Explanation of Terms and Concepts Related to Wind Turbine Infrasound

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Two types of instruments are generally used to measure the pressure flucations that comprise infrasound. The first method uses microphones of the types commonly found on professional grade sound level meters except they are designed to measure sound down to below 0.5 Hz in the infrasonic frequency range. More commonly the sound level meters use microphones that can only measure to frequencies around 6 Hz with unknown performance below that frequency. These instruments, even when using an infrasonic microphone are complex and require a skilled acoustician to avoid mistakes. A second instrumentation method is to use a micro-barometer, which is similar in some ways to a microphone, except that it measures the pressure changes directly and often only measures over the range of 0.05 Hz to at most 100 to 300 Hz. This type of micro-barometer is called a differential pressure micro-barometer because it measures the small changes in air pressure caused by infrasound and not the barometric pressure which is the metric we often find reported with weather news.

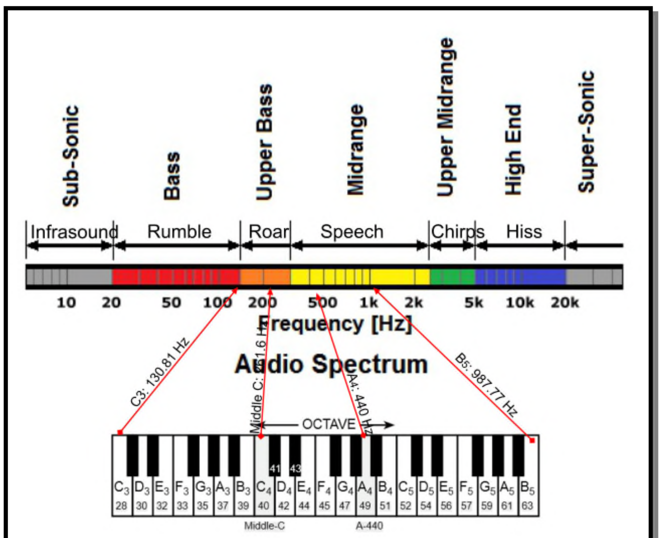

Figure 1: Layout of a piano keyboard. Key numbers are shaded. The notation C_4 means the C-key in the fourth octave.

Figure 1-Range of Sound Frequencies

The advantage of the micro-barometer is that it is much simplier to deploy. The Rand Data Logger used to collect the micro-barometer readings is designed to allow a non-technical person to setup the instruments and start and stop testing with the logger tracking both location and time of the tests using GPS satellites for timing and GPS coordinates. This allows for remote testing with a high degree of certainty that the instrument's readings are accurate. (See instructions in Exhibits)

First, what is infrasound? Infrasound is acoustic energy, sound pressure, just like the low to high frequency sounds that we are accustomed to hearing (see Figure 1). What makes infrasound different is that it is at the lowest end of the acoustical frequency spectrum even below the deep bass rumble of distant thunder or all but the largest pipe organ tones.[1] As the frequency of an infrasonic tone moves to lower frequencies: 5Hz, 2Hz, 1Hz and lower, the sounds are more likely to be perceived as separate pressure pulsations instead of a 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

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1 The lowest tone of the large cathedral pipe organs is approximately 16 Hz, just below the threshold for infrasound. At that frequency some music listeners can hear the organ's tone but for many people it is more of a palpable sensation than an audible sound.

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 turbine tones have the characteristic of rapid pressure change with peak 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.


