Understanding Wind Turbine Sound Issues

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This article is designed to serve as a primer on wind turbine noise issues as evidenced in Maine and New England. It is designed to help laypersons gain a factual understanding of both annoyance and medical effects of wind turbine sound. (For those unfamiliar with basic sound concepts, see Appendix.) This particular topic has been one of considerable interest in Maine in recent years as wind turbine projects have come on line. Even though most wind turbines are well sited and acceptable to residents, a number of others at certain well-known locations (Mars Hill, Freedom and Vinalhaven) have clearly been located too close to residents, and have produced both annoyance and stress related symptoms due to unacceptable sound levels. Unfortunately, the fallout from these particular projects, and questions concerning both the relevance and enforcement of state noise regulations, has had the effect of causing many local areas to pass prohibitive wind turbine siting ordinances, thereby effectively halting wind turbine developments at many locations throughout the state.

Before wind turbines are put into an area, many places in Maine have very low background sound levels. **Generally speaking, the annoyance caused by wind turbine sound is significantly affected by the background sound at a particular area; turbines in areas of considerable background sound are usually found to be less annoying than in locations where little or no masking background exists.** During the summer, there is often a considerable amount of insect noise at night to hide turbine sound, and sometimes, at certain locations, there is leaf and wind noise as well.

Unfortunately, rural Maine happens to be an area where background sound levels, especially at night, can be extremely low; levels as low as 18 dBA during the winter are often recorded, and typical late night sound levels during cold weather conditions (no leaves on the trees or insect noise) are often in the low 20s. This is often compounded by the locations of residential areas, which are usually located in hollows in hilly areas. It is possible for a wind to be blowing nearly 20 mph at the top of a hill and to be dead calm with no masking background on the lee side, a situation which has been seen at Mars Hill and other locations.

The second, and obviously most important factor contributing to wind turbine annoyance, is the sound created by the turbine, including total amount, amplitude modulation, and frequency content of the sound. These three factors tend to vary both with turbine size and setback distance. Turbine sizes can vary from about 100 KW to about 2.5 MW, with each size range producing different levels and types of sound. The total peak and average sound level is the most important factor in controlling turbine annoyance.

Audible sound levels estimated from turbines range from about 25 to 55 dBA (see noise thermometer in appendix.) In general, turbine sound begins when the wind is about 4-5 m/sec at hub height (about 10 mph) has its highest relative level at about 10 m/sec (22 mph) hub height, and peaks at around 12 m/sec (27 mph). (The newer, pitch-regulated turbines do not increase in sound beyond a peak level.) The speed at which turbines produces the most annoying sound varies by turbine and location. At some locations where there is moderate ground level wind shielding, it can be most annoying at cut-in speed, while at other areas with better wind shielding and less ground wind noise to drown out the turbine, it is more annoying at the higher wind speeds. Under certain conditions (turbine operational on hill, residence on lee side, high wind) the turbine can completely drown out all other sound sources, especially late at night. This is the condition under which a large number of sound complaints occur.

On the surface, when compared to sound from other sources, wind turbine sound levels do not appear to be particularly high; residents located near busy two-lane highways in Maine often hear average sound levels at the high end of the turbine sound range. However, when they occur late at night, are on for extended periods of time, and are not drowned out by other noise sources, these levels from wind turbines can be very annoying and hard to ignore. This is why the actual level at which people find turbines annoying is much lower than from other sound sources. Some people (part of the 10-15% of the population which is noise sensitive) find them annoying at levels as low as 35 dBA, while at 45 dBA, a very substantial fraction (often half or more) of residents find the levels annoying. This is one of the reasons why projects built early on with levels in the upper 40s have been found to be very annoying, and is why Maine regulations were recently lowered from 45 to 42 dBA for most projects.

