Wind Turbine Acoustic Noise

A white paper

Prepared by the

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Introduction

Wind turbines generate sound via various routes, both mechanical and aerodynamic. As the technology has advanced, wind turbines have gotten much quieter, but sound from wind turbines is still an important siting criterion. Sound emissions from wind turbine have been one of the more studied environmental impact areas in wind energy engineering. Sound levels can be measured, but, similar to other environmental concerns, the public's perception of the acoustic impact of wind turbines is, in part, a subjective determination.

Noise is defined as any unwanted sound. Concerns about noise depend on:

1. the level of intensity, frequency, frequency distribution and patterns of the noise source;
2. background sound levels;
3. the terrain between the emitter and receptor
4. the nature of the receptor; and
5. the attitude of the receptor about the emitter.

In general, the effects of noise on people can be classified into three general categories:

1. Subjective effects including annoyance, nuisance, dissatisfaction
2. Interference with activities such as speech, sleep, and learning
3. Physiological effects such as anxiety, tinnitus, or hearing loss.

In almost all cases, the sound levels associated with wind turbines large & small produce effects only in the first two categories, with *modern* turbines typically producing only the first. The third category includes such situations as work inside industrial plants and around aircraft. Whether a sound is objectionable will depend on the type of sound (tonal, broadband, low frequency, or impulsive) and the circumstances and sensitivity of the person (or receptor) who hears it. Because of the wide variation in the levels of individual tolerance for noise, there is no completely satisfactory way to measure the subjective effects of noise or of the corresponding reactions of annoyance and dissatisfaction.

Operating sound produced from wind turbines is considerably different in level and nature than most large scale power plants, which can be classified as industrial sources. Wind turbines are often sited in rural or remote areas that have a corresponding ambient sound character. Furthermore, while noise may be a concern to the public living near wind turbines, much of the sound emitted from the turbines is masked by ambient or the background sounds of the wind itself.

The sound produced by wind turbines has diminished as the technology has improved. As blade airfoils have become more efficient, more of the wind energy is converted into rotational energy, and less into acoustic energy. Vibration damping and improved mechanical design have also significantly reduced noise from mechanical sources.

The significant factors relevant to the potential environmental impact of wind turbine noise are shown in Figure 1 [Hubbard and Shepherd, 1990]. Note that all acoustic technology is based on the following primary elements: Sound sources, propagation paths, and receivers. In the following sections, after a short summary of the basic principles of sound and its measurement, a review of sound generation from wind turbines, sound propagation, as well as sound prediction methods is given.

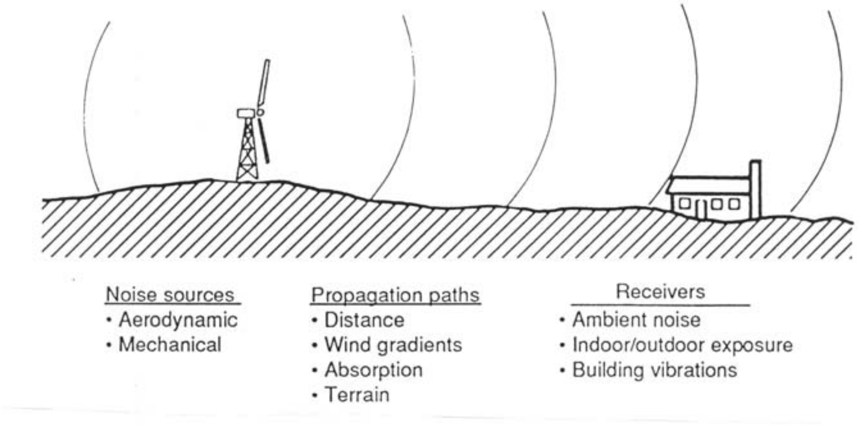

Figure 1: Examples of sources, receivers, and propagation paths

Noise and Sound Fundamentals

Sound and Noise

Sounds are characterized by their magnitude (loudness) and frequency. There can be loud low frequency sounds, soft high frequency sounds and loud sounds that include a range of frequencies. The human ear can detect a very wide range of both sound levels and frequencies, but it is more sensitive to some frequencies than others.

Sound is generated by numerous mechanisms and is always associated with rapid small scale pressure fluctuations, which produce sensations in the human ear. Sound waves are characterized in terms of their amplitude or magnitude (see below), wavelength (λ), frequency (f) and velocity (v), where v is found from:

$$v = f\lambda$$

The velocity of sound is a function of the medium through which it travels, and it generally travels faster in more dense mediums. The velocity of sound is about 340 m/s (1115 ft/s) in air at standard pressures.

Sound frequency denotes the “pitch” of the sound and, in many cases, corresponds to notes on the musical scale (Middle C is 262 Hz). An octave is a frequency range between a sound with one frequency and one with twice that frequency, a concept often used to define ranges of sound frequency values. The frequency range of human hearing is quite wide, generally ranging from about 20 to 20 kHz (about 10 octaves). Finally, sounds experienced in daily life are usually not a single frequency, but are formed from a mixture of numerous frequencies, from numerous sources.

Sound turns into noise when it is unwanted. Whether sound is perceived as a noise depends on subjective factors such as the amplitude and duration of the sound. There are numerous physical quantities that have been defined which enable sounds to be compared and classified, and which also give indications for the human perception of sound. They are discussed in numerous texts on the subject (e.g., for wind turbine sound see Wagner, et al., 1996) and are reviewed in the following sections.

Measurement Scales: Sound Power, Pressure and Intensity

It is important to distinguish between the various measures of the magnitude of sounds: sound power level and sound pressure level. Sound power level is the power per unit area of the sound pressure wave; it is a property of the source of the sound and it gives the total acoustic power emitted by the source. Sound pressure is a property of sound at a given observer location and can be measured there by a single microphone.

Because of the wide range of sound pressures to which the ear responds (a ratio of 10^5 or more for a normal person), sound pressure is an inconvenient quantity to use in graphs and tables. In addition, the human ear does not respond linearly to the amplitude of sound pressure, and, to approximate it, the scale used to characterize the sound power or pressure amplitude of sound is logarithmic [see Beranek and Ver, 1992]. Whenever the magnitude of an acoustical quantity is given in a logarithmic form, it is said to be a level in decibels (dB) above or below a zero reference level.

Sound intensity, I, is defined as the power of the sound per unit area, and so can be measured in watts/m^2, but is more commonly measured in units of decibels, as:

$$I = 10\log_{10}\left(-I/I_0\right)$$

where the reference intensity, I_0, is often the threshold of hearing at 1000 Hz: $I_0 = 10^{-12}$ W/m^2.

Because audible sound consists of pressure waves, sound power is also quantifiable by its relation to a reference pressure. The sound power level of a source, L_W, in units of decibels (dB), and is given by:

$$L_W = 10\log_{10}\left(P/P_0\right)$$

with P equal to the sound power level in units of power density and P_0 a reference sound power (often $P_0 = 2 \times 10^{-5}$ N/m^2).

The sound pressure level (SPL) of a sound, L_P, in units of decibels (dB), is given by:

$$L_p = 20\ \log_{10}\left(p/p_0\right)$$

with p equal to the effective (or root mean square, RMS) sound pressure and p_0 a reference RMS sound pressure (usually 2×10^{-5} Pa). [See Nave, 2005. This Hyperphysics website, by Georgia State University, is an excellent introduction to sound and hearing.]

The human response to sounds measured in decibels has the following characteristics:

- Except under laboratory conditions, a change in sound level of 1 dB cannot be perceived.
- Doubling the energy of a sound source corresponds to a 3 dB increase

- Outside of the laboratory, a 3 dB change in sound level is considered a barely discernible difference.
- A change in sound level of 5 dB will typically result in a noticeable community response.
- A 6 dB increase is equivalent to moving half the distance towards a sound source
- A 10 dB increase is subjectively heard as an approximate doubling in loudness
- The threshold of pain is an SPL of 140 dB

Figure 2 illustrates the relative magnitude of common sounds on the dB scale. For example, The threshold of pain for the human ear is about 200 Pa, which has an SPL value of 140 dB.