Figure 2 - Large Utility Box Fan

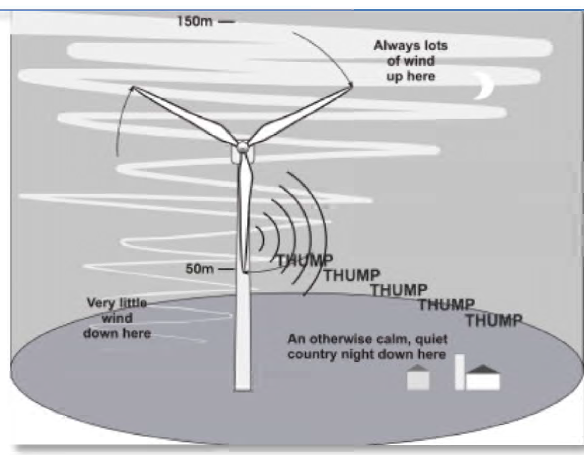
Further, these tones and pulsations are entirely predictable based on established and accepted first principles of aerodynamics, and other engineering fields. With respect to how and what type of noise is produced, utility scale wind turbines may be considered to be similar to large industrial scale 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. 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.[2] These pressure pulsations appear as tones during analysis but are not heard as tones by most people. Instead they report feeling the pressure changes as pulsations, internal organ vibrations, or as a pain (like ear aches one might have on a rapidly descending airplane). In some cases, particularly when there are strong tones near the 0.25 frequency which is associated with sea and air sickness there are also complaints of vestibular disturbances such as nausea (of the type common for motion sickness) or other more complex symptoms. This frequency is called the Blade Pass Frequency often abbreviated as BPF. For modern upwind utility scale wind turbines this frequency is almost always at or below 1Hz.

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



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

2 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.

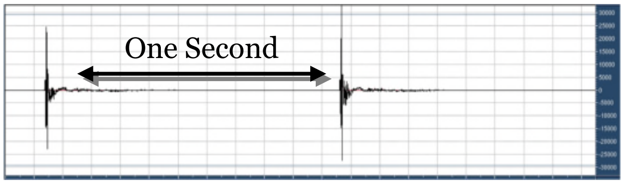


Figure 4-Idealized acoustic energy pulses at 1 Hz from blade/tower interaction at 20 rpm

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.

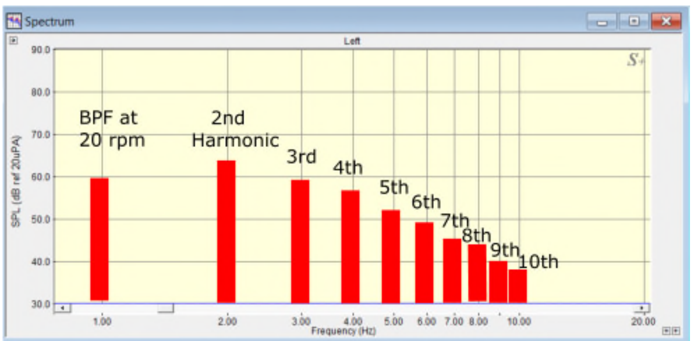


Figure 5-Harmonics of fundamental BPF at 1 Hz.

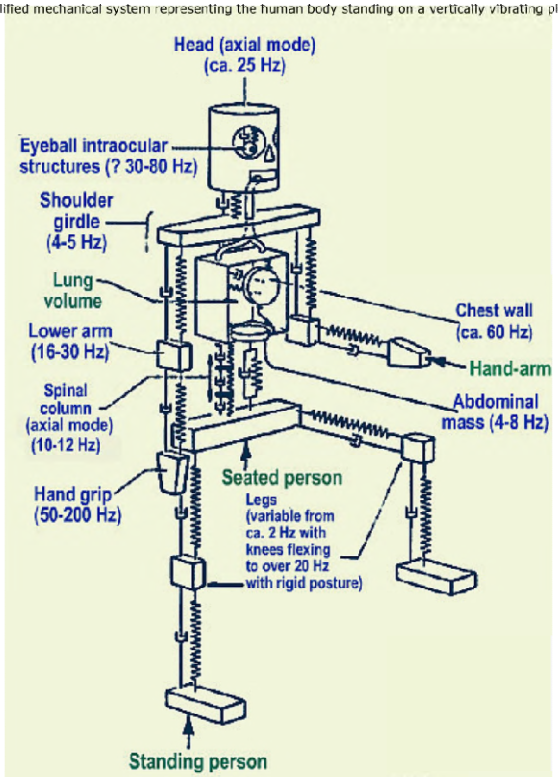
When studies commissioned by the wind industry investigate wind turbine infrasound the test protocols are not selected/designed to address its characteristics. Instead of designing test protocols around these predictable characteristics of wind turbine noise the acousticians who have conducted tests for infrasound often use standard acoustical microphones that are not sensitive to sound below 2-3 Hz, 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 are 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 report only band filtered and averaged values for the tones or pulsations when those filters have limitations in the infrasound frequency range that cause 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, especially when pulsating, 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.

