Automated detection and analysis of amplitude modulation at a residence and wind turbine

Jonathan Cooper (1) and Tom Evans (1)

(1) Resonate Acoustics, 97 Carrington Street, Adelaide, Australia 5000

ABSTRACT

A small degree of amplitude modulation is a normal feature of wind turbine noise but most assessment guidelines for wind farm noise state that, where excessive amplitude modulation occurs, an additional penalty should be applied to the measured noise. Excessive amplitude modulation is typically defined as a situation where the peak to trough levels (either overall or in particular frequency bands) exceed a nominated level. The assessment of amplitude modulation outdoors at receptor locations near wind farms over a wide range of wind conditions can be difficult due to the need to undertake unattended measurements in an environment where background noise regularly interferes with the measurements. This paper describes a methodology for the assessment of amplitude modulation over an extended period at a residence, and the specific techniques used to identify amplitude modulation resulting from the wind farm. The methodology has been employed at an operational wind farm and the results at both a residence and wind turbine assessed to identify conditions which contribute to modulation judged to be ‘excessive’ using the modulation test provided in New Zealand Standard 6808:2010.

INTRODUCTION

Amplitude modulation is a feature of all wind turbine noise (the characteristic “swish” noise). It is widely documented that the guidelines and standards used to assess wind farm noise have been developed on the basis that there will be a small degree of amplitude modulation in the sound from the turbines (SA EPA, 2009; Standards New Zealand, 2010; Standards Australia, 2010).

While these standards and guidelines envisage that some degree of amplitude modulation is a normal characteristic of the turbines, they also seek to apply a penalty to the wind turbine noise if this modulation is greater than normal and therefore deemed excessive. Wind turbine noise which exhibits excessive amplitude modulation might sometimes be described as having a “thump” character, rather than the more typical “swish”. An example of the normal “swish” noise from the turbine blades, which transitions suddenly to become a repetitive “thump” is available on the internet (Bowdler, 2013).

This paper does not seek to investigate dose response relationships to amplitude modulation, although it is acknowledged that further research is required here to define new criteria for the assessment of amplitude modulation. Instead, this paper provides an outline of an algorithm which was developed to allow assessment of the wind turbine noise amplitude modulation against the criteria provided in Appendix B of New Zealand Standard 6808:2010 *Acoustics – Wind farm noise* (NZS 6808:2010).

Additionally, the results of the assessment of amplitude modulation at a residence adjacent to a wind farm and at a turbine near the residence are provided, to examine factors which influence the level of modulation at both the source and receiver.

BACKGROUND

The normal amplitude modulation which is a characteristic of all wind turbine noise is widely agreed to be the result of two main sources; the highly directive trailing edge noise which radiates noise 45 degrees from directly in front of the blade as it moves through the air, and convective (Doppler) amplification, which also increases levels in front of the direction of travel of each blade (Oerlemans, 2007). As the blade is constantly in motion and changing its position relative to a stationary observer, the angle of the observer to the blade is constantly changing, and with changing orientation, the strength of the source towards the observer is constantly varying.

Early investigations suggested that yaw error and the directionality of noise radiated from the moving blade were the cause of amplitude modulation, with no correlation to wind shear or turbulence intensity (Flow Solutions, 1999). However, it should be noted the studied turbine was much smaller than modern turbines, making wind shear effects due to differences in velocity over the height of the rotor less likely to occur.

There have been several suggestions as to the cause for increased amplitude modulation under some conditions. In 2003, Van den Berg suggested that increased amplitude modulation may be caused by large scale atmospheric turbulence ingested by the turbine, when the blade may be at a non-optimal angle of attack. It was also suggested that increased amplitude modulation occurred during periods of higher wind shear, when there is a large differential in wind velocity over the rotor of the turbine. This difference in velocity over the rotor during high shear conditions will result in the blades at the top of the rotation having different angle of attack to those at the bottom of the rotation. The theory that the amplitude modulation may be due to high wind shear suggests that generation of the amplitude modulation will be greater at the source during the night time period, and on flat sites rather than those with complex terrain.

