Bulletin of Science, Technology & Society
http://bst.sagepub.com/

Wind Turbine Acoustic Investigation : Infrasound and Low-Frequency Noise––A Case Study

Stephen E. Ambrose, Robert W. Rand and Carmen M. E. Krogh

Bulletin of Science Technology & Society 2012 32: 128 originally published online 17 August 2012
DOI: 10.1177/0270467612455734

Bulletin of Science, Technology & Society
32(2) 128–141
© 2012 SAGE Publications
Reprints and permission:
sagepub.com/journalsPermissions.nav
DOI: 10.1177/0270467612455734
http://bsts.sagepub.com

Wind Turbine Acoustic Investigation: Infrasound and Low-Frequency Noise—A Case Study

Stephen E. Ambrose[1], Robert W. Rand[2], and Carmen M. E. Krogh[3]

Abstract

Wind turbines produce sound that is capable of disturbing local residents and is reported to cause annoyance, sleep disturbance, and other health-related impacts. An acoustical study was conducted to investigate the presence of infrasonic and low-frequency noise emissions from wind turbines located in Falmouth, Massachusetts, USA. During the study, the investigating acousticians experienced adverse health effects consistent with those reported by some Falmouth residents. The authors conclude that wind turbine acoustic energy was found to be greater than or uniquely distinguishable from the ambient background levels and capable of exceeding human detection thresholds. The authors emphasize the need for epidemiological and laboratory research by health professionals and acousticians concerned with public health and well-being to develop effective and precautionary setback distances for industrial wind turbines that protect residents from wind turbine sound.

Keywords

wind turbines, infrasound, low-frequency noise, physiological symptoms, adverse health effects

Introduction

Industrial wind turbines (IWTs) are being situated near human habitation in increasing numbers. In some communities individuals who are exposed to wind turbines report experiencing negative impacts including adverse health effects. Falmouth Massachusetts, USA is a community located in a quiet rural environment where there were reports of negative health effects from locating IWTs too close to residences. Some Falmouth residents have identified wind turbine noise as a cause of negative effects.

During a noise study investigating acousticians experienced adverse health symptoms similar to those described by residents living at the study location and near other IWT sites. The onset of adverse health effects was unexpected and persisted for some time after leaving the study area.

This case study provides wind turbine noise measurements and other technical data and describes the symptoms experienced by the investigators and explores the plausibility that wind turbine low-frequency energy could contribute to reported adverse health effects.

Background

Falmouth, Massachusetts, U.S. Wind Turbines

Falmouth, Massachusetts recently installed three IWTs (Vestas, V82, 1.65 MW); two owned by the town located at the municipal wastewater treatment plant (WIND1 and WIND2) and one privately owned at a nearby industrial park (NOTUS). This area has a limited amount of daytime business activity and only a distant highway with low traffic volumes at night. The area is representative of a quiet rural environment with widely spaced houses. WIND1 and NOTUS are installed with the nearest residences approximately 400 m (1,300 feet) and 520 m (1,700 feet), respectively.

The WIND1 and NOTUS IWTs were installed over several months, with WIND1 being the first to come on line in March 2010. A short time later, neighbors began to complain about excessive noise coming from WIND1. Later that year, NOTUS began operation and similar complaints came in from other neighbors. Complaints continued for months and neighbors were reporting that they could not adjust to the fluctuating sound, the endless swish and thumps. They found the noise to be intrusive and disruptive to normal at home activities. WIND2 was not operating during this study.

These fluctuating audible sounds or amplitude modulations are the routine characteristic of IWTs and can be disturbing

---

[1] S.E. Ambrose & Associates, Windham, ME, USA
[2] Rand Acoustics, Brunswick, MA, USA
[3] Killaloe, Ontario, Canada

Corresponding Author:
Stephen E. Ambrose, S.E. Ambrose & Associates, 15 Great Falls Road, Windham, ME 04062, USA
Email: seaa@myfairpoint.net

and stressful to exposed individuals (G. Leventhall, 2006). During moderate wind speeds the IWT noise was clearly audible outdoors and for some, indoors. At times the noise included an audible low-frequency tone that came and went. Neighbors commented that the wind turbine noise was more noticeable indoors and it interfered with their relaxation and sleep.

The town responded to the numerous and persistent complaints by requiring postoperational noise surveys to determine if there were justifications for complaints. Neighbors responded by hiring legal counsel and had independent noise measurements performed and evaluated for adverse impacts. Most measurements were conducted by experienced acousticians. The primary acoustic quantifier measured was the average A-weighted sound level (dBA). The sound levels generally ranged from the mid-30s to mid-40s dBA. Some noise-level variations were due to differences for time of day, wind speed, and wind direction (upwind or downwind). Measured sound levels were fairly consistent from each survey provider. However, the acoustic reports had little effect on complaint resolution.

Falmouth Health Complaints

After WIND1 and NOTUS IWT started up, neighbor complaints included adverse health symptoms. They had days where they were unable to enjoy the previous peace and tranquility while at home, unable to relax, felt tense, and felt a strong desire to be someplace else. They noticed some relief when outdoors. The lessening of adverse effects when outdoors and the indoor worsening are consistent with the findings of low-frequency noise (LFN) effects exposure (Burt, 1996). Typically, the indoor A-weighted sound level is lower than the outdoor, especially when indoor human activity is at a minimum. The house exterior walls provide more middle- to high-frequency band attenuation than for the low and very low bands. Therefore, the average A-weighted sound level by itself may not be a useful measurement indicator for determining the potential for IWT complaints.

Some complainants described having significant difficulties living in their home with reports of experiencing headaches, ear pressure, dizziness, nausea, apprehension, confusion, mental fatigue, lassitude (inability to concentrate, lethargy). These were worse when IWTs were operating during moderate to strong winds. A few neighbors moved their bedrooms into the basement in an attempt to get a good night's sleep. Others were forced to leave their home to sleep farther away at a family or friend's house or even in a motel. These symptoms (DeGagne & Lapka, 2008; Schust, 2004) and behavior patterns (H. G. Leventhall, 2004) are consistent with LFN exposure suggesting that IWT low-frequency energy may be a factor.

Study Objectives

The purpose of the study was to confirm or deny the presence of infrasound (very-low-frequency noise, acoustic waves, or pressure pulsations less than 20 Hz) and LFN emissions (20-200 Hz) created by an IWT. The combination of infrasound and low-frequency noise is defined as ILFN. If ILFN was present the study was to determine: (a) if it was greater than or uniquely distinguishable from the ambient background levels and (b) if it exceeded human detection thresholds. It was not the intention of this study to determine the precise mechanism that linked the IWT to the physiological or psychological symptoms being reported by residents.

The scope of this study was conducted at one home that is representative of many other households that have complained about noise and adverse health effects. The investigators assessed differences between outdoor and indoor measurements.

Acoustic Measurements and Methodology

Acoustic measurements were made with precision sound measurement instruments and dual-channel computer-based signal analyzer software. These instruments were capable of measuring very-low-frequency energy, as low as 1 Hz. Frequency response was flat (within 1 dB) to 2 Hz and 6 Hz for the two primary measurement channels. Prior to computer analysis, the microphone and preamplifier frequency response were corrected to flat (1-6 Hz) using manufacturer data sheets. Instruments are itemized in Table 1.

Each sound-level measurement system was independently field-calibrated (end-to-end) prior to and verified after the survey measurements with an acoustic sound-level calibrator (Brüel & Kjær, Type 4230 or Larson Davis CAL200), generating a 1,000 Hz tone with 94 dB sound pressure level (SPL) reference 20 µPa root mean square (RMS). Sound-level meters and acoustic calibrators had current laboratory calibration certificates traceable to National Institute of Standards and Technology.

The ANSI (American National Standards Institute) filter characteristics of Type 1 instrumentation have a long impulse response time at low frequencies. At 1 Hz, the ANSI 1/3 octave band impulse response is close to 5 seconds. Thus, ANSI filters do not capture the fast peak pressure changes occurring in the low and infrasonic frequencies (Bray & James, 2011).

To observe fast peak pressure changes, signal analysis was improved by using an external digital filter in series with the digital recording playback output, and then analyzing the digital data with a fast Fourier transform (FFT) signal analyzer with short time length (<128 milliseconds).

