here, with much reduced amplitude, there seem to be several frequencies where the four spaces have peaks together beginning at 0.7 Hz. While only a slight blip is evident at 0.7 Hz in Figure 5, clear peaks are evident at 1.4 and 2.1 Hz, and a couple of the microphones also show peaks at 2.8 Hz. It is somewhat surprising that we can even measure these considering the low power setting on the day R3 was measured.

The measurements support the hypothesis developed above that the primary frequencies are very low, in the range of several tenths of a Hz up to several Hz. The coherence analysis shows that only the very low frequencies appear throughout the house and are clearly related to the blade passage frequency of the turbine. As Figures 4 shows, the house is acting like a cavity and indeed at

5 Hz and below, where the wavelength is 60 m or greater, the house is small compared to the wavelength.

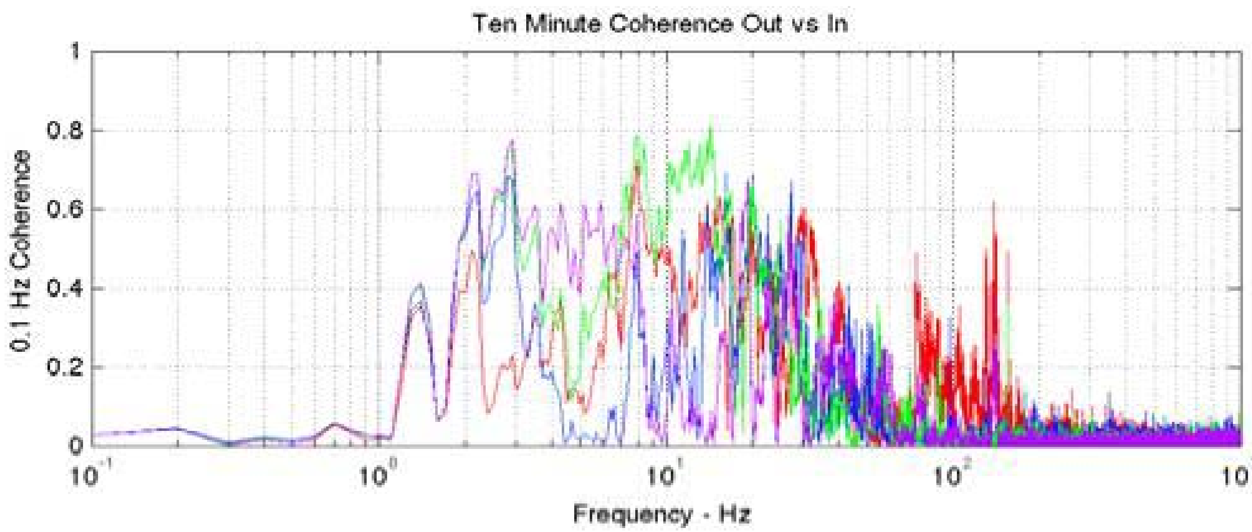

Figure 5: R2-5T204657- coherence with outdoor-ground plane microphone;; Living Room-Blue, Upstairs Bed Room- Orange, Family Room- Turquoise, Basement-Purple

While we would have liked to have been able to draw conclusions on measurements at all three sites, that was not possible because Duke Energy was not generating much power during the measurements of R1 and R3, and even just over 50% during the measurements at R2.

3. The motion sickness hypothesis

3.1 The Navy's Nauseogenic Region

As a starting point we consider a paper by Kennedy *et al*. (1987) entitled: "Motion Sickness Symptoms and Postural Changes Following Flights in Motion-Based Flight Trainers." This paper was motivated by Navy pilots becoming ill from using flight simulators. The problems encountered by the Navy pilots appear to be similar to those reported by 5-6 of the Shirley residents. This 1987 paper focused on whether the accelerations in a simulator might cause symptoms similar to those caused by motion sickness or seasickness. Figure 6 (Figure 1 from the reference) shows the advent of motion sickness in relation to frequency, acceleration level and duration of exposure. To develop these data, subjects were exposed to various frequencies, acceleration levels and exposure durations, and the Motion Sickness Incidence (MSI) was developed as the percentage of subjects who vomited. Figure 7 show two delineated regions. The lower region is for an MSI of 10%. The top end of this region is for an exposure duration of 30 minutes and the bottom end is for eight hours of exposure. The upper delineated region has the same duration limits but is for an MSI of 50%.

