Meteorological stability impacts on wind turbine noise assessments

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ABSTRACT

Current wind farm noise regulations stipulate wind speed dependant criteria (referenced to wind speed at the hub height of the turbines), under the assumption that during high-wind speed conditions (when wind turbines generate higher noise levels), there will be a corresponding high wind speed and masking noise level at nearby receivers. However, under very stable conditions, high wind speeds at the turbine hub height will create significant noise, while low wind speeds at the receiver will not be sufficient to provide a masking effect. This has been considered in assessment guidelines by filtering day/night background data, but this approach ignores the impact of changes in the level and spectral content of turbine noise due to high shear velocities across turbine blades. This paper examines meteorological data in the vicinity of an undisclosed future wind farm site in South Australia, which was used to filter noise and wind speed data based on stability criterion, and discusses the potential impact on the noise criteria used for wind farm developments.

INTRODUCTION

Wind turbine noise assessments are undertaken based on the unique combination of wind turbine generators producing more noise at higher wind speeds (generally up to the rated power of the turbine), with increased wind generally providing higher background noise levels at sensitive receivers (due to wind noise in trees and vegetation) which masks the higher noise from the wind turbine generators (with Regulators providing a minimum noise limit depending on the prescribed level of amenity, typically no less than 35 dBA).

In the past, wind farm standards and guidelines have sought to correlate background noise levels, and wind turbine generator noise levels based on wind speeds referenced at 10 metres above ground level, on the false assumption that there the wind profile remains constant. Van den Berg (2003) highlighted that wind profiles vary significantly depending upon atmospheric stability. His work on a wind farm in north-western Germany, outlined the deficiencies associated with conducting assessment based on wind speeds at a reference height of 10 metres above ground level, and how for a given wind speed at 10 metres, sound immission levels may vary by up to 15 dB between the day-time and night-time. In Australia, the effects of atmospheric stability continue to be ignored by Consultants, Regulators and the Courts (Taralga Wind Farm, 2007; Gullen Range Wind Farm, 2010).

More recently, standards and guidelines applicable to wind farm developments (including the South Australian 'Wind farms environmental noise guidelines', New Zealand Standard NZS 6808-2010 'Acoustics – Wind farm noise', and Australian Standard AS 4959-2010 'Acoustics – Measurement, prediction and assessment of noise from wind turbine generators') recognise that environmental effects such as ground topography and atmospheric stability will have an impact on the wind shear profile (i.e. how much the wind speed changes with height above ground level), and have sought to take this into account by referencing all wind speeds to the hub height of the wind turbine generators. But this is only part of the solution; while the hub height wind speed will enable an accurate prediction of noise levels at ground level due to wind speeds experienced by the wind turbine generator, during stable atmospheric conditions, wind speeds (and the corresponding background noise levels) can be significantly lower at ground level at nearby residential properties. This is not currently taken into account in any international standards.

Kochanowski and Mackenzie (2008) originally demonstrated the shift of background noise criteria curves for different stability conditions, where more stable conditions generally result in lower background noise levels for a given hub-height wind speed as shown in Figure 1. Without including a penalty for tonal or modulation characteristics, it was demonstrated that the noise criteria were exceeded by up to 4 dBA (as opposed to the approach defined in the guidelines which showed no exceedances).

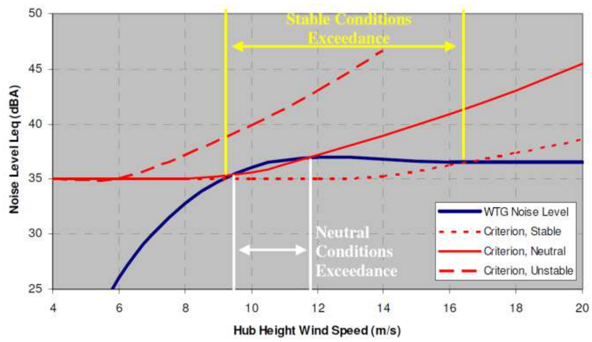

Figure 1: Noise assessment for various stabilities (Kochanowski & Mackenzie (2008))

As an extension to the original work by Aurecon, this paper examines the role of atmospheric stability on aerodynamic noise generation (in particular, low frequency tonal noise generation and modulation), and how the associated noise may interact with the stability-filtered background noise criteria to present an adverse acoustic environment at sensitive residential receivers.

ENVIRONMENT

Noise Propagation

Noise propagation from wind turbine generators is complex and the accuracy of wind farm modelling undertaken for development authorisation purposes depends upon the assumptions and the methods used for this assessment.

Other than for long-range military applications related to impulsive noise sources, environmental acoustic assessments have ordinarily relied upon empirical methods such as CONCAWE or ISO 9613 to predict the influence of meteorology on sound propagation. This is in contrast to air quality assessments which use a finite/boundary element model using hourly synoptic data across a year to predict worst case ground level concentrations of pollutants. Kaniyal and Mackenzie (2008) suggested that this method could be applied to environmental noise assessments similar to the approach developed in Europe with the HARMONOISE project as described by Heimann (2003).

ISO 9613 incorporates a methodology to account for atmospheric absorption of noise which is dependent upon both air temperature and relative humidity. Generally higher frequencies (above 1kHz) will be more readily absorbed by the atmosphere, and therefore for receivers located large distances from a noise source (i.e. residences greater than 1 km from wind turbine generators) noise will often be dominated by frequencies between 63 Hz and 500 Hz.