Field testing was conducted in general accordance with applicable ANSI Standards, ANSI S12.18-1994 ("Procedures for Outdoor Measurement of Sound Pressure Level," Method 1) and S12.9-1993/Part 3 ("Procedures for Short-Term Measurements with an Observer Present"). Indoor-outdoor simultaneous measurements were made using two microphones to determine the outside-to-inside level reduction (OILR) for the exterior walls and roof. The OILR

Table 1. Instrument List

Instrument	Manufacturer	Model
Microphone	Brüel & Kjær	4165
Preamplifier	Larson Davis	2221
Microphone	GRAS	40AN
Preamplifier	Larson Davis	902
Sound level meter	Larson Davis	824
Calibrator	Brüel & Kjær	4230
Audio interface	Sound Devices	USBPre2
Recorder	M-Audio	Microtrack II
Software	Pioneer Hill	SpectraPLUS 5.0
Microphone	Svantek	SV22
Preamplifier	Svantek	SV12L
Sound level meter	Svantek	949
Calibrator	Larson Davis	CAL200
Audio interface	ROGA	DAQ2
Recorder	TEAC	DR100

measurements were performed in accordance with ASTM E966-02 (ASTM, 2010). The indoor microphone was fitted with a 4-inch windscreen and mounted on a microphone stand in the master bedroom at a location where the reported adverse symptoms were more pronounced. The outdoor microphone was fitted with a 4-inch windscreen and placed inside a RODE Blimp for improved wind and shock mount protection. The entire outdoor system was mounted on a tripod, positioned 5 feet above the ground, and located away from house and trees. Wind speeds were light at the outdoor microphone position. In addition to noise measurements, weather, temperature, and wind speed data were collected.

The A- and C-weighting, octave band, and FFT analysis were performed with SpectraPLUS software in real time and recording mode on-site. The recorded data were analyzed off-site using the postprocessing features. G-weighted sound levels were computed using FFT settings for octave band analysis of the G-filtered 4, 8, 16, and 31.5 Hz octave bands using the G-weighting corrections which are the average value for the one-third octave bands comprising each full octave band (ISO 7196:1995, "Acoustics–Frequency Weighting"). While coarse in approach, the method was determined to be a usable trade-off between analysis time, accuracy, and computational requirements. It should be noted that the dBG levels obtained using the ANSI octave band filtering would not capture the highest peak pressure changes, so data reported are considered to understate the peak dBG levels.

Octave band (Hz)	4	8	16	31.5
dBG correction (dB)	−16	−4	+7.7	−4

The A-, C-, G-weighting and unweighted (dBL) filter functions are shown in Figure 1.

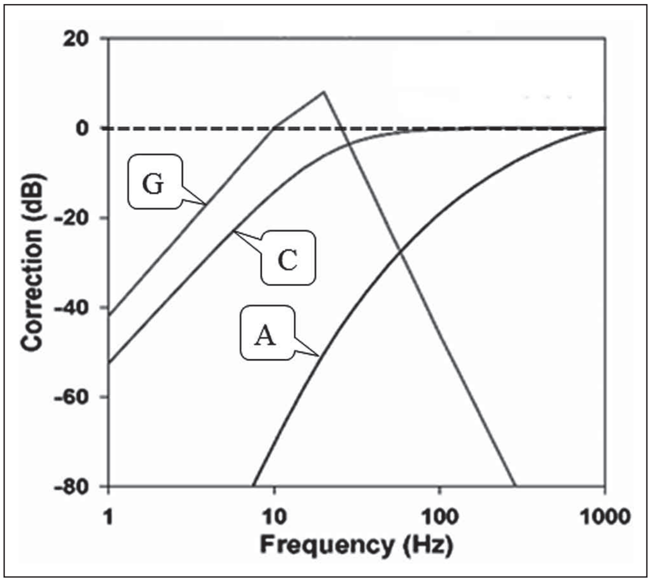

Figure 1. Weighting functions
Source. Adapted with permission from figure located at http://oto2.wustl.edu/cochlea/wt4.html

The A- and C-weighting filters discount frequency-level contributions below 1,000 Hz and 20 Hz, respectively. The G-weighting was created for evaluating infrasound, peaking at 20 Hz with rapid declines above and below which follow the recognized hearing response to pure sine waves, with a slope of 12 dB per octave. Unweighted (or dBL; dashed line) has flat frequency response over the entire bandwidth.

Weather Conditions

The survey was started in the late afternoon of April 17, 2011 (Day 1) and concluded in the morning of April 19, 2011 (Day 3). The weather conditions were representative of pleasant warm, windy spring days with cool, calmer nights.

Outdoor measurements were made when weather conditions were favorable for measurements (ground-level winds ≤ 9 mph [miles per hour] and no precipitation). Observed weather conditions and the nearest publicly accessible met tower are presented in the appendix.

Wind Turbine Operations

In the spring of 2011, Falmouth imposed a maximum wind speed restriction on their WIND1 in an effort to mitigate neighbors' complaints. WIND1 operation was modified to curtail power generation whenever the hub-height wind speeds exceeded 10 m/s. The town did not curtail NOTUS even though it was close to neighbors. The manufacturer has a setting to trip units off when the hub-height wind speed exceeds 32 m/s.

Results

Observations and Comments

> Day 1: Hub-height wind speeds were from the west at 20 to 25 m/s, gusts exceeding 30 m/s (66 mph, gale force aloft). Surface winds were light from the southeast, contrary to upper level westerly winds. At night, the hub-height wind speed slowly decreased to light, whereas the surface wind speed decreased to nearly calm.

Outdoor noise measurements were first made on arrival at the study house. The NOTUS turbine was clearly audible (520 m distant) and WIND1 (1,220 m distant) was off.

Within 20 minutes of setting up work stations inside the study house, the investigators started to experience a loss of well-being and continued to worsen with time. They had difficulty performing routine survey and measurement tasks: connecting instruments, assessing for proper operation, and calibration. They experienced inability to stay focused using a computer or track survey scope of work.

After repeated efforts, it was determined that reliable indoor measurements were not possible because of debilitation. No meaningful measurements were acquired at ML-1 during the first evening when winds were strong.

Near midnight the wind speed started to decrease, prompting an effort to leave the house to attempt outdoor noise measurements nearer NOTUS. These measurements are discussed in more detail in the "Sound Level Versus Distance Measurement" section.

> Day 2: Light pre-dawn hub-height wind speed slowly increased during the morning to above 18 m/s and continued throughout the day and decreased to light in the early evening. During the early night the wind speed remained light.

NOTUS noise was dominating with outdoor and indoor levels in the low 40s and 20s dBA, respectively. Spectral, one third, and full octave band sound levels were viewed with computer-based frequency analysis software for several hours during the day. Infrasound and low frequencies were of special interest and these had the highest unweighted SPLs. Outdoor–indoor (OILR) measurements were conducted. Digital recordings were made for a postprocessing at a later date.

> Day 3: After midnight the wind speed increased to strong and decreased to light at sunrise.

Normal workday sounds from nearby commercial activity were intermittently audible. There were faint noises from diesel equipment operating at a nearby sandpit, light traffic on Rte. 28, 1,700 m (5,600 feet) away and an occasional vehicle on the nearest road, 300 m (1,000 feet) away). NOTUS was stopped and WIND1 was inaudible but operating in light winds as observed by ILFN modulations detectable on analyzer. This presented an opportunity to obtain digital recordings with WIND1 operating alone in light winds at ML-1. The wind died and the survey was concluded mid-morning.

Figure 2. NOTUS measurement locations

Sound Level Versus Distance Measurement

Sound-level measurements and recordings were made at four distances to show the noise level decrease with increasing distance and the distance for blending into the background acoustic environment. This technique can be called "level versus distance," "walk-away," or "stepped distance."

Measurements with digital recordings were made at three locations trending north-northeast away from NOTUS (MLA, B, and C at 80, 250, & 410 m (260, 830, 1,340 feet), respectively) in the Falmouth Technology Park, as shown in Figure 2. Measurements were ceased when it started to rain after 1:30 a.m. The fourth location (ML-1) was to the southeast at the survey residence (at 520 m or 1,700 feet). NOTUS noise was dominant at all measurement locations.

Investigator Assessment

IWT power outputs were obtained from the NOTUS and WIND1 websites. Figure 3 shows the power output and wind speed.