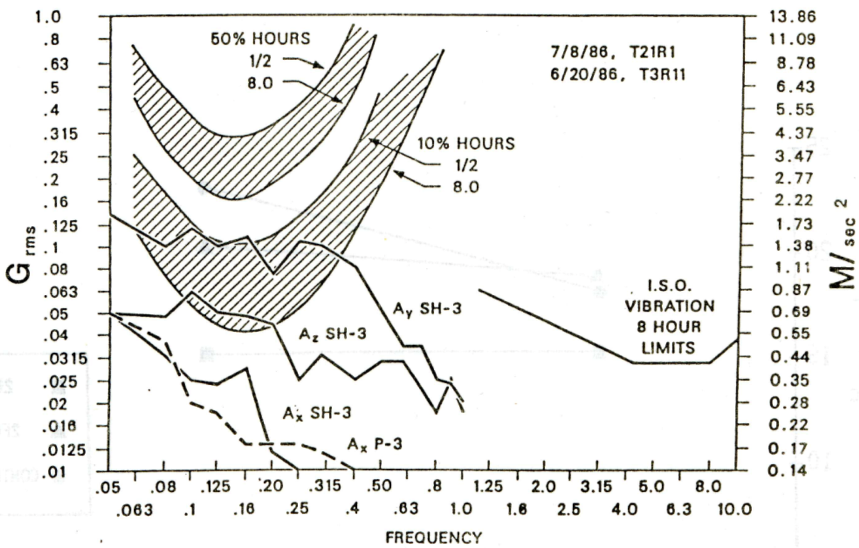

Figure 6: The Navy's nauseogenic region

What is important here is the range encompassed by the delineated regions of Figure 6. Essentially, this nauseogenic condition occurs below 1 Hz; above 1 Hz it appears that accelerations of 1G would be required for the nauseogenic condition to manifest itself. While the Navy criteria are for acceleration, in Shirley we are dealing with pressures in a closed cavity, the house. The similarity between force on the vestibular components of the inner ear from acceleration and pressure on these from being in a closed cavity suggests that the mechanisms and frequencies governing the nauseogenic region are similar for both pressure and acceleration.

As the generated electric power of a wind turbine doubles the sound power doubles and the blade passage frequency decreases by about 1/3 of an octave (Møller and Pedersen, 2011). The wind turbines at Shirley have a blade passage frequency of about 0.7 Hz. This suggests that a wind turbine producing 1 MW would have a blade passage frequency of about 0.9 Hz, and on Figure 6, a change from 0.7 Hz to 0.9 Hz requires a doubling of the acceleration for the same level of response. Thus, it is very possible that this nauseogenic condition has not appeared frequently heretofore because older wind farms were built with smaller wind turbines. However, the 2.5 MW, 0.7Hz wind turbines clearly have moved well into the nauseogenic frequency range.

3.2 Motion Sickness Like Symptoms, and their Implications

Motion sickness, or kinetosis (from the Greek to move) is generally related to the vestibular, visual, and somatosensory systems. (cf. Griffin, 1990). A common theory of the cause of kinetosis is that of sensory conflict: the information received from two or more sensory systems conflict (eg., visual inputs in a closed room and vestibular inputs from a rolling boat) producing symptoms similar to that of ingesting a poisonous substance. The result is an evolutionary protective response to rid the body of a harmful foreign substance. Thus, motion sickness is not really a sickness, but rather is a natural reaction to unusual input information.

At the start of this study the working hypothesis was that wind turbine noise somehow, because of the nauseogenic regions similarity, created symptoms that were similar to those of motion sickness. We now have a much simpler hypothesis--like movies and videos, wind-turbine acoustic emissions trigger motion sickness in those who are susceptible; it is another form of *pseudo-kinetosis.*

At Shirley, of the50 people who reported symptoms after the introduction of wind turbines to the area, 5 of those 50 people reported symptoms similar to motion sickness. We simply have no information on other area residents, except for these 50, and do not know how many of the other residents are participating. Based on the sample of 5 out of 50, we can say that the incidence of motion sickness symptoms at Shirley is 10% or less, a figure that is clearly in line with the expected percentage of those in the general population affected by motion sickness. In fact, Montavit (**2013**) indicates that “about 5 to 10 percent of the population is extremely sensitive to motion sickness; 5 to 15 percent are relatively insensitive; and about 75 percent are only subject to it to a ‘normal’, i.e. limited degree.”