Noise shadowing is also an important meteorological effect which occurs when receivers upwind of a noise source experience less noise than those in a downwind position. Smith et al (2012) notes that:

> curvature of the sound rays is caused by refraction due to the variation of convected speed of sound with height. Refraction is independent of frequency, but energy is scattered into the upwind shadow zone by diffraction, which makes the depth of the upstream shadow zone frequency dependant.

Temperature inversions occurring within the lowest 50 m to 100 m of the atmosphere can increase noise levels measured on the ground. They are most commonly caused by radiative cooling of the ground at night leading to the cooling of the air in contact with the ground. This is especially prevalent on cloudless nights with little wind providing very stable conditions. International Standard ISO 9613 'Acoustics – Attenuation of sound during propagation outdoors' is referenced in the majority of relevant guidelines and standards, and takes into account 'propagation under a well-developed moderate ground based temperature inversion'.

Manning (1981) proposes an alternative method for taking into account atmospheric stability, based on the Pasquill stability categories A through F (and sometimes G). In this model, categories E, F and G represent stable through to very stable meteorological conditions where a temperature inversion is likely to occur. The Pasquil stability categories provide a relatively easy method of describing atmospheric stability at the wind farm site, and can be used as a basis for predicting the impact of meteorological stability (and associated wind shear effects) on sensitive receivers.

To provide a conservative model of future wind farm developments and at least partially take into account the effect of stability on noise propagation Bowdler et al (2009) proposes that noise propagation from wind farms be assessed using ISO 9613, with attenuation attributable to the barrier effect limited to no more than 2 dBA and ground reflection to be taken into account by modelling the ground as completely hard and fully reflective (i.e. a 3 dBA increase in noise levels at the receiver). This was determined from extensive studies using a "*high powered loudspeaker sound source in differing complexities of topography as a function of meteorological conditions*" (Bass, Bullmore and Sloth, 1998).

Bullen (2012) investigated the prediction methodologies used for Australian conditions, and described how the current noise prediction models such as the ISO 9613-2 algorithm and the CONCAWE (commonly modelled using the proprietary software such as SoundPLAN) are similar:

> Only basic corrections for different meteorological conditions (although CONCAWE corrections are somewhat more detailed than those in ISO 9613), and in particular they do not allow for any interaction between meteorology and shielding, which is known to be important in determining the likely increase in noise levels under adverse conditions

To overcome the deficiencies of the ISO 9613 and CONCAWE algorithms, HARMONOISE model has been developed in Europe as noted recently by Bullen (2012). When applied to noise prediction for wind farms, the Harmonoise algorithm takes into account downward sound refraction (i.e. in the case of a temperature inversion under stable conditions) by curving the intervening terrain between the source and receiver downward, thereby reducing the effect of any shielding.

Wind Conditions

Wind climate affects the power and noise generated by the turbine. The velocity profile and turbulence conditions are key factors and are affected by terrain, local topography, and atmospheric stability.

Turbulence due to Mechanic Friction

The interaction of the wind with the ground roughness causes a local decrease in momentum close to ground level. Turbulent mixing transports the momentum deficit through higher regions of the boundary layer. Hence a velocity profile is developed with low velocity wind close to the ground, increasing with height above ground level to the flow velocity at the upper limit of the boundary layer:

$$\bar{u}(z) = \frac{u_*}{k} ln\left(\frac{z}{z_o}\right) \quad \text{or} \quad \frac{\bar{u}(z_1)}{\bar{u}(z_2)} = \left(\frac{z_1}{z_2}\right)^{\alpha} \qquad (1)$$

With $\bar{u}(z)$ is the mean wind speed at height z, u^* is the friction velocity, κ is the Von Karman constant, z_0 is the roughness length, and α is the power law exponent. Another important expression is the turbulence intensity, $I_u(z) = \sigma_u(z)/\bar{u}(z)$, which describes the random variation of wind speed relative to the mean.

Expressions form the basis of wind engineering to assess wind loads on structures, with AS 1170 (2011) providing a relevant code based approach (Gaekwad & Mackenzie (2013)). AS 1170 also provides guidance for velocity profiles affected by changes in surface roughness, and more specific topographic features (hills, escarpments etc.). Stull (1988) provides a summary of topographic effects on velocity profiles, with particular reference to stable and neutral conditions (introducing the Brunt-Vaisala frequency and the Froude Number) as shown in Figure 2 and described below:

- Stable – The kinetic energy of the flow can be insufficient to lift the air over the hill.
- Neutral – The flow is accelerated up the upwind slope and decelerated down the down-wind slope.

Belcher & Hunt (1998) provide a useful account of previous work to estimate mean and turbulent velocity profiles for flow over topographic features for neutral conditions. Physical scale models (wind tunnel) provide the best accuracy for neutral conditions, while meso scale (TAPM/WRF) models provide good accuracy to simulate convective effects.

