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Tonal noise from wind turbines

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Summary

Wind turbine noise is composed of aerodynamic noise produced by the blades rotating through the air and mechanical noise associated with components such as the gearbox and generator. Currently more focus is afforded to aerodynamic noise as this typically dominates the noise emission from a turbine, but mechanical noise requires consideration particularly as it can result in low frequency tonal emissions. This paper presents an analysis of noise emissions from several different makes of wind turbines that exhibit tonality when measured at the turbine in the frequency range from 50 to 200 Hz. In each case, the tone emitted by the turbine was found to modulate at the blade pass frequency and was often more prominent under upwind and crosswind conditions. Furthermore, the tones could also be detected as audible at residences at relatively large distances from the wind farm. The application of the different tonal assessment methodologies contained in IEC 61400-11 and the Simplified and Reference methods in ISO 1996-2 to the wind turbine noise is discussed, as well as the potential for these audible tones to cause annoyance at residences. Improvements to wind turbine noise guidelines are suggested to assist with the analysis of tonal noise, and improve the implementation of mitigation of mechanical noise during the design stage of turbines.

1. Introduction

Wind turbine noise is composed of aerodynamic noise produced by the blades rotating through the air and mechanical noise associated with components such as the gearbox and generator. Aerodynamic noise generally controls the overall noise levels and is the source of amplitude modulation from turbines, but mechanical noise also requires consideration particularly where it may result in tonal noise from the turbines.

Generally much more focus has been afforded to aerodynamic noise in recent years, as evidenced by investigations into amplitude modulation by both RenewableUK and the Institute of Acoustics. Typically, tonal noise has been considered to an issue largely confined to the past (Moorhouse et al, 2007) and to be not a significant issue for modern wind turbines based on turbine sound power test reports (Tonin, 2012).

Sound power test reports for modern wind turbines, including tonality tests, are conducted based on the procedures outlined in IEC 61400-11 Edition 2.1 (IEC, 2006) or the more recent IEC 61400-11 Edition 3 (IEC, 2012). As evidenced by a recent study of tonality at Hallett Hill Wind Farm, IEC 61400-11 only requires tonality from wind turbines to be assessed across limited wind speed and direction ranges (Cooper et al, 2013). In this instance, a tone occurred at ~124 Hz which was audible at the residence but not under the downwind conditions for which IEC 61400-11 requires a tonality test to be conducted.

This paper presents an analysis of noise emissions from several different makes of wind turbines that exhibit tonality when measured at the turbine in the frequency range from 50 – 200 Hz. The tones were related to mechanical noise from the turbines and, in many cases, the

tone emitted by the turbine was found to modulate at the blade pass frequency and was more prominent under upwind and crosswind conditions. Findings of the tonality assessment at residences at a distance from the relevant wind farms are also presented and discussed.

The implications of current tonality assessment methodologies for these wind turbine tones are discussed, and improvements to current procedures suggested.

2. Tonality assessment procedures

A brief overview of the primary tonality assessment procedures or tonality tests applied to wind turbines is provided in the following sections.

2.1 IEC 61400-11

IEC 61400-11 defines the standard test procedure for both determining sound power levels and tonal audibility (ΔL_a) for wind turbines. Tonal audibility is a measure of how audible a tone is, with an audibility of 0 dB indicating a tone is just audible to the average listener.

The IEC 61400-11 methodology involves calculation of the tone level for possible tones in selected 10-second spectra and calculation of the masking noise level within the critical bandwidth around the tone. For low frequencies, the critical bandwidth is 100 Hz wide. Tonal audibility is then calculated as the difference between the tone level and the masking noise level, adjusted by a frequency dependent audibility criterion.

IEC 61400-11 Edition 2.1, which was the applicable standard from 2006-2012, has specific data collection requirements that limit the data to be assessed at the turbine. The two one-minute periods nearest to each integer wind speed from 6 to 10 m/s (at standardised 10 m height) are assessed. Additionally, only downwind (±15°) measurements are considered in the assessment. For every possible tone, the tonal audibility determined for each of the 12 10-second periods at each integer wind speed are then energy-averaged to determine the overall tonal audibility for the tone at that wind speed.

The IEC 61400-11 methodology is intended for application during a sound power test of a turbine and the assessment is carried out during measurements at an approximate distance of hub height plus half rotor diameter downwind of the turbine. Despite this, it is possible to apply the tonal audibility calculation methodology specified within the standard to data collected at other locations, such as residences (Cooper et al, 2013). In that study, a method was described where tonal audibility was determined for each consecutive two-minute period.

The updated version of IEC 61400-11 (Edition 3) was released in 2012. The key difference in tonality assessment procedures between Edition 2.1 and Edition 3 is that Edition 2.1 only considered the two minutes of downwind data gathered nearest to integer wind speeds of 6 to 10 m/s, while Edition 3 considers all downwind data gathered over a similar wind speed range (0.8 to 1.3 times the wind speed at 85% rated power). The use of all data within this wind speed range, rather than only a small sample of data to determine the tonal audibility, is an improvement in the new version of the standard. The average level of tonal audibility over a large number of measurements provides a far more consistent and repeatable measure of the tonal noise emissions. However, IEC 61400-11 Edition 3 still only requires the assessment to be conducted over downwind (±15°) conditions and over a limited wind speed range.

Neither version of IEC 61400-11 specifies an acceptable level of tonal audibility or a penalty to apply to audible tones. Both require reporting of tones with a tonal audibility of greater than or equal to -3 dB.

2.2 ISO 1996-2

Annex C of ISO 1996-2:2007 (ISO, 2007) details another narrowband tonality assessment methodology for the calculation of tonal audibility, referred to as the objective method. This

methodology is broadly similar to that specified in IEC 61400-11 although differs slightly in practice including through the consideration of noise pauses which are local maxima with a probability of a tone.

Unlike IEC 61400-11, ISO 1996-2 does provide guidance on acceptable levels of tonality audibility and the associated penalty to be applied to tonal noise. For tonal audibilities greater than 4 dB, the applicable penalty is the audibility less 4 dB up to a maximum penalty of 6 dB. No tonal penalty is applicable where the tonal audibility is less than 4 dB.

The objective method from Annex C of ISO 1996-2 is specified as the reference method for the assessment of tonality in NZS 6808:2010 (Standards New Zealand, 2010), used throughout New Zealand and in the state of Victoria, Australia.

Annex D of ISO 1996-2 also includes a simplified method for the assessment of the audibility of tones, comparing the level difference between a one-third octave band where a possible tone exists and each adjacent one-third octave band. Annex D states possible level differences for the detection of a prominent discrete tone as:

- 15 dB for low frequency one-third octave bands (25 Hz to 125 Hz)
- 8 dB in middle-frequency bands (160 Hz to 400 Hz)
- 5 dB in high-frequency bands (500 Hz to 10 kHz).

The simplified method from Annex D of ISO 1996-2 is specified as the reference tonal assessment method in the New South Wales Draft Planning Guidelines: Wind Farms (NSW DPI, 2011).

2.3 Joint Nordic Method Version 2

The Joint Nordic Method Version 2 (Pedersen et al, 1999) is another narrowband method for the calculation of tonal audibility. Version 2 was the basis for, and is practically identical to, the objective narrowband method from Annex C of ISO 1996-2 and specifies the same sliding tonal penalty scale.