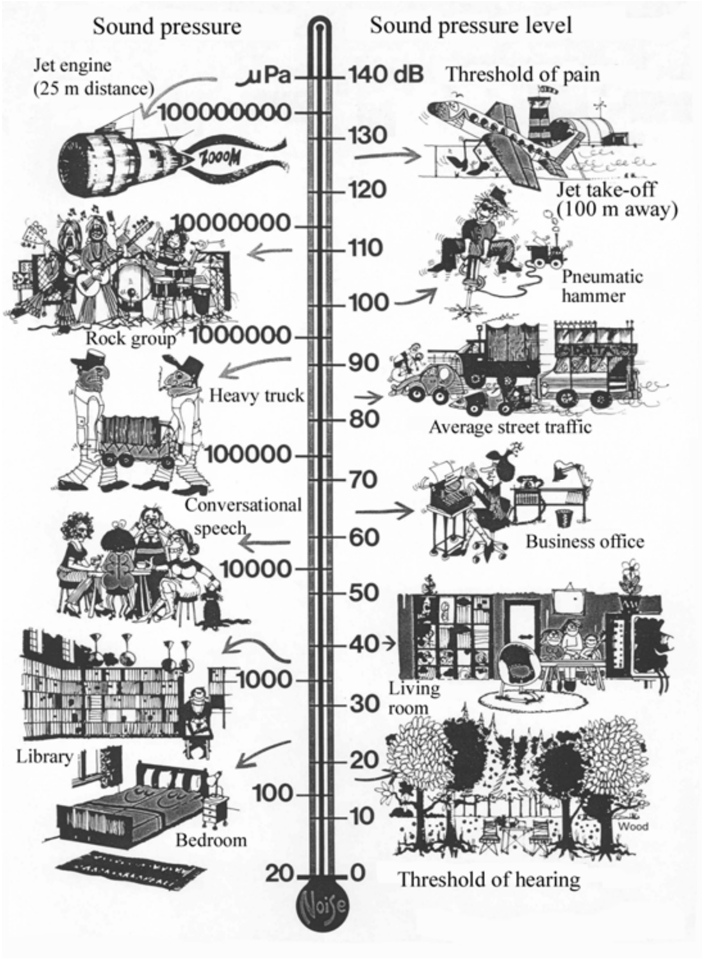

Figure 2: Sound Pressure Level (SPL) Examples (Bruel and Kjaer Instruments)

Measurement of Sound or Noise

Sound pressure levels are measured via the use of sound level meters. These devices make use of a microphone that converts pressure variations into a voltage signal which is then recorded on a meter (calibrated in decibels). As described above, the decibel scale is logarithmic. A sound level measurement that combines all frequencies into a single weighted reading is defined as a broadband sound level. For the determination of the human ear's response to changes in sound, sound level meters are generally equipped with filters that give less weight to the lower frequencies. As shown in Figure 3, there are a number of filters that accomplish this:

- A-Weighting: This is the most common scale for assessing environmental and occupational noise. It approximates the response of the human ear to sounds of medium intensity.
- B-Weighting: this weighting is not commonly used. It approximates the ear for medium-loud sounds, around 70 dB.
- C-Weighting: Approximates response of human ear to loud sounds. It can be used for low-frequency sound.
- G-Weighting: Designed for infrasound

The weighting is indicated in the unit, e.g. measurements made using A-weighting are expressed in units of dB(A). Details of these scales are discussed by Beranek and Ver [1992].

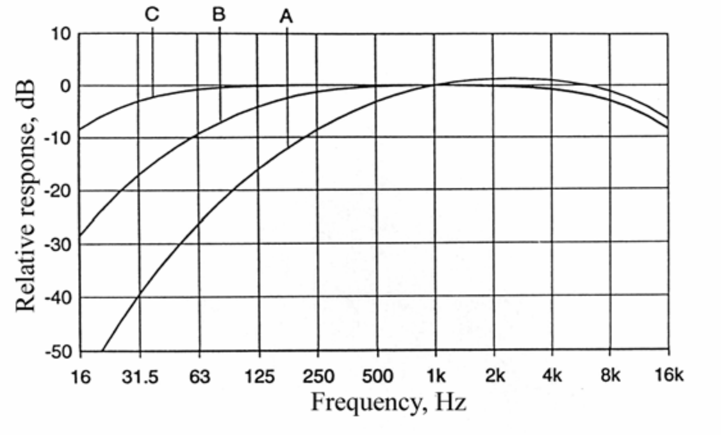

Figure 3: Definition of A, B, and C Frequency Weighing Scales [Beranek and Ver, 1992]

Once the A-weighted sound pressure is measured over a period of time, it is possible to determine a number of statistical descriptions of time-varying sound and to account for the greater community sensitivity to nighttime sound levels. Terms commonly used in describing environmental sound include:

- L_{10}, L_{50}, and L_{90}: The A-weighted sound levels that are exceeded 10%, 50%, and 90% of the time, respectively. During the measurement period L90 is generally taken as the background sound level.
- L_{eq}: *Equivalent Sound Level:* The average A-weighted sound pressure level which gives the same total energy as the varying sound level during the measurement period of time. Also referred to as $L_{A\ eq}$.
- L_{dn}: *Day-Night Level:* The average A-weighted sound level during a 24 hour day, obtained after addition of 10 dB to levels measured in the night between 10 p.m. and 7 a.m.

dB Math

From the comments above it can be seen that decibels do not add numerically as linear measures of other physical things do. Figure 4 shows how to add the decibels of two sound sources that are within 12 dB of each other.

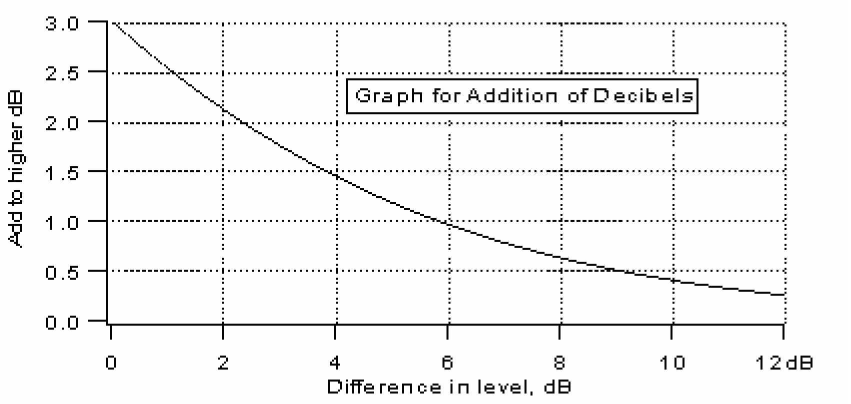

Figure 4: Addition of two sound levels.

For example, when adding two sound sources together, one being 9.5 dB(A) louder than the second, the resultant is approximately 10 dB(A) louder than the second source. It can be seen that when the sound from two sources more than 10 dB(A) apart are combined, the total sound pressure level in decibels is very close to the louder one, with little or no contribution from the softer sound.

Infrasound & Low Frequency Sound

Terminology: Low frequency pressure vibrations are typically categorized as *low frequency sound* when they can be heard near the bottom of human perception (10-200 Hz), and *infrasound* when they are below the common limit of human perception. Sound below 20 Hz is generally considered infrasound, even though there may be some human perception in that range. Because these ranges overlap in these ranges, it is important to understand how the terms are intended in a given context.