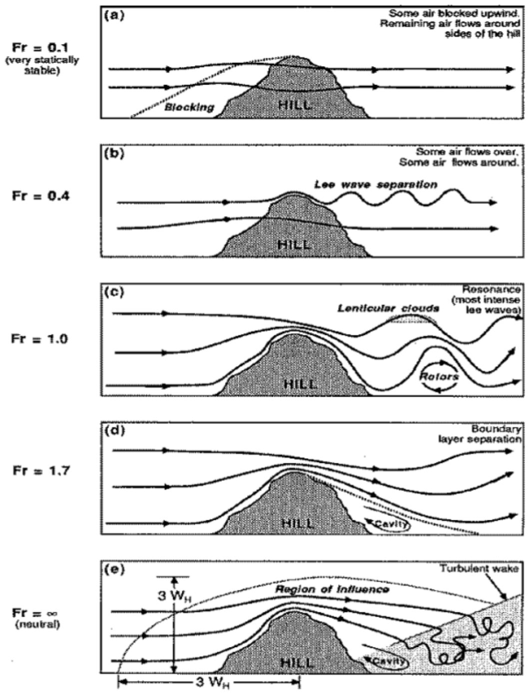

Figure 2: Idealised flow over an isolated hill (Stull (1988))

<u>Turbulence due to Thermic Friction</u>

Atmospheric stability has a significant effect on the mean and turbulent velocity profile. Diurnal cooling and heating of the surface takes place causing different stability conditions due to thermal stratification affecting buoyancy. Monin-Obukhov used similarity theory to show that the mean velocity profile can be rewritten by including a stability parameter:

$$\bar{u}(z) = \frac{u_*}{k}\left[ln\left(\frac{z}{z_o}\right) - \psi\left(\frac{z}{L_{MO}}\right)\right] \qquad (2)$$

Where $\psi\left(\frac{z}{L_{MO}}\right)$ is the stability parameter, with L_{MO} the Monin-Obukhov length as defined in Table 1 (from Wharton & Lundquist, 2012) for rural roughness ($z_o \approx 0.10m$) and Figure 3 showing corresponding mean velocity profiles. These parameters provide a means of assessing the variance of stability conditions with time of day or wind speed (DVV/Risø, 2002).

Table 1: Stability parameters

Conditions	L_{MO} (m)	α	$I_u(80m)$
Very Stable (F)	0 to 50	>0.3	<8%
Stable (E)	50 to 250	0.2-0.3	8-10%
Neutral (D)	$\|L_{MO}\| > 250$	0.15-0.2	10-20%
Unstable (C)	-250 to -15	0.1-0.15	20-30%
Very Unstable (B)	-15 to 0	0.08 – 0.1	>30%

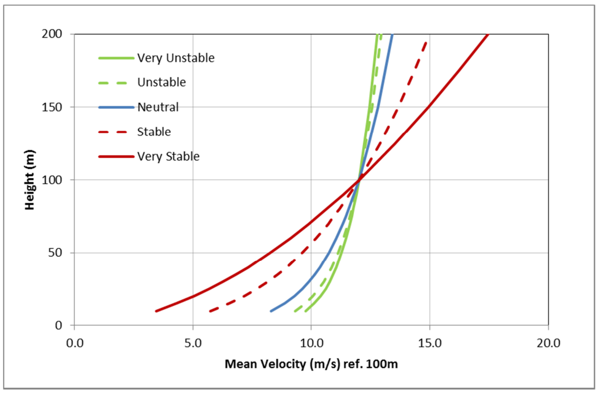

Figure 3: Mean velocity profile with stability

EVIDENCE OF STABILITY

Aurecon's assessment of meteorological data monitored at a wind farm in South Australia in early spring demonstrates a similar diurnal pattern of stability. Figure 4 shows the calculated average power-law exponents based on the measured met mast data wind speeds, and predicted wind speeds using TAPM software analysis.

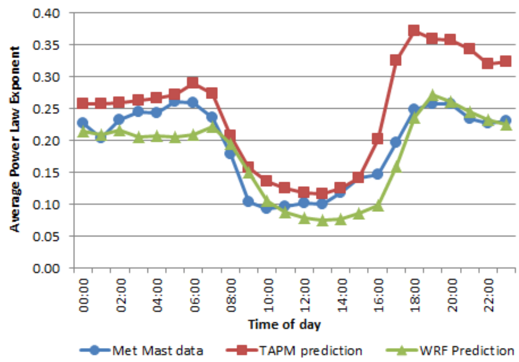

Figure 4: Stability vs. Time for a South Australian wind farm (2011 met mast data, 2008 TAPM prediction, and 2011 WRF prediction)

Figure 4 demonstrates a general trend of increased stability during the night-time and early morning periods, however the occurrence of stable and very-stable periods has been 'averaged-out' is not shown. Based on the work by Irwin (1978) comparing the variations in power-law exponent as function of Pasquill stability class and surface roughness, z_0, the measured data was sorted according to stability class. A surface roughness of z_0 = 0.10 m was used (corresponding to terrain with trees and long grass). Figure 5 presents the stability class frequency distribution for each hour of the day over the spring measurement period.

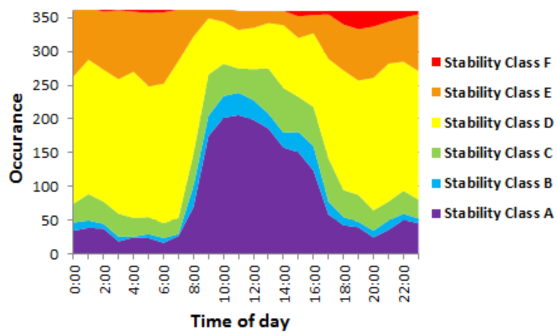

Figure 5: Diurnal stability class distribution

As expected, the stable conditions occur predominantly during the late evening and early hours of the morning, while unstable conditions are more likely to occur during the daytime. The number of stable and very stable (categories E and F) 10-minute periods shown occurring during the night-time hours indicates that stable conditions are a feature of the wind farm site assessed by Aurecon, during early spring.

Lundquist (2010) conducted a study of the impression of wind farm "underperformance" in the United States, and the role of varying atmospheric stability on wind farm power output. For the 2010 assessment, a large dataset consisting of two on-site met mast and SODAR data, along with turbine power output and hub height wind speeds was collected over a whole year (i.e. four seasons).

