SOURCES OF WIND TURBINE NOISE AND SOUND PROPAGATION

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The mechanism of noise generation by wind turbines is a subject not yet fully understood. A large number of complex flow phenomena occur, each of which generate sound in particular frequency bands. The purpose of this paper is to provide a brief description of the current state of technology in respect of noise generation from a wind turbine in a complex meteorological atmosphere and reliable methods of noise prediction to sensitive receptors.

INTRODUCTION

According to the recent report of an Australian Senate Committee inquiry into noise from wind farms, in 2009 there were 85 wind farms in Australia the majority of which were installed in Victoria, South Australia and Western Australia. South Australia accounts for 48 percent of the total generating capacity of wind turbines [1].

Wind farms are located in rural areas where they have the capacity to be intrusive if not properly planned and managed. Objection to a wide range of adverse amenity impacts (including noise) from wind farms has prompted the formation of community groups opposing wind farms in a similar way to those which were formed in opposition to aircraft and motorways. According to the inquiry report, there is a sense of distrust by those community groups of wind farm developers, government authorities and the legal system resulting in a belief by some people that “there is something mysterious about wind farm noise” and “that government and developers are covering something up” [Ref 1, para 2.22 page 9].

At a technical level, there is no doubt that noise from wind turbines is a complex issue. It is the objective of this paper to describe the mechanisms of noise generation from wind turbines as they are currently known.

ANATOMY OF A WIND TURBINE

The energy of the wind is converted into mechanical energy by turning blades attached to a hub and rotor. The rotor is connected to a generator which converts mechanical energy into electrical energy [2].

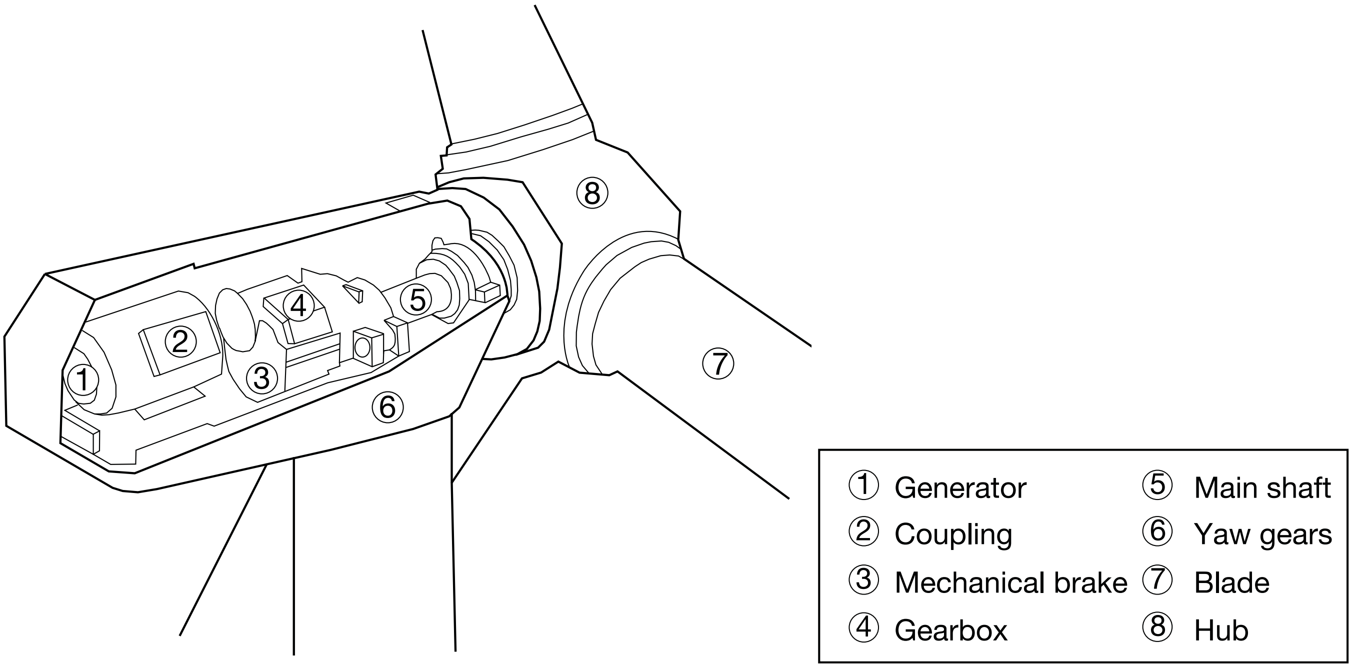

Figure 1. Typical construction of a wind turbine nacelle and arrangement of blades

The conventional 'horizontal axis wind turbine' (referring to the axis on which the blades and hub rotate) consists of four main elements: nacelle, rotor, tower and footing.