Infrasound is always present in the environment and stems from many sources including ambient air turbulence, ventilation units, waves on the seashore, distant explosions, traffic, aircraft, and other machinery[1]. Infrasound propagates farther (i.e. with lower levels of dissipation) than higher frequencies.

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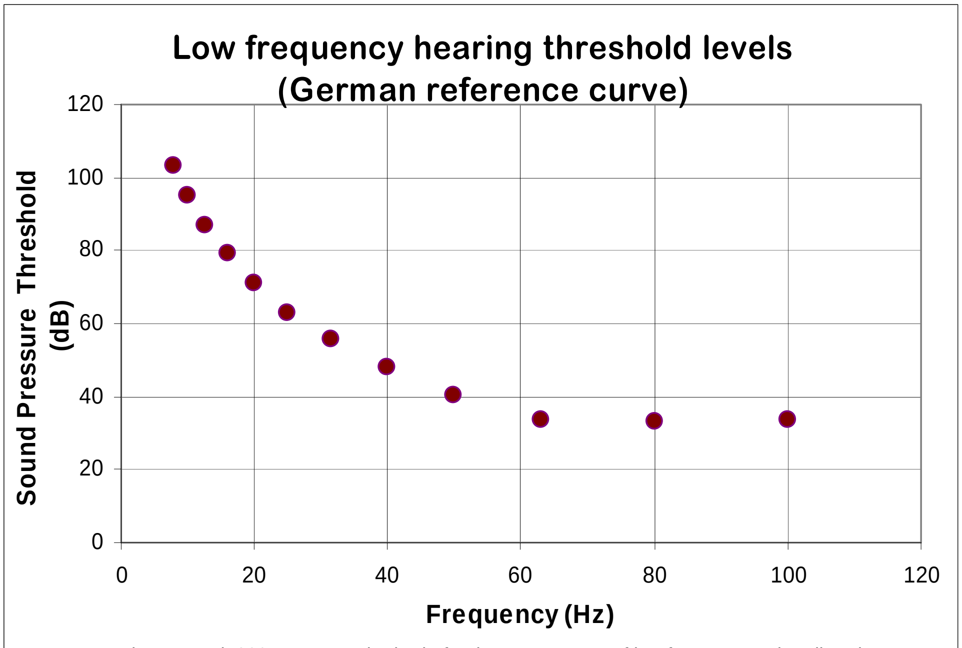
[1] To place infrasound in perspective, when a child is swinging high on a swing, the pressure change on its ears, from top to bottom of the swing, is nearly 120 dB at a frequency of around 1 Hz. [Leventhall, 2004]

Some characteristics of the human perception of infrasound and low frequency sound are:

- Low frequency sound and infrasound (2-100 Hz) are perceived as a mixture of auditory and tactile sensations.
- Lower frequencies must be of a higher magnitude (dB) to be perceived, e.g. the threshold of hearing at 10 Hz is around 100 dB; see Figure 5
- Tonality can not be perceived below around 18 Hz
- Infrasound may not appear to be coming from a specific location, because of its long wavelengths.



source: Moorhouse et al, 2005: Proposed criteria for the assessment of low frequency noise disturbance

Figure 5: Typical perception threshold of human ear for low frequency sound as a function of pressure

The primary human response to perceived infrasound is annoyance, with resulting secondary effects. Annoyance levels typically depend on other characteristics of the infrasound, including intensity, variations with time, such as impulses, loudest sound, periodicity, etc. Infrasound has three annoyance mechanisms:

- A feeling of static pressure
- Periodic masking effects in medium and higher frequencies
- Rattling of doors, windows, etc. from strong low frequency components

Human effects vary by the intensity of the perceived infrasound, which can be grouped into these approximate ranges:

- 90 dB and below: No evidence of adverse effects
- 115 dB: Fatigue, apathy, abdominal symptoms, hypertension in some humans
- 120 dB: Approximate threshold of pain at 10 Hz
- 120 – 130 dB and above: Exposure for 24 hours causes physiological damage

There is no reliable evidence that infrasound below the perception threshold produces physiological or psychological effects.

Sound from Wind Turbines

Sources of Wind Turbine Sound

There are four types of sound that can be generated by wind turbine operation: tonal, broadband, low frequency, and impulsive:

1. Tonal: Tonal sound is defined as sound at discrete frequencies. It is caused by components such as meshing gears, non-aerodynamic instabilities interacting with a rotor blade surface, or unstable flows over holes or slits or a blunt trailing edge.
2. Broadband: This is sound characterized by a continuous distribution of sound pressure with frequencies greater than 100 Hz. It is often caused by the interaction of wind turbine blades with atmospheric turbulence, and also described as a characteristic "swishing" or "whooshing" sound.
3. Low frequency: Sound with frequencies in the range of 20 to 100 Hz is mostly associated with *downwind* rotors (turbines with the rotor on the downwind side of the tower). It is caused when the turbine blade encounters localized flow deficiencies due to the flow around a tower.
4. Impulsive: This sound is described by short acoustic impulses or thumping sounds that vary in amplitude with time. It is caused by the interaction of wind turbine blades with disturbed air flow around the tower of a downwind machine.

The sources of sounds emitted from operating wind turbines can be divided into two categories: 1) Mechanical sounds, from the interaction of turbine components, and 2) Aerodynamic sounds, produced by the flow of air over the blades. A summary of each of these sound generation mechanisms follows, and a more detailed review is included in the text of Wagner, et al. [1996].

Mechanical Sounds

Mechanical sounds originates from the relative motion of mechanical components and the dynamic response among them. Sources of such sounds include:

1. Gearbox
2. Generator
3. Yaw Drives
4. Cooling Fans
5. Auxiliary Equipment (e.g., hydraulics)

Since the emitted sound is associated with the rotation of mechanical and electrical equipment, it tends to be tonal (of a common frequency), although it may have a broadband component. For example, pure tones can be emitted at the rotational frequencies of shafts and generators, and the meshing frequencies of the gears.

In addition, the hub, rotor, and tower may act as loudspeakers, transmitting the mechanical sound and radiating it. The transmission path of the sound can be air-borne or structure-borne. Air-borne means that the sound is directly propagated from the component surface or interior into the air. Structure-borne sound is transmitted along other structural components before it is radiated into the air. For example, Figure 6 shows the type of transmission path and the sound power levels for the individual components for a 2 MW wind turbine [Wagner, et al., 1996]. Note that the main source of mechanical sounds in this example is the gearbox, which radiates sounds from the nacelle surfaces and the machinery enclosure.

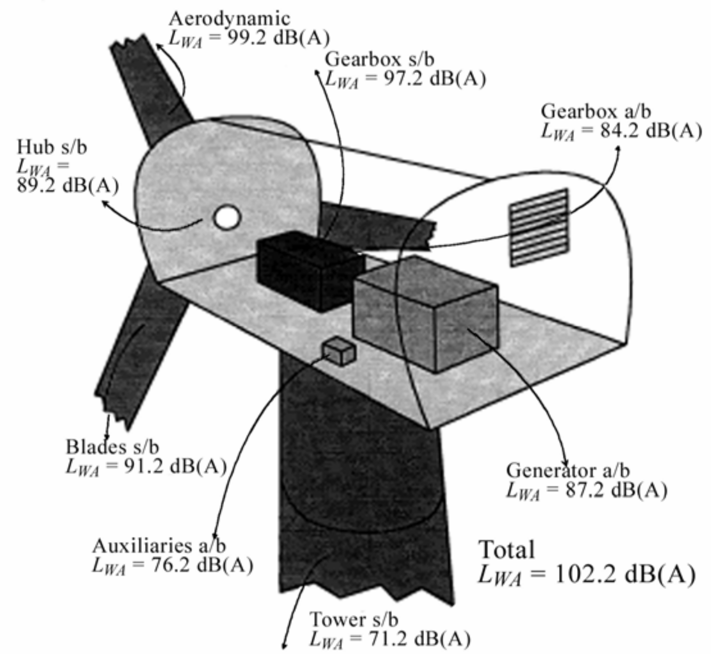


Figure 6: Components and Total Sound Power Level of a Wind Turbine, showing structure-borne (s/b) and airborne (a/b) transmission paths [Wagner, 1996].