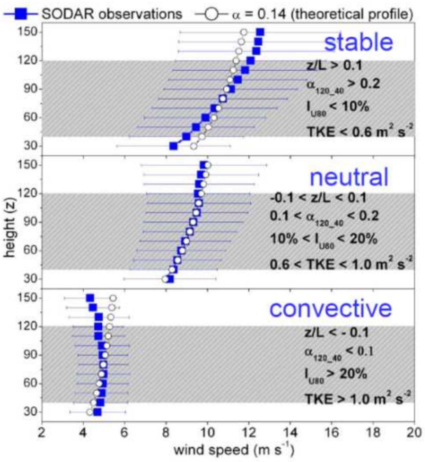

Figure 6: Measured mean velocity profiles across rotor disk demonstrating stability impact

AERODYNAMICS OF TURBINES

It is useful to consider aerodynamics of turbines and control mechanisms used to optimise power generation under a range of wind conditions.

It can be shown simplistically (no rotation imparted to the flow) that the optimum power extracted from the wind is given by (introducing an axial induction factor $a = (U - V_1)/U$, with V_1 the velocity passing through the rotor and U the incoming wind speed), the performance (or power) coefficient, $C_P = 4a(1 - a^2)$. The maximum efficiency occurs for $a = 0.33$ with $C_{P_{max}} = 0.59$ (after Betz), with it not possible to extract 100% of the potential power from the wind flow through the turbine. However further inefficiencies occur as the flow is rotated after passing through the turbine (included as a radial induction factor, a') and mechanical or electrical inefficiencies (associated with the bearings and generator) further reduce the performance.

The torque (and thrust or drag) acting on a blade are affected by its profile and angle of incidence of the apparent wind. Given the length of blades, the local wind speed will have minimal influence on the angle of attack at the blade tip, while close to the blade root the local wind speed will have significant impact given the slow tangential speed of the blade element, hence the blade must be twisted to avoid stall.

Lift and drag coefficients for blade profiles are measured in a wind tunnel with typical results shown in Figure 7. It can be seen from Figure 7 that the angle of incidence (or attack) is relatively small prior to stall (±15º), outside of which drag increases and lift drops significantly (this of course depends on the airfoil profile).

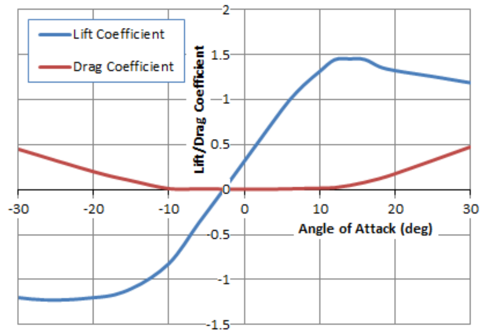

Figure 7: Lift and Drag Coefficients for typical blades

Defining the tip speed ratio (TSR) as $\lambda = \Omega R/U$, the performance coefficient is dependent on λ (which governs the angle of attack and therefore lift) and the blade twist angle, θ (which affects the angle of attack). There is an optimal performance coefficient for an optimum tip speed ratio. The TSR is typically 8-10 for modern wind turbines, and this is used to design the blade (changes in twist, chord and profile) along its span.

Performance coefficients can be defined for given blade configurations, with typical curves (blue and green curves) shown in Figure 8. Also shown in Figure 8 is the power curve generated by a wind turbine which is given by:

$$P = \eta C_P(\lambda, \theta)\tfrac{1}{2}\rho U^3 \pi R^2 \quad (3)$$

Where ρ is the density of air, R is the radius of the turbine rotor, and η is the mechanical/electrical efficiency.

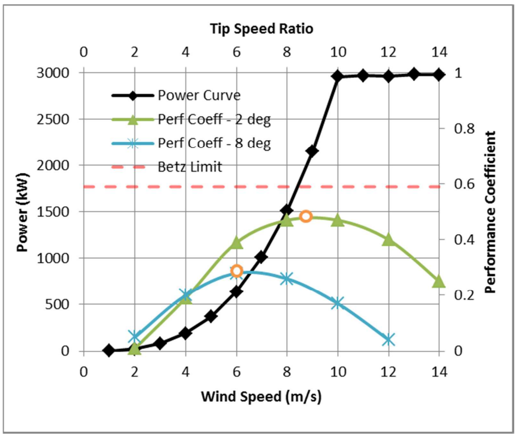

Figure 8: Variation of Power and Performance Coefficient with Tip Speed Ratio

In the past, turbines ran at a constant speed to enable ease of connection to the power grid, with power limited as the blades stalled, thereby reducing lift (but also generating noise). Active or assisted stall was also employed, with the blade pitched out of the wind to stall.

Modern turbines use variable speed control (with direct drive of the generator rather than via a gearbox improving efficiency), with the blade pitch regulated above rated power to reduce lift thereby reducing the performance coefficient.

- Below rated power, the turbine is operated at fixed pitch and variable speed with a fixed tip speed ratio up to rated power. This is shown as the green curve in Figure 8.

- Above rated power, the turbine speed is held constant hence the TSR reduces with increasing wind speed. The blades are pitched to maximise the performance coefficient. This is shown as the blue curve in Figure 8. The turbine speed and pitch are regulated using an anemometer mounted on the hub behind the rotor.