Table 2 was created to correlate the NOTUS IWT power output, measured dBA, dBG, and dBL data at ML-1 and adverse health effects experienced by the investigators at ML-1 during the operating conditions of the NOTUS wind turbine.

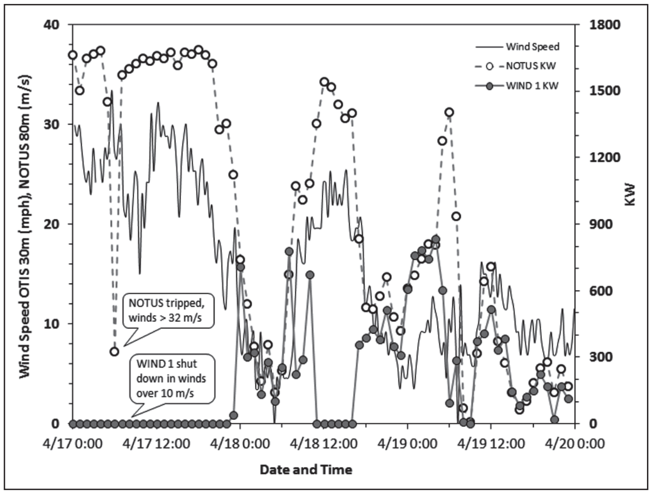

Figure 3. Wind turbine wind speed and power output

Figure 4 was created by combining Table 2 with Figure 3 to show the relationship of NOTUS power output, wind speed, and health states experienced by the investigators.

WIND1 was configured with an operational cap at 10 m/s and was off during the higher wind speeds. The investigators were most noticeably affected when the IWT power output was highest, with wind speeds more than 10 m/s at hub height for NOTUS while at the study location (at 520 m).

Figure 4 also shows the hours when the investigators were not as severely affected. Symptoms moderated during the first night when IWT power output dropped when nighttime noise measurements were made near NOTUS, and later while sleeping. When the power output increased (with wind speed greater than 10 m/s) during the following morning, symptoms returned, yet slowly went away (with increased distance from the IWT) after leaving the area for breakfast. On returning to the study house (at 520 m) the symptoms quickly set in again and remained strong until late afternoon when IWT power output dropped with lower wind speeds. The investigators left for an evening meal and symptoms moderated somewhat, yet, even with the increased distance from the IWT, the symptoms continued strongly enough to suppress appetite and affect thinking. When the investigators went to bed they had fitful sleep with numerous awakenings. Concurrently, IWT power output increased during the night, with average hub-height wind speeds fluctuating above and below 10 m/s during the early morning hours. In the morning, winds decreased to light, with NOTUS stopped and WIND1 turning in the distance (at 1,220 m).

Onsite Analysis Conducted on Day 2

A representative outdoor noise spectrum (RMS) was plotted with the outer hair cells (OHCs) and inner hair cells (IHCs) dBG thresholds, as shown in Figure 5A. The graph shows that the NOTUS 22.9-Hz tone exceeds the OHC threshold of 45 dB at 22.9 Hz. The 129-Hz tone exceeded the IHC threshold and was confirmed as audible outdoors (see, *OHC and IHC*) in the "Discussion" section).

The simultaneously measured indoor noise spectrum (RMS) is shown in Figure 5B. The graph shows that the NOTUS 22.9-Hz tone again exceeds the OHC threshold. The 129-Hz tone was less audible than outdoors. The spectrum was amplitude modulated and the averaged spectrum does not reveal the peak sound levels which may have exceeded the audibility threshold.

Time-History Tone Analysis

NOTUS noise levels and frequency content noticeably fluctuated with time. It would be appropriate to analyze these variations versus time focusing on the 22.9-Hz tone because it was shown to be detectable by the OHC. A 20 to 24 Hz 10th order digital bandpass filter was inserted between the digital recording output and the analysis input channel for SpectraPLUS software set to acquire FFT frames at 23-millisecond intervals using Hamming weighting. These furnished the band-limited tonal energy at 22.9 Hz free of ANSI filter response times.

Figure 6 shows the indoor time history of 22.9-Hertz amplitude variations above and below the OHC threshold of 45 dB. This graph shows amplitudes as high as 60 dB, which is 10 dB higher than the 50 dB average. The total fluctuation, maximum to minimum exceeds 50 dB.

This graph shows that the OHC is receiving pressure events nearly every 43 milliseconds at least 50% of the time during the measurement. The 22.9-Hz tone was not audible because it was not strong enough to exceed the IHC threshold (approximately 72 dB at 22.9 Hz).

Time-History dBG Analysis

Indoor and outdoor recordings with NOTUS operating were made on the afternoon of Day 2 and with NOTUS not operating due to very light wind on the morning of Day 3. This enabled time-history plots showing the dBG differences between NOTUS "ON" and NOTUS "OFF" for both indoors and outdoors as shown in Figure 7A and B. These data illustrate amplitude modulations exceeding 60 dBG. They were acquired through ANSI filter octave bands corrected to dBG. Because of ANSI filter impulse response times, they do not capture the highest peak pressure levels.

Indoors, the NOTUS "ON" dBG levels were about 20 dB higher than when "OFF." Outdoors, the NOTUS "ON" versus "OFF" dBG difference was about 10 dB.

Sound Level Versus Distance Measurement

Outdoor sound levels decrease at about 6 dB per doubling of distance (6 dB/dd) as depicted by the inverse square law for acoustic frequencies. Sound level versus distance measurements were plotted using a semilog scale for distance. This graphing method typically shows the drop of sound level as a straight line as the distance increases.

Table 2. NOTUS Operations, ML-1 Sound Levels, and Adverse Health Effects

Hub wind speed (m/s)	NOTUS output (kW)	Location	dBA	dBG	dBL	Symptoms experienced
Day 1: 25, gusts: 35	1,600-1,700	Indoors	n/a	n/a	n/a	Nausea, dizziness, irritability, headache, loss of appetite, inability to concentrate, need to leave, anxiety
		Outdoors	n/a	n/a	n/a	Felt miserable, performed tasks at a reduced pace
Night 1: 0-9	150-350	Indoors	18-20	n/a	n/a	Slept with little difficulty
Day 2: 20, gusts: 30	1,350-1,500	Indoors	18-24	51-64, pulsations	62-74, pulsations	Dizzy, no appetite, headache, felt miserable; performed tasks at a reduced pace. Desire to leave
		Outdoors	41-46	54-65, pulsations	60-69, pulsations	Dizzy, headache, no appetite. Slow. Preferred being outdoors or away
Night 2:	150-350	Indoors	18-20	n/a	n/a	Slept fitfully, woke up
Day 3: calm to 6	OFF	Indoors	18-20	39-44, random	50-61, random	Improvement in health. Fatigue and desire to leave
		Outdoors	32-38	49-54, random	57-61, random	Improvement in health. Fatigue and desire to leave

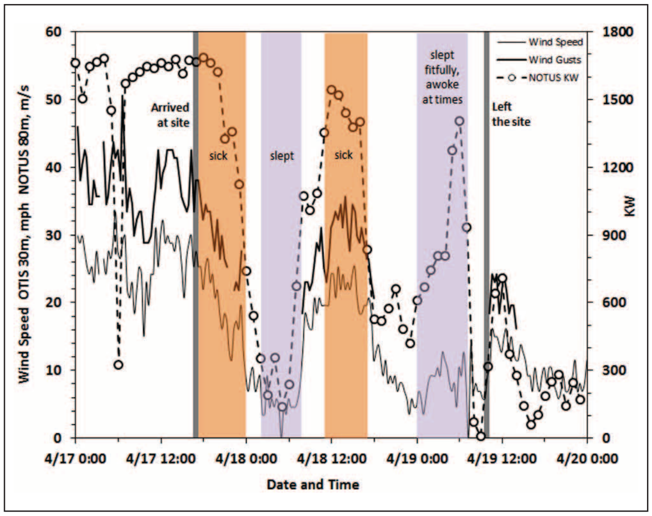

Figure 4. Survey operations at ML-1

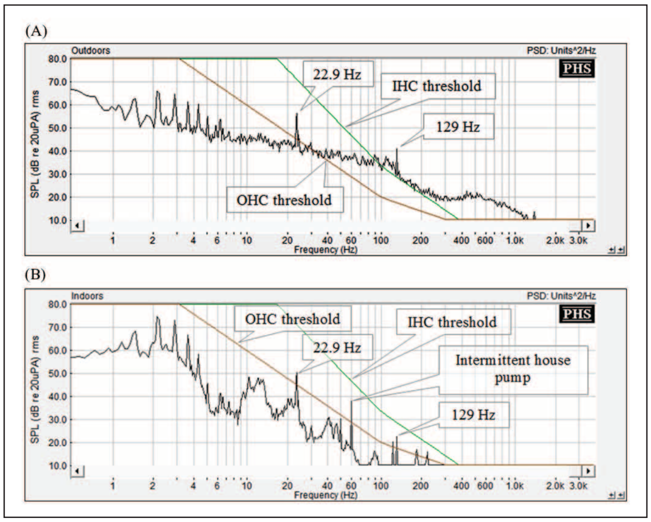

Figure 5. (A) Outdoor and (B) indoor NOTUS sound levels (averaged) versus outer hair cell (OHC) and inner hair cell (IHC) thresholds

The "stepped distance" data combined with the data at ML-1 show that the NOTUS noise level decreases with distance uniformly, as shown in Figure 8.