Aerodynamic Sounds

Aerodynamic broadband sound is typically the largest component of wind turbine acoustic emissions. It originates from the flow of air around the blades. As shown in Figure 7, a large number of complex flow phenomena occur, each of which might generate some sound. Aerodynamic sound generally increases with rotor speed. The various aerodynamic sound generation mechanisms that have to be considered are shown in Table 1 [Wagner, et al., 1996]. They are divided into three groups:

1. *Low Frequency Sound:* Sound in the low frequency part of the sound spectrum is generated when the rotating blade encounters localized flow deficiencies due to the flow around a tower, wind speed changes, or wakes shed from other blades.
2. *Inflow Turbulence Sound:* Depends on the amount of atmospheric turbulence. The atmospheric turbulence results in local force or local pressure fluctuations around the blade.
3. *Airfoil Self Noise:* This group includes the sound generated by the air flow right along the surface of the airfoil. This type of sound is typically of a broadband

nature, but tonal components may occur due to blunt trailing edges, or flow over slits and holes.

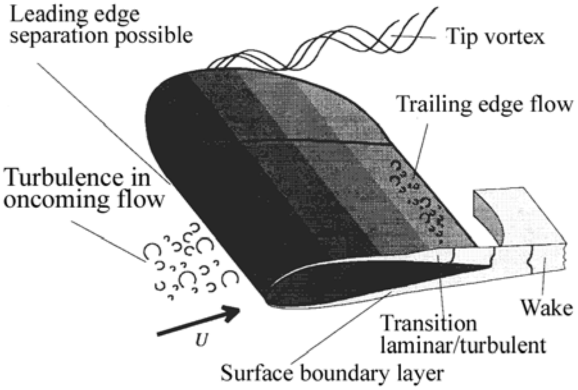


Figure 7: Schematic of Flow around a Rotor Blade [Wagner, 1996].

Table 1: Wind Turbine Aerodynamic Sound Mechanisms [Wagner et al., 1996]

Type or indication	Mechanism	Main characteristics & importance
Low-frequency sound		
Steady thickness noise; steady loading noise	Rotation of blades or rotation of lifting surfaces	Frequency is related to blade passing frequency, not important at current rotational speeds
Unsteady loading noise	Passage of blades through tower velocity deficit or wakes	Frequency is related to blade passing frequency, small in cases of upwind rotors, though possibly contributing in case of wind farms
Inflow turbulence sound	Interaction of blades with atmospheric turbulence	Contributing to broadband noise; not yet fully quantified
Airfoil self-noise		
Trailing-edge noise	Interaction of boundary layer turbulence with blade trailing edge	Broadband, main source of high frequency noise (770 Hz < f < 2 kHz)
Tip noise	Interaction of tip turbulence with blade tip surface	Broadband; not fully understood
Stall, separation noise	Interaction of turbulence with blade surface	Broadband
Laminar boundary layer noise	Non-linear boundary layer instabilities interacting with the blade surface	Tonal, can be avoided
Blunt trailing edge noise	Vortex shedding at blunt trailing edge	Tonal, can be avoided
Noise from flow over holes, slits and intrusions	Unstable shear flows over holes and slits, vortex shedding from intrusions	Tonal, can be avoided

Infrasound from Wind Turbines

When discussing infrasound from wind turbines, it is particularly important to distinguish between turbines with downwind rotors and turbines with upwind rotors. Some early wind turbines did produce significant levels of infrasound; these were all turbines with downwind rotors. The downwind design is rarely used in modern utility-scale wind power turbines.

Upwind rotors emit broad band sound emissions, which include low frequency sound and some infrasound. Note that the "swish-swish" sound is amplitude modulation at blade passing frequencies of higher frequency blade tip turbulence and does NOT contain low frequencies.

One example of low frequency sound and infrasound from a modern turbine is shown in Figure 8 . The magnitudes of these are below the perception limits of humans, which are shown in Figure 5.

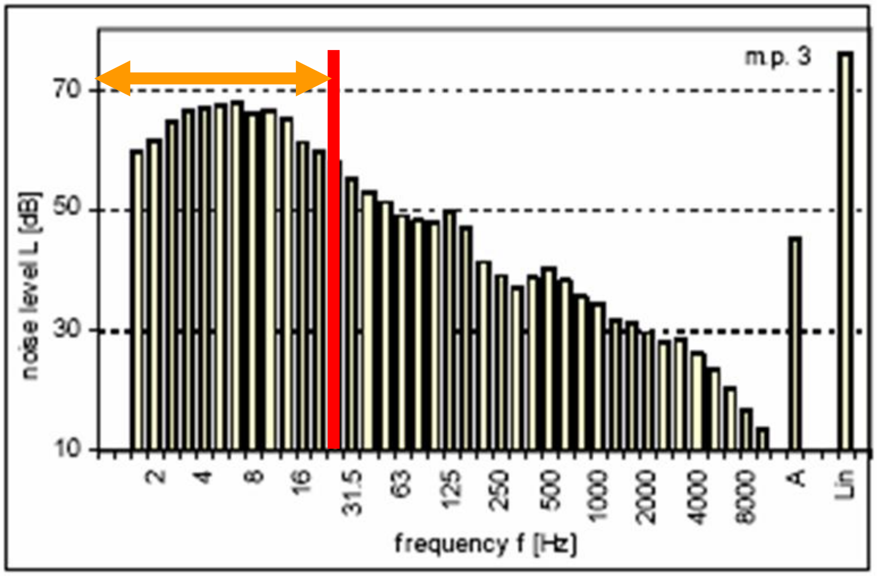


Figure 8: Example of 1/3 octave sound spectra downwind of a Vestas V80. The infrasound levels (range marked by the arrow) are below human perception level

Sound Reduction Methods for Wind Turbines

Turbines can be designed or retrofitted to minimize mechanical sound. This can include special finishing of gear teeth, using low-speed cooling fans and mounting components in the nacelle instead of at ground level, adding baffles and acoustic insulation to the nacelle, using vibration isolators and soft mounts for major components, and designing the turbine to prevent sounds from being transmitted into the overall structure. Efforts to reduce aerodynamic sounds have included [Wagner, et al., 1996] the use of lower tip speed ratios, lower blade angles of attack, upwind rotor designs, variable speed operation and most recently, the use of specially modified blade trailing edges.

Recent improvements in mechanical design of large wind turbines have resulted in significantly reduced mechanical sounds from both broadband and pure tones. Today, the sound emission from modern wind turbines is dominated by broadband aerodynamic sounds [Fégeant, 1999].

Sounds from Small Wind Turbines

Sound is likely to be one of the most important siting constraints for small wind turbines. Small wind turbines (under 30 kW capacity) are more often used for residential power or for other dedicated loads. These systems may be grid-connected or stand-alone systems. Due to the proximity of human activity, these applications could potentially result in noise complaints. Small wind turbines are in many cases louder than large turbines. Small wind turbines may also operate at higher tip speeds or turned partially out of the wind (this is known as furling, and is a common power limiting mechanism for high winds). These operating modes may aggravate sound generation. It is not always easy to obtain reliable sound measurements from the manufacturers of smaller wind turbines, especially at the wind speeds that might be a concern. For all of these reasons it is important to carefully consider sounds from small wind turbines. Below are three examples of studies of sound levels from wind small turbines.