Referring to Figure 4, under stable conditions, high wind speeds occur above the rotor, reducing the tip speed ratio significantly below that assumed for maximum performance, while below the hub the low wind speeds increase the TSR. As the performance coefficient drops either side of the optimal TSR, there is the potential for stall (either static or dynamic) to occur at some point on the blade as the blade moves above or below the hub. This is shown in Figure 9 below, with the turbine operating below rated speed (left), and increasing pitched into the wind at and above rated speed (right).

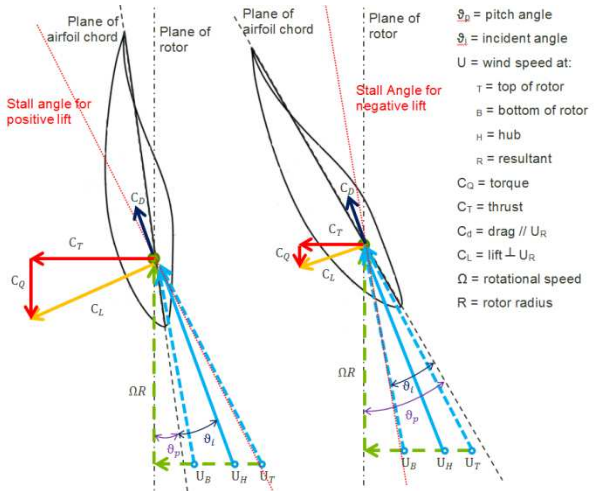

Figure 9: Blade element forces and angles

SOURCES OF NOISE

Wind turbine generators create noise through several sources, including mechanical and aerodynamic. While mechanical sources (such as the gearbox and yaw drive) can contain both tonal and broadband noise characteristics important for a wind farm assessment, this paper focuses only on aerodynamic noise sources, and the impact of meteorological stability.

Aerodynamic Noise Sources

Airflow self-noise is related to the smooth flow interaction with the blade airfoil producing turbulence in the airfoil boundary layer and wake, while turbulent inflow noise relates to atmospheric turbulence causing unsteady pressures on the turbine blade which results in broadband noise.

Oerlemans (2011) provides a good summary of aerodynamic self-noise mechanisms (as shown in Figure 10 below):

a) Trailing edge noise occurs as eddies in the turbulent boundary layer on the outer part of large blades move past the trailing edge of the blade, creating broadband noise.

b) Laminar-boundary-layer-vortex-shedding-noise occurs where a laminar boundary layer exists over the blade, and trailing edge noise radiated upstream can cause layer instabilities / laminar turbulent transition, which in turn radiates as trailing edge noise. This is a source of tonal noise from turbines, but can be controlled by ensuring a turbulent boundary layer around the blade.

c) At high angles of attack, separated flow noise will occur due to turbulent build-up on the suction side of the airfoil and in the wake of the turbine blade, as vortices are shed from the trailing edge. This separation-stall noise is generally broadband in nature and will increase with higher angles of attack.

d) Blunt-trailing edge noise occurs where the trailing edge of a blade is above a critical value, and is generally prevented by proper design of turbine blades.

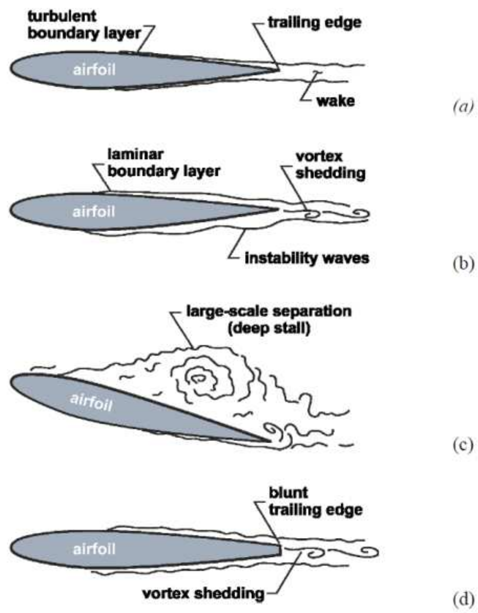

Figure 10: Airfoil Self-Noise Mechanisms (Oerlemans (2011))

Leading Edge Tonal Noise

As discussed, most of the research work to date has focused on reducing broadband trailing edge noise, with noise from stall neglected given the ability of variable speed, pitch-regulated modern turbines to apparently avoid stall. However, as presented herein, under very stable conditions, modern turbines operate at or very near to stall below hub height under high winds.

Moreau et al (2008) recently studied noise of a NACA0012 airfoil near stall. Moreau found that "*the stall condition is found to have an extraneous sound source at low frequencies on top of the trailing-edge noise. It is characterised by two specific tones at Strouhal numbers of 0.31 and 0.56*.". Importantly the Reynolds Number for Moreau's work was $1.5\text{x}10^5$ (referenced to the chord length).

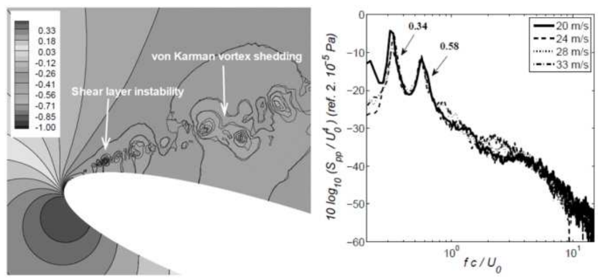

Figure 11: Shear layer instability at stall (Moreau et al (2008))

Estimates have been carried out for an operating wind turbine (3MW), with the results shown in Figure 12. Two tones are possible depending on the run speed of the turbine, with below rated power just above cut-in (9.6rpm), tones at about 40Hz and 70Hz were predicted, slowly increasing to tones at and above rated speed (13.6rpm) of about 60Hz and 100Hz.