1. *Nacelle*: Meaning 'small boat' in French, the nacelle sits on top of the tower and houses the gearbox and generator (see Figure 1). The hub connecting the blades is attached to it at one end. Nacelles are of varying sizes, depending mainly on the design and size of the generator, and may weigh between 20 and 70 tonnes. The nacelle revolves horizontally on the tower ('yawing') to allow the rotor to face the wind regardless of its direction.
2. *Rotor*: The rotor consists of a hub and blades with a shaft connecting them to the gearbox and generator. Most turbines have three blades, commonly made of carbon fibre, plastic, fibreglass or epoxy, which are aerodynamically designed for maximum energy generation and minimum noise. Fixed-speed turbines automatically adjust their blade angle to maintain constant rotation speed in all wind conditions. Variable-speed turbines rotate faster as the wind speed increases, and use power electronics to ensure correct voltage and frequency of output. Blades may exceed 40 metres in length, giving a rotor diameter of 80 to 120 metres.
3. *Tower*: Towers are typically between three and five metres in diameter at the base and taper to about two metres at the top. Their height varies with the size of the generator and the length of the blades and may be as high as 120 metres. The height is necessary to gain access to higher and less variable wind speeds than those at ground level. All modern wind farms use tubular steel towers. Earlier overseas developments used steel lattice towers [3].
4. *Footing*: Footings are generally a concrete slab below ground, 7-12 metres or more in diameter, and 1-2 metres in depth. The base is topped with a circular plinth which contains the turbine tower 'holding down' bolts. Once the footing is installed and the tower erected, the excavation is back-filled and the area landscaped to the base of the tower.

Wind turbines are either fixed-speed machines or more commonly variable speed. Fixed-speed turbines idle (turn slowly) until a “cut-in” wind speed is reached, typically 4 to 5 m/s (metres per second) measured at the hub. “Cut-in” is the point at which the generator starts to produce electricity. Beyond that point, the rotors quickly reach constant operating speed of 15 to 30 revolutions per minute. The control system of the turbine maintains the operating speed by constantly adjusting the pitch of the blades in response to changes in wind speed.

Variable speed turbines allow more efficient conversion of energy from the wind with hub speeds varying from about 14 to 18 revolutions per minute. The conversion of a variable electrical output to a fixed line frequency and amplitude is accomplished by electronics.

All turbines automatically stop rotating when they reach a “cut-out” wind speed, typically 25 m/s measured at the hub. Whether fixed or variable speed, all wind turbines are designed to maintain a reasonable stable quality of power output regardless of variations in wind speed.

WIND TURBINE SOUND CHARACTERISTICS

The combination of noise sources from a wind turbine can generally be described as a mechanical noise (such as a car running or a train in continuous motion) combined with an aerodynamic swishing sound (described as like a stick being swung through the air quickly). There are four types of sound generated by wind turbine operation: tonal, broadband, low frequency/infrasound, and impulsive:

1. Tonal: Tonal sound is defined as sound at discrete frequencies. It is caused by components such as meshing gears, non-aerodynamic structural resonances, or unstable flows over holes or slits or a blunt trailing edge. Tonal sound is not usually a problem in modern turbines as evidenced by examination of numerous test certification documents from manufacturers such as Vestas, RE Power and GE.
2. Broadband: This is sound characterized by a continuous distribution of sound pressure with frequencies greater than 100 Hz. It is caused by the interaction of boundary layer turbulence with the trailing edge of the turbine blades and is also described as a characteristic "swishing" or "whooshing" sound [4]. The variation in sound level and character is called “modulation” or “amplitude modulation” and is probably the most predominant source of noise in modern wind turbines.
3. Low Frequency/Infrasound: Low frequency sound contains frequencies in the range 20 to 100 Hz and is mostly associated with downwind rotors (turbines with the rotor on the *downwind* side of the tower which are no longer common). It is caused when the turbine blade encounters localized air stream disturbance from the tower [5]. Infrasound is sound with frequencies below 20Hz [6] and is generated to some extent by air turbulence impinging on the blade leading edge but probably more so by flow perturbation over the blade as it passes in front of the tower, however the true sources of infrasound are yet to be proven [4].
4. Impulsive: This sound is described as regular short acoustic impulses or a “thumping” sound occurring at the rate of about one per second (the blade passing frequency). It is caused by the interaction of wind turbine blades with disturbed air flow around the tower of a downwind machine. It has also been observed to occur in modern upwind rotors [7]. It may also be the low frequency components remaining in the acoustic signal after sound propagation through the atmosphere has attenuated the high frequency components. However, the precise mechanism of impulsive noise is in dispute.

