Wind Turbine Noise Issues

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prepared by the

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Introduction

Wind turbines generate noise from multiple mechanical and aerodynamic sources. As the technology has advanced, wind turbines have gotten much quieter, but noise from wind turbines is still a public concern. The problems associated with wind turbine noise have been one of the more studied environmental impact areas in wind energy engineering. Noise levels can be measured, but, similar to other environmental concerns, the public's perception of the noise 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 noise levels; 3) the terrain between the emitter and receptor; and 4) the nature of the noise receptor. The effects of noise on people can be classified into three general categories (National Wind Coordinating Committee, 1998):

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 produce effects only in the first two categories. Workers in industrial plants, and those who work around aircraft can experience noise effects in the third category. Whether a noise is objectionable will depend on the type of noise (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 noise 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 noise character. Furthermore, while noise may be a concern to the public living near wind turbines, much of the noise emitted from the turbines is masked by ambient or the background noise of the wind itself.

At the present time, the noise 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 noise. 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: Noise 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 noise generation from wind turbines, noise propagation, as well as noise prediction methods are given.

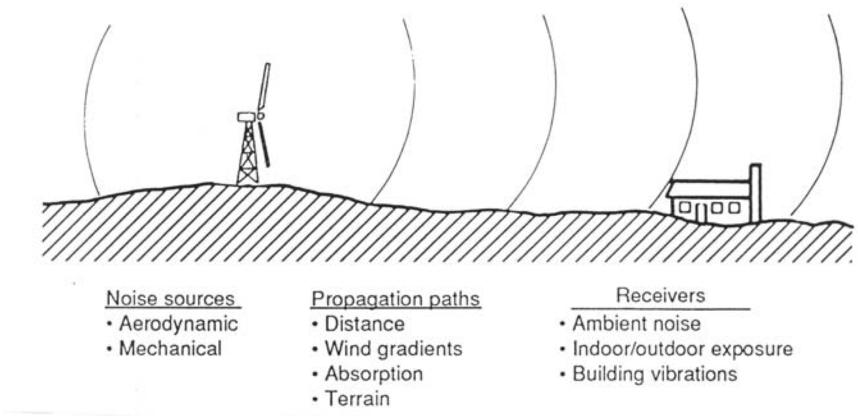

Figure 1. Sound Pressure Level (SPL) Examples

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 (or pitch) determines the 'note' at which it sounds, 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 noise see Wagner, et al., 1996) and are reviewed in the following sections.

Sound Power and Pressure Measurement Scales

It is important to distinguish between the two measures of the magnitude of sounds: sound power level and sound pressure level. Sound power level is 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.

The sound power level of a source, L_W, in units of decibels (dB), is given by:

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

with P equal to the sound power of the source and P_0 a reference sound power (usually 10^{-12} Watts).

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

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

with p equal to the effective (or root mean square, rms) sound pressure and p_0 a reference rms sound pressure (usually $20\ 10^{-5}$ Pa).

Figure 2 gives some examples for various sound pressure levels on the decibel scale. The threshold of pain for the human ear is about 200 Pa, which has an SPL value of 140 dB.

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 noise, 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 (such as A, B, and C) that accomplish this. The most common scale used for environmental noise assessment is the A scale, and measurements made using this filter network are expressed in units of dB(A). Details of these scales are discussed by Beranek and Ver (1992).