Two trend lines are included; the lower dashed line shows the dBA sound levels decreasing at a predictable 6 dB per distance doubling (6 dB/dd). The dBA trend line is faired through a wind speed of 8 m/s per the NOTUS specification wind speed. The upper dashed line is for unweighted sound levels, which was controlled by frequencies below 20 Hz. The unweighted sound levels decrease at about 3 dB/dd, which is representative of cylindrical spreading.

Noise levels at the study house showed that the indoor levels were more than 20 dBA quieter than outdoors. However, the unweighted dBL levels were several dB higher indoors than outdoors, indicating that the house was providing reinforcement (amplifying) of the very low frequencies.

House Noise Reduction

Measurements were made with the NOTUS "ON" with hub-height wind speeds averaging about 20 m/s. One-minute duration transfer function analysis measured the difference between outside and inside noise levels. The difference is shown by narrow band frequency (FFT) in Figure 9A, and by full-octave bands in Figure 9B.

The two graphs show the OILR by the two exterior master-bedroom walls and roof. Negative values indicate attenuation

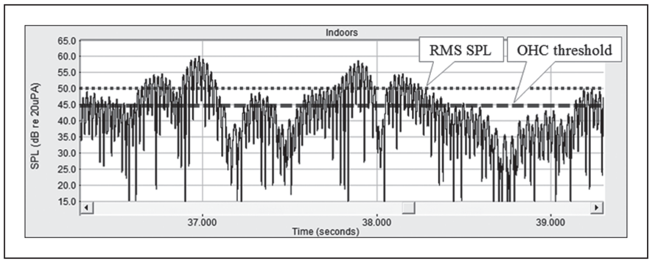

Figure 6. 22.9-Hz tone and OHC threshold
Note. OHC = outer hair cell; RMS = root mean square; SPL = sound pressure level.

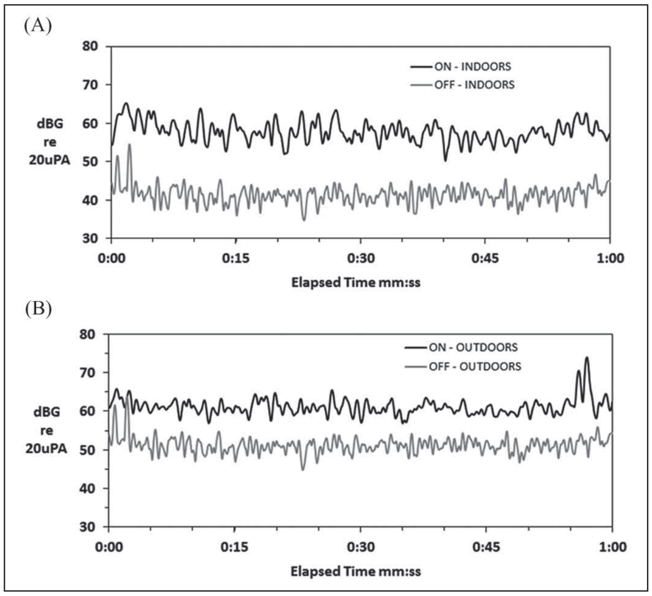

Figure 7. (A) Indoor and (B) outdoor dBG levels

and positive values show amplification. The graphs show high-frequency attenuation of 20 dB or more, about 15 dB in the 31.5-Hz octave band, and about 10 dB in the 8- and 16-Hz octave bands. The very low-frequency bands show amplification of about 3 and 8 dB in the 4- and 2-Hz bands, respectively.

Because of the house structure dramatically influencing interior very-low-frequency levels, the meter measurement units were changed from the log scale (dB) to a linear Pascal to expand the "*y*"-axis scale. The outdoor and indoor octave band Pascal levels are shown in Figure 10A and B, respectively. These are averaged levels and do not illustrate the dynamic amplitude modulation.

The difference between indoors and outdoors time history is shown in Figure 11. The outdoors graph shows the influence of higher frequencies that are not present indoors due to structure attenuation. Dynamic amplitude modulation is clearly visible.

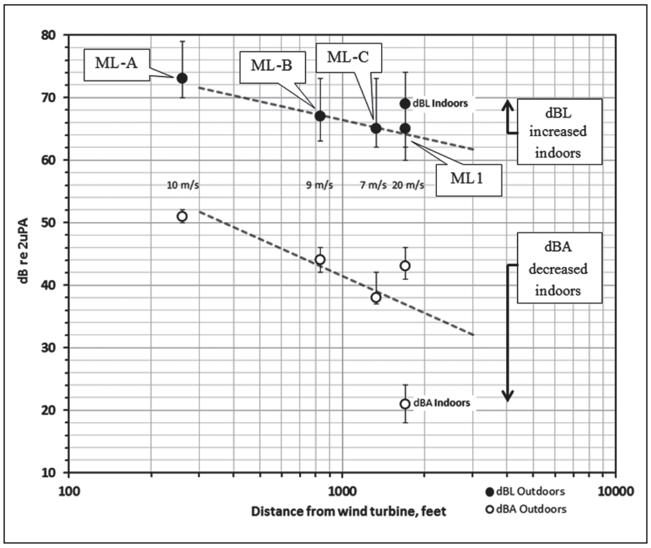

Figure 8. NOTUS root mean square (RMS) sound level versus distance

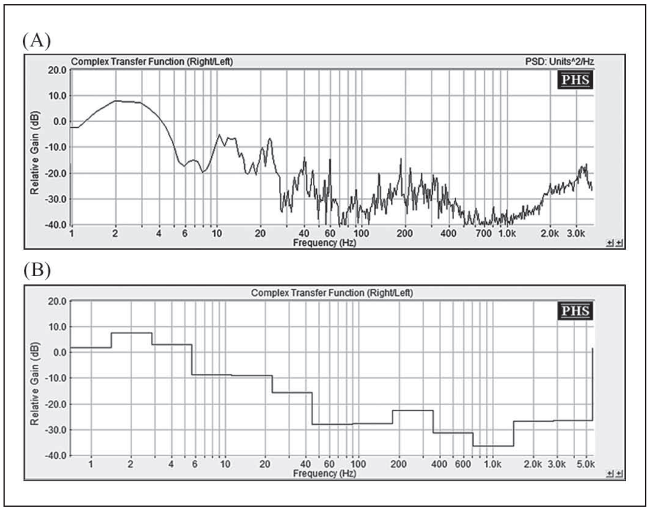

Figure 9. Outside-to-inside level reduction: (A) fast Fourier transform and (B) octave band

Acoustic Coupling

The comment "It's like living inside a drum" has been made by many neighbors living near IWT sites. These comments suggest that IWT low-frequency energy is being acoustically coupled into the interior space. Coherence analysis was used to determine the relationship between outdoor and indoor acoustic signals. Coherence values approaching 1.0 have a strong correlation and when less than 0.7 there is significantly less correlation. Figure 12 presents the coherence analysis results with the strong correlation, 0.7 to 1.0 highlighted.