2.4 ETSU methodology

The UK guideline ETSU-R-97 (DTI, 1997) advised caution on tonal noise from wind farms stating “it had been our experience, confirmed by the survey reported in Chapter 5, that where complaints have been made over noise from existing wind farms the tonal character of the noise has been the feature that has caused greatest annoyance.” It reviewed methods for assessment current in 1997 and recommended a narrowband assessment methodology largely based on the Joint Nordic Method Version 1, which was current at the time.

Peaks in the spectrum are classed as a tone if the level is more than 6 dB above the logarithmic average of the sound pressure levels of the rest of the lines within the critical band, excluding the line either side of the peak. The audibility is determined on the basis of the difference between the tonal and masking energy as per other methodologies, with the distinction that the tone level used is the arithmetic mean of the top 10% of tone levels rather than the energy averaged level. This will result in a higher tonal audibility level being calculated for time-varying tones.

ETSU-R-97 specifies penalties to be applied depending on the tonal audibility, as per Figure 1. The maximum applicable penalty is 5 dB for tonal audibilities of 6.5 dB and greater.

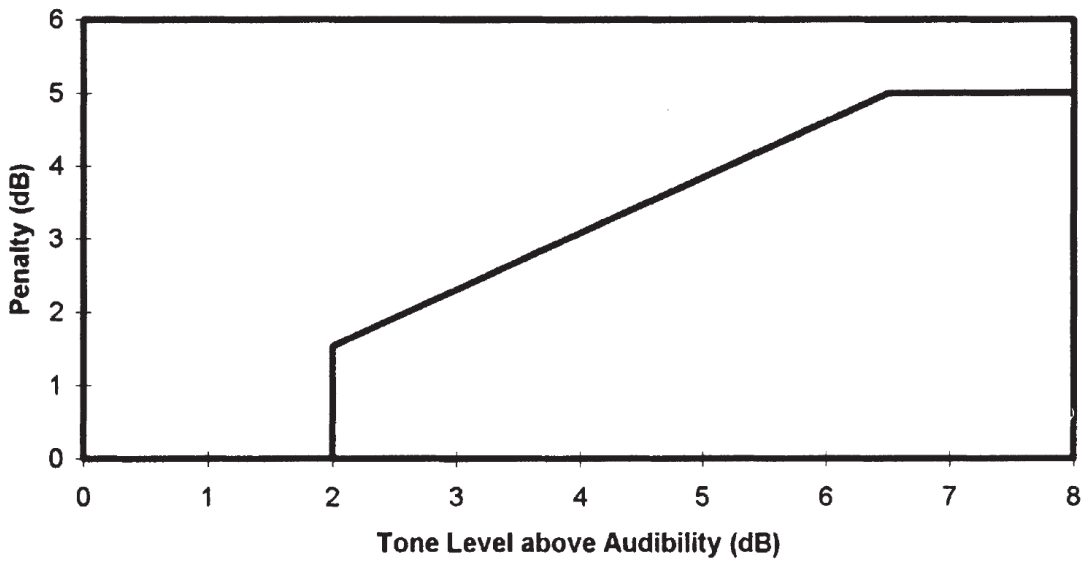

Figure 1 – Tonal penalty to be applied, taken from ESTU-R-97

3. Wind turbine tests

Detailed tonality assessments were carried out during sound power tests of seven wind turbines (A to F) from three different manufacturers. The turbines have a rated power between 2 and 3 MW and a hub height between 70 and 90 m, and are installed at Australian wind farms.

The measurements and assessment were carried out in general accordance with IEC 61400-11 Edition 2.1 with a sound level meter installed on a circular acoustically reflective ground board at a distance within 20% of the turbine hub height + ½ rotor width. The important distinctions from the IEC 61400-11 methodology were that:

- The measurement period was extended, with measurements duration from two days up to 20 days.
- All periods have been assessed for tonality, not just downwind conditions for wind speeds of 6 to 10 m/s at standardised 10 m height.
- Rather than selecting the two one-minute periods closest to each integer wind speed, the tonal audibility of each consecutive two-minute period during the measurements has been assessed as per IEC 61400-11 Edition 2.1 using a 2 Hz bandwidth.

3.1 Overall tone occurrence

Figure 2 presents the percentage of the measurement time for which an audible tone was detected in accordance with IEC 61400-11. An audible tone has been taken to be a tone with audibility greater than 0 dB. Specific frequencies are not shown on Figure 2 for commercial reasons but the horizontal axis covers a frequency range from approximately 50 to 200 Hz, with each point representing a 2 Hz step as per the bandwidth.

From Figure 2, it can be seen that each of the turbines tested exhibit audible tones for a reasonably large percentage of the time. Each of these tones is related to a mechanical feature of the turbine, with a gear tooth meshing frequency commonly matching the frequency of the audible tone. Because of this, the audible tones occur across varying frequencies as rotational speeds change and this should be noted in interpreting Figure 2. For example, the highest tonal peak for WTG B occurs 12% of the time within a particular 2 Hz band but occurs for a total of 28.6% of the time across the 8 Hz range at which it may be detected.