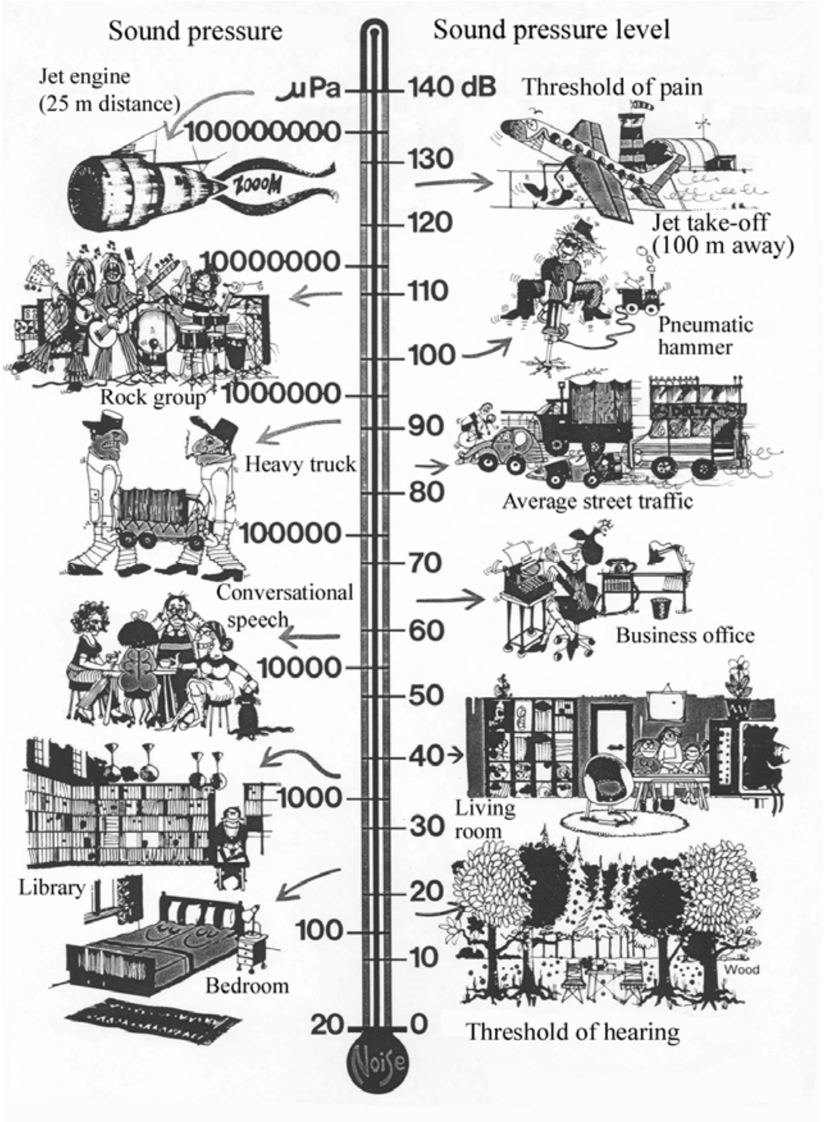

Figure 2. Sound Pressure Level (SPL) Examples (Bruel and Kjaer Instruments)

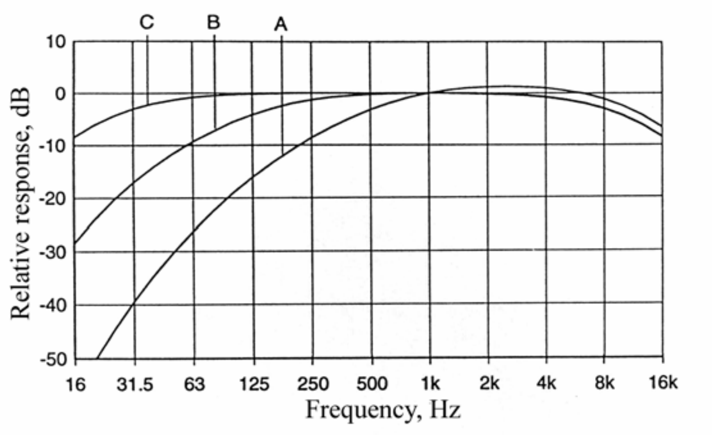

Figure 3. Definition of A, B, and C Frequency Weighing Scales (Beranek and Ver, 1992)

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(A) 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(A) 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, and almost always causes an adverse community response.
- The threshold of pain is an SPL of 140 dB(A)

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 noise levels. Common descriptors include:

1) L_{10}, L_{50}, L_{90}. The A-weighted noise levels that are exceeded 10%, 50%, and 90% of the time, respectively. During the measurement period L_{90} is generally taken as the background noise level.