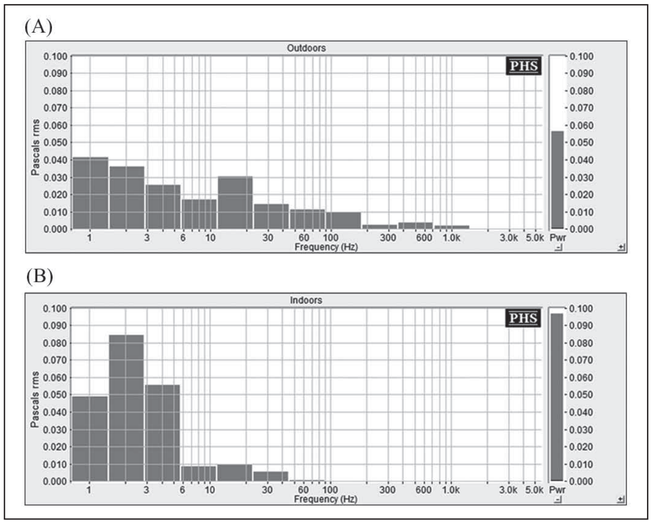

Figure 10. (A) Outdoor and (B) indoor sound pressure in Pascals

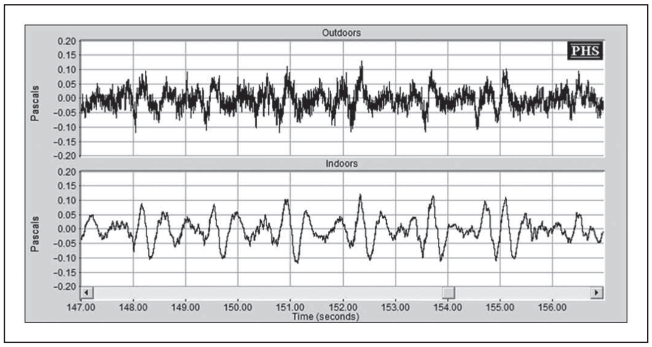

Figure 11. Pressure fluctuation time history in Pascal

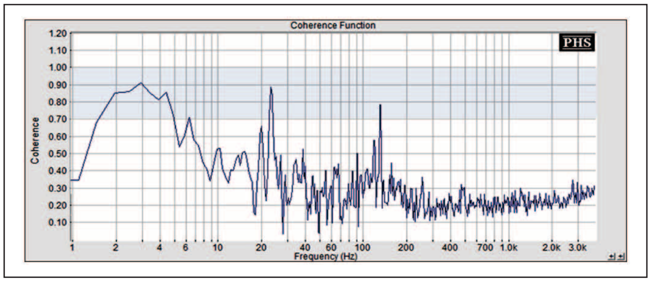

Figure 12. Coherence, outdoors to indoors

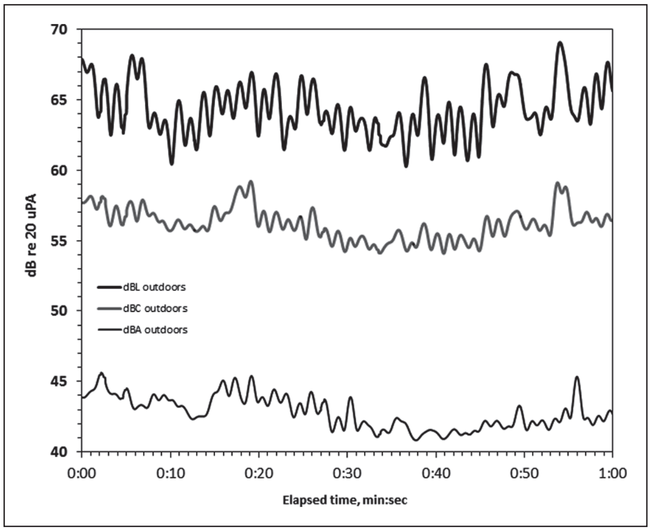

Figure 13. Outdoors sound levels: NOTUS "ON" (April 18, 2011)

The highlight banding shows which frequencies inside the house are judged to be directly coupled to the outside energy. High coherence was evident for the very low infrasonic frequencies and at 22.9 and 129 Hz.

Dynamic Amplitude Modulation Measurements

Wind turbine noise has a unique sound characteristic that distinguishes it from other man-made and environmental noise due to the strong dynamic amplitude modulation caused by the blades. Overall dBA, dBC, and dBL acoustic signatures were graphed as level versus time, as shown in Figure 13. The amplitude modulation was occasionally audible as indicated in the dBA time history. The dBL time history has higher amplitude modulations than dBA and dBC because there is no filter reduction for lower frequencies and, the strong amplitude modulations occurring at the blade pass frequency are revealed.

A comparison of the overall dBL indoors versus outdoors shows that the indoors levels are about 2 to 8 dB higher than outdoors, as shown in Figure 14. This graph also shows that the amplitude modulation increased in range indoors with rise and fall exceeding 10 dB per second.

The increase in the dBL levels and amplitude modulation indoors is consistent with and supports neighbors' comments that it is worse indoors than outdoors.

NOTUS "ON" and "OFF"

Outdoor measurements with NOTUS "ON" show stronger pulsation fluctuations than when NOTUS is "OFF," as shown in Figure 15.

Pressure Pulsation Exposure and Dose Response

It is generally accepted that human response and cumulative effect to intrusive noise exposure increases with number of peak noise events and peak level. This is consistent with the gradual onset over some 20 minutes of adverse health effects experienced by the investigators at ML-1 on the first day and the repeated onset of symptoms when returning to ML-1 during the survey.

For total unweighted sound exposure, the investigators were exposed to dynamically modulated pressure pulsations

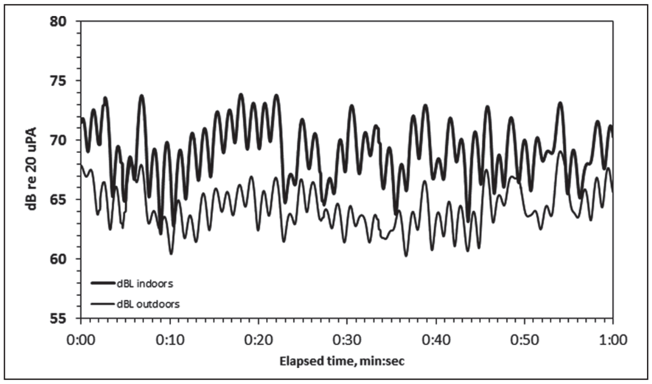

Figure 14. Acoustic pressure fluctuation time history (indoors versus outdoors; April 18, 2011, 3:22 p.m.)

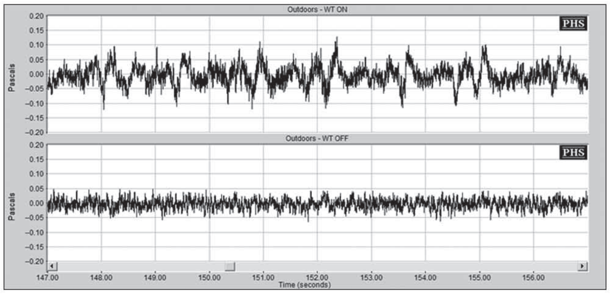

Figure 15. NOTUS "ON" and "OFF" sound pressure levels outdoors, ML-1

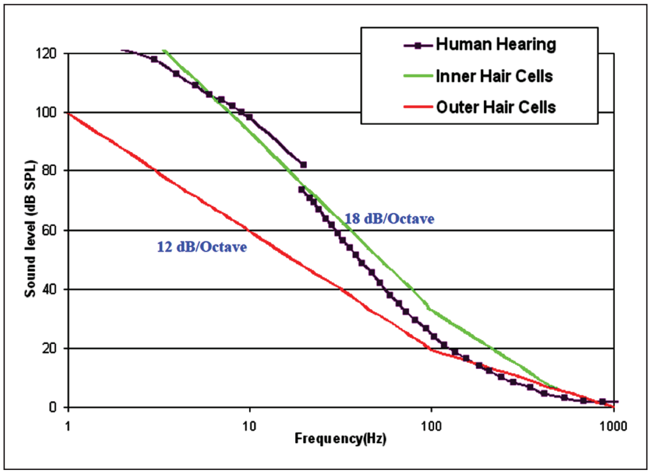

Figure 16. Human audibility curves

every 1.4 seconds (NOTUS blade pass rate) at the study house (Figure 15). After being indoors for 15 minutes, the pulsations totaled 642 peak pressure events. Every hour there were 2,570 pressure events. When the physiological effects were worst (at 5 hours exposure) the total exposure was 12,800 blade-pass peak pressure events. The time-history data suggest that over 50% of the peak pressure impacts exceeded the 60 dBG physiological OHC threshold (see *OHCs and IHCs* in the "Discussion" section).