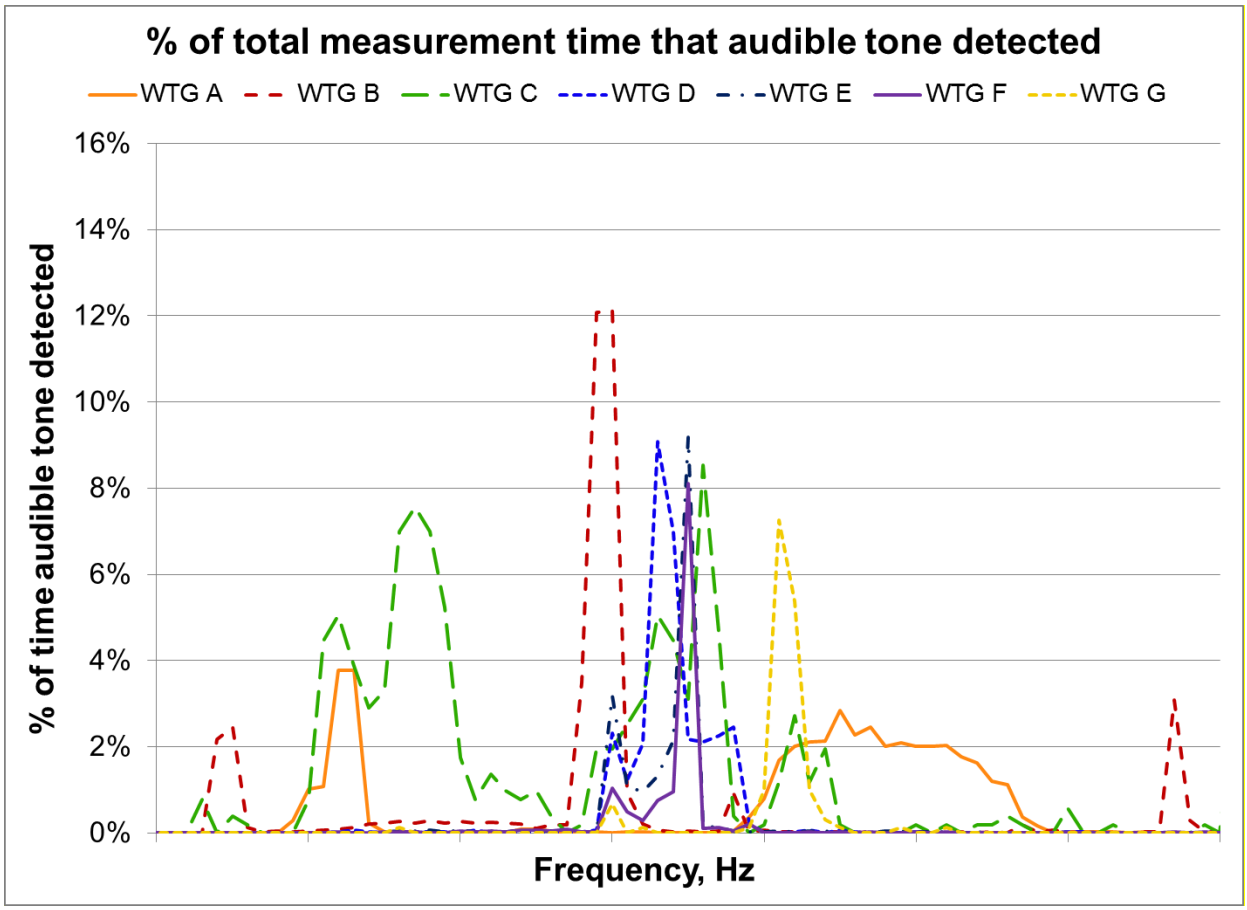

Figure 2 – Percentage of time for which audible tone detected at turbine

Of interest, WTG E and WTG F are the same model of wind turbine with the same gearbox but installed at different sites. The frequencies at which audible tones occur are identical, and the percentage of time for which they occur are similar when considering the different wind conditions that may occur during two separate tests. This indicates that the tones are a feature of the design of the turbine and are not a result of a maintenance issue related to a particular turbine. WTG D is also the same turbine type as WTG E and WTG F but has an older variant of the same make of gearbox. This turbine produces an audible tone at a slightly lower frequency than the other two turbines, corresponding to a slightly lower gear tooth mesh frequency of this gearbox.

Figure 3 presents the distribution of tonal audibility for the main detected tones at six of the turbines for which extended data was available. It can be seen that the tonal audibility of each tone can vary quite significantly between two-minute periods. While the majority of two-minute tonal audibilities are below 8 dB, there is a wide variation in levels below this and occasional periods of higher tonal audibility.

This variation in tonal audibility at the turbine highlights a shortcoming of the tonal assessment methodology specified in IEC 61400-11 Edition 2.1, as assessing only the two one-minute periods closest to each integer wind speed may have markedly different results between two assessments. The approach specified in IEC 61400-11 Edition 3 whereby the determined tonal audibility of each 10-second spectrum is averaged is therefore more likely to provide a repeatable result.

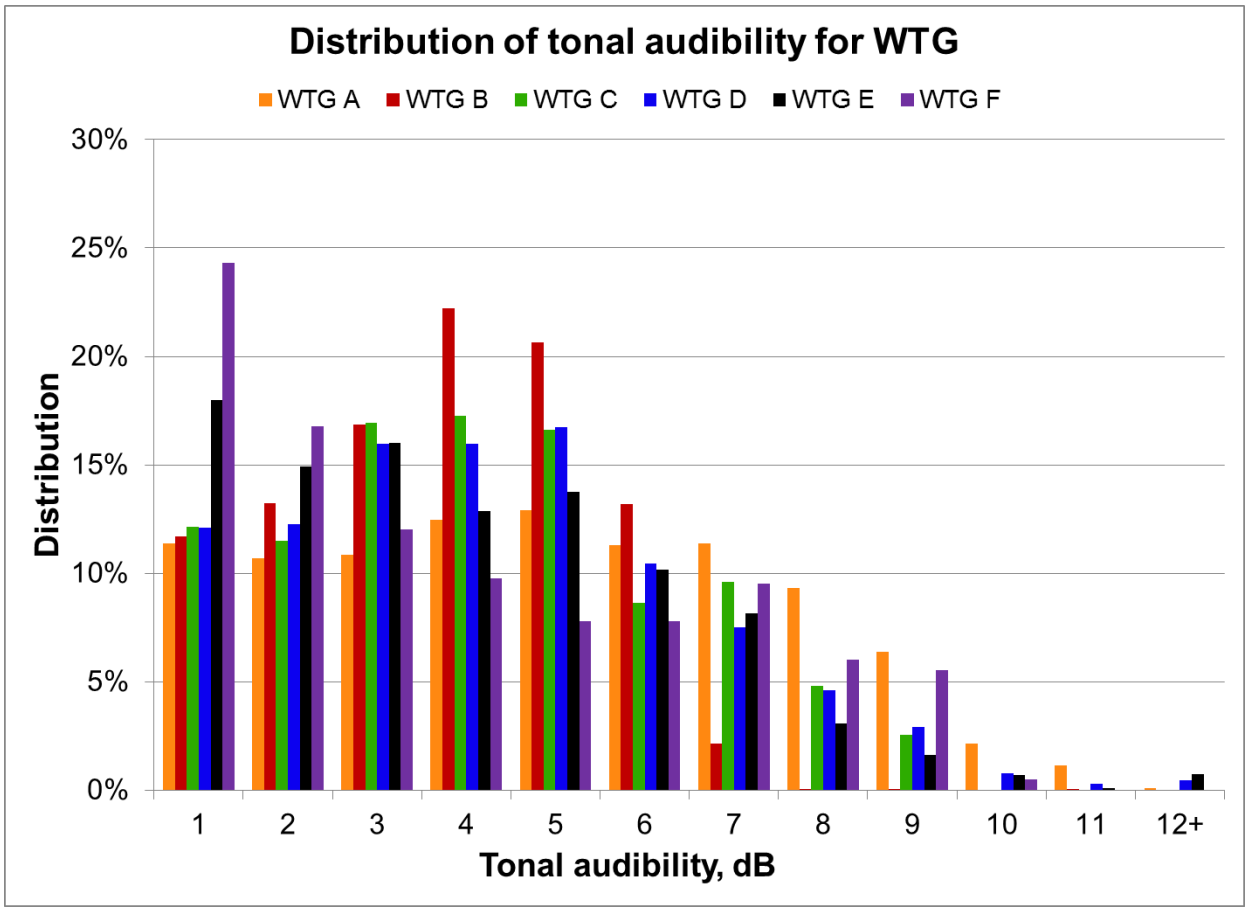

Figure 3 – Distribution of tonal audibility at the turbine

3.2 Wind speed and direction dependence

A common feature of the audible tones detected at each WTG was that they were all highly dependent on wind speed and direction. This is consistent with the findings of our previous investigation into an ~124 Hz tone at a residence near a wind farm where the highest levels of audibility occurred under crosswind and upwind conditions, and at relatively low wind speeds (Cooper et al, 2013).

As an illustration of this, tone occurrence (taken to be where the tone was detected with audibility greater than 0 dB) is shown against wind speed and direction for tones at WTG B and WTG E in Figure 4 and **Error! Reference source not found.**Figure 5 respectively. Note that 0º corresponds to upwind conditions with respect to the measurement location, 180º downwind and ±90º crosswind on either side of the nacelle.