2) 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.

3) L_{dn}. Day-Night Level. The average A-weighted noise 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 noise sources that are within 12 dB(A) of each other.

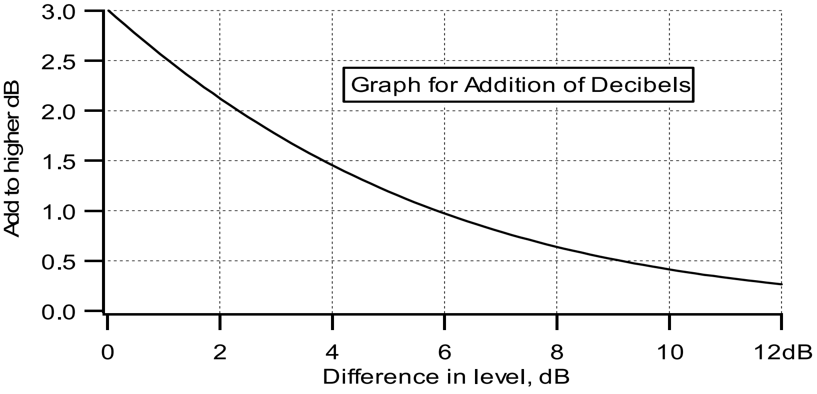

Figure 4. Addition of two sound levels.

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 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.

Sources of Wind Turbine Noise

Sources of Wind Turbine Noise

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

1) Tonal. Tonal noise is defined as noise at discrete frequencies. It is caused by wind turbine 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 noise 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 "whoosing" sound.

3) Low frequency. Noise with frequencies in the range of 20 to 100 Hz is mostly associated with downwind turbines (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 noise 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 noise emitted from operating wind turbines can be divided into two categories: 1) Mechanical, and 2) Aerodynamic. The primary sources of mechanical noise are the gearbox and the generator. Mechanical noise is transmitted along the structure of the turbine and is radiated from its surfaces. Aerodynamic noise is produced by the flow of air over the blades. A summary of each of these noise mechanisms follows. A more detailed review is included in the text of Wagner, et al. (1996).

Mechanical Noise

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

- Gearbox
- Generator
- Yaw Drives
- Cooling Fans
- Auxiliary Equipment (e.g., hydraulics)

Since the emitted noise 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 noise and radiating it. The transmission path of the noise can be air-borne or structure-borne. Air-borne means that the noise is directly propagated from the component surface or interior into the air. Structure-borne noise is transmitted along other structural components before it is radiated into the air. For example, Figure 5 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 noise in this example is the gearbox, which radiates noise from the nacelle surfaces and the machinery enclosure.