Rotational Speed (rpm)	9.6		13.6	
Rotational Speed (rad/s)	1.01		1.42	
Blade Radius	55		55	
	TIP		TIP	
Location on Blade	55		55	
Speed of Blade (m/s)	55		78	
Blade Thickness	0.13		0.13	
Chord Length	0.43		0.43	
Reynolds Number (Re_c)	1.6E+06		2.3E+06	
Reynolds Number (Re_t)	4.8E+05		6.8E+05	
Strouhal	0.34	0.58	0.34	0.58
Frequency (Hz)	43	74	61	105

Figure 12: Estimated Tonal Noise from an Airfoil's Leading Edge

Modulation and Dynamic Stall Effects

Additionally, given this low frequency noise is generated as each blade passes in a stall/near-stall region above and below the hub, this could also explain the modulation characteristics to which the community objects during period of high wind shear. There is also the potential for dynamic stall effects (hysteresis) to maintain effective stall conditions despite the apparent angle of inflow reducing from that causing stall (Leishman, 2002).

ATMOSPHERIC STABILITY – ASSESSMENT METHODS

South Australia Wind Farms Guidelines Approach

The South Australia Wind farms environmental noise guidelines requires that all wind speeds be referenced to hub height in an effort to take into account the effects of meteorological stability at the wind farm site. The guidelines state:

> It may be acceptable to convert the results from a different measurement height (for example meteorological tower sensors) to the hub height provided the wind shear model used to do this is clearly stated and accepted by the EPA. Atmospheric stability conditions should be taken into account to ensure accurate conversation of the data from the different height.

The wind shear model commonly used is the wind profile power law as per equation (1). A regression analysis is undertaken based on the measured background noise levels and corresponding hub height wind speeds, with a linear, quadratic or cubic polynomial line of best fit (whichever provides the highest correlation coefficient) used to quantify the background noise level for each hub height wind speed.

While the effect of wind shear is taken into account for each 10-minute interval, performing regression analysis on all data points throughout the survey (and for all on-site stability conditions) results in significant data for the very stable conditions being lost or 'averaged-out'.

ETSU-R-97 Approach

ETSU-R-97 by The Working Group on Noise from Wind Turbines (1996) recognises that for the purposes of deriving a 'background noise plus 5' criteria for wind farms, the differences between day-time and night-time noise levels should be taken into account, with separate noise limits applying for each period. However, while wind shear is acknowledged within the document, it does not progress the assessment requirements through to strictly include the effects of turbine noise levels under different stability conditions.

Even where the background noise analysis is separated into day and night, under highly stable conditions (i.e. high wind shear) shifts the noise curve resulting in higher predicted noise levels. Bowdler (2009) notes that '*in the UK it is now becoming common to shift the background noise curve to the right*". Cox et al (2012) in their review of ETSU-R-97 'Where ETSU is Silent' outlines the risks associated with ignoring shear effects, and applied Bowdler's methodology to a sample wind farm (Winwick) where "*it is believed that an offset of 3m/s to be a modest and reasonable correction to apply to the predicted noise curves*". It is noted that this adjustment would be specific to the on-site conditions for each wind farm, and would need to be calculated separately for other sites. Figure 13 demonstrates the impact of a 3 m/s offset (i.e. adjusted for wind shear), bringing the predicted noise levels *above* the derived criteria curve (noting there is some contention regarding the minimum noise limit).

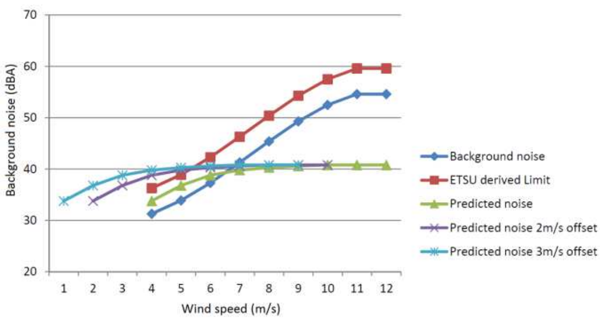

Figure 13: Wind shear correction based on wind speeds at 10m above ground level (Cox et al (2012))

Australian and New Zealand Standards

Australian Standard AS 4959-2010 recognises that stability effects on wind turbine noise are important, and stipulates that all wind turbine sound power levels and background noise data are reference to the hub height of the proposed turbines as "*this approach is likely to better represent… atmospheric stability and wind shear related effects that may occur*", which is consistent with the South Australia Guidelines approach. AS 4959-2010 also provides scope for additional investigation in terms of stability effects, stating:

> Consideration should be given to carrying out separate correlations of background sound levels with wind speed for different wind directions and/or times of day, particularly where atmospheric stability issues are apparent or suspected.

However, gives no further guidance on how such correlations should be undertaken in terms of atmospheric stability classes, time-of-day or other analysis procedures.

Similarly, New Zealand Standard NZS 6808-2010 references all wind speeds to hub height and has a provision for investigation of stability effects, stating:

> If there are markedly different groups within the scatter plot then separate scatter plots may be required for different conditions, including wind directions and times-of-day.

IEC 61400-11

In order to reduce the impact of wind speed variability over the range from cut-in to rated speed, Smith and Chiles (2012) investigated the data binning approach proposed for IEC 61400-11 version 3. One of the major changes with the latest version 3 is that the high-order regression analysis has been replaced with bin-analysis, with a bin size of 0.5 m/s, and the arithmetic average of the wind speeds in each bin.