In our meeting with affected residents discussed above, it was stated that each person affected by the wind farm noise in the form of motion sickness symptoms was also motion sickness sensitive

The same is true for Rob Rand and Steve Ambrose who are two acoustical researchers who have themselves reported suffering strong symptoms from low-frequency wind-turbine emissions. It appears individuals who exhibit motion sickness symptoms in response to infrasound, the motion sickness symptoms play a prominent role, and the motion sickness symptoms (listed in Table 1) account for about one half or more of a person's total symptoms, and the total symptoms are sufficiently strong such that these residents abandon their homes, also suffer from motion sickness. The count is two of two people, the father and son at

Shirley, who exhibit motion sickness symptoms to the degree indicated above to wind-turbine acoustic emissions; both are sensitive to motion sickness.

Assume that sensitivity to motion sickness and sensitivity to wind-farm acoustic emissions in the form of motion sickness like symptoms to the degree indicated above are totally uncorrelated and that the probability of sensitivity to motion sickness is 15 percent, a rather high estimate.[v] The probability of finding four people in succession who each reports sensitivity to both motion sickness and wind-turbine emissions to the degree indicated above is (15/100) to the 4th power, which is 0.0005. This is just about 1 in 2,000. Said another way, the probability that sensitivity to wind-farm emissions in the form of motion sickness like symptoms that are so strong that these people abandon their homes and sensitivity to motion sickness are unrelated is just about 1 in 2,000. The clear conclusion is that these four people are affected by wind turbine acoustic emissions, and this particular form of sensitivity to wind-farm emissions and sensitivity to motion sickness are directly related.

The implications of finding a group of people sensitive to wind turbine emissions are important. Therefore we decided to search for more cases. Searching the United States, Canada and Australia yielded three more cases (two from Australia and one from the USA), and all three were sensitive to motion sickness. The probability of finding just three cases in succession is about 1 in 300 which is statistically very significant by itself, but the probability of finding 7 individuals who meet the criteria given above is (0.15) to the 7th power; less than 2 in 1,000,000. Our conclusion stands.

It has been suggested that people's fears create their reactions. At least for those sensitive to motion sickness, this does not appear to be the case. Rather, psychological factors, e.g. fear, is endemic to motion sickness and can amplify its effects significantly. Just the thought of going on a boat or in a plane can trigger motion sickness symptoms in a sensitive person; symptoms that exacerbate the problem. Aversion to the sources of motion sickness is a normal reaction in individuals who are sensitive to motion sickness, so it is not surprising that people who are sensitive to motion sickness and are adversely affected by wind farms, have an aversion to being near wind farms. This is a normal reaction in motion sensitive people that goes with motion sickness and is not unique to wind turbines or related to "not liking" wind turbines, so, it can be expected that those who become ill due to low-frequency noise from wind turbines will have an aversion to wind turbines that is more complex than simply "disliking" the sound or appearance of the turbine[vi].

As noted above, unaccustomed motions and accelerations confuse the brain. For example, during a car trip, nerves and muscle receptors don’t register any movement, since the body itself is sitting still. The eyes, on the other hand, send the brain a message of fast motion. The equilibrium organ in the inner ear delivers information of curves, acceleration and/or ascents which contradict the messages from the other two sources. This contradictory flood of impulses and information overburdens a healthy sense of equilibrium which the brain, in turn, interprets as a danger situation. It then releases stress hormones, which in turn create symptoms of dizziness and nausea.

So to induce a sense of motion where none exists and thereby create the sensory conflict that is requisite to induce motion sickness requires that the acoustic signal cause the vestibular system to "tell the brain" it is accelerating when the ocular system is telling the brain there is no motion.

4. Excitation of the otolith

4.1 The middle ear and inner ear

This main question relates to the fact that the Navy criteria are based on acceleration, while the wind-turbine acoustic emissions are very low-frequency acoustic pressure waves.

In the following, we show only that it appears 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 to 0.7 Hz.

The following discussion analyzes the linear motion sensing function of the ear, and explains how the ear could respond to wind turbine emissions. Figure 7 shows the ear (Obrist 2011). We are concerned primarily with the inner ear which is shown in blue in this figure.

Figure 8 shows just the inner ear which contains the cochlea, the organ that divides a sound wave into frequencies ranging from about 10 Hz to about 20 kHz (Obrist 2011). The inner ear also contains the vestibular system which controls and facilitates balance and motion. The system of semicircular canals appears to have evolved in order to be able to sense rotational movements of the head while remaining rather insensitive to forces arising either from translational acceleration of the body or gravity: the cupulae normally have a similar specific gravity to that of the endolymph. The vestibular perception of translational forces is thought to originate normally from sensory systems (maculae) located within the utricle and saccule. The maculae consists of flat gelatinous masses (otollithic membrane) covered with minute crystals (otoconia) connected to an area of the utricle and saccule by cells, including hair cells. A suitably oriented translational force will cause the mass to exert a shear force, resulting in a variation in the firing rate of the hair cells. The maculae cover an area of a few square millimeters. They are located on the floor and lateral wall of the utricle and, in an orthogonal plane, on the anterior wall of the saccule (Griffin 1990).