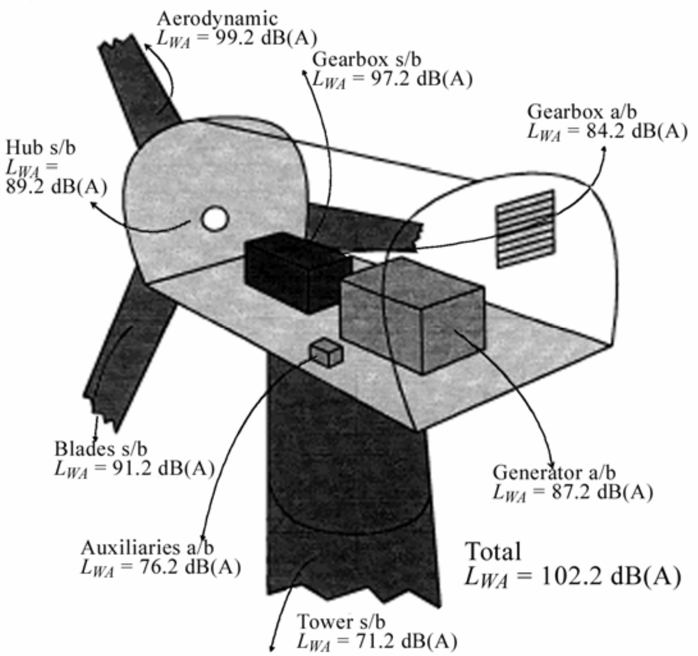

Figure 5. Components and Total Sound Power Level of a Wind Turbine

Aerodynamic Noise

Aerodynamic noise originates from the flow of air around the blades. As shown in Figure 6, a large number of complex flow phenomena occur, each of which might generate some noise. Aerodynamic noise generally increases with rotor speed. Aerodynamic broadband noise is typically the largest source of wind turbine noise. The various aerodynamic noise mechanisms that have to be considered are shown in Table 1 (Wagner, et al., 1996). They are divided into three groups:

1) Low Frequency Noise. This group is related to the low frequency part of the sound spectrum. This type of noise 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 Noise. 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 noise generated by the air flow right along the surface of the airfoil. This type of noise is typically of a broadband nature, but tonal components may occur due to blunt trailing edges, or flow over slits and holes.

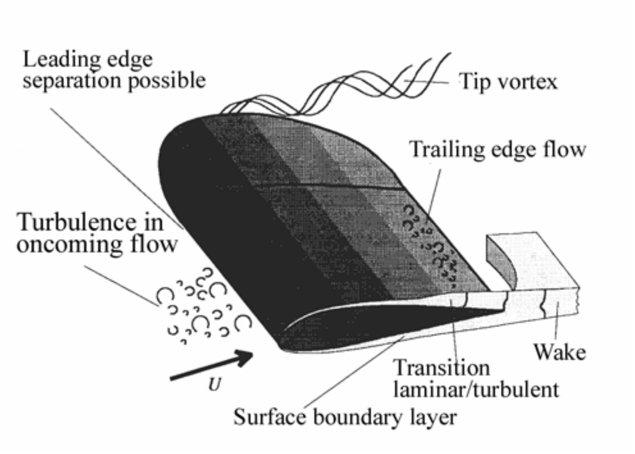

Figure 6. Schematic of Flow Around a Rotor Blade

Type or indication	Mechanism	Main characteristics and importance
Low-frequency noise		
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 turbines/ possibly contributing in case of wind farms
Inflow turbulence noise	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

Table 1 Wind Turbine Aerodynamic Noise Mechanisms

Noise Reduction Methods for Wind Turbines

Turbines can be designed or retrofitted to minimize mechanical noise. 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 noises from being transmitted into the overall structure. Efforts to reduce aerodynamic noise have included (Wagner, et al. (1996) the use of lower tip speed ratios, lower blade angles of attack, upwind turbine 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 noise from both broadband and pure tones. Thus the noise emission from modern wind turbines is dominated by broadband aerodynamic noise [Fégeant, 1999].

Noise and Wind Turbine Operation

Wind turbine generated noise is a function of wind speed and of other aspects of the design of the wind turbine. Wind turbines may have blades which are rigidly attached to the rotor shaft and that always operate at a constant speed. Other designs may have blades that can be pitched (rotated around their long axis). 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 noise 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 noise generation.

Aerodynamic noise generation is very sensitive to speed of translation at the very tip of the blade. To limit the generation of aerodynamic noise, large modern wind turbines limit the rotor rotation speeds to keep the tip speeds under about 65 m/s. 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 (with ratings less than 30 kW) are also often variable speed wind turbines. These smaller wind turbine designs do not always limited the rotor tip speed in high winds to about 65 m/s. This can result in greater noise generation than would be expected, compared to larger machines. This is also perhaps due to the lower investment in noise reduction technologies in these designs. Some smaller wind turbines regulate power in high winds by turning out of the wind. This type of operation may affect the nature of the sound generation from the wind turbine.

Noise Propagation

In order to predict the sound pressure level at a distance from a known power level, one must determine how the sound waves propagate. In general, as noise propagates without obstruction from a point source, the sound pressure level decreases. The initial energy in the noise 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 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 noise 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 considerable differences in sound pressure levels between upwind and downwind positions.