Smith and Chiles found that the IEC 61400-11 version 3 data binning methodology (while not as thoroughly developed, data binning is also allowed for in NZS 6808), offers some advantages over regression curves by removing some variability. However, both the regression analysis and the bin analysis will be susceptible to significant low wind speed data during highly stable conditions being ‘averaged-out’ if stability conditions are not considered.

Annex C of IEC 61400-11 version 2.1 recognises the effect of atmospheric stability on overall noise emission, however is provided only as an informative annex to the measurement standard. It is noted that within the IEC standard, “*estimates or measurement of the turbulence intensity during acoustic measurements*” is only an optional requirement for the reporting on the acoustic data. Without measuring wind turbine noise under a range of stability conditions, including highly stable (which may be unintentionally avoided during the measurements if not carefully considered), it is impossible to confirm if worst-case noise emissions from the wind turbine generator have been measured and allowed for in any environmental noise assessment upon which the data is based.

Whilst measuring wind turbine generator noise in accordance with IEC 61400-11 will generally contain an element of uncertainty given the constraints of time, budget and meteorological forecasting, consideration should be given to a thorough analysis of the site specific stability conditions prior to undertaking the measurements. Wherever possible the measurements should include noise measurements undertaken during the most stable conditions possible (e.g. during the early hours of the morning at a time of very low cloud cover).

Similarly for special audible characteristics associated with the wind turbines (tonality and amplitude modulation), the measurement standard stipulates only that tonality should be reported for integer wind speeds, with no importance placed upon the stability conditions under which the tonal noise measurements were conducted. As outlined previously, the relationship between highly stable conditions and wind turbine blade stall will likely impact on measurements of special audible characteristics, and should be accounted for. There is a risk that where tonality measurements have been used to justify the absence of any special audible characteristics (based on measurements conducted during unstable day-time conditions), site specific stability conditions may result in tonality at relevant receivers, thereby imposing a tonal penalty where none has previously been considered.

New South Wales Industrial Noise Policy Approach

In terms of the probability and occurrence of stable conditions, the NSW Industrial Noise Policy approach (not strictly applicable to wind farm noise) requires analysis of temperature inversions only where inversions (i.e. highly stable conditions) are expected to occur “30% of the total night-time during winter (June, July and August)”, corresponding to approximately 2 nights per week. Comparison of the measured or predicted occurrence of stable conditions (e.g. through TAPM / WRF modelling) and the 30% occurrence criterion should be undertaken during acoustic assessment of future wind farm developments to highlight the risk of meteorological conditions having an adverse impact on the acoustic environment.

RECOMMENDED APPROACH

The potential for stall or near-stall noise effects to generate tonal and modulation effects should require manufacturers of turbines to carry out sound power and tonal audibility measurements under a range of power law exponents. Wind farm assessments should be amended to require the regression analysis be filtered according to stability or power law exponent ranges. These can be readily determined from met mast data as wind speeds are monitored at multiple heights. Alternatively, sigma-theta can be calculated to define stability (as per the methodology given in Appendix E of the NSW industrial noise policy). This approach is shown in Figure 14 below (Connell Wagner, 2008).

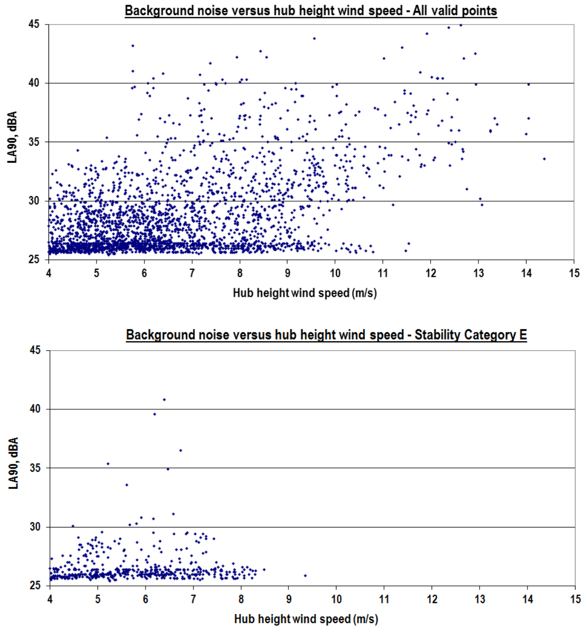

Figure 14: Background noise levels filtered on stability conditions

CONCLUSION

Atmospheric stability plays an important role in wind farm noise, and while acknowledged within the Australia, New Zealand and International Standards, is not sufficiently incorporated into wind farm assessment requirements. Current regulations generally require all wind speeds be referenced to the WTG hub height under the mistaken assumption that this will sufficiently cater for varying atmospheric stability conditions.

Current standards and regulations which reference all wind speeds to hub height do not sufficiently cater to wind turbines operating in a highly stable atmospheric environment, where a combination of high hub height wind speeds and low ground level wind speeds result in high noise levels at receiver locations, with the low ground level wind speeds providing insufficient background noise to mask the WTG noise. Other adverse acoustic impacts which occur during highly stable conditions include blade stall over some sections of the rotor leading to increased separated flow noise and potential tonal noise impact, which would otherwise not be evident during stable conditions.

Therefore as a starting point, it is proposed that the wind farm analysis (either regression or bin), should be separated based on meteorological stability category, separating the regression plots for each location into unstable, neutral and stable categories, which would take into account the effect of high wind shear which may occur during very stable conditions (and would be site specific).