A study of sound produced by a 10 kW Bergey wind turbine at Halibut Point State Park in Rockport, MA, includes measured sound pressure levels under a variety of wind conditions and at a variety of distances from the wind turbine base [Tech Environmental, 1998]. The study showed that under some conditions the wind turbine sound at 600 feet (182 m) from the wind turbine base increased sound levels by 13 dB(A). The study estimated that a buffer zone of 1,600 feet would be required to meet Massachusetts noise regulations (note that this model has been redesigned since that installation, so current models might not require as large a setback.) Finally, the study also mentioned that under high wind conditions in which the wind turbine sound was masked by the wind-induced background sound, as determined by the broadband sound pressure levels, the wind turbine could still be heard due to the presence of helicopter-like thumping sounds during furling. Similar sounds have been described coming from other small wind turbines [Gipe, 2001]. These low-frequency and periodic sounds are not included in the standard A-weighted sound pressure measurements prescribed in the MA DEP regulations.

In another study, sound measurements were made by the National Renewable Energy Laboratory on a 900 Watt wind turbine, the Whisper 40 [Huskey and Meadors, 2001]. This wind turbine has a rotor diameter of 2.1 m (7 ft) and was mounted on a 30 ft tower. The rotor rotates at 300 rpm at low power. The rotation speed increases to 1200 rpm as the rotor rotates out of the wind (“furls”) to limit power in high winds. This operation results in a blade-tip speeds between 33 and 132 m/s. Figure 9 illustrates the sound pressure level (with the background sound removed) and the background sound levels at a distance of 10 meters (33 ft) from the wind turbine base. Between 6 and 13 m/s the sound pressure levels due to the operation of the turbine increased more than 13 dB. This is a very large increase in sound level and would be experienced as more than a doubling of the sound level. Moreover, it increased enough that the background sound level, which also increased with wind speed, was not enough to mask the wind turbine sound until the wind speed increased to over 13 m/s (30 mph).

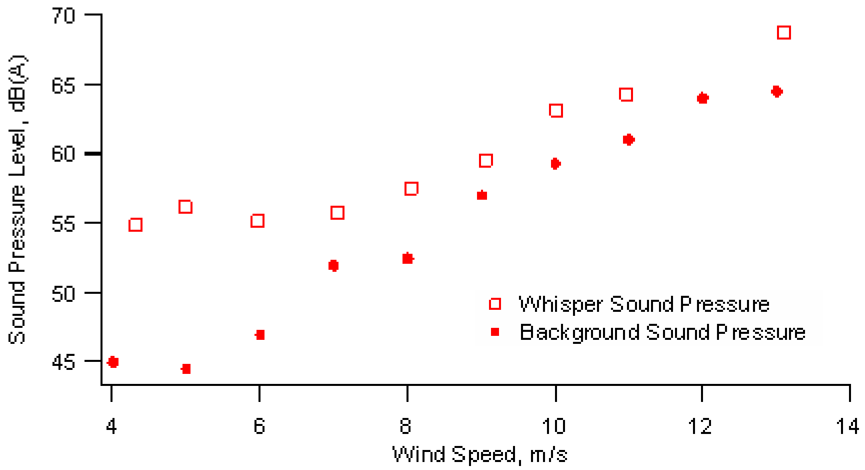


Figure 9: Measured sound power levels of a Southwest Whisper 900 wind turbine

In the third study, the National Renewable Energy Laboratory [Migliore, 2003] performed acoustic texts on eight small wind turbines ranging from 400 watts to 100 kW in rated power, using procedures based on international standards for measurement and data analysis, including wind speeds down to 4 m/s in most cases. A summary of the results are shown in Figure 10, which shows a very wide variety of sound levels. This figure illustrates that measurement in winds over 10 m/s are useful for some of the turbines considered.

Sound measurement standards for small wind turbines: The IEC 61400-11 standard (described below under Noise Standards and Regulations) may not be adequate for estimating sound levels from some small wind turbines. For instance, in contrast to the broad-band aerodynamic sounds from large wind turbines, some small wind turbine designs lead to irregular sounds that may be quite audible at higher wind speeds. Whereas the IEC standard requires the measurements at 6-10 m/s, measurements a lower and higher wind speeds should be included for small wind turbines. In addition, measurement standards do not require the measurement of thumping sounds and other irregular sounds that can be found objectionable. The possibility of irregular sounds and loud sounds in high-wind should be considered when siting small wind turbines in populated areas.

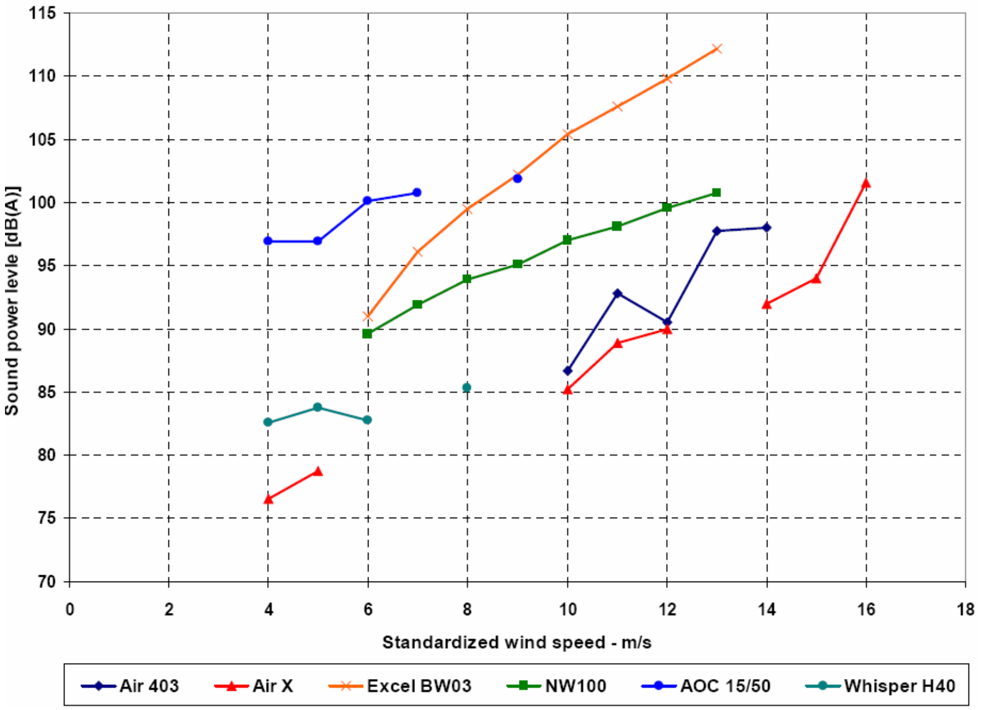


Figure 10: Summary of NREL study of small wind turbine sound: sound pressure level vs. wind speed, with the sound recorded downwind from the turbine [Migliore, 2003]

Factors that Affect Wind Turbine Sound

Wind turbine generated sound that is perceived at any given location is a function of wind speed, as well as turbine design, distance, ambient sound levels and various other factors, which are explored below.

Wind Turbine Design and Sound Emissions

All large, modern wind turbines available commercially today in the US are upwind, horizontal axis, variable pitch, and many have some variability of rotational speed. There are, however, other designs that have been used historically and may appear again in some form.

Several basic design characteristics can influence sound emissions. Wind turbines may have blades which are rigidly attached to the hub and thence to the rotor shaft. Other designs may have blades that can be pitched (rotated around their long axis). Some have rotors that always turn at a constant or near-constant speed while other designs might change the rotor speed as the wind changes. Wind turbine rotors may be upwind or downwind of the tower. Other things being equal, each of these designs might have different sound emissions because of the way in which they operate. In general, upwind rotors as opposed to downwind rotors, lower rotational speeds and pitch control result in lower sound generation.