The occurrence of pressure events at 22.9 Hz (Figure 6) is much higher. The acoustic pressure at 22.9 Hz dropped well below OHC threshold and then peaked over OHC threshold but not over the IHC threshold, at a rate of more than 82,000 per hour and more than 400,000 in 5 hours. If 50% of the 22.9-Hz pressure levels were detected by the OHC that would result in more than 200,000 stimulations to the OHCs in a 5-hour period.

Discussion

Human Detection Thresholds

Sound pressure is the small alternating deviation above and below atmospheric pressure due to the propagated wave of compression and rarefaction. The unit for sound pressure is the Pascal (symbol: Pa). SPL or sound level is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. It is measured in decibels (dB) above a standard reference level. The commonly used "zero" reference sound pressure in air is 20 µPa RMS, which is usually considered the median threshold of human hearing (at 1 kHz). Some 16% of the population is about 6 dB more sensitive than the median, and some 2% is 12 dB more sensitive. The percentage of people who are more sensitive who choose to live in quieter rural areas is unknown. That is, those living in quiet areas may have sensitivity shifted toward lower thresholds and self-select quieter areas.

Frequency is measured by the number of waves per second or Hertz (Hz). The average range of hearing is 20 to 20,000 Hz with the greatest sensitivity in 1,000 to 4,000 Hz range. At the most sensitive frequency around 4 kHz, the amplitude of motion of the eardrum is about 10 to 9 cm, which is only about 1/10 the diameter of a hydrogen atom. Thus, the ear is very sensitive, detecting signals in the range of atomic motion.

Outer Hair Cells and Inner Hair Cells

There are two types of hair cells in the cochlea where sound pressure is converted to nerve impulses; the IHCs and the OHCs. The IHCs are fluid connected and velocity sensitive, responding to minute changes in the acoustic pressure variations based on frequency, with sensitivity decreasing at a rate of −6 dB per downward octave. IHCs detect audible sounds and they are insensitive to low-frequency and infrasonic acoustic energy. In contrast, the OHCs are mechanically connected, or DC-coupled, to movements of the sensory structure and respond to infrasound stimuli at moderate levels, as much as 40 dB below IHC thresholds. The approximate threshold for physiological response by OHCs to infrasound is 60 dBG.

Figure 16 shows the IHC and OHC responses compared with ISO 2003 and Møller and Pedersen (2011) audibility measurements. Adapted with permission, from figure located at http://oto2.wustl.edu/cochlea/romesalt.pdf

OHC responses to infrasound are maximal when ambient sound levels are low. Furthermore, low-frequency sounds produce a biological amplitude modulation of nerve fiber responses to higher frequency stimuli. This is different from the amplitude modulation of sounds detected by a sound-level meter (Salt & Lichtenhan, 2011).

Adverse Health Effects

A 2011 Ontario Review Tribunal Decision found that wind turbines can harm humans if placed too close to residents stating,

> This case has successfully shown that the debate should not be simplified to one about whether wind turbines can cause harm to humans. The evidence presented to the Tribunal demonstrates that they can, if facilities are placed too close to residents. The debate has now evolved to one of degree. (*Erickson v. Director*, 2011)

Some individuals exposed to wind turbines report experiencing adverse health effects which include physiological and psychological symptoms as well as negative impacts on quality of life (Harry, 2007; Krogh, Gillis, Kouwen, & Aramini, 2011; Nissenbaum, Aramini, & Hanning, 2011; Phipps, Amati, McCoard, & Fisher, 2007; Shepherd, McBride, Welch, Dirks, & Hill, 2011; Thorne, 2011). In some cases the adverse effects are severe enough that some individuals have elected to abandon their homes. In other cases, homes of individuals reporting health effects have been purchased by the wind energy developer (Krogh, 2011). The World Health Organization's (1948) definition of health includes physical, mental, and social well-being. Adverse impacts associated with IWTs fall within the WHO definition of health.

Pierpont (2009) describes symptoms reported by individuals living near wind turbines. Symptoms include "sleep disturbance, headache, tinnitus, ear pressure, dizziness, vertigo, nausea, visual blurring, tachycardia, irritability, problems with concentration and memory, and panic episodes associated with sensations of internal pulsation or quivering when awake or asleep." G. Leventhall (2009) states,

> I am happy to accept these symptoms, as they have been known to me for many years as the symptoms of extreme psychological stress from environmental noise, particularly low frequency noise . . . what Pierpont describes is effects of annoyance by noise–a stress effect . . .

An expert panel review commissioned by the American Wind Energy Association and Canadian Wind Energy Association stated that these symptoms are not new and have been published previously in the context of "annoyance" to environmental sounds and are an example of the "well-known stress effects of exposure to noise" associated with noise annoyance (Colby et al., 2009).

Wind turbine sound is perceived to be more annoying than other equally loud sources of noise (Pedersen, Bakker, Bouma, & van den Berg, 2009). Higher levels of annoyance may be partly explained by wind turbine noise amplitude modulation, lack of night time abatement, and visual impacts. Wind turbine tonal and audible low-frequency sound are also plausible causes of wind turbine noise annoyance (Møller & Pedersen, 2011) and reported health effects (Minnesota Department of Health, 2009) and, may play an important part in the cause for adverse community reaction to large IWTs installed close to residences in quiet areas. Complaints associated with wind turbine low-frequency noise are often more prevalent indoors than outdoors. Recently there have been recommendations to address the impacts of wind turbine low-frequency noise (Howe Gastmeier Chapnik Limited, 2010; The Social and Economic Impact of Rural Wind Farms, 2011).

Wind turbine noise standards and most regulations are based on the averaged A-weighting metric which suppresses the amplitude of low-frequency noise predictions in modeling and application submittals. Averaged A-weighted sound-level measurements are unsatisfactory when individuals are annoyed by low-frequency sound and amplitude modulation (H. G. Leventhall, 2004; Richarz, Richarz, & Gambino, 2011). The A-weighting filter severely attenuates low-frequency signals (the primary frequency range of most community noise complaints) and essentially eliminates acoustic signals below 20 Hz where "infrasound" is located in the acoustic frequency spectrum.

Low-frequency vibration and its effects on humans are not well understood and sensitivity to such vibration resulting from wind turbine noise is highly variable among humans (National Research Council, 2007). Whether exposure to wind turbine infrasound can contribute to adverse effects in humans is a subject of considerable debate. There are aspects of infrasound from wind turbines that are not unanimously accepted by all technical and medical practitioners (Howe Gastmeier Chapnik Limited, 2010). Some discount wind turbine infrasound as a concern on the basis that levels are below the hearing threshold (Colby et al., 2009; G. Leventhall, 2006). It is noted that other noise sources can generate infrasonic energy, such as surf and thunderstorms. However, wind turbine low-frequency energy presents a recurring and/or unpredictable pressure signature, with audibility or delectability occurring over a much longer period of time than other environmental sources of low-frequency energy.

An audible or detectable acoustic or pressure signature is valuable for subsequent monitoring of system design and correlating with complaints and exploring the plausibility that wind turbine low-level low-frequency energy could contribute to reported adverse health effects.

Infrasonic thresholds for human perception have been found to be lower than those previously estimated based on traditional sinusoidal hearing tests. There is evidence indicating that vestibular system does respond to sound we cannot hear (Salt & Hullar, 2010). Infrasound is understood by acousticians to refer inaudible acoustic energy for frequencies less than 20 Hz. There is increasing evidence that the OHC can detect nonsinusoidal pressure fluctuations at lower amplitudes than the IHC. Current research estimates that sound levels of 60 dBG for frequencies from 5 to 50 Hz can stimulate the OHC for the human ear (Salt & Kaltenbach, 2011).

Cochlear microphonic responses to infrasound recorded in endolymph of the third turn of the guinea pig cochlea are suppressed by the presence of higher frequency sounds. This suggests that the physiologic response to infrasound may be maximal when heard under quiet conditions, such as that may occur in a quiet bedroom in the vicinity of a wind turbine (Salt & Lichtenhan, 2011).

