

rumble/thump or other form of audible sound. A tone is a concentration of acoustic energy in a narrow frequency range. It is like the sound of a whistle or a stringed instrument playing a single note.

20Hz is often, incorrectly, presumed to be the lower limit of human hearing and sounds are generally considered to be infrasonic if their frequency is less than 20Hz. Sounds in these lower frequency ranges have some characteristics that are different from the more audible frequencies. One major difference is that infra and low frequency sounds travel farther than high frequency ones, which make them a potential problem at significant distances from the emitter. This is especially true in otherwise quiet rural or wilderness areas.

Infrasound produced by rotating machines is distinctive from background infrasound because the energy will be concentrated in narrow frequency bands (tones) that are related to the rotational speed of the drive shaft, the number of blades, and the number of structures that the blades “pass-by” during a rotation. On the other hand, infrasound from natural processes, such as thunder storms, high winds, fires, earthquakes, etc. will not produce tones, but instead produce infrasound that covers a wider, broader frequency range without concentration of energy in narrow ranges or at single frequencies. Unlike mid and high frequency sound, infrasound is not blocked by common construction materials. As such, it is often more of a problem inside homes which are otherwise quiet than it is outside the home where other mid and high frequency sounds of community activity moderate its perceptibility.

For example, a simple sinusoidal 1 Hz tone has a high and low pressure point every 1 second. One (1) Hz means the pressure wave cycles from positive to negative and back in one second. Under normal atmospheric conditions the length of this positive-negative wave is about 340 meters (1115 feet). The pressure wave is very large compared to most homes and structures. This pressure wave is normally depicted as having a sinusoidal envelope with pressure rising and falling gradually with it.

The shape of the pressure wave produced as the wind turbine’s blades pass the tower or traverse a region with turbulent air is not sinusoidal. Instead it is more dynamic with large changes in pressure over short periods of as little as few milliseconds. The wind turbine infrasound time signature is much more complex than a simple

sinusoidal wave. Dr. Malcolm Swinbanks has shown in a recent paper that if the waveform is not sinusoidal, but, instead has much of the acoustic energy concentrated in a short duration pulse, the potential for perceiving the pressure change/pulse is increased relative to what would be expected for perception of a sinusoidal waveform with equivalent energy. Thus, his work shows why it is expected that some people can feel a pressure wave with a short duration pulse of 50 to 100 milliseconds with a rapid rise to the peak pressure falling back to the lower pressure for the rest of the second. Wind



Figure 2 - Large Utility Box Fan

turbine tones have the characteristic of rapid pressure change with peak

Appendix 1: Terms and concepts related to wind turbine infrasound
 sound pressure levels 10 to 30 dB higher than the average when averaged over periods of a second or longer.
 This is covered in more detail later in this appendix.

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Further, these tones and pulsations are entirely predictable based on established and accepted first principles of aerodynamics, and other engineering fields. With respect to how and what type of noise is produced, utility scale wind turbines may be considered to be similar to large industrial scale cooling fans. The primary difference is that instead of using electricity to produce air movement, they use air movement to produce electricity. There is an extensive literature on how to design quiet fans and how to diagnose fan noise

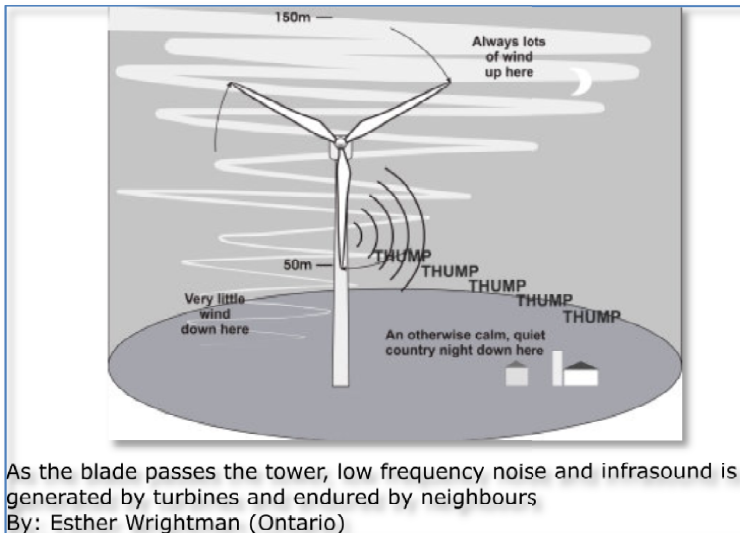
problems. There is an engineering society devoted to understanding how to properly use fans (The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE)). This group was active in addressing Sick Building Syndrome during the last half of the last century.