Aerodynamic sound generation is very sensitive to speed at the very tip of the blade. To limit the generation of aerodynamic sounds, large modern wind turbines may limit the rotor rotation speeds to reduce the tip speeds. Large variable speed wind turbines often rotate at slower speeds in low winds, increasing in higher winds until the limiting rotor speed is reached. This results in much quieter operation in low winds than a comparable constant speed wind turbine.

Small wind turbines (under 30 kW) are also often variable-speed wind turbines. These smaller wind turbine designs may even have higher tip speeds in high winds than large wind turbines. This can result in greater sound generation than would be expected, compared to larger machines. This is also perhaps due to the lower investment in sound reduction technologies in these designs. Some smaller wind turbines regulate power in high winds by turning out of the wind or “fluttering” their blades. These modes of operation can affect the nature of the sound generation from the wind turbine during power regulation.

Sound Propagation

In order to predict the sound pressure level at a distance from source with a known power level, one must determine how the sound waves propagate. In general, as sound propagates without obstruction from a point source, the sound pressure level decreases. The initial energy in the sound is distributed over a larger and larger area as the distance from the source increases. Thus, assuming spherical propagation, the same energy that is distributed over a square meter at a distance of one meter from a source is distributed over 10,000 m^2 at a distance of 100 meters away from the source. With spherical propagation, the sound pressure level is reduced by 6 dB per doubling of distance. This simple model of spherical propagation must be modified in the presence of reflective surfaces and other disruptive effects. For example, if the source is on a perfectly flat and reflecting surface, then hemispherical spreading has to be assumed, which also leads to a 6 dB reduction per doubling of distance, but the sound level would be 3 dB higher at a given distance than with spherical spreading. Details of sound propagation in general are discussed in Beranek and Vers [1992]. The development of an accurate sound propagation model generally must include the following factors:

- Source characteristics (e.g., directivity, height, etc.)
- Distance of the source from the observer
- Air absorption, which depends on frequency
- Ground effects (i.e., reflection and absorption of sound on the ground, dependent on source height, terrain cover, ground properties, frequency, etc.)
- Blocking of sound by obstructions and uneven terrain
- Weather effects (i.e., wind speed, change of wind speed or temperature with height). The prevailing wind direction can cause differences in sound pressure levels between upwind and downwind positions.
- Shape of the land; certain land forms can focus sound

A discussion of complex propagation models that include all these factors is beyond the scope of this paper. More information can be found in Wagner, et al. (1996). For estimation purposes, a simple model based on the more conservative assumption of hemispherical sound propagation over a reflective surface, including air absorption is often used [International Energy Agency, 1994]:

$$L_p = L_w - 10 \log_{10}\left(2\pi R^2\right) - \alpha R$$

Here L_p is the sound pressure level (dB) a distance R from a sound source radiating at a power level, L_w, (dB) and α is the frequency-dependent sound absorption coefficient. This equation can be used with either broadband sound power levels and a broadband estimate of the sound absorption coefficient (α = 0.005 dB per meter) or more preferably in octave bands using octave band power and sound absorption data. The total sound produced by multiple wind turbines would be calculated by summing up the sound levels due to each turbine at a specific location using the dB math mentioned above.

An example of the sound that might be propagated from a singe large modern wind turbine is shown in Figure 11. This example assumes hemispherical sound propagation and uses the formula presented above. In this case the wind turbine is assumed to be on a 50 m tower, the source sound power level is 102 dB(A), and the sound pressure levels are at estimated at ground level.

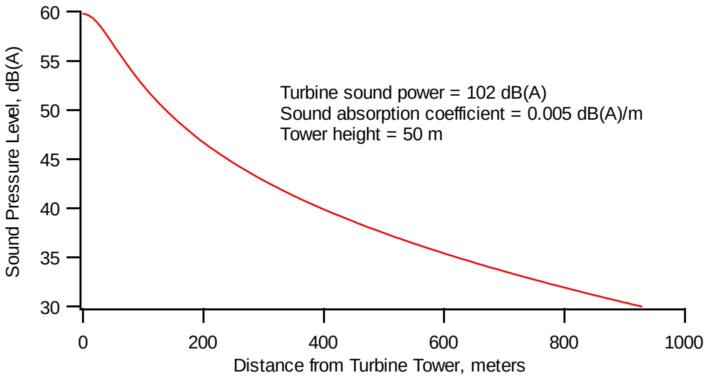


Figure 11: Example of propagation of sound from a large wind turbine

The location of the receptor is also significant. Upwind of a wind turbine there may be locations where no sound is heard. On the other hand sound may be propagated more easily downwind.

Ambient Sounds & Wind Speed

The ability to hear a wind turbine in a given installation also depends on the ambient sound level. When the background sounds and wind turbine sounds are of the same magnitude, the wind turbine sound gets lost in the background.

Ambient baseline sound levels will be a function of such things as local traffic, industrial sounds, farm machinery, barking dogs, lawnmowers, children playing and the interaction of the wind with ground cover, buildings, trees, power lines, etc. It will vary with time of day, wind speed and direction and the level of human activity. As one example, background sound levels measured in the neighborhood of the Hull High School in Hull Massachusetts on March 10, 1992 ranged from 42 to 48 dB(A) during conditions in which the wind speed varied from 5 to 9 mph (2-4 m/s).

Both the wind turbine sound power level and the ambient sound pressure level will be functions of wind speed. Thus whether a wind turbine exceeds the background sound level will depend on how each of these varies with wind speed.

The most likely sources of wind-generated sounds are interactions between wind and vegetation. A number of factors affect the sound generated by wind flowing over vegetation. For example, the total magnitude of wind-generated sound depends more on the size of the windward surface of the vegetation than the foliage density or volume [Fégeant, 1999]. The sound level and frequency content of wind generated sound also depends on the type of vegetation. For example, sounds from deciduous trees tend to be slightly lower and more broadband than that from conifers, which generate more sounds at specific frequencies. The equivalent A-weighted broadband sound pressure generated by wind in foliage has been shown to be approximately proportional to the base 10 logarithm of wind speed [Fégeant, 1999]:

$$L_{A,eq} \propto \log_{10}(U)$$

The wind-generated contribution to background sound tends to increase fairly rapidly with wind speed. For example, during a sound assessment for the Madison (NY) Windpower Project, a project in a quiet rural setting, the background sound was found to be 25 dBA during calm wind conditions and 42 dBA when the wind was 12 mph (5.4 m/s). Background sound generated during sound measurements on a small wind turbine are shown in the Figure 12 [Huskey and Meadors, 2001]. The graph includes a logarithmic fit to that data based on the model mentioned above.

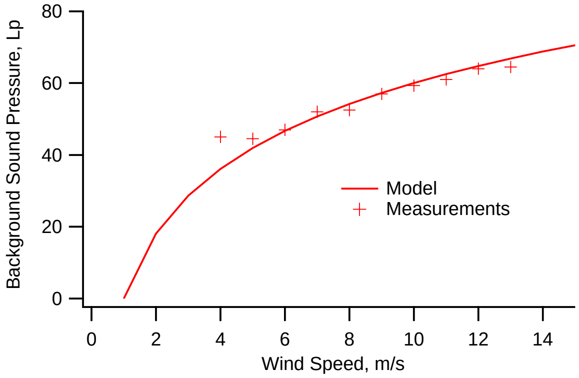


Figure 12: Sample background noise measurements as a function of wind speed

Sound levels from large modern wind turbines during constant speed operation tend to increase more slowly with increasing wind speed than ambient wind generated sound. As a result, wind turbine noise is more commonly a concern at lower wind speeds [Fégeant, 1999] and it is often difficult to measure sound from modern wind turbines above wind speeds of 8 m/s because the background wind-generated sound masks the wind turbine sound above 8 m/s [Danish Wind turbine Manufacturers Association, 2002].