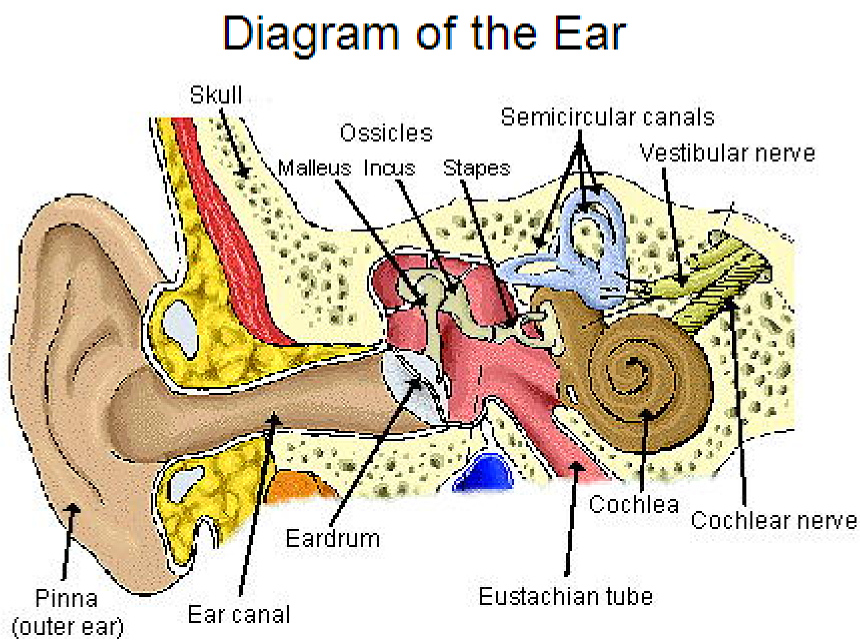

Figure 7: The three parts of the ear

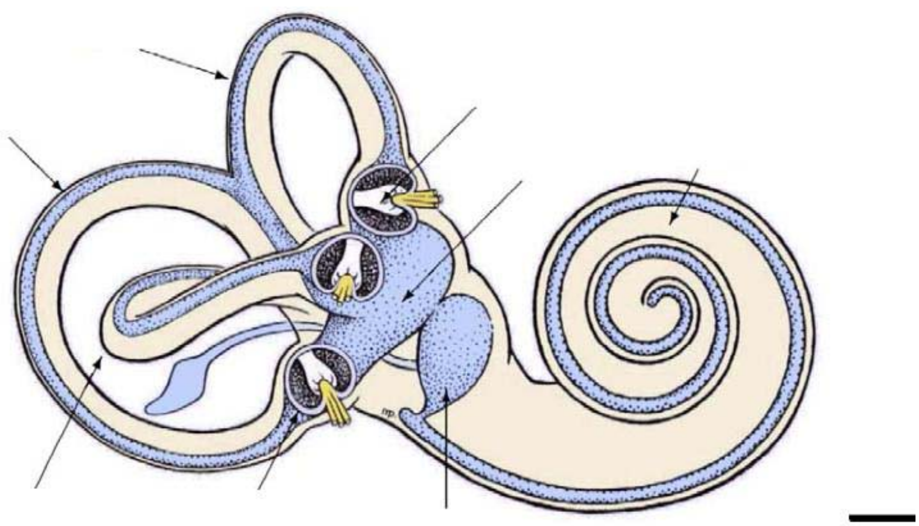

Figure 8: The inner ear

These six inner ear organs, the cochlea, the three SCCs, the saccule, and the utricle, open into the inner space of the inner ear termed the vestibule. The inner part of the inner ear is filled with endolymph which has properties similar to water (Obrist, 2011; Grant and Best, 1987). 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 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 (Obrist, 2011). The difference between the impedance of air and the impedance of the perilymph would produce a loss of about 29 dB at the air/fluid interface. To match the impedances, the middle ear consisting of the area of the tympanic membrane, the three middle ear ossicles and the area of the footplate of the stapes provides a mechanical transformer that matches this discontinuity. At high frequencies the tympanic membrane develops modes that affect the transmission of sound across the middle ear. Low frequencies do not create these vibration modes and the membrane vibrates as a “plate.” The lower limit to the auditory range is limited by the length of the basialar membrane of the cochlear which, in turn, affects the length of the travelling wave on the membrane and, consequently, the lower limit of hearing.