SOURCES OF WIND TURBINE NOISE

The total noise generated by a wind turbine is made up of several components, broadly grouped as mechanical noise and aerodynamic noise. Whenever the wind speed is below “cut-in”, the blades rotate very slowly or are stationary and “parked” and consequently there is minimal noise generated. When the turbine is operating between wind speeds of approximately 4m/s and 30m/s measured at hub height, the sound power level monotonically increases, a typical example of which is shown in Table 1.

Table 1. Sound power level for Vestas V90-3.0MW (80m Hub)

U_s m/s	4	5	6	7	8	9
Lw dB(A)	97.9	100.9	104.2	106.1	107.0	106.9

U_s m/s is the wind speed in m/sec at a standardised anemometer height of 10m. Lw is sound power level re 10^{-12} watts.

Mechanical Noise

Sources of mechanical noise include the following:

- Gearbox
- Generator
- Yaw Drives
- Cooling Fans
- Auxiliary Equipment (e.g., hydraulics), and
- Application of parking brakes

Since the emitted sound is associated with the rotation of mechanical and electrical equipment, it tends to be tonal 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. However, in modern turbines (other than the brief application of parking brakes in some turbines), mechanical noise is not usually audible above aerodynamic noise.

Aerodynamic Noise

Aerodynamic noise associated with the passage of air over the blades is typically the most important component of wind turbine acoustic emissions. A large number of complex flow phenomena occur, each of which generate sound in particular frequency bands. Aerodynamic sound level generally increases with rotor speed.

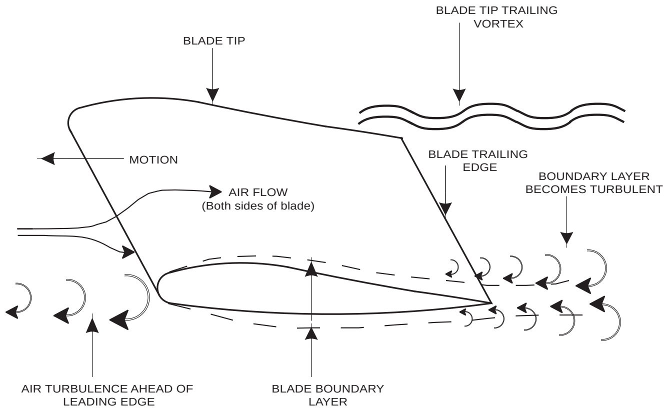

Figure 2. Aerodynamic noise sources associated with wind turbine blade (blade shown cut to reveal cross-section)

By reference to Figure 2, the various aerodynamic sound generation mechanisms may be grouped as follows:

1. *Trailing Edge Noise*: The flow of air over the turbine blade creates a boundary layer attached to its upper and lower surfaces typically 25mm thick. The flow transitions to a turbulent state as it reaches the trailing edge of the blade and sound is generated by the interaction of the turbulence eddies with the trailing edge. This is the major source of noise in modern wind turbines with most of the energy in the frequency range 250-1000Hz [4]. A very important observation by Doolan [4] is that trailing edge noise has a cardiod directivity characteristic associated with dipole aerodynamic sources with its predominant lobe oriented towards the leading edge of the blade. In other words, there is an inherent directivity associated with aerodynamic noise emitted from wind turbines which has not to date received much attention in the literature. On the downward movement of the blades, the change in orientation of the asymmetric directivity pattern associated with the trailing edge noise source described earlier, results in a frequency modulation which is colloquially described as a "swish" [8-10]. Associated with the "swish" is an amplitude modulation of the sound at the blade passing frequency. The swish amplitude is defined as the difference between the minimum and maximum dB(A) sound level during one revolution of the blades [8].
2. *Impulsive Noise*: As stated in the various noise guidelines and standards referred to later in this paper, there is a level of "swish" which is a normal characteristic of wind turbines. However, an increased level of amplitude modulation is reported as a "thumping sound" by several investigators [8] and is referred to in this paper as "impulsive noise" to distinguish it from a normal level of amplitude modulation or "swish" as described above. However, it is important to note that the term "amplitude modulation" in the various standards and guidelines pertaining to wind farm noise includes what is referred to here as "impulsive noise". Although various possible causes for impulsive noise have been suggested such as blade noise directivity, blade-tower interaction, variation of wind speed over the rotor and interaction between the noise from two or more turbines, the mechanism is not well understood [8]. A study by Salford University concluded that of 155 wind farm sites surveyed, only four exhibited instances of impulsive noise generation and at those sites, impulsive noise occurred for 7-15% of the time which was managed by operational means [11]. A study of three other wind farms in the UK which were reported to have a low frequency noise problem concluded that the cause of annoyance was amplitude modulation especially at night [12].