It should be remembered that average sound pressure measurements might not indicate when a sound is detectable by a listener. Just as a dog's barking can be heard through other sounds, sounds with particular frequencies or an identifiable pattern may be heard through background sounds that is otherwise loud enough to mask those sounds. Sound emissions from wind turbines will also vary as the turbulence in the wind through the rotor changes. Turbulence in the ground level winds will also affect a listener's ability to hear other sounds. Because fluctuations in ground level wind speeds will not exactly correlate with those at the height of the turbine, a listener might find moments when the wind turbine could be heard over the ambient sound.

Noise Standards and Regulations

There are standards for measuring sound power levels from utility -scale wind turbines, as well as local or national standards for acceptable noise power levels. Each of these is reviewed here. As of this writing (February 2005), there are no sound measurement standards for small wind turbines, but both the American Wind Energy Association and the International Electrotechnical Commission (IEC) are working on future standards.

Turbine Sound Power Measurement Standards

The internationally accepted standard to ensure consistent and comparable measurements of utility-scale wind turbine sound power levels is the International Electrotechnical Commission IEC 61400-11 Standard: Wind turbine generator systems – Part 11: Acoustic noise measurement techniques [IEC, 2002]. All utility-scale wind turbines available today in the US comply with IEC 61400-11. It defines:

- The quality, type and calibration of instrumentation to be used for sound and wind speed measurements.
- Locations and types of measurements to be made.
- Data reduction and reporting requirements.

The standard requires measurements of broad-band sound, sound levels in one-third octave bands and tonality. These measurements are all used to determine the sound power level of the wind turbine at the nacelle, and the existence of any specific dominant sound frequencies. Measurements are to be made when the wind speeds at a height of 10 m (30 ft) are 6, 7, 8, 9 and 10 m/s (13-22 mph). Manufacturers of IEC-compliant wind turbines can provide sound power level measurements at these wind speeds as measured by certified testing agencies.

Measurements of noise directivity, infrasound (< 20 Hz), low-frequency noise (20-100 Hz) and impulsivity (a measure of the magnitude of thumping sounds) are optional.

Measured sound power levels for a sampling of wind turbines are presented in Figure 13 as a function of rated electrical power. The data illustrate that sound emissions from wind turbines generally increases with turbine size. The graph also shows that wind turbine designers' efforts to address noise issues in the 1990's and later have resulted in significantly quieter wind turbines than the initial designs of the 1980's.

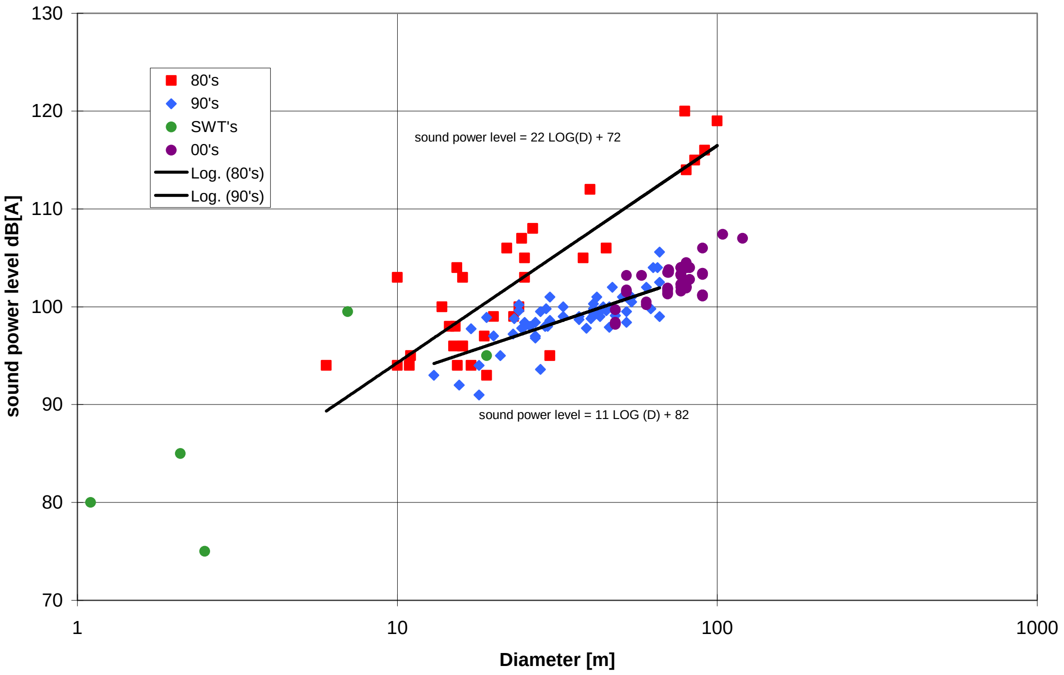


Figure 13: Sample wind turbine measured sound power levels

Community Standards for Determining Acceptable Sound Pressure Levels

At the present time, there are no common international noise standards or regulations for sound pressure levels. In most countries, however, noise regulations define upper bounds for the noise to which people may be exposed. These limits depend on the country and may be different for daytime and nighttime.

For example, in Europe, as shown in Table 2, fixed noise limits have been the standard [Gipe, 1995].

Country	Commercial	Mixed	Residential	Rural
Denmark			40	45
Germany				
(day)	65	60	55	50
(night)	50	45	40	35
Netherlands				
(day)		50	45	40
(night)		40	35	30

Table 2: Noise Limits of Sound Pressure Levels, L_{eq} (in dB(A)) in Various European Countries

In the U.S., although no federal noise regulations exist, the U.S. Environmental Protection Agency (EPA) has established noise guidelines. Most states do not have noise regulations, but many local governments have enacted noise ordinances to manage community noise levels. Examples of such ordinances for wind turbines are given in the latest Permitting of Wind Energy Facilities Handbook [NWCC, 2002].

The Massachusetts Department of Environmental Protection (DEP) regulates noise emissions as a form of air pollution under 310 CMR 7.00, “Air Pollution Control.” These can be found at http://www.mass.gov/dep/air/laws/7a.htm. The application of these regulations to noise is detailed in the DEP’s DAQC Policy Statement 90-001 (February 1, 1990). The regulation includes two requirements. First, any new broadband sound source is limited to raising noise levels no more than 10 dB(A) over the ambient baseline sound level. The ambient baseline is defined as the sound level that is exceeded 90% of the time, the L_{90} level. Second, “pure tones”, defined here as an octave band, may be no greater than 3 dB(A) over the two adjacent octave bands. All these readings are measured at the property line or at any inhabited buildings located within the property.

It should be pointed out that imposing a fixed noise level standard may not prevent noise complaints. This is due to the changing of the relative level of broadband background turbine noise with changes in background noise levels [NWCC, 2002]. That is, if tonal noises are present, higher levels of broadband background noise are needed to effectively mask the tone(s). In this respect, it is common for community noise standards to incorporate a penalty for pure tones, typically 5 dB(A). Therefore, if a wind turbine meets a sound pressure level standard of 45 dB(A), but produces a strong whistling, 5 dB(A) are subtracted from the standard. This forces the wind turbine to meet a standard of 40 dB(A).

A discussion of noise measurement techniques that are specific to wind turbine standards or regulations is beyond the scope of this paper. A review of such techniques is given in Hubbard and Shepherd [1990], Germanisher Lloyd [1994], and Wagner, et al. [1996].

Sample Noise Assessment for a Wind Turbine Project

Much of the interest in wind turbine noise is focused on the noise anticipated from proposed wind turbine installations. When a wind turbine is proposed near a sensitive receptor, a noise assessment study is appropriate; these studies will typically contain the following four major parts of information:

1. An estimation or survey of the existing ambient background noise levels.
2. Prediction (or measurement) of noise levels from the turbine(s) at and near the site.
3. Identification of a model for sound propagation (sound modeling software will includes a propagation model.)
4. Comparing calculated sound pressure levels from the wind turbines with background sound pressure levels at the locations of concern.