The tone occurrence shown in Figure 4 for WTG B is for the lowest frequency tone at the WTG in Figure 2. While Figure 2 indicates that this tone may only have an overall occurrence during the measurements of 5%, Figure 4 demonstrates that this tone regularly occurs under wind speeds greater than 10 m/s. The reason that this tone was only detected for 5% of the total measurement period was due to a general lack of higher wind speeds during the monitoring, indicating that an understanding of the wind conditions during an assessment is important.

The tone occurrence for WTG E in Figure 5 shows a high dependence on both wind speed and wind direction. The tone does not occur under downwind conditions and is more prevalent under crosswind than upwind conditions. It is also generally limited to lower wind speeds, although it does occasionally occur under higher speed crosswind conditions.

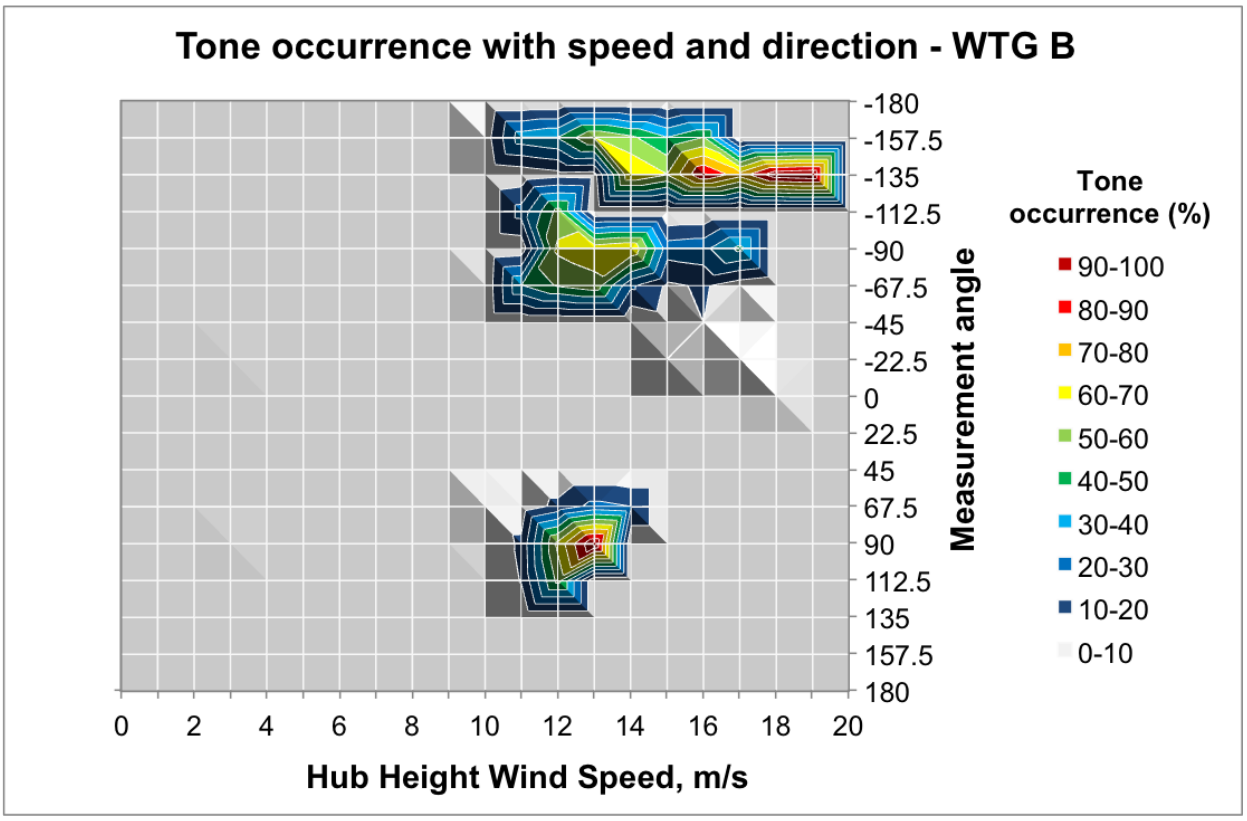

Figure 4 – Tone occurrence with wind speed and direction for WTG B

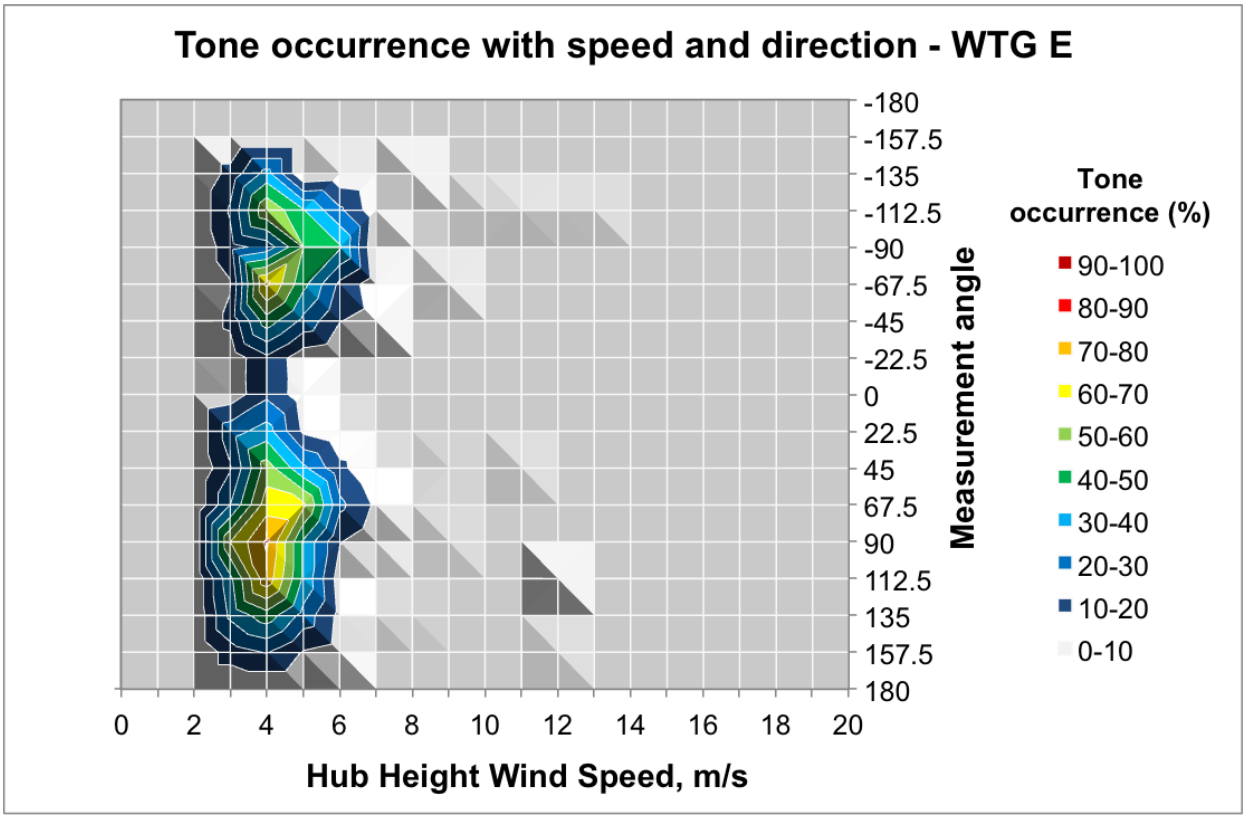

Figure 5 – Tone occurrence with wind speed and direction for WTG E

Due to this high dependence of tone occurrence on wind speed and wind direction, the current IEC 61400-11 Edition 3 requirement to only assess tonality under downwind ±15º and for wind speeds across a range of approximately 8 – 14 m/s (depending on power curve) may not result in identification of audible tones. In our experience with the seven WTGs tested and reported in

this paper, it is likely that a test under the IEC 61400-11 required wind speed and direction range would have failed to detect an audible tone at all but one of the WTGs.