In my opinion, an engineer who is familiar with principles of fan design and engineering, in particular an acoustical engineer who is familiar

with why some fans are noisy and others are not, should be able to translate that knowledge to making a

reasonable prediction of the sounds that wind turbines will produce. Based on that prediction the acoustician should be able to design a protocol to test for that type of noise. This appendix has explained a little about the unique characteristics of wind turbine sounds in the infrasound region such that the reader can see instruments sensitive to infrasonic tones and short rapid pulsations in the infrasound region are required. The sounds to be measured occur as tones and harmonics starting at the blade pass frequency and that the tones show large pulsations attributed to blade/tower and other aerodynamic conditions that cause the blade to lose lift or otherwise produce a short duration pressure pulses.

This is a good time to take a review of what has been said. Of most importance is that the greatest acoustic energy concentrations will be found at frequencies related to the speed of the drive shaft and the number of blades. As the blade passes the tower, the resulting pressure wave is produced.³² These pressure pulsations appear as tones



As the blade passes the tower, low frequency noise and infrasound is generated by turbines and endured by neighbours
 By: Esther Wrightman (Ontario)

Figure 3- Wind turbine blade and tower interactions producing pressure pulsations

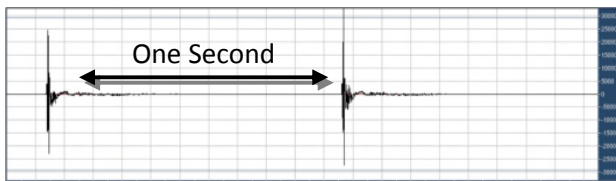


Figure 4-Idealized acoustic energy pulses at 1 Hz from blade/tower interaction at 20 rpm

³² There are other causes of these pulsations related to blade interactions with turbulence in the in-flow air stream. But, for the purpose of this paper the focus is on the blade and tower interactions.

during analysis but are not heard as tones by most people. Instead they may feel the pressure changes as pulsations, internal organ vibrations, or as a pain (like ear aches or migraines). This frequency is called the Blade Pass Frequency often abbreviated as BPF.

For modern utility scale wind turbines this frequency is at 1 Hz or lower. A three bladed wind turbine with a

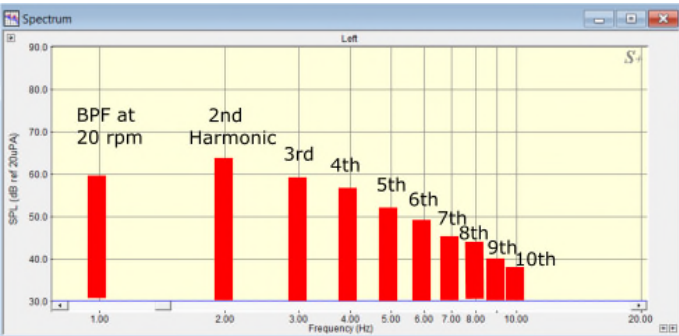


Figure 5-Harmonics of fundamental BPF at 1 Hz.

hub rotation of 20 revolutions per minute (rpm) has a BPF of 1 Hz. When wind turbine blades rotate past the tower a short pressure pulse (figure 4) occurs producing a burst of infrasound. When analyzed the result is a well defined array of tonal harmonics below 10 Hz. (red bars in figure 5) For impulsive sound of this type the harmonics are all “phase-correlated.” This means the peaks of each occur at the same time. The peaks add together in a linear fashion with their individual

maximum sound pressures all coinciding. Thus, for an impulse having 4 equal amplitude harmonics (BPF, 2nd, 3rd and 4th) each of the same amplitude, the peak level is +12 dB. 10 equal harmonics would produce a peak level of +20 dB.