The annoying character of wind turbine sound is primarily due to **amplitude modulation,** which causes the sound level to go up and down continually, by a range of up to 6 decibels, making it very hard to ignore. The sound also has an azimuthal variation; even though it may be quieter to the side of a turbine, the increased amplitude modulation may actually make the sidewind case more annoying than being directly downwind. And, unlike the situation with regard to continuously occurring sound (fans, busy highways), it is very difficult to become accustomed to uneven sound. In fact, many residents have reported being *more* annoyed with turbine sound over time rather than less. The effect is particularly pronounced with very large turbines featuring relatively low rotation rates, where the amplitude modulation is at its greatest.

The **frequency content** of the turbines is also of considerable importance. Larger turbines generate noticeably more low frequencies than do so smaller ones. This is due to the fact that low frequency sound is better generated by movement over larger areas, corresponding to the longer wavelength of such sound. In general, there is a shift of about one one-third octave band of the spectrum between mid-sized (600 KW) and very large turbines (2.5 MW). This is corresponds to about a 4-5 dB change in each 1/3 octave band, a clearly noticeable difference. This shift, coupled with the higher amplitude modulation, accounts for the fact that larger turbines are perceived to be more noticeable than smaller ones, and are usually found to be more annoying. An examination of wind turbine annoyance shows, in fact, shows very few locations where turbines of 750 KW or less are found to be annoying.

Consequently, necessary setback distances vary considerably with turbine size; smaller turbines, with less total noise, amplitude modulation and low frequency sound, need considerably less setbacks than do the very large ones. A very simple formula for minimum setbacks, which works surprisingly well in most cases for initial estimation, is that the total setback should be about one foot per KW + 300 feet. So in other words, a 600 KW turbine would have a minimum setback of at least 900 feet, while a 2.5 KW turbine would have a minimum setback of about 2800 feet. (More than a half mile!) This formula gives remarkably good results for most cases of interest as an initial screening tool. In practice, it is adjusted for turbine sound level and background level, but the actual numbers don't tend to vary from this formula by more than a few hundred feet.

One of the problems associated with larger turbines (above 1 MW) is the production of **infrasound,** defined as sound which has a frequency content lower than audible sound, usually about 20 Hz. Infrasound exists in the environment in low levels, and is, in fact, quite prevalent in many areas, including windy and coastal locations. In fact, measurements have often shown that infrasound background levels at many locations often exceed those expected or measured from wind turbines. Infrasound has the property that it tends to travel through walls much more readily than normal sound. It also tends to travel further than regular sound, and to propagate over and around barriers more readily as well due to its long wavelength. Consequently, it can be relatively actually more noticeable inside than outside late at night, where the ear has more high frequency stimuli to distract it.

Infrasound can also be measured; accurate equipment exists to capture infrasound levels with frequencies as low as 1/3 Hz, which would include the blade passage frequency (about 2/3 Hz.) of larger wind turbines. It is important to note that infrasound is *not* the same as low frequency modulation of higher pitched sound. This is often a topic of confusion when many people mistake the low frequency periodic amplitude modulation of wind turbine sound with infrasound. In fact, wind turbine blade passage generates *both at the same frequency* as it occurs; an amplitude modulation of higher pitched sound along with an actual infrasound blade passage pulse occurring at the blade passage frequency, an effect similar to the higher pitched blade passage frequency of most fans.

A significant problem in assessing the effects of infrasound is that it is, in fact, not audible by the usual hearing mechanism in the outer ear. That is why determining what constitutes an acceptable infrasound level is difficult; most people can't "hear" it at all. Consequently, it has been very difficult to establish appropriate standards for infrasound exposure, and at present, no such standards have been, to my knowledge, incorporated in any sound ordinances. However, it is believed that the inner ear *is* sensitive to infrasound at levels produced by larger wind turbines, and is responsible for the fact that it *may* be detected as either vertigo or motion sickness near very large wind turbines under very quiet conditions. **These symptoms are sometimes part of a range of effects commonly known as "wind turbine syndrome", which consists of a number of observed medical responses to exposure to wind turbines.** These can include headaches, dizziness, vertigo, and other associated effects. These symptoms have been primarily seen at locations with turbines that have relatively high sound levels (over 40 dBA) and relatively low masking background, a situation which unfortunately occurs at a number of locations in Maine.