3.3 Modulation of tones

In our previous study of a tone at a residence near Hallett Hill Wind Farm (Cooper et al, 2013) it was identified that the tone was not steady in nature and, when assessed at the turbine, the tone was modulated at blade pass frequency, although with some randomness in level that was possibly due to variation in loading on the gearbox due to wind gusts. The blade pass modulation of the tone, a small degree of Doppler shift, as well as its directivity, indicated that the tone was radiated off the turbine blades. The modulation of the tone is shown by the multiple side bands of the tonal peak at 122.5 Hz in Figure 6, with the side bands spaced at blade pass frequency.

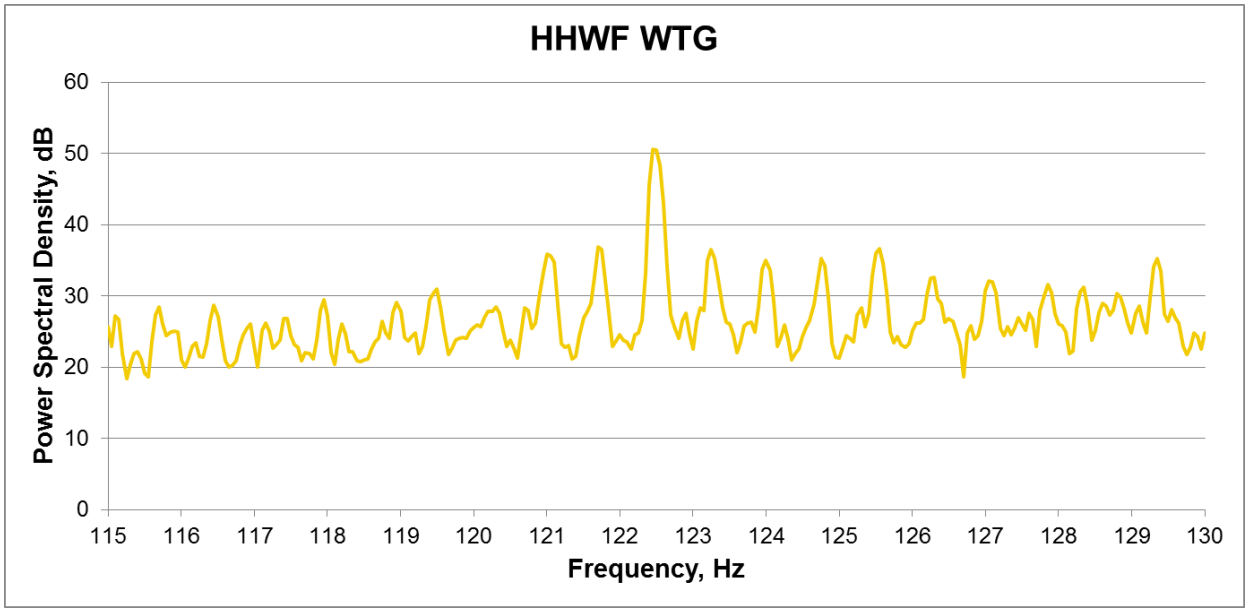

Figure 6 – Power Spectral Density for tone at Hallett Hill Wind Farm turbine showing multiple side bands

This same pattern of modulation was identified for the main low frequency tones from each of the WTGs in this paper. As an example, Figure 7 shows the same blade pass frequency side bands for the audible low frequency tone produced by WTG D.

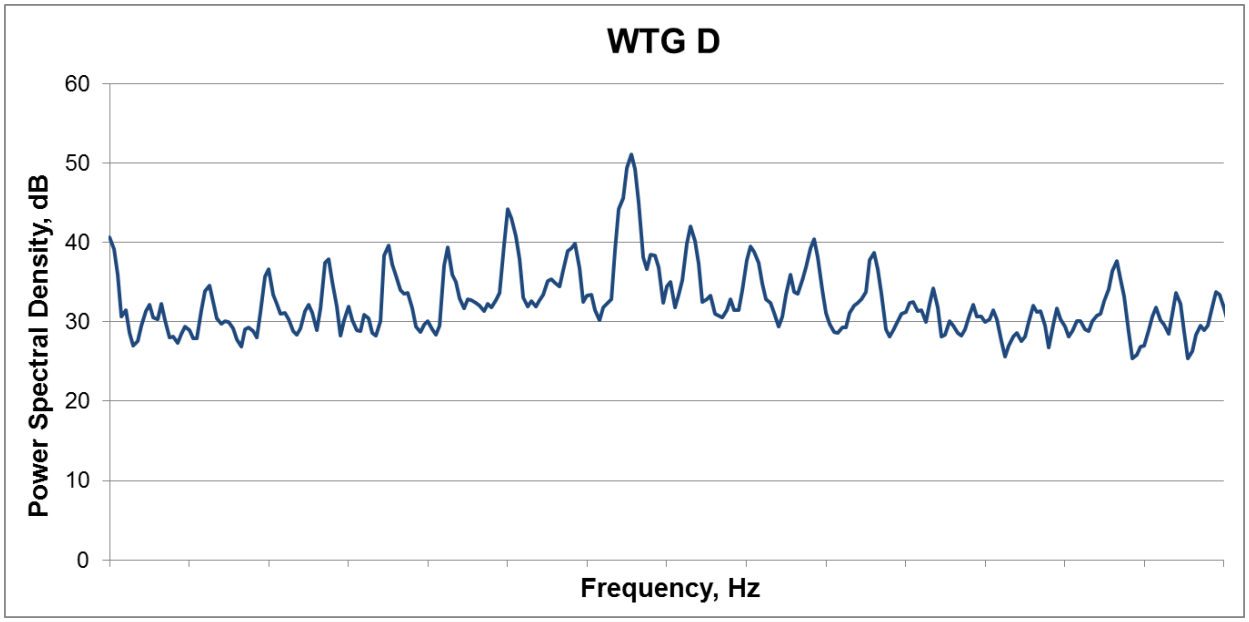

Figure 7 – Power Spectral Density for tone at WTG D turbine showing multiple side bands

The modulation of the low frequency tones at the turbine indicates that, for each low frequency tone, the blades are the main emission paths.

4.0 Tonality at residences

4.1 Propagation to and occurrence at residences

While the level of tonal audibility at the turbine is of interest, it is of little practical concern if these tones are not audible at residences. Audible low frequency tones at residences may result in annoyance for residents, as well as introducing a potential risk of non-compliance with local regulations for wind farm operators. Measures to mitigate audible tones from wind turbines, such as tuned mass dampers (Cooper et al, 2013), can be difficult and costly to implement.