Sleep disturbance is one of the most common adverse health effects reported by neighbors living near IWTs (Hanning & Evans, 2012; Minnesota Department of Health, 2009). The investigators experienced sleep disturbance, especially during the second night when hub-height wind speeds were greater than 10 m/s. The indoor sound level was low at around 20 dBA and was below levels typically recommended to minimize sleep disturbance.

Sleep disturbance during this study was experienced by the investigators and reported by the home owners. A first assessment of the analyzed noise level data appears to show a stronger correlation with the 60-dBG threshold than it does with dBA-weighted sound levels. Recorded noise level analysis shows that NOTUS produces a strong 0.7-Hz blade-pass modulation and a strong 22.9-Hz tone sufficient to be detected by the OHC but remain inaudible.

Conclusions

Noise and Pressure Pulsations

This study revealed dynamically modulated low-frequency and infrasonic energy produced by NOTUS. The acoustic energy from NOTUS was found to be greater than and uniquely distinguishable from the ambient background levels without NOTUS operating. NOTUS produced dynamic infrasonic modulations that were not present when the wind turbine was off. NOTUS “ON” produced tonal energy at 22.9 and 129 Hz, which were found to be strongly coupled to the study house interior. Amplitude modulations below 10 Hz were amplified indoors, suggesting a whole house acoustic cavity response.

The dBG levels indoors were dynamically modulated at the blade-pass rate and tonal frequencies and exceeded the vestibular physiological threshold guideline of 60 dBG.

Adverse Health Effects

A dose-response relationship to peak pressure events detected by the OHC is supported by the gradual onset of adverse health symptoms while near the IWT. At SPLs associated with worsened health symptoms, NOTUS produced low-frequency pressure pulsations that could be detected by the ears’ OHCs but not by the IHCs. Health effects moderated when dBG levels fell well below the 60-dBG guideline when the wind turbine was OFF, or when well away (several miles) from NOTUS.

The rapid onset of adverse health effects during the study confirms that wind turbines can harm humans if placed too close to residents. During the study, investigators without a preexisting sleep deprivation condition, not tied to the location nor invested in the property, experienced similar adverse health effects described and testified to by residents living near the wind turbines. Sound measurements acquired during the study indicate that A-weighted sound levels did not correlate to adverse health effects experienced. Adverse health effects experienced by investigators were more severe indoors where dBA levels were approximately 20 dBA lower than outdoors levels. The dBL (unweighted) and dBG (infrasonic-weighting) levels were higher and more strongly amplitude-modulated indoors compared to outdoors. The increase in amplitude modulation indoors was consistent with the stronger adverse health effects experienced indoors.

Wind turbine audible sound is perceived to be more annoying than equally loud transportation or other industrial noise and can be expected to contribute to stress-related health effects. Symptoms reported by some individuals exposed to IWTs can include sleep disturbance, headache, tinnitus, ear pressure, dizziness, vertigo, nausea, visual blurring, tachycardia, irritability, problems with concentration and memory, and panic episodes associated with sensations of internal pulsation or quivering when awake or asleep.

This acoustic study suggests that health effects reported by residents living near wind turbines may not be exclusively related to audible sounds. Inaudible amplitude modulated acoustic energy can be detected by the inner ear and can affect humans more at low ambient sound levels, consistent with complaints of worse conditions indoors than out near IWTs. The study results emphasize the need for epidemiological and laboratory research by health professionals and acousticians concerned with public health and well-being. These findings underscore the need for more effective and precautionary setback distances for IWTs. It appears prudent to include a margin of safety sufficient to prevent inaudible low-frequency wind turbine noise from adversely affecting humans.

Appendix

April 17, 2011

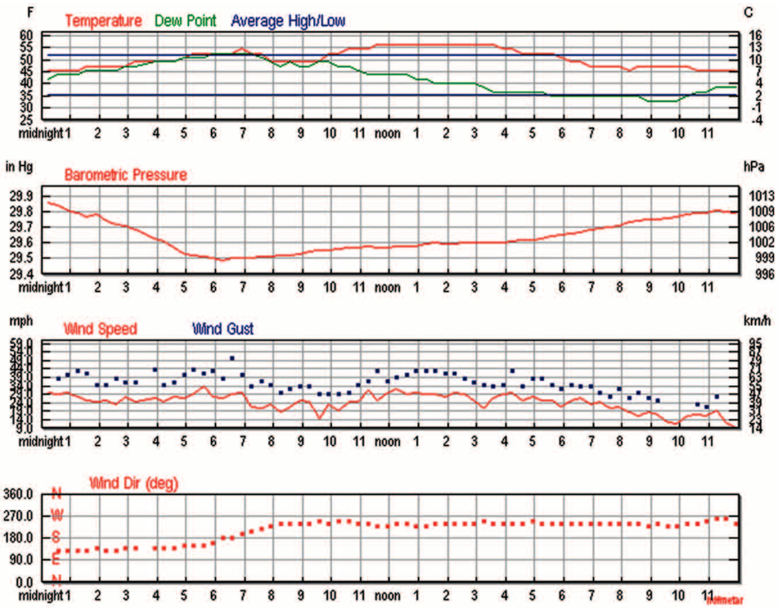

Figure 17. Day 1: Changeable weather with wind speeds 25 to 30 m/s at the hub, gusting to more than 35 m/s. Wind direction west–southwest. Barometer "low" and variable. Sunny and partly cloudy. Temperature 45°F to 50°F

April 18, 2011

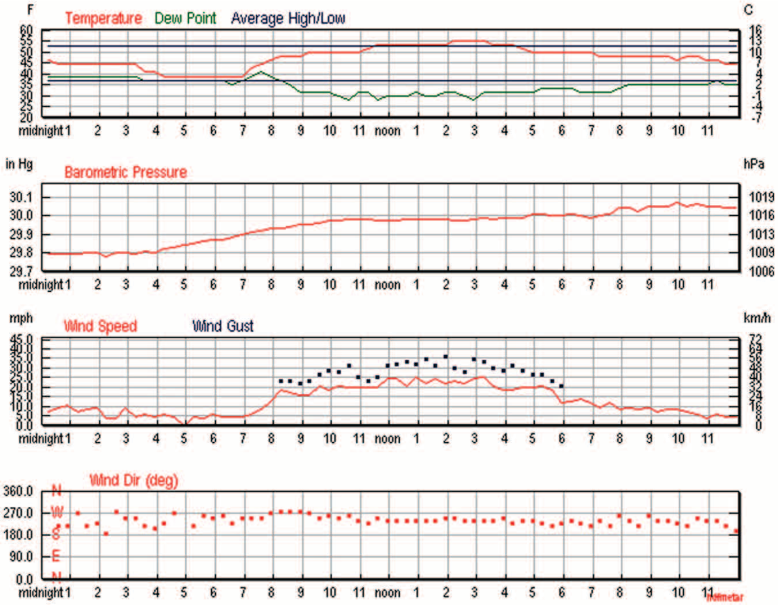

Figure 18. Day 2: Sunny with wind speeds 15 to 20 m/s at the hub, gusting to 25 to 30 m/s. Wind direction west–southwest. Barometer "low" and rising during the day. Temperature 45°F to 50°F

Appendix (continued)

April 19, 2011

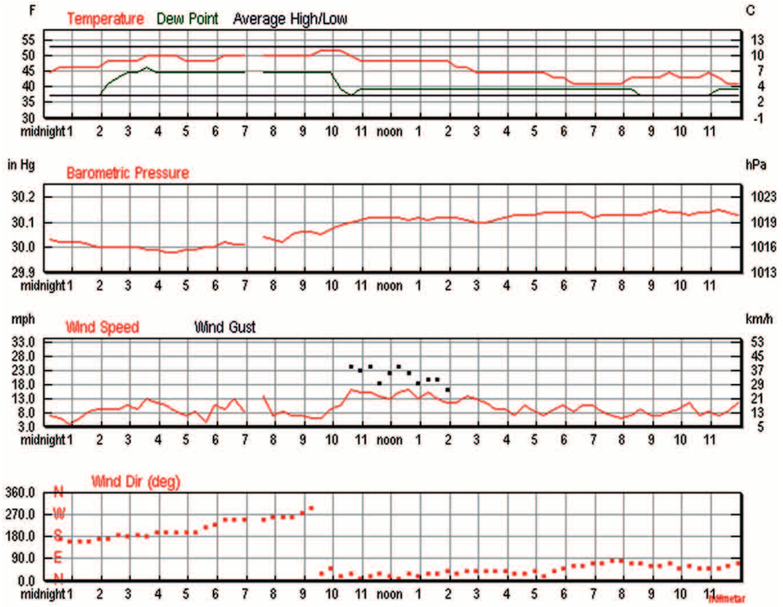

Figure 19. Day 3: Winds stopped in morning and the field study concluded at 9:30 a.m.