While some people have claimed that these are caused directly by turbine noise and vibration, there is, in fact, no evidence of any type that these symptoms are directly caused by wind turbines. It is believed that some of the effects (vertigo, dizziness) may be due to infrasound exposure of the inner ear, while the rest are believed to be stress-related ailments brought on by constant exposure to annoyance. Unfortunately, at present, the exact cause for these symptoms is still not clear; there do not currently exist a sufficient number of well-controlled medical studies which can clearly identify their cause. And, while the methodology of the studies describing them is often poor, nonetheless the existence of these effects cannot be denied.

Given the current uncertainty of our understanding of these effects, and the near-certainty of acrimonious discussion if they occur, a number of towns in Maine have recently passed very restrictive ordinances which have effectively blocked wind turbine development, including requirements of two mile setbacks (!!!!) or extremely low noise thresholds such as 30 dBA, which effectively block turbine development. The two-mile setback criteria in particular, is based on an extremely doubtful set of assumptions concerning wind turbine annoyance methodology, and is not, to my knowledge supported by *any* evidence in Maine that significant wind turbine effects occur at anything close to this distance. Using this same methodology 1.25 mile setbacks in Massachusetts have been proposed despite the fact that there is *almost no evidence anywhere of significant medical symptoms at distances of even half of that at a number of large sized turbine installations in that state.*

Currently, the evidence indicates that there is only a very small percentage of the population, *if any*, which experiences adverse effects from wind turbines at levels below 35 dBA. Consequently, this would be the *lowest* threshold level I would recommend *anywhere*, regardless of the noise background; when windows are shut, it is almost impossible for turbines at this sound level (which would be about 20 decibels inside) to be heard at all at night, and almost no chance that the sound levels would trigger any adverse reactions. And, at areas with higher background sound levels (greater than 30 dBA), which often occurs in Massachusetts (but not typically in Maine), levels as high as 40 or even 42 dBA would be acceptable without causing significant problems for most residents.

An examination of the actual legal state levels at most areas in the Northeast indicates that currently, state regulations (except in Maine and Massachusetts) do not accurately reflect the present state of knowledge about wind turbine sound effects (see Table 1 which shows the permitted nighttime sound level, the controlling factor). Most of these laws were emplaced a couple of decades ago or so, and reflect information concerning noise annoyance from continually operating industrial sources. They were not enacted with wind turbine noise regulation in mind, and are therefore currently under review in a number of states. Massachusetts in particular will be examining this matter in the coming year (I personally will be participating in the study.)

In Maine, the regulations a few years ago allowed sound levels as high as 45 dBA. After much deliberation, Maine DEP recently lowered the levels to 42 dBA at the nearest protected location, namely the property line of the nearest inhabited residence. In effect, this gives a level of close to 40 decibels at each residence under 8 m/sec wind speed, the speed usually measured for each turbine. This level is actually slightly higher than it should be for areas with low nighttime background levels (25 dBA or less) but serves as a reasonable worst-case cap.

Table 1.
State Wind Turbine Sound Regulations

State	Permitted Nighttime Sound Level, (dBA) * See Appendix
Maine	42 (protected locations)
New Hampshire	45
Vermont	45
Connecticut	45-50 depending on source/receiver
Massachusetts	10 over background L90*
New York	6 over background Leq*

When examining wind turbine impacts for compliance purposes, it is important to note that there generally exists significant variation in wind turbine annoyance depending on season, wind direction, wind speed, and time of day. This variation can be used to design a targeted mitigation scheme for a particular turbine or group of turbines. If it is observed that impacted residents are grouped in a similar direction from the turbine, it is possible to turn the turbine off (or down, which lowers the sound levels) late at night when the wind is blowing in the direction of the residents above a certain level. In practice, this can often be an effective method; it can result in effective sound reduction at affected residences while still allowing a project to operate cost effectively. And, at certain areas where only one or two residents are affected near larger turbines, a simple buy out at (slightly above market rates) is often a cost effective remedy for all parties.