For a wind turbine with a hub rotation of 15 rpm, the blade pass frequency would be a tone at 0.75 Hz ((15 passes per minute * 3 blades)/60seconds=0.75Hz). The blade pass frequency will be accompanied by harmonics that will also present as tones with the frequency of each higher harmonic being a multiple of the blade pass frequency. The second harmonic would be at 1.5 Hz and higher harmonics would occur at 2.25, 3.0, and 3.75 Hz.

When studies commissioned by the wind industry investigate wind turbine infrasound the test protocols are not selected/designed to address its characteristics. Instead of designing test protocols around these predictable characteristics of wind turbine noise the acousticians who have conducted tests for infrasound often use microphones that are not sensitive to sound below 2-3 Hz, using standard acoustical microphones and 1/3 octave band analyzers where the filters for the very lowest infrasound ranges have known limitations leading to understating the sound pressure level. These instruments are then set to not measure the short duration sound pressure levels but instead set to do long averages typically of 10 minutes or more. It is easy to understand that if all one has ever measured is wind turbine infrasound using instruments that do report average values for the tones or pulsations and have limitations in the frequency band filters that result in under-reporting the measurements one might conclude that wind turbines do not emit infrasound. However, that conclusion is based on a flawed methodology not a real absence of infrasound from the wind turbine's immissions..

Tones produced by wind turbines are distinctively different from normally occurring background infrasound caused by normal weather and other natural processes which are generally broadband and not tonal.

Measurements inside homes in rural areas that are distant from operating utility scale wind turbines (20 to 50 miles) do not show the tones and pulsations observed in measurements taken in homes near such utilities during times when the wind turbines are rotating/operating.

The ability to use the wind turbine hub rotation speed to link blade rotation speed (and thus operation state of the wind turbines) to the micro barometer test data showing tones provides a method of separating wind turbine operation tones from any other tones in the background infrasound.

Tones at infrasonic and very low frequencies have been associated with body and organ sensations or

involuntary movements for many years as seen in the Resonating Man figure from a 1978 paper by Gunnar Rasmussen who did considerable early work on infra and low frequency sound. When pressures change rapidly, exceeding the ability of mechanisms for balancing internal and external pressures, people may report sensations of stuffiness, fullness, or pain. Many more resonances have been found since that time some of which occur at the cellular or even lower level. Dr. Schomer's work has found military studies from the 1980's of how vibrations at frequencies under 1 Hz cause nausea.

The studies of people in the Shirley community reporting adverse health effects also show a relationship with the times when the wind turbines are operating.

The micro barometer measurements from the Shirley community show that homes within six (6) miles of one or more utility scale wind turbines have infrasonic tones that are present when wind turbines are operating and that change in

Simplified mechanical system representing the human body standing on a vertically vibrating platform