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 noise 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 noise 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(A) per meter) or more preferably in octave bands using octave band power and sound absorption data. The total noise produced by multiple wind turbines would be calculated by summing up the noise levels due to each turbine at a specific location using the dB math mentioned above.

An example of the noise that might be produced by a singe large modern wind turbine is shown in Figure 7. This example assumes hemispherical noise 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.

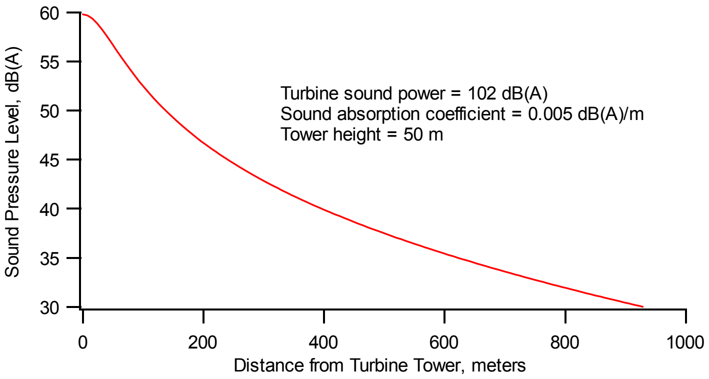

Figure 7. Sample wind turbine noise from a wind turbine

Ambient Noise

The ability to hear wind turbine noise depends on the ambient noise level. When the background noise and wind turbine noise are of the same magnitude, the wind turbine noise gets lost in the background.

Ambient baseline sound levels will be a function of such things as local traffic, industrial noises, 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 noise levels measured in the neighborhood of the Hull High School in Hull Massachusetts on March 10, 1992 ranged from 42-48 dB(A) during conditions in which the wind speed varied from 5-9 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 noise are interactions between wind and vegetation. A number of factors affect the noise generated by wind flowing over vegetation. For example, the total magnitude of wind-generated noise depends more on the size of the windward surface off the vegetation than the foliage density or volume (Fégeant, 1999). The noise level and frequency content of wind generated noise also depends on the type of vegetation. For example, noise from deciduous trees tends to be slightly lower and more broadband than that from conifers, which generate more noise at specific frequencies.

The equivalent A-weighted broadband sound 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 noise tends to increase fairly rapidly with wind speed. For example, during a noise assessment for the Madison Windpower Project, a project in a quiet rural setting, the background noise was found to be 25 dBA during calm wind conditions and 42 dBA when the wind was 12 mph (5.4 m/s). Background noise generated during noise measurements on a small wind turbine are shown in the Figure 8 (Huskey and Meadors, 2001). The graph includes a logarithmic fit to that data based on the model mentioned above.

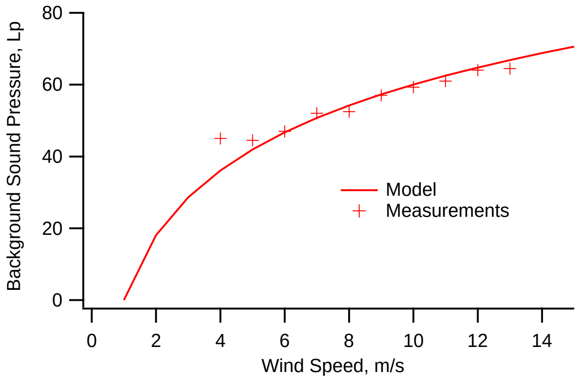

Figure 8. Sample background noise measurements as a function of wind speed

Wind turbine noise from large modern wind turbines during constant speed operation tends to increase more slowly with increasing wind speed than ambient wind generated noise. As a result, noise issues are 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 noise masks the wind turbine noise above 8 m/s (Danish Wind turbine Manufacturers Association, 2002).

It should be remembered that just using sound pressure measurements might not always indicate when a noise is detectable by a listener. Just as a dog's barking can be heard through other noise, sounds with particular frequencies or in an identifiable pattern may be heard through background noise that is otherwise loud enough to mask those noises. Noise 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 noises. 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 noise.