In closing, it can be readily appreciated that wind turbine sound is a complex issue. Successfully addressing it requires coordination between and among developers, manufacturers, residents, and appropriate regulatory agencies.

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Appendix A: Description of Noise Metrics

This Appendix describes the noise metrics used in this paper.

A.1 A-weighted Sound Level, dBA

Loudness is a subjective quantity that enables a listener to order the magnitude of different sounds on a scale from soft to loud. Although the perceived loudness of a sound is based somewhat on its frequency and duration, chiefly it depends upon the sound pressure level. Sound pressure level is a measure of the sound pressure at a point relative to a standard reference value; sound pressure level is always expressed in decibels (dB), a logarithmic quantity.

Another important characteristic of sound is its frequency, or "pitch." This is the rate of repetition of sound pressure oscillations as they reach our ears. Frequency is expressed in units known as Hertz (abbreviated "Hz" and equivalent to one cycle per second). Sounds heard in the environment usually consist of a range of frequencies. The distribution of sound energy as a function of frequency is termed the "frequency spectrum."

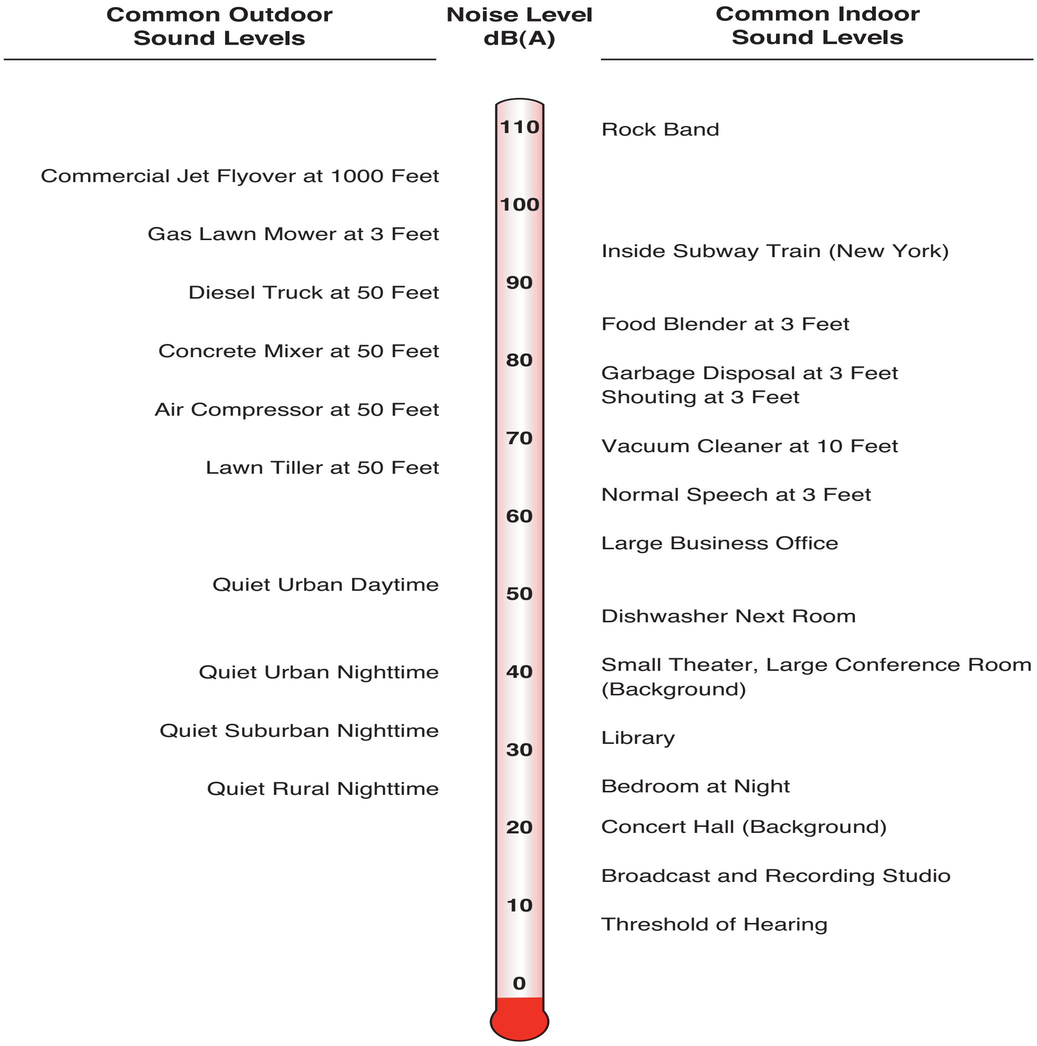
The human ear does not respond equally to identical noise levels at different frequencies. Although the normal frequency range of hearing for most people extends from a low of about 20 Hz to a high of 10,000 Hz to 20,000 Hz, people are most sensitive to sounds in the voice range, between about 500 Hz to 2,000 Hz. Therefore, to correlate the amplitude of a sound with its level as perceived by people, the sound energy spectrum is adjusted, or "weighted."