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



From: Human Body Vibration Exposure and Its Measurement
Gunner Rasmussen (Published circa 1978)

Figure 6-Resonating Man

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 Wisconsin Brown County's Shirley community show that homes within six (6) miles of one or more of the 2.5 MW utility scale wind turbines have infrasonic tones that are present when wind turbines are operating and that change in 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 data on wind turbine infra-sound 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 0.1 Hz 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 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 16 bit integers with a sample every 0.02 seconds or 50 samples per second. The unit is left in place for periods of 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.

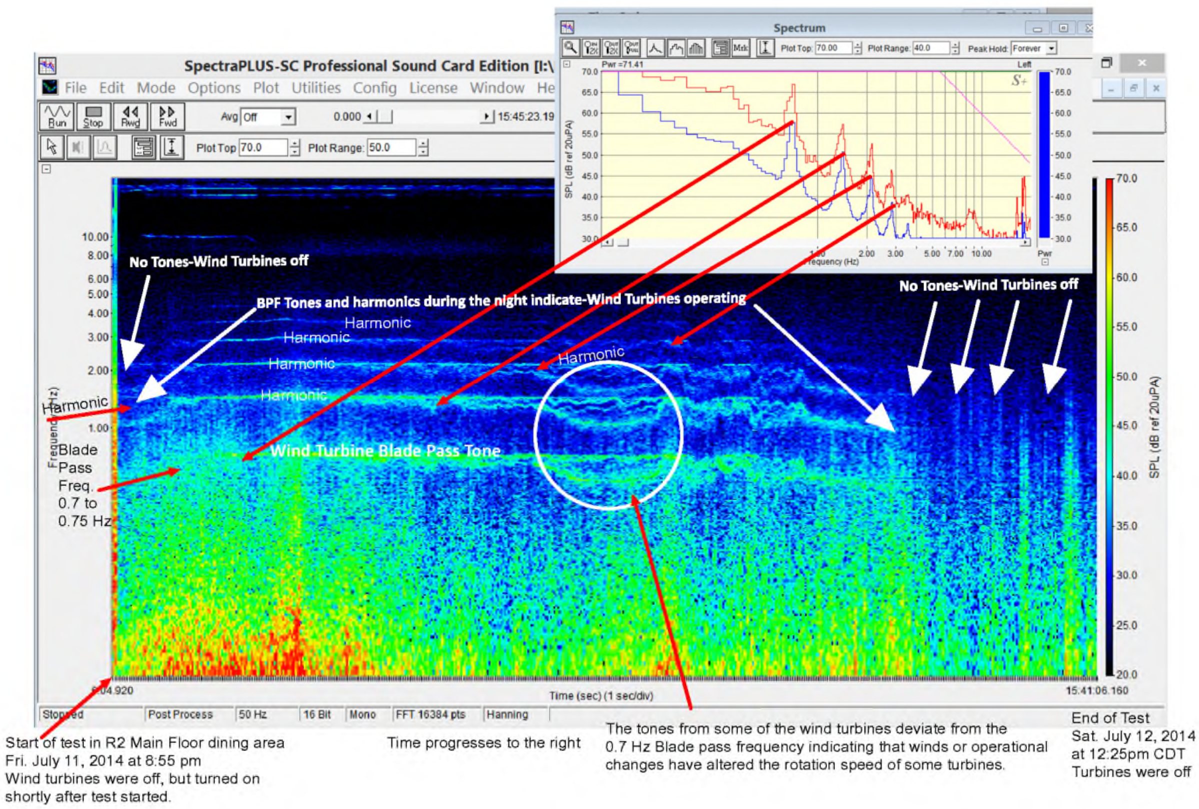


Figure 8-Typical micro barometer spectrogram showing tones from wind turbines during periods of operation