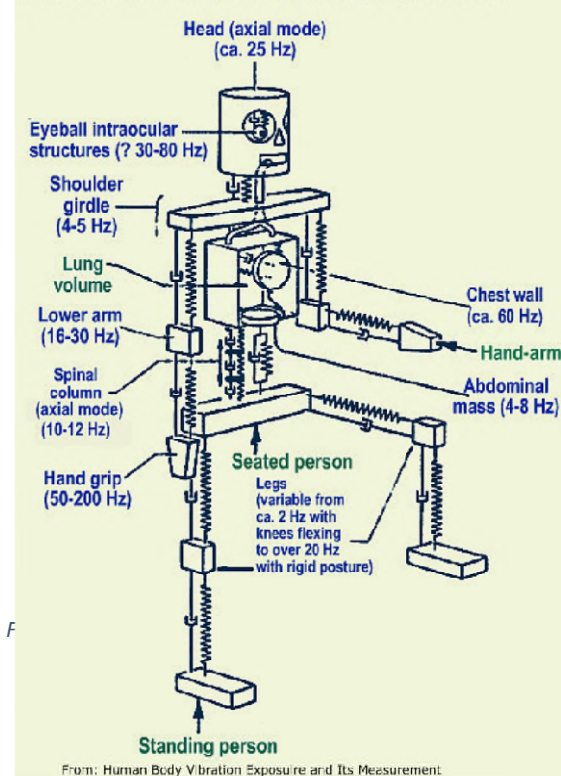


Figure 1 Resonating Man figure from a 1978 paper by Gunnar Rasmussen

frequency as the wind turbine hub speeds change. The sound pressure levels of these tones vary with wind turbine operating conditions and weather, but in general during periods with well defined strong tonal structures, the tones range from long term averages of 60 to 70 dB sound pressure level at homes within a radius of a mile and a quarter. Homes within the core of that radius are subjected to more frequent periods of strong tones because wind direction may be less important for a home with wind turbines surrounding it in all directions. The second and third harmonics are almost always present with some tests showing up to 10 harmonics. The peaks of the acoustic energy associated with the tones and harmonics can be 15 to 25 dB higher than the long term average. These are the peak sound pressures produced when the blade passes in front of the tower, with very short duration (under 100 milliseconds), and rapid rise times.

Based on my observations and interviews of many people who had adverse reactions to utility scale wind turbine this may be perceived by some as a deep, rumble/thump, or by others as a body part vibration or pulsation. Some report headaches or other symptoms that include pain as a characteristic.

Since much of the new study's data was developed from tests using a micro barometer it is worth spending a bit of time describing the Infiltec-20 model that was used.



Figure 7-Infiltec-20 micro barometer.
Resolution: 0.001 Pascals from 0.1 to 20 Hz.
Data sampled 50 times a second in signed
16bit integers. Range: ± 25 Pascals.

A micro barometer is very similar to a standard acoustical instrument's microphone except that it is designed to only respond to sound pressure over the frequency range of 0.05 to 20 Hz. Standard acoustical grade microphones cannot measure sound pressure accurately at frequencies of 3 Hz and lower. Special infrasound microphones are required to measure down to 0.5 Hz or lower. Even with a special infrasound microphone measurement of the lowest 3 Hz is not precise and subject to many sources of artifact. Because the micro barometer is designed to only cover the infrasound range it is a viable and relatively, reliable and low cost measurement tool.

The micro barometer is located in a test home usually in a room or near a location that people have found to produce symptoms or in a spare bedroom. Positioning of the unit is not critical since for the lowest infrasound frequencies the energy appears to be fairly uniform throughout a home. The micro barometer is connected to a data logging device via the RS232 cable. The data logging device receives the pressure measurements as signed 16bit integers with a sample every 0.02 seconds or 50 samples per second. The unit is left in place for hours to days. Often the family hosting the test records notes on a log sheet. In other cases independent observers note the wind turbine operating states.

At the end of a test period the data representing the hours of testing are extracted from the data logger. Using analysis tools the data is converted from a series of pressure readings to sound pressure levels in decibels. A count of 1000 in the data represents 1 Pascal or 94 dB. The data represents many hours of testing and thus a chart showing the entire time span will be very dense. For this type of display I have selected a spectrogram as the display tool.