   To date, there is no clear indication of the conditions that are responsible for impulsive noise and therefore its occurrence cannot be predicted. In the interim, as a precautionary measure, if the effect is associated with high shear winds and enhanced propagating conditions then this could be examined at the planning phase of a development. For example, the adoption of a principle that a relatively high level of wind shear (a coefficient greater than about 0.4) together with a high frequency of occurrence of temperature inversion (% occurrence of classes F+G greater than about 30%) are *prima-facie* conditions for which there is likely to be a risk of occurrence of impulsive noise.
3. *Inflow Turbulence Sound*: This source of noise is due to turbulence in the air stream ahead of the leading edge of the blade interacting with the blade surface. This also has a characteristic dipole directivity pattern but unlike trailing edge noise the frequency generated is around 18Hz [4].
4. *Blade Tip Noise*: This is generated by flow past the blade tip

generating a vortex stream in a similar way to trailing edge noise. However, it is understood to be not as significant a source as trailing edge noise.

5. *Blade-Tower Interaction*: This is an impulsive sound caused by the interaction of the blades with the perturbed up-stream flow caused by the tower. The flow of air around the tower is disturbed (or separated) up-stream of the tower causing the blades to experience a change in lift force and a corresponding production of noise. The frequencies associated with this source are generally infrasonic. The magnitude of the noise level is understood not to be significant for modern wind turbines.

IEC 61400-11 WIND TURBINE SOUND POWER MEASUREMENT

The noise output of a wind turbine generator is universally determined from controlled site tests in accordance with international standard IEC 61400-11 “Wind turbine generator systems – Part 11: Acoustic noise measurement techniques” [6]. The procedure involves measurement of sound levels up close to the turbine and calculating the sound power level of the turbine at integer wind speeds referenced to a 10m high anemometer mast (as in Table 1). Measurements are taken with a microphone fixed to a circular board placed on the ground to reduce the wind noise generated at the microphone and to minimise the influence of different ground types. Measurements of sound pressure levels and wind speeds are made simultaneously over short periods of time and over a wide range of wind speeds. The wind speed is measured at a height z (which may differ from the standard anemometer height of 10m).

As explained later in this paper, the wind speed increases with height above ground, the rate of increase in part depending upon the height of obstructions on the ground such as buildings and vegetation. The height of obstructions on the ground is measured by the surface roughness length z_0. Values of z_0 typically range from 10mm for open flat land to 300mm for suburbs or land with densely planted trees such as forest. The international standard corrects the measured wind speed at height z to specific reference conditions. The reference condition for terrain is a roughness length of 50mm (typical of open vegetated farming land) and the reference condition for the wind speed height is the standard anemometer height of 10m. The standardization is accomplished by use of the following equation:

$$U_s = U_z \left[\frac{\ln\left(\frac{z_{ref}}{z_{0ref}}\right) \ \ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H}{z_{0ref}}\right) \ \ln\left(\frac{z}{z_0}\right)} \right] \qquad (1)$$

where U_s is the corrected wind speed under reference conditions which is correlated with the sound power level of the turbine, U_z is the measured wind speed at anemometer height z, z is the measurement anemometer height, z_{ref} is the standard anemometer reference height of 10m, z_{0ref} is the reference roughness length of 50mm, z_0 is the roughness length at the measurement site, and H is the rotor hub height.