The round window is compliant and responds to the pressure wave that travels up the scala vestibuli and down the scala tympani to create shear forces in the cochlea. These two “tunnels” surround the basilar membrane. Additionally, there is a communication between the scala vestibuli and the vestibular system by means of which acoustic pressure might be transmitted to the otoliths.

4.2 Classical model of the otolith

We have shown there is a plausible path for the infrasound pressures to reach the inner ear and in particular the otoliths. The classical model of the otolith is shown pictorially in Figure 9 (McGrath, 2003). The otoconial layer is a rather dense, firmer layer of the otolith. It thickens at the surface. The otoconial layer 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 (cupula) as a shear force 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 (Grant and Best, 1987); the otolith is measuring force.

4.3 Calculations of forces acting on the otolith

In this section we approximate and compare two potential forces acting on the otoliths: (1) inertial forces due to accelerations, and (2) forces due to the instantaneous pressure in an acoustic wave.

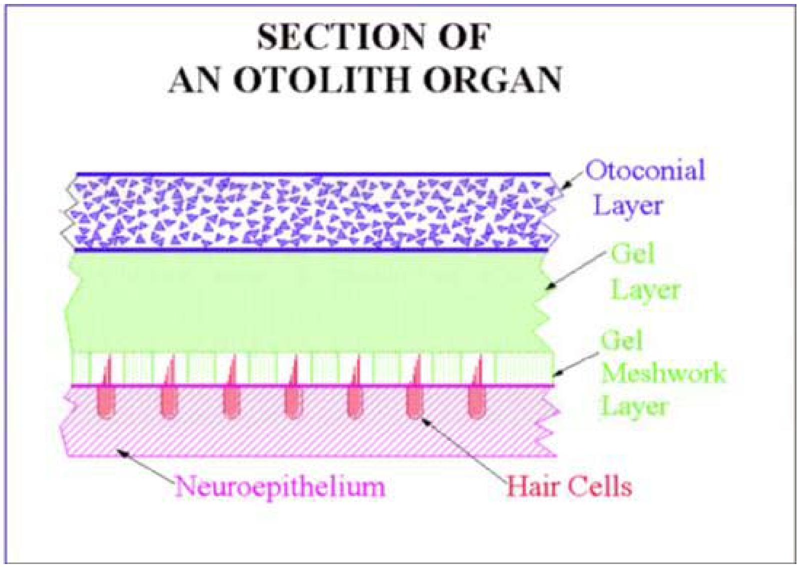

Figure 9: Section of a model otolith organ

Although the more complete solution for modeling the motion of the otolith is given by a parabolic partial differential equation (Grant and Best, 1987), the frequency response of the otoliths is flat from DC to about 10 Hz (McGrath, 2003), the position of the poles in the response being functions of assumptions for values of certain parameters describing physical attributes of the layers and their constituents. For an order of magnitude calculation, we simply consider F= ma, where the acceleration is precisely the acceleration of the head, and the mass is the differential density of the otoconial layer minus the density of the surrounding fluid and the copular membrane times the volume of the otoconial layer. Although calcium carbonate has a density of 2.7 gm/cm^3, the density of the otoconial layer is taken to be 2 gm/cm^3, since it is a combination of the dense calcium carbonate and the less dense gel material. The density of the copular membrane and of the endolymph fluid, which has properties given as being similar to water, is taken as 1 gm/cm^3, so the differential density is 1 gm/cm^3, or 1000 kg/m^3. As can be seen in Figure 8, the otoliths are approximated as round and their diameter is about 1 mm. The reader should note that the exact area encompassed by the otoconial membrane, its size, is not as important as one might think because we are comparing 2 forces, the force due to acceleration of the otoconial layer and the force due to the acoustic pressure on the otoconial layer, each of which is proportional to the same area; the area of the otoliths. The thickness of the otoconial layer has been given as 15 to 20 µm (Grant and Best, 1987). Therefore we calculate: the mass = density*thickness*area or, mass(kg) = 1 (kg/ m^3)*18*10^{-6} m*π*0.5*10^{-3} *m*0.5*10^{-3} * m = 18* π/4*10^{-9} ≈ 1.4*10^{-8} kg.

With reference to fig. 6, we take the acceleration to be 1 m/s^2, so the acceleration force,

$$F_{accel} = 1.4 \times 10^{-8} \text{ N.}$$

In terms of the pressure of an acoustic wave, we take the SPL to be 74 dB which corresponds to 0.1 Pa. Therefore, the acoustic force, F_{acous} = 0.1* π /4*10^{-6} N ≈ 8*10^{-8} N.