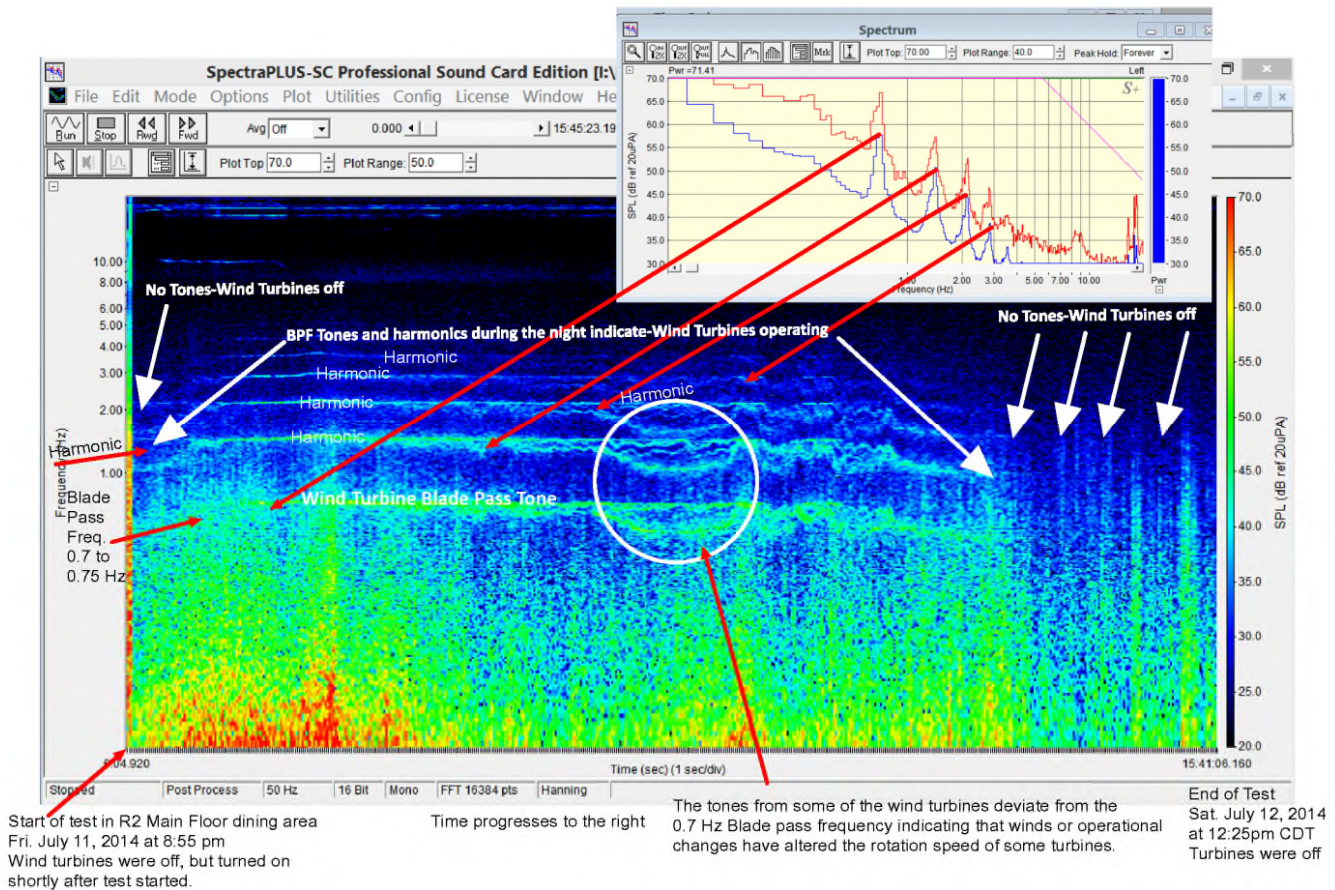


Figure 8-Typical micro barometer spectrogram showing tones from wind turbines during periods of operation

The main report includes a summary of the findings of the study and also additional spectrograms showing the tones and other characteristics at various distances from the Shirley Wind project out to six miles. The micro barometer tests confirm the findings of the Shirley Wind study for the PSC and other earlier noise studies. They extend our understanding of how infrasonic tones are present throughout the homes of people who are experiencing adverse health effects.