An example of the steps in assessing the noise anticipated from the installation of a wind turbine according to the Massachusetts regulations follows.

Ambient Background Levels: Ambient sound levels vary widely and are important for understanding the noise as well as complying with ambient-based regulations. Background sound pressure levels should be measured for the specific wind conditions under which the wind turbine will be operating. In this example it will be assumed that measurements indicate that the L_{90} sound pressure levels are 45 dB(A) at 8 m/s wind speed.

Source Sound Levels: In order to calculate noise levels heard at different distances, the reference sound levels need to be determined. The reference sound level is the acoustic power being radiated at the source, and is not the actual sound pressure level as heard at ground level. Reference sound levels can be obtained from manufacturers and independent testing agencies. Measurements should be based on the standards mentioned above. In this example it will be assumed that the turbine will be on a 50 m tower and has a sound power level of 102 dB(A), as in the previous example of sound propagation from a wind turbine.

Sound Propagation Model: Sound propagation is a function of the source sound characteristics (directivity, height), distance, air absorption, reflection and absorption by the ground and nearby objects and weather effects such as changes of wind speed and temperature with height. One could assume a conservative hemispherical spreading model or spherical propagation in which any absorption and reflection are assumed to cancel each other out. More detailed models could be used that include the effects of wind speed and direction, since sound travels more easily in the downwind direction; however, a conservative model will assume that all directions are downwind at some time. If the hemispherical propagation model is used, then the data in Figure 11 shows the noise levels in the vicinity of the turbine.

Comparison of Calculated Sound Levels with Baseline Sound Levels: Calculated wind turbine sound levels do not include the additional background ambient sound levels. The mathematical relationship governing the addition of dB(A) levels require that if the turbine sound level is no more than 9.5 dB(A) above the ambient noise level, then the total noise levels will be within 10 dB(A) of the ambient sound level. If the ambient sound level is 45 dB(A), then, under Massachusetts regulations, the turbine can generate no more than 54.5 dB(A) at locations of concern. It can be seen from Figure 11 that the sound from the wind turbine would not exceed that limit at all locations more than 75 m (250 ft) from the wind turbine.

Conclusions and Recommendations

Modern, utility-scale wind turbines are relatively quiet; still, when sited within residential areas, noise is a primary siting constraint. The following are recommendations for standards, regulations and siting practices:

- Turbine Standards:
    - Utility-scale turbines: Any incentives to promote wind energy should be provided only to turbines for which the manufacturer can provide noise data based on IEC standards or for turbines which are to be located at sites where there will clearly be no problem.

  - Small turbines: national standards for small wind turbine technology in general are needed. For noise in particular, sound levels should be measured at lower and higher wind speeds, in addition to those measured under the IEC standard. Any operation-mode-dependent, time-dependent and frequency-dependent components also need to be described. These standards need to provide sound measures that provide an accurate representation of issues of interest to potential listeners.

- Noise Regulations:
  - Community noise standards are important to ensure livable communities. Wind turbines must be held to comply with these regulations. Wind turbines need not be held to additional levels of regulations.
  - For small wind turbines: Because of the wide variety of sound levels from small wind turbines, blanket setback limits should not be set *a priori*. However, they should be examined carefully based on the technology proposed.

- Wind turbine siting practice:
  - In order to comply with state noise regulations and to fit within community land use, the siting of wind turbines must take sound levels into consideration.
  - If a wind turbine is proposed within a distance equivalent to three times the blade-tip height of residences or other noise-sensitive receptors, a noise study should be performed and publicized.

References

AWEA (American Wind Energy Association), Procedure for Measurement of Acoustic Emissions from Wind Turbine Generator Systems, Tier I – Standard 2.1 (1989), American Wind Energy Association, Washington, DC, 1989.

Beranek, L. L. and Ver, I. L., Noise and Vibration Control Engineering: Principles and Applications, Wiley, New York, 1992.

Danish Wind turbine Manufacturers Association, www.windpower.dk, 2002.

Fégeant, O., “On the Masking of Wind Turbine Noise by Ambient Noise,” Proc. European Wind Energy Conference, Nice, France, March 1-5, 1999.

Germanisher Lloyd, Regulation for the Certification of Wind Energy Conversion Systems, Supplement to the 1993 Edition, Hamburg, March, 1994.

Gipe, P., Wind Energy Comes of Age, Wiley, New York, 1995.

Golec, M., Golec, Z., Cempel, C., “Noise of Wind Power Turbine V80 in a Farm Operation”, Proceedings of the First international Meeting on Wind Turbine Noise: Perspectives for Control, Berlin, October 17-18, 2005.

Goodman, N., "The Environmental Impact of Windpower Development in Vermont: A Policy Analysis," Proc. Windpower '97, AWEA, pp 299- 308, 1997.

Hubbard, H. H. and Shepherd, K. P., "Wind Turbine Acoustics," NASA Technical Paper 3057 DOE/NASA/20320-77, 1990.

Huskey, A. Meadors, M., Wind Turbine Generator System Acoustic Noise Report for the Whisper H40 Wind Turbine, National Wind Technology Center, Boulder, CO, June 1, 2001.

IEC (International Electrotechnical Commission), IEC 61400-11: Wind turbine generator systems – Part 11: Acoustic noise measurement techniques. Document No. 88/166/FDIS. Publication of the IEC Central Office, Geneva Switzerland, 2002.

International Energy Agency: Expert Group Study on Recommended Practices for Wind Turbine Testing and Evaluation, 4. Acoustics Measurements of Noise Emission from Wind Turbines, 3. Edition 1994.

International Organization for Standardization, ISO:7196, Frequency weighting characteristics for infrasound measurements, 1995

Leventhall G, Notes on Low Frequency Noise from Wind Turbines with special reference to the Genesis Power Ltd Proposal, near Waiuku NZ Prepared for Genesis Power/ Hegley Acoustic Consultants, 4th June 2004, Surry UK. Available at: http://www.windenergy.org.nz/documents/2004/040604-LeventhallReport-LowFrequency.pdf

Manwell et al., Wind Energy Explained, Wiley, Chichester, West Sussex, 2004

Migliore, P. et al, 2003, Acoustic Tests of Small Wind Turbines October 2003. NREL: P. Migliore, J. van Dam, and A. Huskey. Available at: http://www.wind.appstate.edu/reports/NRELAcousticTestsofSmallWindTurbines.pdf

Moorhouse et al, 2005: Proposed criteria for the assessment of low frequency noise disturbance February 2005 Contract no NANR45, Prepared for Defra by Dr. Andy Moorhouse, Dr. David Waddington, Dr. Mags Adams. University of Salford, UK.

National Wind Coordinating Committee, NWCC, Permitting of Wind Energy Facilities: A Handbook," RESOLVE, Washington, D. C, 2002. Available at http://www.nationalwind.org/publications/permit/permitting2002.pdf

Nave, C..R. Hyperphysics: Sound and Hearing: Sound Intensity and Sound Pressure, http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html, Georgia State University, 2005. Referenced January 18, 2006.

Snow, D. J., Low frequency noise and vibrations measurement at a modern wind farm, Harwell Laboratory Energy technology Support Unit, 1997.

Tech Environmental, Inc., Acoustical Analysis of Bergey Wind Turbine, Halibut Point State Park, A report prepared for the Massachusetts Department of Environmental Management, June 1998.

Wagner, S., Bareib, R. and Guidati, G., Wind Turbine Noise, Springer, Berlin, 1996.

Windtest, Report of acoustical emissions of a wind turbine generaotr system of the type V-52-850kW 103 dBa, Report WT 2454/02, 2002.