The standardising procedure enables the sound power level of wind turbines measured under different environmental conditions to be directly compared with each other under reference conditions. However, in applying the quoted sound power level of turbines to a new project site, one cannot simply assume those sound power levels relate to the 10m anemometer wind speeds measured at the project site because the roughness length could be different to the reference conditions. One would need to use a variation of equation (1) to recalculate U_s for the project site (U_s') with the appropriate roughness length z_0' applicable to the project site. In the author’s experience, this has not been common practice when assessing noise from new projects as it was presumably assumed that project sites can be equated to “open vegetated farming land” having a roughness length of 50mm. Furthermore, as discussed below in this paper, the wind speed gradient does not only depend upon the terrain roughness length but also on meteorological conditions. Therefore, the recalculated value of U_s' for the project site may not necessarily apply to all meteorological conditions. If instead the reference wind speed for sound power level measurements is quoted at hub height rather than at the 10m standard anemometer height this avoids those complications. This is the preferred method recommended in current wind standards and guidelines.

The quantification of noise characteristics is also described in the standard such as tonality, infrasound, low-frequency noise, impulsive noise, amplitude modulation and any other characteristics (such as bangs and screech). Caution should however be used in applying those noise characteristics measured close to the turbine as they may not apply at larger distances. The reason is that characteristics such as impulsive noise and amplitude modulation may not be evident close to the turbine due to the directional properties of aerodynamic noise referred to earlier. Also, testing during the daytime may avoid the incidence of amplitude modulation and impulsive effects if they occur at night in high wind shear situations.

WIND SPEED PROFILE

The effect of wind speed profile and atmospheric stability on wind turbine sound propagation has been studied and reported extensively by van den Berg [7]. In a non-complex terrain up to a height of about 200 m above ground level, wind speed is not constant but usually increases with height. The reason is that wind close to the ground is influenced by the roughness of the ground surface and therefore experiences friction resulting in the formation of a boundary layer over this height range. The wind profile is reasonably well approximated as a power-law of the form:

$$U_z = U_r \left[\frac{z}{z_r} \right]^{\varepsilon} \qquad (2)$$

where U_z is the scalar mean wind speed at height z above ground level, U_r is the scalar mean wind speed at some reference height Z_r, commonly 10 m, and ε is the power-law exponent. The power-law exponent ε typically varies from about 0.1 on a sunny afternoon to about 0.6 during a cloudless night. The larger the power-law exponent, the larger the vertical gradient in the wind speed. Although the power-law is a useful engineering approximation of the average wind speed profile, actual profiles will deviate from this relationship.

Site-specific values of the power-law exponent may be determined for sites with two levels of wind data by solving equation (2) for ε:

$$\varepsilon = \left[\frac{1\text{n}(U_z) - 1\text{n}\ (U_r)]}{1\text{n}(Z) - 1\text{n}\ (Z_r)} \right] \quad (3)$$

The wind profile power-law exponent is a function of stability, surface roughness and the height range over which wind speeds are determined. Stability refers to the state of the atmosphere close to the ground. An unstable atmosphere occurs when the ground heats the lower air during the day and the upper air remains cold. This is an unstable situation because the hot air, being less dense, is prone to rise and to be replaced with the upper cold air which, being denser, gravitates downwards to replace it. This vertical motion and mixing of air destabilizes the horizontal air-flow pattern and causes the wind speed to be less variable with height. At sunset, the ground cools quickly and the adjacent air also cools. The warmer air, being less dense, gradually disperses to the higher altitudes. The vertical mixing described above subsides and the situation now becomes stable (warm air at the upper levels and cold air at the lower levels). This is referred to as a temperature inversion. In a stable atmosphere, horizontal air-flow becomes laminar (i.e. moves essentially horizontally over the ground) and, in the absence of vertical disturbances, is capable of developing a strong horizontal shear gradient with the upper air moving faster than the lower air. However, strong winds may disperse a temperature inversion due to mixing effects.

Surface roughness is also a factor affecting the power-law exponent. In general terms, the rougher the ground surface (for example forest compared to open grass), the greater will be the power-law exponent. As stability and surface roughness vary depending upon wind direction and season of the year, they should be determined independently for each of those time categories. Typical values of power-law exponent which occur in various stability situations are given in Table 2 [13,14]. The atmospheric stability classifications A-G in Table 2 are termed the Pasquill-Gifford classification.