In the absence of background noise, the level of tonal audibility is unlikely to significantly attenuate with distance from the turbine. The level of the tonal peak is likely to attenuate at largely the same rate as the level of the critical masking bandwidth that, for low frequency tones, is approximately 100 Hz wide and centred on the tonal peak. Therefore, as long as the tonal peak remains above the hearing threshold, the difference between the tone and the masking level will remain largely the same with distance. In reality, ambient noise at the residence within the critical masking bandwidth will mean that the level of tonal audibility will decrease compared to the level at the turbine. As the level of ambient noise at the residence will depend on a wide range of factors including time of day and wind speed, it makes it difficult to predict the level of tonal audibility at a residence even when the level of tonal audibility at the turbine is known.

At most of the wind farms containing the turbines WTG A to WTG G, long-term (10 days or greater) tonality assessments have been conducted at adjacent residences. The procedure for these long-term tonality assessments is defined in our previous paper (Cooper et al, 2013) but consists of assessing the tonal audibility of each consecutive two-minute period in accordance with IEC 61400-11 Edition 2.1. Tonal frequencies at the residence are compared to tonal frequencies at the turbine, and audio recording used to determine the source of the tone at the residence where there is a potential that it was caused by the turbine.

The results of the assessment of tonality at residences indicates that audible low frequency tones in the frequency range of approximately 50 – 200 Hz are likely to occur at distances of up to two kilometres from the nearest turbines. In one case, an audible tone was detected at a distance of three kilometres from the nearest turbines but at a low level of tonal audibility.

As for the tones at the turbines, wind speed and direction is a key factor in tone occurrence at a residence. In addition, time of day becomes an important factor as there tends to be less masking noise at night time. Figure 8 presents the tone occurrence (audibility greater than 0 dB) with wind speed and time of day at a residence approximately 800 metres from the nearest wind turbine. The wind turbines installed at the wind farm are of type WTG D as shown in Figure 2. It is clear that occurrence is significantly greater under night time conditions, a finding consistent with our previous study at a different residence near a different wind farm (Cooper et al, 2013). While the tone may not be a regular occurrence at the residence on an overall basis, it can occur 50 to 60% of the time at night under low wind speed conditions.

Wind speed and direction were also important determinants of the tone at the residence, with the tone more prominent under low wind speeds and upwind through crosswind directions. These conditions were consistent with the periods at the turbine for which the tone occurred more regularly.

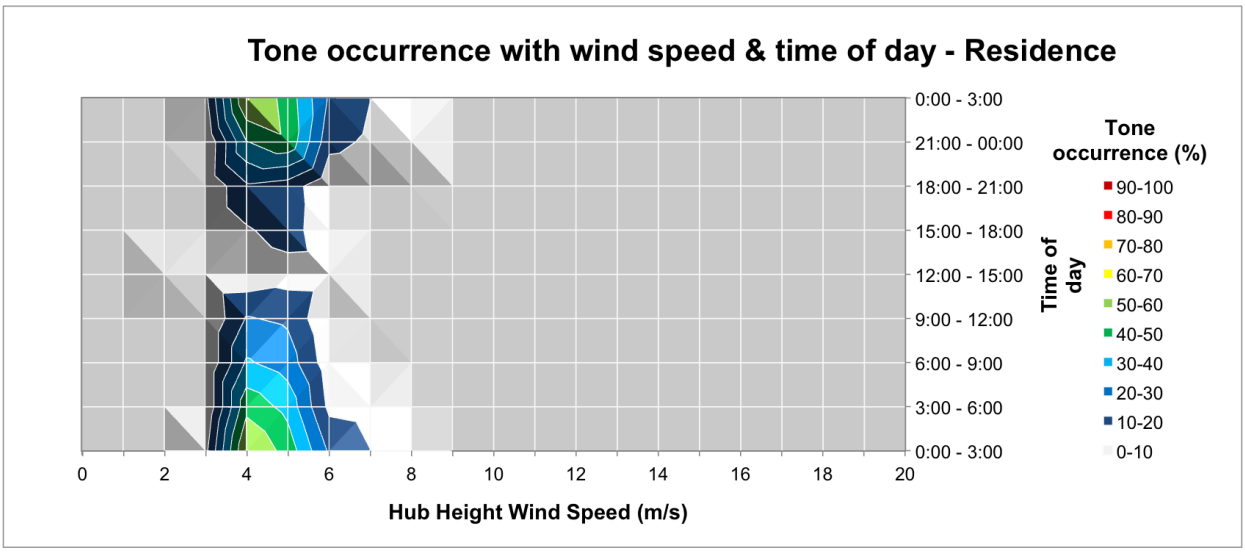

Figure 8 – Tone occurrence with wind speed and time of day for residence

To provide temporary mitigation of the tone, the wind farm operator switched off several of the nearest turbines at night. The nearest remaining operating turbines were over two kilometres away. Figure 9 presents the level of tonal audibility at the residence both when all turbines were operating (day) and when the nearest turbines were shutdown (night). It is apparent that the tonal audibility during the daytime is markedly higher than night despite more masking noise. The tonal audibility at the residence is clearly controlled by the nearest turbines.

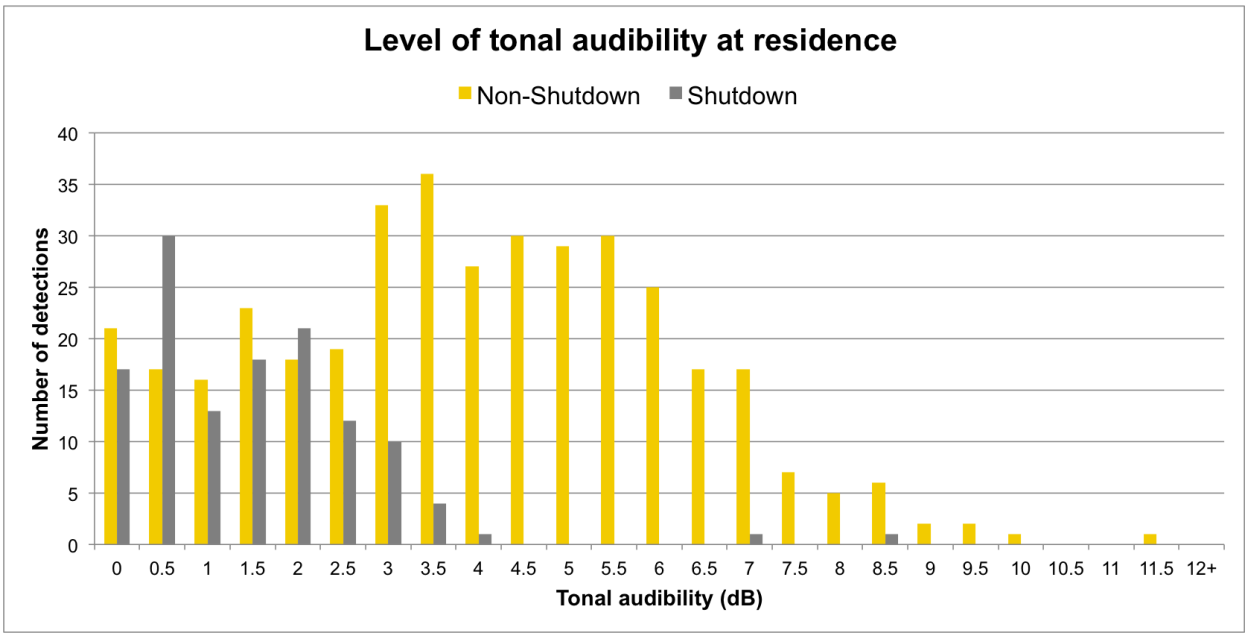

Figure 9 – Level of tonal audibility at residence during shutdown and non-shutdown periods

Similar results were obtained from tonality assessments at other residences adjacent to the tested wind turbines. Figure 10 presents tone occurrence with wind speed and time of day at a residence 1700 m from a wind farm comprised of WTG A. A similar pattern can be seen with a tone occurring more often at night. In this case the tone was more regularly detected at higher wind speeds at the turbine, and this is reflected in the occurrence at the residence.