4.4 Excitation of the otoliths

More recent research tends to confirm the model presented above for the excitation of the saccule. It is shaped similarly to a hemi-sphere with the base of the hemi-sphere rigidly attached to the temporal bone and the otoconial layer on the top where under the force of acceleration shear forces can be set up in the cupula. However there is radically new information about the utricle. Uzun-Coruhlu *et al.* (2007) have used x-ray microtomography and a method of contrast enhancement to produce data revealing "that the saccular maculae are closely attached to the curved bony surface of the temporal bone as traditionally believed, but the utricular macula is attached to the temporal bone only at the anterior region of the macula"(see Figure 10). This radically changes the model for excitation of the utricular macula. According to Uzun-Coruhlu *et al.* in the classical view of the utricular macula "... the sub-surface of the utricular macula is implied (if not actually stated) to be rigid; these models do not accommodate the ‘‘floating’’ utricular macula which we have shown and which is consistent with other anatomical evidence (e.g. Schuknecht, 1974). Since the hair cell receptors on the utricular macula are stimulated by forces there would be a major difference in modeling the sensory transduction of the macula to such forces if the forces acted on a tenuously supported flexible membrane or acted on a membrane which is rigidly attached to bone. As an example, modeling the magnitude of utricular hair cell displacement to an increased dorso-ventral g-load during centrifugation will be quite different if the whole membrane is deflected by the g-load or if it remains fixed in place. The latter rigid attachment has been explicitly or tacitly assumed, whereas our results show the macula is not rigidly attached to bone.

> "The key information which is now required for realistic modeling of utricular transduction is information about the flexibility of the utricular membrane to determine the extent to which it would be deflected by such forces."

Essentially, Uzun-Coruhlu *et al.* are saying that the excitation of the otolith in the utricle depends on the flexibility of the utricular macula. Since the macula is not rigidly attached to the temporal bone, the classical model for excitation of the otolith by an acceleration does not work. One way for inertial forces on the otolith to create bending forces is if the stiffness of the utricular membrane varies with position. Then inertial forces on the otolith will make the otolith "bulge" where it is less stiff and contract where it is stiffer, producing bending forces that will trigger the hair cells. Precisely the same thing will happen if the force is externally applied through the endolymph as when the force is internally applied through the otoconial layer. In this model, if there is external force on the utricle, it will expand where it is less stiff, and contract where it is stiffer. In particular, the pathway described earlier should cause the utricular macula to signal the brain in virtually identical fashion to signals generated by inertial forces.

4.5 An example that indicates these theories may be correct

The pressure in the endolymph is a scalar; its "direction" is everywhere normal to the surface. Therefore, in contrast to true inertial forces which are vectors, the acoustic pressure will always excite the same hair cells independent of the orientation of the head. So, one who experiences this effect should always feel the same motions. And this is exactly what both Steve Ambrose and Rob Rand, who are both acoustical consultants, each experienced. Rob Rand, one of the acoustical researchers on this project, the one who is sensitive to wind turbine acoustic emissions, said of his work in Falmouth, MA in April 2011: "I went outside hoping to feel better. I looked straight at a tree with my eyes, and my brain said the tree was about 20 to 30 degrees elevated and about 20 to 30 degrees to the right. Then I tried to focus on a bush looking straight at it, and again my brain said the bush was off to the right and elevated at about the same angle as before; and the same for the house. For everything I looked at, immediately my brain would say it was elevated and off to the right." Steve Ambrose had exactly the same experience, only not the same angles.

5. Conclusions

The wind turbine clearly emits acoustic energy at the blade passage frequency, which for the Nordex N100 is 0.7 Hz and about the first 6 harmonics of 0.7 Hz. This very low infrasound was only found at R2, but that was the only day in which significant power was being generated (about 58%).

Most residents do not hear the wind-turbine sound; noise annoyance is not an issue. The issue is physiological responses that result from the very low-frequency infrasound and which appears to be triggering motion sickness in those who are acoustic pressure that reaches the otolith through the eardrum and middle ear