Table 2. Typical default power-law exponents ε for urban and rural wind profiles

Stability Class	**Typical Occurrence**	**Urban Exponent**	**Rural Exponent**
A	Unstable. Sunny day with light winds	0.15	0.07
B	Mildly unstable	0.15	0.07
C	Weakly unstable	0.20	0.10
D	Neutral: Overcast conditions regardless of wind speed	0.25	0.15
E	Weakly stable	0.30	0.35
F	Stable: Clear sky, light winds and moderate temperature inversion present	0.30	0.55
G	Extremely unstable: Found in arid rual areas. Strong temperature inversion present	>0.30	>0.55

Figure 3 shows, by way of example, the variation in wind speed with height for three typical cases indicated in Table 2, that is A, D and E. On a sunny day with light winds (Class A), the wind speed does not vary significantly with height. The wind speed at the standard anemometer height of 10m does not differ substantially from the wind speed at a hypothetical turbine hub height of 70m. On a clear night (Class E), the wind speed at the turbine hub height may be substantially higher than at 10 metres, in this case it is twice the value measured at the standard anemometer height. However, the power-law exponent should be calculated from wind speed data for each specific site.

It should now be clear that the rotor blades sweep through a wind that changes speed with height above ground level and having a gradient dependent upon meteorological conditions and the nature of the landscape and so the mechanisms producing aerodynamic noise previously described are found to be in cyclic synchronism with that complex airflow pattern. This interaction of machine and its environment is what makes turbine noise a unique noise source.

EFFECT OF WIND SPEED PROFILE ON SOUND PROPAGATION

Sound is convected by the wind, that is, the wind carries the sound with it. Sound travels at a speed of approximately 340m/sec and so in a 5m/sec wind at a given height (in the same direction as the sound) it will travel at a speed of 345m/sec. If the wind speed increases with height, then sound “rays” at a higher altitude will travel faster than sound “rays” close to the ground. The net result is that the “rays” bend towards the ground. Those rays which would have dispersed into the air and thus would not have been audible are bent towards the ground and amplify the sound traveling along the ground. This enhances the sound level when the wind blows from the source to the receiver. When the wind blows from the receiver to the source, one may think in terms of the wind “blowing the sound rays” away and hence the sound is attenuated. The degree to which the sound is enhanced or attenuated is affected by the power-law exponent. The greater the power-law exponent, the greater the wind effect. Hence, on sunny days (Class A), for the same wind speed measured at the standard 10m height, the effect of wind is not as great as on clear nights (Classes E-G).