Noise Standards and Regulations

There are both standards for measuring sound power levels from wind turbines and local or national standards for acceptable noise power levels. There are also accepted practices for modeling sound propagation. Each of these is reviewed here.

Turbine Sound Power Measurement Standards

A few standards exist to ensure consistent and comparable measurements of wind turbine sound power levels. These include:

- American Wind Energy Association Standard: Procedure for Measurement of Acoustic Emissions From Wind Turbine Generator Systems, Tier I - 2.1 (AWEA, 1989)
- International Electrotechnical Commission IEC 61400-11 Standard: Wind turbine generator systems – Part 11: Acoustic noise measurement techniques (IEC, 2001)

The IEC 61400-11 standard is used in Europe and often in the US. 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 in narrow-bands. These measurements are all used to determine the sound power level of the wind turbine and the existence of any specific dominant sound frequencies. Measurements of noise directivity, infrasound (frequencies below 20 Hz which cannot be heard, but can cause problems such as building vibration), low-frequency noise between 20 and 100 Hz and impulsivity (a measure of the magnitude of thumping sounds) are optional. 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).

Wind turbine manufacturers should be able to provide sound power level measurements at a variety of wind speeds. These data have usually been determined by certified testing agencies using the standards mentioned here.

Sample sound power levels for a small variety of wind turbines are presented in Figure 9 as a function of rated electrical power. The data were selected from manufacturer's literature or from discussions with manufacturers. Most of these data are for operation with wind speeds of 8 m/s at a height of 10 m. The data illustrate that as wind turbines have increased in size, noise emissions have remained moderately constant. This is a result of the efforts of designers to address noise issues.

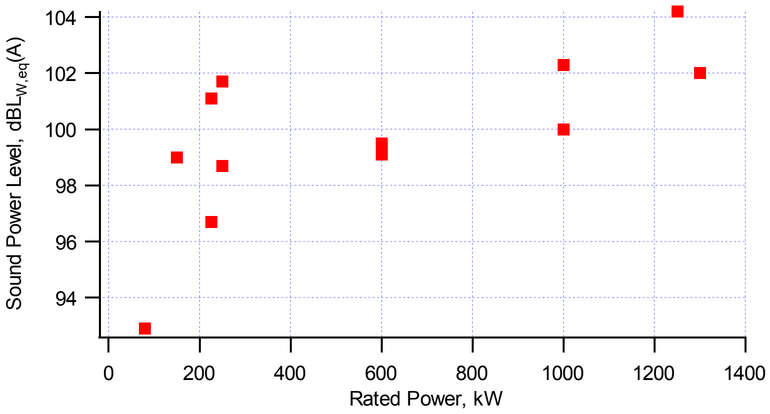

Figure 9. Sample measured wind turbine sound power levels

Community Standards for Determining Acceptable Sound Pressure Levels

At the present time, there are no common international noise standards or regulations. 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 are often different for daytime and nighttime.

For example, in Europe, as shown in Table 2, fixed noise limits are 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} (dB(A)) in Different 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, 1998).

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 www.state.ma.us/dep/bwp/daqc/files/regs/7a.htm. The application of these regulations to noise is detailed in the DPE’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 exceed 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, 1998). 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 power 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 real 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. An appropriate noise assessment study in this situation should contain the following four major parts of information.

1. A 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. Identifying a model for sound propagation.
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. It is very important to measure the background sound pressure levels for the wind conditions in 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).

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, and is not the actual sound level heard. 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.

Noise 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. Often upwind of a wind turbine there are locations where no sound is heard. On the other hand sound may be propagated more easily downwind. If the hemispherical propagation model is used, then the data in Figure 7 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 7 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.

Noise from Small Wind Turbines

Small wind turbines (those 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. These applications result in potential noise complaints due to the proximity of human activity. As mentioned above, small wind turbines may also operate at higher tip speeds or turned partially out of the wind. These operating conditions may aggravate noise generation. It is also 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 noise from small wind turbines.