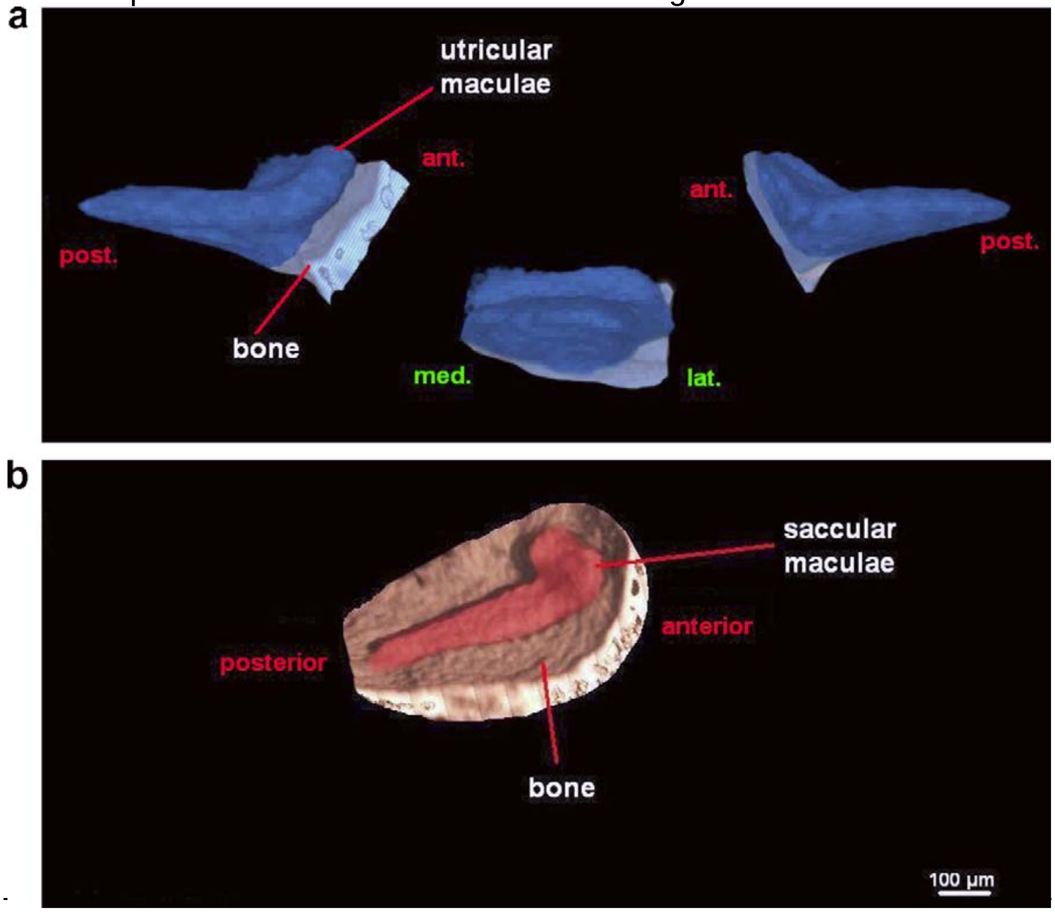

Figure 10: 3-D rendered images of the utricular and the saccular maculae of guinea pig. (a) Illustrates the 3-D rendered images of the three views of the macula as it rotates around a dorso-ventral axis to show the attachment of the macula to the bony wall of the utricle which occurs only at the anterior-most region. (b) Shows the 3-D rendered image of the saccular maculae clearly bound to curved bone.

susceptible to it. It has been shown that the probability that sensitivity to motion sickness and sensitivity to wind turbine acoustic emissions are unrelated is less than 2 in 1,000,000. This statement is sufficient to make clear a relation between wind turbines and motion sickness symptoms in what appears to be a small fraction of those exposed. This finding does not prove our hypothesis that the otoliths are responding to the wind turbine infrasonic emissions. Rather, we can say that the pathway for inducing this condition appears to be the same as airborne transmission through the middle ear and thence to the vestibular sensory cells, but confirmatory research of the pathway is recommended.

Finally, it is shown that the force generated on the otoliths by the pressure from the infrasonic emissions of the wind turbines is perhaps 1.5 to 3 times larger than the force that would be generated by an acceleration that was in accordance with the US Navy's Nauseogenic Criteria (Figure 7 herein). That is, a 0.5 to 0.7 Hz "tone" at 74 dB produces about the same to 1.5 times the force as does a 2 m/s^2 acceleration.

6. Additional research and data collection recommendations

The questions raised by this paper require answers. With the possible exception of study A below, a test facility is required to accomplish the research outlined below, and it probably could be used for study A. The facility would be a small room, perhaps 10 ft by 12 ft by 8 ft high, and, depending on location, would need to be in a soundproof enclosure. Excitation would be with special transducers; possibly an air-modulated loudspeaker. The main requirement is that the facility extend down to very low frequencies (0.05 Hz or lower). Some of the potential testing is very briefly described below. Potential tests:

- **A.** Perform the "sensing" tests outlined in Appendix A of this paper.
- **B.** Demonstrate electric signals going to the brain that emanate from the otoliths; signals that are in sync with the wind turbine emissions. This testing would need to be done on an animal such as a cat or Guinea Pig.
- **C.** Develop an understanding of why this phenomenon seems to affect residents near only a small minority of wind farms.
- **D.** Establish who is and who is not affected by wind turbine infrasonic emission in various ways, and why.