Amplitude modulation is currently the focus of a large body of research being funded by RenewableUK (Cand, 2012). One part of that work is to investigate causes of amplitude modulation, and a summary of the causes of both normal and excessive amplitude modulation was provided by the research group last year (Smith, 2012). They suggest that the non-uniform flow over the rotor of the turbine (due to either a wind gust or wind shear) is a likely cause of excessive amplitude modulation, but note that propagation effects due to the change in height of the source may also contribute to excessive amplitude modulation upwind of the turbines.

ASSESSMENT CRITERIA

This paper focuses on the assessment of amplitude modulation against the requirements of NZS 6808:2010. As the South Australian *Wind farms environmental noise guidelines* (SA EPA, 2009) and Australian Standard AS 4959 (Standards Australia, 2010) do not provide specific criteria for excessive amplitude modulation, NZS 6808:2010 is the only finalised assessment document used in Australia that does.

Section B3.2 of Appendix B of NZS 6808:2010 states the following with regards to the assessment of amplitude modulation:

> …. modulation special audible characteristics are deemed to exist if the measured A-weighted peak to trough levels exceed 5 dB on a regularly varying basis, or if the measured third-octave band peak to trough levels exceed 6 dB on a regular basis in respect of the blade pass frequency.

A draft guideline document for the assessment of wind farm noise was prepared by the Environment Protection Authority Victoria (EPA Victoria) and circulated for information and comment to members of the Australian Acoustical Society. That draft document provides further information on how the test in NZS 6808:2010 should be applied in Victoria:

> The interim test method specifies peak to trough level differences in respect of the blade pass frequency. The blade pass frequency should be measured directly from the rotational speed of the wind turbine during sound level measurements under the interim test method. The rotational speed/blade pass frequency may vary during the measurements and the analysis should be for the specific blade pass frequency at all times. The peak to trough level difference should only be determined for adjacent peaks and troughs at this varying frequency.
>
> The test method requires the peak to trough level differences to be occurring regularly. For this guide the average level difference should be taken over a 2 minute time period. If the level difference thresholds are exceeded within any 2 minute period within a 10 minute measurement, then the +5 dB adjustment should be applied to that wind farm sound level LA90(10 min).

A 5 dB adjustment is applied to the individual $L_{A90,10\ min}$ periods in which amplitude modulation is found to exceed the 5 dB A-weighted or 6 dB third octave peak to trough criteria in any 2-minute period in that measurement.

METHODS FOR ASSESSING MODULATION

Two methods have previously been used for calculating the level of amplitude modulation. The first, and easiest method to apply, uses the simple visual examination of the time series (typically sampled at 100 ms time intervals) to pick off the local maxima and minima. The level of amplitude modulation is then calculated as average difference between the maxima and minima. This method is easy to apply for a short measurement (for example 2 minutes), but impractical when the analysis seeks to identify the level of amplitude modulation continuously over days or weeks at a wind farm site.

The second method that has been previously used to calculate the level of amplitude modulation uses more intensive signal analysis to determine the RMS level of modulation. This is normally achieved using one of the following methods:

- Double application of a spectrum analysis to a measured signal. The first spectrum analysis is used to provide short time series levels (typically 100 ms levels) as either an overall A-weighted level or in third octave bands (analysis potentially undertaken in real time on the sound level meter). A power spectrum is then taken of the 100 ms data, to calculate the frequency of modulation and level of the amplitude modulation (Lee, 2009).
- The raw audio signal is band filtered into third octave bands, and a Hilbert transform used to calculate the signals envelope. A power spectrum is then taken of the band limited enveloped signal, to determine the modulation frequency and level in that band (McCabe, 2011).

The advantage of the more intensive signal analysis techniques is that they can be used to automatically calculate the level of amplitude modulation during long-term measurements of several weeks duration. The disadvantage of these methods is the susceptibility to extraneous noise, which may be falsely identified as amplitude modulation, or may make identification of the level of amplitude modulation due to the wind farm noise indistinguishable from other sources.

The more intensive methods also determine the RMS level of amplitude modulation, rather than a peak to trough level like the visual inspection. In practice, the blade pass modulation is not a perfect sine wave in shape, so RMS assessment techniques cannot be used to determine amplitude modulation for assessment against a peak to trough criterion as required by NZS 6808:2010. RMS assessments could be used to determine the level of modulation against a RMS modulation criterion, but these criteria for wind turbine noise do not exist at the present time. One aim of the work being undertaken for RenewableUK was the development of the dose response relationship for the RMS level of modulation for wind turbine noise (Cand, 2012).