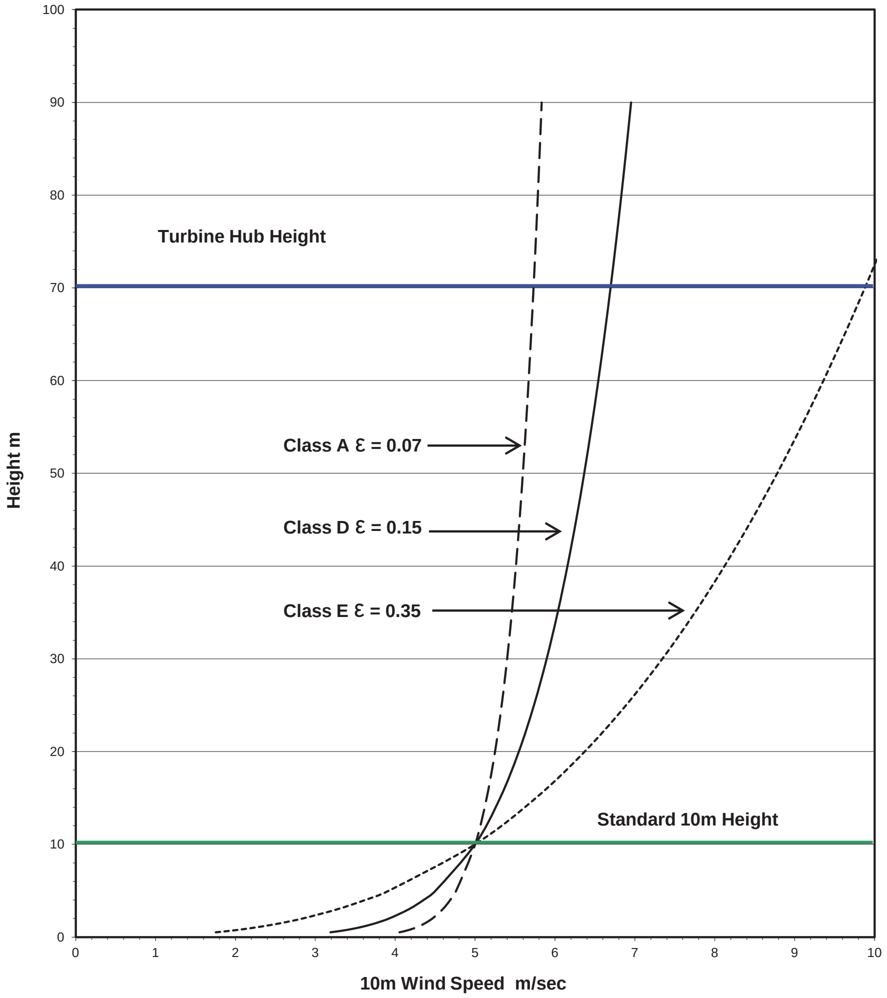

Figure 3. Wind speed profiles with equal speed of 5m/sec at 10m height (above ground level)

VERTICAL TEMPERATURE GRADIENT

During the day, the air temperature generally decreases with height as a consequence of the ground heating the lower air and not the upper air. This is termed a “temperature lapse” and, for the reasons discussed above, is an unstable situation. At night, the reverse occurs and the ground cools quickly, in turn cooling the lower air whilst the higher air remains warm due to its poor thermal conductivity. This is termed a “temperature inversion” and, again for the reasons stated above, is a stable situation. When overcast, the effect of cloud cover is to make the air generally constant in temperature and this is termed a “neutral” situation. The stability of the air is expressed in terms of the Stability Category A-G which was previously introduced in Table 2. Categories A-C, for example are classed as a temperature lapse, Category D is a neutral situation and Categories E-G are temperature inversions as shown in Table 3 [14].

Table 3. Stability categories based on vertical temperature gradient

Stability Class	Typical Occurrence	Vertical Temp Gradient C°/100m
A	Unstable. Sunny day with light winds	<-1.9
B	Mildly unstable	-1.8
C	Weakly unstable	-1.6
D	Neutral: Overcast conditions regardless of wind speed	0
E	Weakly stable	1.5
F	Stable: Clear sky, light winds and moderate temperature inversion present	3.0
G	Extremely unstable: Found in arid rual areas. Strong temperature inversion present	≥ 4

EFFECT OF VERTICAL TEMPERATURE GRADIENT ON SOUND PROPAGATION

Sound travels faster in warmer air. If the temperature increases with height (ie. in a temperature inversion), then sound “rays” at a higher altitude will travel faster than sound “rays” close to the ground. The net result is that the “rays” bend towards the ground. As for the discussion above in the case of wind, those rays which would have dispersed into the air and thus would not have been audible are bent towards the ground and amplify the sound traveling along the ground. This enhances the sound level when there is a temperature inversion. However, unlike wind, the enhancement occurs in all directions no matter where the receiver is located relative to the source. If the temperature decreases with height (ie. in a temperature lapse), the sound “rays” are convected upwards and hence the sound is attenuated. The degree to which the sound is enhanced or attenuated is affected by the vertical temperature gradient. The greater the gradient, the greater the effect. Hence, on sunny days (Class A), sound is generally reduced and on clear nights (Classes E-G) the sound is enhanced. The combined effects on noise of a wind speed gradient and temperature gradient are additive.

NOISE PREDICTION MODELS

There are three principal methods used in Australian codes and guidelines for the prediction of noise levels from wind turbine sites [15-17], namely, the simple geometrical model, ISO9613-2 and CONCAWE. The factors affecting sound propagation are:

- Distance
- Air absorption
- Ground effect (because the ground is not a perfect reflector and the effect of sound reflection and refraction from the ground is dependent on the source height, terrain cover, ground properties and frequency)
- Blocking of sound by obstructions and uneven terrain
- Weather effects (wind speed and the variation of wind speed or temperature with height), and
- Shape of the land (certain land forms can focus sound).

Simple Geometric Model

A simple model based on the more conservative assumption of hemispherical sound propagation over a reflective surface including air absorption is recommended in Australian Standard AS4959 as follows [18]:

$$Lp = Lw - 10\log(2\pi R^2) - \alpha R \qquad (4)$$

where Lw is the sound power level of the turbine (dB re 10^{-12} watts), R (metres) is the distance between the source and the receptor, and the term αR takes into account the absorption of sound as it passes through the air. α is expressed in octave band frequencies and is given in Table 4.