Results from the type of research indicated above will facilitate development of methods to mitigate and/or prevent these types of problems. Prevention and mitigation may not be so difficult. In particular, the eight-turbine installation in Shirley is very spread out; R1 and R3 are near two turbines while R2 has one turbine that should be 6 dB higher in level than the next nearest turbine. Another place where these seasickness like problems are known to have occurred is in Massachusetts with a one-turbine installation. These findings begin to suggest that having several asynchronous turbines at roughly the same level might preclude the motion sickness problem by breaking up the regular repetition rate inherent when there is just 1 nearby turbine or when there is synchronous operation. This would suggest that in a site with many turbines, only some residences on the perimeter would have the potential for only one nearby turbine.

Currently the wind turbine industry presents only A-weighted octave band data down to 31 Hz, or frequently 63 Hz, as a minimum. They have stated that the wind turbines do not produce low frequency sound energies. The measurements at Shirley have clearly shown that low frequency infrasound is clearly present and relevant. A-weighting is inadequate and inappropriate for description of this infrasound. In point of fact, the A-weighting, and also the C and Z-weightings for a Type 1 sound level meter have a lower tolerance limit of -4.5 dB in the 16 Hz one-third-octave band, a tolerance of minus infinity in the 12.5 Hz and 10 Hz one-third-octave bands, and are totally undefined below the 10 Hz one-third-octave band. Thus, the International Electro-technical Commission (IEC) Wind Turbine measurement standard needs to include both infrasonic measurements and a standard for the instruments by which they are measured.

7. Endnotes

i. The wind farm dialogue has been marred by misstatements on all sides. This quotation of Tesarz *et al.*, (1997) brings to mind one notable misstatement: "If you can't hear it, it can't hurt you." This paper shows that quotation to be a misstatement.

ii. The family in the closest dwelling, R-2, reported that the wife and their then 2-year old son had the problems; the husband did not have problems. The husband would not sell the house because he did not want to stick someone else with the problems, was making payments on the loan because he would not default, and they have purchased a second, smaller house that they also make payments on. These residents reported that their baby son, then 2 years old, would wake up 4 times a night screaming. This totally stopped upon their leaving the vicinity of the wind turbines, and he now sleeps 8 hours and awakens in a normal state for a 2 year old, basically happy. The couple in the middle-distance house, R-1, were living in their camper because they had nowhere else to live that they could afford. Of course the camper is kept several miles from the wind farm. They and two or their adult children, a son and a daughter, were all sensitive to motion sickness and had motion sickness symptoms. The son and daughter each lived in a nearby community and visited very often.

iii. These were the four family members discussed in note ii, above. The mother and father moved from their house because the problems they were experiencing, the majority of which for the father are contained in the Table 1 list. The son and daughter each apparently lives far enough away that the emissions are not a problem to them where they live, but the son reports on two trips to the parents abandoned house to use a shop area there to work on his car. Both times he developed strong motion sickness symptoms and only goes "there for very short periods of time now, and only when absolutely necessary." This is taken to be essentially equivalent to abandoning a home in that his parent’s home is nearby and could readily be used by him, but he chooses to only go there "when absolutely necessary" because he feels so bad when he goes there. The two residents that were selected from the 50 at Shirley with symptoms are the father and the son. About one half of the father's symptoms are in the Table 1 list, they are strong and include nausea, and they have abandoned their home. The son is included because nearly all his symptoms are from the Table 1 list, they are very strong, and he no longer goes to or uses a house that is available to him except when absolutely necessary. In contrast, the mother's major problem centers on pain in the ears, and the daughter's situation is less clear.

iv. Participating households are those that receive a share of the proceeds in exchange for agreeing to not complain about the wind turbines; additional monies are paid to participants who have wind turbines or ancillary facilities or equipment on their property.

v. Montavit (2013) states that 5 to10 percent of the population are "extremely sensitive," and that 5 to 15 percent are "relatively insensitive." So 5 to 10 percent of the population is probably closer to the percentage that we should be using rather than 15 percent.

vi. The effect shown here for wind-turbine emission is certainly not unique to wind turbines. Rather, it appears that these effects would occur with any low infrasonic source. This finding may explain some of the reports that have been present in the literature for over 40 years.

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