Acknowledgments

Authors Stephen E. Ambrose and Robert W. Rand would like to acknowledge the residents of Falmouth who welcomed them into their homes, extended their hospitality, communicated their experiences, and provided their time and assistance.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The data collected in the sound study were partially funded by a local resident through a grant for the purpose of conducting an independent investigation.

References

ANSI S12.18-1994 [R2004]. *American National Standard procedures for outdoor measurement of sound pressure level*. Retrieved from http://webstore.ansi.org/RecordDetail.aspx?sku=ANSI/ASA+S12.18-1994+(R2009)

ANSI/ASA S12.9-1993/Part 3 [R2008]. *American National Standard quantities and procedures for description and measurement of environmental sound. Part 3: Short-term measurements with an observer present*. Retrieved from http://webstore.ansi.org/RecordDetail.aspx?sku=ANSI/ASA+S12.9-1993/Part+3+(R2008)

ASTM (2010). *Standard guide for field measurements of airborne sound insulation of building facades and facade elements. Definition: outdoor-indoor level reduction, OILR—in a specified frequency band, the difference between the time-averaged exterior sound pressure and the space-time average sound pressure in a room of a building* (ASTM Designation: E 966–02). Retrieved from http://www.techstreet.com/standards/astm/e966_10e1?product_id=1788819

Bray, W., & James, R. (2011, July). *Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception*. Paper presented at Noise-Con 2011. Retrieved from http://www.windaction.org/documents/33315

Burt, T. (1996). Sick building syndrome: Acoustical aspects. *Indoor and Built Environment, 5*, 44-59. Retrieved from http://ibe.sagepub.com/content/5/1/44

Colby, W. D., Dobie, R., Leventhall, G., Lipscomb, D. M., McCunney, R. J., Seilo, M. T., & Søndergaard, B. (2009, December). *Wind turbine sound and health effects: An expert panel review*. Washington, DC: American Wind Energy Association and Canadian Wind Energy Association. Retrieved from http://www.canwea.ca/pdf/talkwind/Wind_Turbine_Sound and_Health_Effects.pdf

DeGagne, D. C., & Lapka, S. D. (2008). Incorporating low frequency noise legislation for the energy industry in Alberta, Canada. *Journal of Low Frequency Noise, Vibration and Active Control, 27*, 105-120.

Erickson v. Director. (2011). Ministry of the Environment, Environmental Decision Case Nos. 10-121 and 10-122. Retrieved from http://www.ert.gov.on.ca/english/decisions/index.htm

Hanning, C., & Evans, A. (2012). Wind turbine noise. *British Medical Journal, 344*, e1527.

Harry, A. (2007, February). *Wind turbines, noise and health*. Retrieved from http://docs.wind-watch.org/wtnoise_health_2007_a_harry.pdf

Howe Gastmeier Chapnik Limited. (2010, December 10). *Low frequency noise and infrasound associated with wind turbine generator systems: A literature review* (Rfp No. Oss-078696). Mississauga, Ontario, Canada: Ministry of the Environment.

ISO (1995). *Acoustics—Frequency-weighting characteristic for infrasound measurements* (ISO 7196:1995). Retrieved from http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=13813

Krogh, C. (2011). Industrial wind turbine development and loss of social justice? *Bulletin of Science, Technology & Society, 31*, 321-333.

Krogh, C., Gillis, L., Kouwen, N., & Aramini, J. (2011). WindVOiCe, a self-reporting survey: Adverse health effects, industrial wind turbines, and the need for vigilance monitoring. *Bulletin of Science, Technology & Society, 31*, 334-345.

Leventhall, G. (2006). Infrasound from wind turbines: Fact, fiction or deception. *Canadian Acoustics, 34*, 29-36.

Leventhall, G. (2009). *Wind turbine syndrome: An appraisal*. Hearing before the Public Service Commission of Wisconsin.

Leventhall, H. G. (2004). Low frequency noise and annoyance. *Noise & Health, 6*, 59-72.

Minnesota Department of Health. (2009, May). *Public health impacts of wind turbines*. Retrieved from http://www.health.state.mn.us/divs/eh/hazardous/topics/windturbines.pdf

Møller, H., & Pedersen, C. S. (2011). Low-frequency noise from large wind turbines. *Journal of the Acoustical Society of America, 129*, 3727-3744.

National Research Council. (2007). *Environmental impacts of wind energy projects*. Washington, DC: National Academies Press.

Nissenbaum, M., Aramini, J., & Hanning, C. (2011, July). *Adverse health effects of industrial wind turbines: A preliminary report*. Paper presented at the 10th International Congress on Noise as a Public Health Problem (ICBEN) 2011, London, England. Retrieved from http://www.windvigilance.com/about-adverse-health-effects/resource-centre

Pedersen, E., Bakker, R., Bouma, J., & van den Berg, F. (2009). Response to noise from modern wind farms in the Netherlands. *Journal of the Acoustical Society of America, 126*, 634-643.

Phipps, R., Amati, M., McCoard, S., & Fisher, R. (2007). *Visual and noise effects reported by residents living close to Manawatu wind farms: Preliminary survey results*. Retrieved from http://docs.wind-watch.org/phipps-visualnoiseeffects.pdf

Pierpont, N. (2009). *Wind turbine syndrome: A report on a natural experiment*. Santa Fe, NM: K-Selected Books.

Richarz, W., Richarz, H., & Gambino, T. (2011). *Correlating very low frequency sound pulse to audible wind turbine sound, Aercoustice Engineering Limited, Ontario, Canada*. Fourth International Meeting on Wind Turbine Noise, Rome, Italy.

Salt, A. N., & Hullar, T. E. (2010). Responses of the ear to low frequency sounds, infrasound and wind turbines. *Hearing Research, 268*, 12-21. doi:10.1016/j.heares.2010.06.007

Salt, A. N., & Kaltenbach, J. A. (2011). Infrasound from wind turbines could affect humans. *Bulletin of Science, Technology & Society, 31*, 296-302. doi:10.1177/0270467611412555

Salt, A. N., & Lichtenhan, J. (2011, April 12-14). *Responses of the inner ear to infrasound*. Paper presented at the Fourth International Meeting on Wind Turbine Noise, Rome, Italy.

Schust, M. (2004). Effects of low frequency noise up to 100 Hz. *Noise & Health, 6*, 73-85.

Shepherd, D., McBride, D., Welch, D., Dirks, K. N., & Hill, E. M. (2011). Evaluating the impact of wind turbine noise on health-related quality of life. *Noise & Health, 13*, 333-339.

The social and economic impact of rural wind farms. (2011, May 17). Public hearing before the Senate Community Affairs References Committee, Commonwealth of Australia. Retrieved from http://www.aph.gov.au/senate/committee/clac_ctte/impact_rural_wind_farms/index.htm

Thorne, B. (2011). The problems with noise numbers for wind farm noise assessment. *Bulletin of Science, Technology & Society, 31*, 262-290.

World Health Organization. (1948, April 7). *Preamble to the constitution of the World Health Organization as adopted by the International Health Conference, New York, 19-22 June, 1946; signed on 22 July 1946 by the representatives of 61 States* (Official records of the World Health Organization, no. 2, p. 100).

Bios

Stephen E. Ambrose has more than 35 years of experience in industrial noise control. Board Certified and Member INCE since 1978, he runs a small business providing cost-effective environmental noise consulting services for industrial and commercial businesses, municipal and state governments, and private citizens.

Robert W. Rand has more than 30 years of experience in industrial noise control, environmental sound and general acoustics. A Member INCE since 1993, he runs a small business providing consulting, investigator, and design services in acoustics.

Carmen M. E. Krogh, BScPharm, provided research and reference support. She is a retired pharmacist with more than 40 years of experience in health. She has held senior executive positions at a major teaching hospital, a professional association, and Health Canada. She was former Director of Publications and Editor-in-Chief of the *Compendium of Pharmaceutical and Specialties (CPS)*, the book used in Canada by physicians, nurses, and other health professions for prescribing information on medication.