While the low frequency tone detected at this residence was relatively low in audibility (less than 4 dB), the tonal audibility at the turbine was typically only 1 to 2 dB higher, indicating a relatively low level of attenuation of the tone level above the masking noise across the 1,700 m distance to the residence.

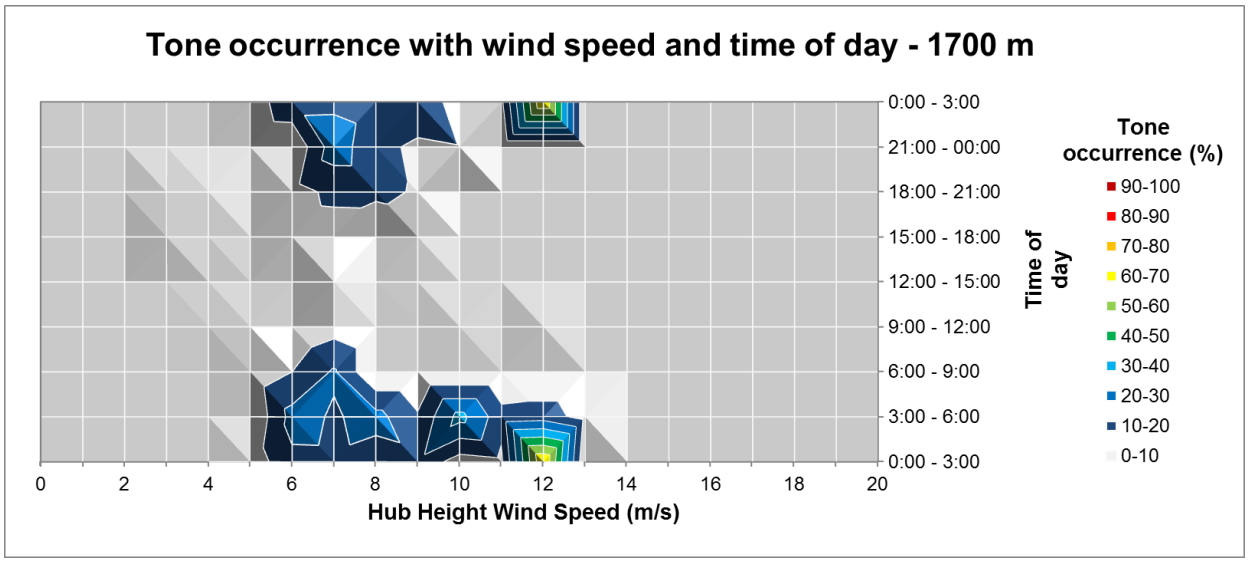

Figure 10 – Level of tonal audibility at residence at 1700 m from WTG A

4.2 ISO 1996-2

The tonal audibility methodology used for this paper has primarily been the methodology specified in IEC 61400-11 Edition 2.1 with specific changes as required to allow the methodology to be applied over extended periods during testing at either a turbine or a residence. As part of our previous study we compared the tonality assessment results at a residence located approximately 1.5 kilometres from a wind farm, assessing the change in tonal audibility between the IEC 61400-11 methodology and the ISO 1996-2 methodology for the same dataset. Figure 11 presents the results of this comparison.

It can be seen that, despite small changes between the two methods, the results are largely equivalent. The ISO 1996-2 methodology actually results in a higher level of occurrences at the residence of tones with audibility greater than zero. This suggests that the results presented in this paper can be broadly applied to the ISO 1996-2 methodology and, by extension, the Joint Nordic Method Version 2.

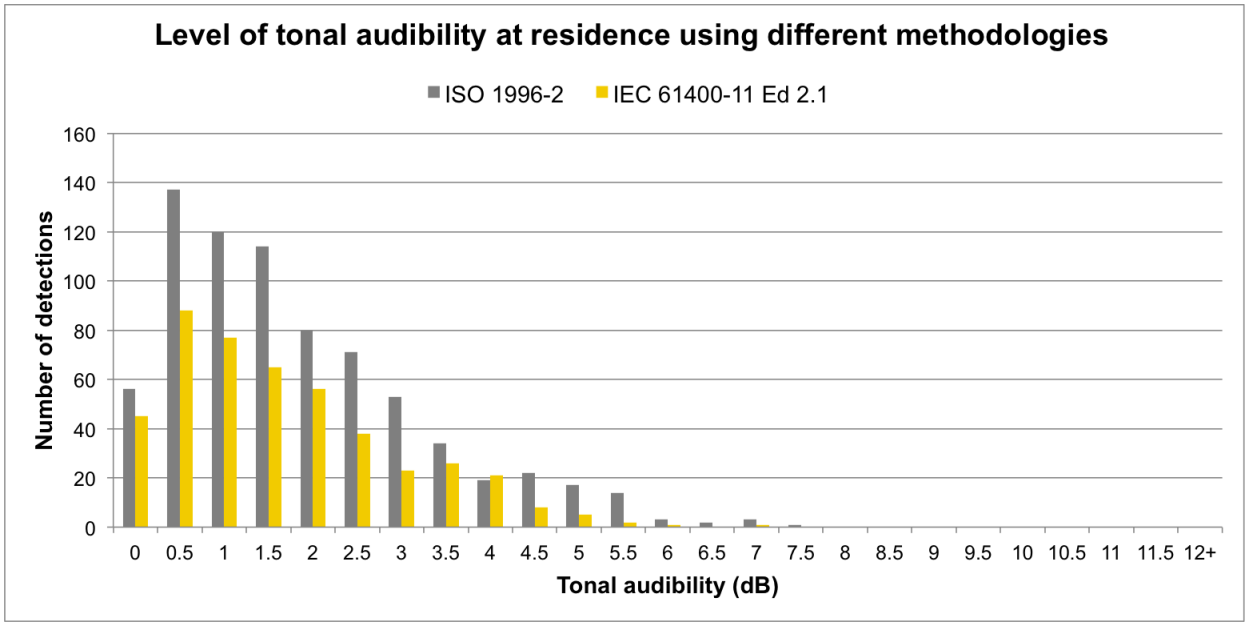

Figure 11 – Level of tonal audibility at residence for IEC 61400-11 and ISO 1996-2 methodologies

It is worth noting that application of the simplified one-third octave band method for tonality from Annex D of ISO 1996-2 would not result in a tone being detected at any of the turbines included in this paper, let alone at any residences near the wind farm. At a wind turbine where a tonal

audibility of 7 to 8 dB was detected, the corresponding minimum emergence of the one-third octave band above both adjoining one-third octave bands was 5 to 6 dB, well below the 15 dB level difference specified for low frequencies by Annex D of ISO 1996-2. This is consistent with findings of a study of tonal transformer hum in the low frequency region, where the audibility of the hum was found to be clearly audible even where the 15 dB level difference was not achieved (Gange, 2011).