The weighting system most commonly used to correlate with people's response to noise is "A-weighting" (or the "A-filter") and the resultant noise level is called the "A-weighted noise level" (dBA). A-weighting significantly de-emphasizes those parts of the frequency spectrum from a noise source that occurs both at lower frequencies (those below about 500 Hz) and at very high frequencies (above 10,000 Hz) where we do not hear as well. The filter has very little effect, or is nearly "flat," in the middle range of frequencies between 500 and 10,000 Hz. A-weighted sound levels have been found to correlate better than other weighting networks with human perception of "noisiness." One of the primary reasons for this is that the A-weighting network emphasizes the frequency range where human speech occurs, and noise in this range interferes with speech communication. The figure below shows common indoor and outdoor A-weighted sound levels and the environments or sources that produce them.

A.2 Equivalent Sound Level, Leq

The Equivalent Sound Level, abbreviated L_{eq}, is a measure of the total exposure resulting from the accumulation of A-weighted sound levels over a particular period of interest – for example, an hour, an 8-hour school day, nighttime, or a full 24-hour day. However, because the length of the period can be different depending on the time frame of interest, the applicable period should always be identified or clearly understood when discussing the metric. Such durations are often identified through a subscript, for example L_{eq1h}, or $L_{eq(24)}$.

L_{eq} may be thought of as a constant sound level over the period of interest that contains as much sound energy as (is "equivalent" to) the actual time-varying sound level with its normal peaks and valleys. It is important to recognize, however, that the two signals (the constant one and the time-varying one) would sound very different from each other. Also, the "average" sound level suggested by L_{eq} is not an arithmetic but a logarithmic, or "energy-averaged" sound level. Thus, the loudest events may dominate the noise environment described by the metric, depending on the relative loudness of the events.



A.3 Statistical Sound Level Descriptors

Statistical descriptors of the time-varying sound level are often used instead of, or in addition to L_{eq} to provide more information about how the sound level varied during the time period of interest. The descriptor includes a subscript that indicates the percentage of time the sound level is exceeded during the period. The L_{50} is an example, which represents the sound level exceeded 50 percent of the time, and equals the median sound level. Another commonly used descriptor is the L_{10}, which represents the sound level exceeded 10 percent of the measurement period and describes the sound level during the louder portions of the period. The L_{90} is often used to describe the quieter background sound levels that occurred, since it represents the level exceeded 90 percent of the period.

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