For example, noise measurements have been 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 noise removed) and the background noise levels at a distance of 10 meters (33 ft) from the wind turbine base. Between 6 and 13 m/s the wind turbine sound pressure increases over 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 noise until the wind speed increased to over 13 m/s (30 mph).

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 noise at 600 ft (182 m) from the wind turbine base increased noise levels by 13 dB(A). The study estimated that a buffer zone of 1600 ft be required to meet Massachusetts noise regulations! Finally, the study also mentioned that under high wind conditions in which the wind turbine noise was masked by the wind-induced background noise, as determined by the broadband sound pressure levels, the wind turbine could still be heard due to the presence of helicopter-like thumping sounds. Similar sounds have been described coming from other small wind turbines (Gipe, 2001). These low frequency sounds are missed by the standard A-weighted sound pressure measurements prescribed in the DEP regulations.

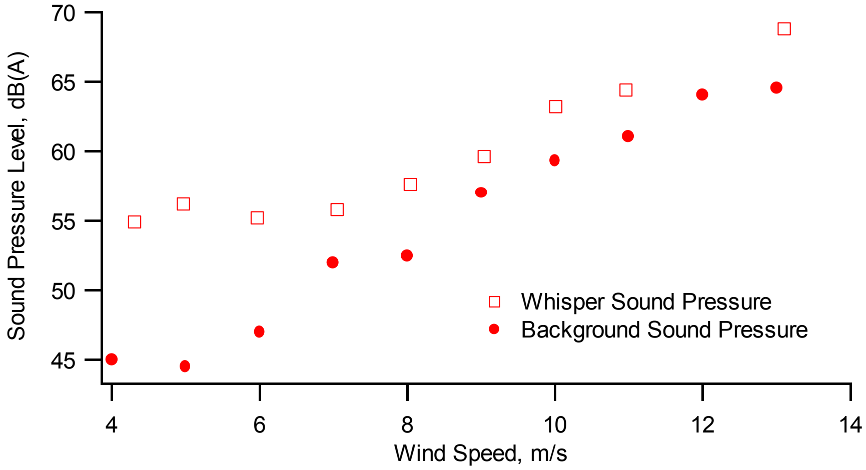

Figure 9. Sample measured wind turbine sound power levels

It can be seen that measurements prescribed in the often-used IEC 61400-11 standard that only include measurements between 6 and 10 m/s (13-22 mph) may not be adequate for estimating wind turbine noise from small wind turbines. In addition, measurement standards no not require the measurement of thumping sounds and other irregular sounds that can be found objectionable.

Conclusions and Recommendations

A number of improvements in standards and regulations are needed to ensure that communities can reliably anticipate noise from wind turbines and to ensure that the data are available to make those sound estimations:

- Guidelines for defining acceptable noise from wind turbines in Massachusetts should be expanded. These should include not only the present DEP criteria for broadband noise and pure tones, but also criteria for impulsive and other sounds and guidelines for the appropriate consideration of background noise levels at different wind speeds.
- 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.
- Setbacks should be defined for turbines for which no data is available.
- Clearer state standards are needed for the measurement of background noise and the estimation of wind turbine noise in assessments of wind turbine projects. These should include standards for measuring background noise as a function of both time of day and wind speed and standards for appropriate propagation models that include the effects of

reflection and absorption of sounds in grasslands, woodlands, and pavement or urban areas and appropriate values for air absorption.

- Standards are also needed for the measurement of noise from small wind turbines. These standards should include measurements to higher wind speeds and measurements that include all the variety of operating modes that might be encountered and that include unusual noise conditions, including time dependent and frequency dependent components such as thumping and whistles. These standards need to provide sound measures that provide an accurate representation of issues of interest to potential listeners.

- Further study of small wind turbine noise is needed to adequately define the types of noise generated by small wind turbines. An understanding of the character of the noise generated by small wind turbines needs to be included in any new measurement and reporting standard and in community noise regulations.

- Finally, manufacturers of small wind turbines need to make comprehensive sound power level measurements, based on new standards, available to the public.

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