4.3 Modulation at residences

At the turbines, the low frequency tones were regularly found to modulate at blade pass frequency. At the residences, the tone modulated but typically in a more random manner as:

- A number of out-of-phase turbines contributed to the audible tone at the residences meaning that modulation from the individual turbines resulted in more random total level at the residence.
- Relatively small differences in frequency in the tonal contributions from each turbine could contribute to a more rapid beating effect in the tone level at the residence. For example, a tone at 122 Hz from one turbine and at 124 Hz from another turbine could potentially result in a 2 Hz modulation at the residence.

When reviewing audio data collected at each residence, these effects contributed to variations in modulation at the residence. While the tone would never be described as steady at any of the residences, at various times it could modulate at blade pass frequency, or beat with a semi-regular frequency or was randomly modulated. This contributed to a noise that could be described as droning and, in some cases, could be mistaken for distant bass music.

The modulation of the low frequency tones could contribute to increased annoyance. In a study into subjective reactions to steady and beating low frequency tones, Moorhouse et al (2005) suggested that subjects were “more tolerant of the steady tones than of the corresponding beating tone by 3-5 dB.”

5.0 Discussion

The data presented in this report indicates that wind turbines have the potential to produce low frequency tonal noise from mechanical components at residential locations adjacent to the wind farm. This may occur even where a turbine test report prepared in strict accordance with IEC 61400-11 Edition 2.1 or Edition 3 indicates that no audible tones were present during the test. These seven turbines are the only seven that we have tested in this manner and yet each demonstrates an audible tone that may not have been detected during a test in accordance with IEC 61400-11. This introduces two key risks for wind farm operators.

The most obvious risk is that the presence of low frequency audible tones, particularly from sources that fluctuate in level and are in otherwise quiet environments, have the potential to result in annoyance. As Leventhall noted in response to an Australian Senate enquiry into wind farms “nearly every low frequency environmental noise problem has been caused by audible tones” (Leventhall, 2012).

The second risk is that acoustic guarantees provided to wind farm operators by wind turbine suppliers are often provided on the basis that noise from the wind turbine is not tonal when assessed in accordance with the relevant version of IEC 61400-11. This effectively limits any tonality assessment of a turbine to only downwind conditions over a limited wind speed range, which may not be the wind speed range over which an audible tone actually occurs. If an audible tone were detected at a different wind speed or wind direction, then a tonal penalty may still be applicable under local regulations even though the acoustic guarantee has not been failed.

5.1 Potential for annoyance

As described in this paper, low frequency audible tones detected from the wind turbines have been measured at residences at up to three kilometres from the nearest wind turbine. The overall occurrence of the tones at residences was typically relatively low, but they could last all night given the right conditions.

The overall tonal audibility at the residences is generally low, with occurrences of tonal audibility greater than 6 dB relatively rare in most cases. These tones would attract penalties of 2 to 4 dB under the methodologies outlined in Annex C of ISO 1996-2 and ETSU-R-97. However, the modulating nature of these low frequency tones has the potential to result in a somewhat higher level of annoyance than the steady tones on which these Standards are based. The frequencies at which the tones were detected as audible, generally in the range of 50 to 150 Hz, also potentially correspond to typical room mode frequencies within residential homes. The presence of room modes could result in increased annoyance indoors relative to outdoors.

While this paper is not able to conclude that low frequency audible tones in the range of 50 to 200 Hz are a source of annoyance in all cases where wind farm noise complaints occur, we note that we are aware of complaints from residents at some of the sites at which the tested turbines are installed. In these cases, the residents identified the noise as being worse under weather conditions which are likely to result in audible tonality based on testing at the site. However, in no instance did the resident specifically use the word “tonality”, instead ascribing complaints instead to low frequency noise and, in one case, infrasound.

Wind farm noise has gathered attention over recent years and claims of health effects from infrasound have been raised by interest groups in Australia (Chapman et al, 2013), but current evidence suggests that this is a largely psychological effect driven by fears around wind farms and infrasound (Crichton et al, 2013). Notwithstanding the above, where actual complaints do occur around noise from wind farms, low frequency audible tones are a much more plausible cause of annoyance than infrasound that has been shown to be many orders of magnitude below established thresholds (Evans et al, 2013). Despite this, there continue to be studies in Australia in response to wind farm complaints that are focussed on infrasound and do not examine more plausible causes. While it is not clear whether these audible low frequency tones are in fact a source of significant annoyance for residents in all cases where complaints occur, it is suggested that there would be benefit to improving tonality assessment procedures around wind farms given the increased scrutiny that wind farm noise is under in some countries.

5.2 Suggested improvements to assessments

The main issue that arises with regards to tonality assessments of wind turbines is that the current IEC 61400-11 Edition 3 only requires testing under a narrow range of wind directions and a limited range of wind speeds. As shown in this paper, these conditions do not necessarily correspond to those conditions where audible low frequency tones tend to occur. Therefore, an improvement to the Standard to require testing under a wider range of conditions, at least during turbine design and development, is considered to be of great benefit. An understanding among wind farm operators of the current limitations on test reports advising on tonality for turbines according to the IEC Standard, as well as potential variations between the same turbine make with different gearbox types, is also important.

Currently, one wind turbine manufacturer has commenced the ALARM project in partnership with component manufacturers, with the aim of eliminating tonal noise from components in the concept and design phase of turbines (Vanhollebeke, 2014). Improved testing procedures through the IEC 61400-11 would assist in providing detailed feedback on the outcomes of these improvements in turbine design. Improvements in turbine design to reduce these audible low frequency tones is important because, as well as potentially causing annoyance to residents,

the difficulty in retrofitting treatments to operating wind turbines producing an audible tone can be significant (Cooper et al, 2013).

In addition to improvements in the testing of wind turbines during the design stage, improvements are also possible in the assessment of potential tonal noise issues at residences. Where a tone is believed to be a potential cause of a complaint, some conclusions that have arisen from our assessments to date are:

- The assessment has to take account of different conditions and different times of day. This makes attended subjective measurements difficult and often impractical. New sound monitoring equipment is making unattended high-quality audio monitoring more practical, and this provides a mechanism to undertake tonality assessments across reasonable durations (Cooper et al, 2013).
- As some of these tones occur in the lower frequency range, appropriate windshields are important for outdoor monitoring. Wind-induced noise at these frequencies on a microphone can overestimate the masking noise that is actually present in an environment.
- Simplified one-third octave band assessments do not appear to provide sufficient rigour to the assessment of low frequency tones from wind turbines.

6.0 Conclusions

This paper presents the findings of detailed tonality assessments conducted on seven different wind turbines from three manufacturers. In each case, the turbine was found to emit an audible low frequency tone in the range of 50 to 200 Hz.

The tones were typically modulated at blade pass frequency and predominantly occurred under wind speeds and directions not tested under the current IEC 61400-11 Standard. These tones were also detected at residences at up to three kilometres from the wind farm and, while the audibility was not always at a high level, the modulating nature of the tone may have the potential to result in annoyance for some residents.

Improvements to current methodologies are suggested to assist in more accurate assessment of tonality from wind turbines. It is hoped that improvements in these assessment methodologies would improve the identification of tonal noise during the turbine design phase, where mitigation measures are likely to be much easier to implement than on site.

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