Table 4. Atmospheric absorption coefficient α dB/m

Octave Band Freq Hz	63	125	250	500	1k	2k	4k	8k
α dB/m	.0001	.0004	.0011	.0023	.0041	.0087	.0264	.0937

The total sound pressure level produced by multiple wind turbines is calculated by logarithmic summation of the sound pressure levels from each turbine at a specific location. The ETSU review of a model similar to that described in the standard concluded that the predicted levels lie within about 1-2dB(A) of the levels measured in the presence of a 6m/sec positive wind vector (10m height) between source and receiver [19]. Other evidence however suggests that the model may not be conservative in specific topography [20].

If the receptor is located indoors, then the sound is reduced a further 10 dB(A) for a typical residence with open windows. With windows closed the decrease is typically 15 dB(A) or more, depending upon the glazing thickness and the window type. However, this relates only to the dB(A) scale. Much lower values of outdoor-to-indoor sound attenuation have been measured for infrasound, in some instances close to zero attenuation [21].

ISO 9613-2

The ISO 9613 noise prediction model is described in Part 2 of the international standard. It is part empirically based and part theoretically based. It calculates noise levels under conditions favourable to the propagation of noise. Favourable conditions are defined to be a 1m/s to 5m/s component of wind speed blowing from the source to the receiver or a well developed moderate temperature inversion. The ISO model also includes the effects of terrain, excess attenuation due to ground effects and acoustic screening.

The accuracy of output from the ISO model was validated by ETSU [19]. The project aimed to quantify the variation in noise level experienced at varying distances from an omni-directional loudspeaker noise source located between 15m to 30m above ground level on three different sites representing ‘flat’, ‘rolling’ and ‘complex’ topography. At each site, sound pressure levels were continuously monitored at up to 15 locations around the noise source over periods of up to 6 weeks. The measurement locations extended from less than 50m to over 900m from the noise source. Simultaneous measurements of important meteorological parameters were also undertaken including wind speed, wind direction, wind shear, temperature, temperature gradient, atmospheric pressure and rainfall.

Under conditions of a 6m/s positive vector wind speed (10m height) on flat, rolling and complex terrain sites, the accuracy was found to be within 1.5dB(A). The only observed exceptions occurred in the presence of marginal or partial acoustic screening, and also where the ground falls away significantly between the source and receiver.

In order to account for these situations, it was proposed in the report that the excess attenuation attributable to barriers should be limited to no more than 3dB(A). This is because it has been observed experimentally that the presence of a positive component of wind from the source to the screened receiver significantly reduces the effective barrier performance.

Where the ground falls away significantly between the source and receiver, such that the mean propagation height is at least 1.5 times that over flat ground and particularly where the ground falls away steeply from the receiver, it was recommended that 3dB(A) be added to the calculated sound pressure level. This correction factor is based on experimentally measured levels. It accounts for the reduction in excess ground attenuation due to the increased height of propagation.

Provided the suggested correction factors are applied to the output of the ISO 9613 model, the report states that agreement is achieved to within 2dB(A) of noise levels measured under practical 'worst case' conditions at distances of up to 1,000 metres from a noise source. Also, based on the observed scatter of measured sound pressure levels under these same conditions, it concluded that the one standard deviation spread of data above the calculated levels will be below 1dB(A), even at the furthest distances from the source. It therefore concluded that an 85% level of confidence can be placed on the noise levels measured in practice not exceeding the calculated level by more than 1dB(A). The accuracy of the model at distances beyond 1,000 metres at which, in Australia at least, most residential dwellings will usually be located, is under investigation [eg. reference 23].

CONCAWE

The CONCAWE prediction method was developed for use in predicting noise from power stations and validated in areas of relatively flat terrain [22]. As a consequence of the large deviations noted in the model predictions for wind farm noise, the ETSU study [19] did not recommend use of the model. Recent studies of the model in Australia confirm that it is accurate under some circumstances but not in others [23].

CONCLUSIONS

The fact that wind turbines interact with the environment which propagates the sound they generate makes this source of noise unique amongst other autonomous mechanical noise sources. This paper has provided an introduction into the complex mechanisms involved and a simple view of the current state of understanding of the technology relating to the generation and propagation of wind turbine noise.

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