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REFERENCES

Bass, J.H., Bullmore, A. & Sloth, E. 1998, 'Development of a Wind Farm Noise Propagation Prediction Model', Contract JOR3-CT95-0051.

Belcher, S.E. and Hunt, J.C.R. 1998, 'Turbulent Flow over Hills and Waves', *Annu. Rev. Fluid Mech.*, vol. 30, 507-538.

Bowdler, D. Bullmore, A. Davis, B. Hayes, M. Jiggins, M. Leventhall & McKenzie, A. 2009, 'Prediction and assessment of wind turbine noise', *Acoustics Bulletin March/April 2009*, pp. 35-27.

Bowdler, D. 2009, 'Wind Shear and its Effect on Noise Assessment of Wind Turbines', viewed 20 August 2013, <http://www.dickbowdler.co.uk>

Bullen, R. 2012, 'The Harmonoise noise prediction algorithm: Validation and use under Australian conditions', *Proceedings of Acoustics 2012*, Fremantle, Australia

Connell Wagner 2008, 'Glen Innes Wind Farm - Environmental Impact – Noise Issues', NSW Planning Application.

Cox, R. Unwin, D. & Sherman T. 2012, *Wind Turbine Noise Impact Assessment Where ETSU is Silent*.

DNV/Risø 2002, 'Guidelines for Design of Wind Turbines', 2nd Edn, Det Norske Veritas & Risø National Laboratory.

Environment Protection Authority 2009, *Wind farms environmental noise guidelines*, Environment Protection Authority, South Australia.

ETSU-R-97 (1996) *The assessment and rating of noise from wind farms*, The Working Group on Noise from Wind Turbines.

Fugslang, P. & Madsen, H.A. 1996, *Implementation and Verification of an Aeroacoustic Noise Prediction Model for Wind Turbines*, RisØ-R-867(EN), RisØ National Laboratory, Roskilde, Denmark.

Gaekwad, J. & Mackenzie, N. 2013, 'Dynamic assessment of wind sensitive stadium structures', *Proceedings of Acoustics 2013*, Victor Harbor, South Australia.

Gullen Range Wind Farm, 2010, [2010] NSWLEC 1102

Heimann, D. 2003, 'Influence of meteorological parameters on outdoor noise propagation', *Euronoise*, Naples, 113-IP.

International ElectroTechnical Comission 2006, *IEC 61400-11 Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*.

International Organisation for Standardisation 1996, ISO 9613-2:1996 *Acoustics – Attenuation of sound during propagation outdoors Part 2: General method of calculation*.

Irwin, J. 1978, 'Technical Note: A theoretical variation of the wind profile power-law exponent as a function of surface roughness and stability', *Atmospheric Environment*, vol. 13, pp. 191-194.

Kaniyal, A. & Mackenzie, N. 2008, 'Environmental impact assessment of biomass power station WA in terms of noise impacts', *Proceedings of Acoustics 2008*, Geelong, Victoria.

Kochanowski, R. & Mackenzie, N. 2008, 'Atmospheric Stability Specific Noise Criteria and Noise Prediction for Wind Farms', *Proceedings of Acoustics 2008*, Geelong, Victoria.

Leishmann, J.G. 2002, 'Challenges in Modelling the Unsteady Aerodynamics of Wind Turbines', 21st ASME Wind Energy Symposium and the 40th AIAA Aerospace Sciences Meeting, Reno, NV.

Lundquist, J.K. 2010, Atmospheric Stability Impacts on Wind Turbine Performance, *Wind Energy R&D Workshop at NCAR*.

Manning, C.J. 1981, *The Propagation of Noise from Petroleum and Petrochemical Complexes to Neighbouring Communities*. CONCAWE Report No. 4/81.

Moreau, S. Christophe, J. & Roger, M. 2008, 'LES of the trailing-edge flow and noise of a NACA0012 airfoil near stall', *Centre for Turbulence Research, Proceedings of the Summer Program 2008*, pp. 317-329.

Oerlmans, S. 2011, *Wind turbine noise: primary noise sources*, National Aerospace Laboratory, Amsterdam.

Smith, M. & Chiles, S. 2012, 'Analysis techniques for wind farm sound level measurements', *Acoustics Australia*, vol. 40, No. 1, pp. 51-56.

Smith, M. Bullmore, A.J. Cand, M.M. & Davis, R. 2012, 'Mechanisms of amplitude modulation in wind turbine noise', *Proceedings of Acoustics 2012*, Nantes, France.

Standards Australia 2010, *Acoustics – Measurement, prediction and assessment of noise from wind turbine generators*, AS 4959-2010, Standards Australia, Sydney.

Standards Australia 2011, *Structural design actions Part 2: Wind actions*, AS 1170.2:2011, Standards Australia, Sydney.

Standards New Zealand 2010, *Acoustics – Wind farm noise*, NZS 6808:2010, Standards New Zealand, Wellington.

Stull, R.B. 1988, *Introduction to Boundary Layer Meteorology*, Reidel Publishing, Dordrect, Netherlands.

Swalwell, K. 2012, Wind Turbine Performance with Shear and Turbulence, *Clean Energy Week 2012 Wind Turbine Performance Session*.

Taralga Wind Farm, 2007, [2007] NSWLEC 59

Van den Berg, G.P. 2003, 'Effects of the wind profike at night on wind turbine sound', *Journal of Sound and Vibration 277 (2004)*, pp. 955-970.

Wharton, S. & Lundquist. J 2012, 'Assessing atmospheric stability and the impacts on wind characteristics at an onshore wind farm', *Wind Energy*, vol. 14, pp. 525-546.