IMPLEMENTATION OF A HYBRID METHOD

To allow the assessment of amplitude modulation against the criteria contained in Appendix B of NZS 6808:2010 over an extended period of time, a hybrid method was developed. This method uses frequency analysis to find the frequency of blade pass modulation, and then a peak finding algorithm to identify individual peaks and troughs, and therefore the difference in level for each blade pass. The frequency analysis to find the blade pass frequency was on 100 ms third octave band results rather than an envelope of an audio signal as NZS 6808:2010 requires the use of 100 ms third octave results for calculating the modulation depth.

The amplitude modulation detection algorithm allowed the automated detection of amplitude modulation in both the A-weighted and one-third octave band data at the residence for a dataset of several weeks duration.

The third octave and A-weighted data required for the assessment of amplitude modulation in accordance with NZS 6808:2010 was gathered in 100 ms intervals using a SVAN 979 sound level meter. Audio data was stored for the full duration of the measurements on a second adjacent sound level meter, which allowed review of the source of the amplitude modulation if the average level of modulation during a two-minute period exceeded the modulation criteria.

Rotational speed data was initially sourced from the nearest turbines to the residence, as directed by the draft guideline document developed by EPA Victoria. However, review of the results of the assessment indicated that it was not possible to find a turbine, or group of turbines where the rotational speed of the turbines was consistently representative of the rate of blade pass modulation at the residence. There were times when blade pass was audible at the residence when the nearest turbines were not operating (showing 0 rotational speed), but other periods when the modulation was controlled by the nearest turbines. Additionally, rotational speed data was available as only average speeds in 10-minute periods, with changes in speed throughout the period not recorded.

Identification of blade pass frequency bands

The first step in the implementation of an automated blade pass identification algorithm was to determine the modulation frequency of the wind turbine noise in each 2 minute measurement period. As indicated above, the rotational speed data sourced from the turbines was not found to provide a reliable indicator of the modulation frequency.

To use the data stored in 100 ms intervals at the residence to find the blade pass frequency, it was necessary to identify the frequency bands (third octave bands and/or A-weighted, C-weighted and Linear levels) in which blade pass modulation could be regularly detected.

The power spectrum of the 100 ms sound pressure levels (measured in dB) in all third octave, overall A-weighted, overall C-weighted and overall Linear bands was calculated, to identify repetitive patterns and hopefully therefore blade pass in each of the bands. Figure 1 shows a simple example when there is very little extraneous noise and blade pass modulation occurring in the 100ms overall A-weighted noise level stored over the majority of a 2 minute period at the residence. The modulation is particularly clear during the first half of the measurement. The power spectrum of the 100ms data in dB presented in Figure 1 is included as Figure 2, calculated using a Hanning window with 50% overlap and resolution of 0.05 Hz.

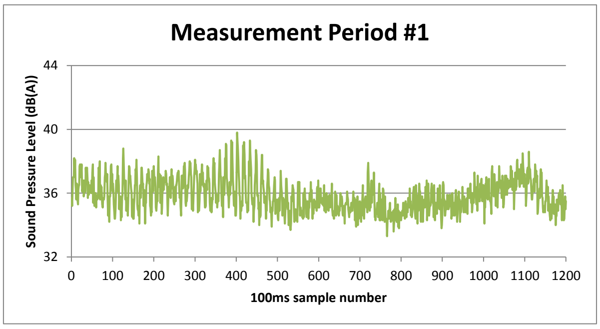

Figure 1. Blade pass modulation visible in the overall A-weighted 100 ms measurements over a 2 minute period.

The significant peak on the graph in Figure 2 indicates the modulation frequency of the 100 ms noise levels presented in Figure 1 to be 0.65 Hz. The peak to trough level of the modulation (based on the false assumption of perfect sine wave modulation) would be calculated by multiplying the square root of the peak at 0.65 Hz by 2√2, as the peak to peak level of any sinusoidal wave is 2√2 times the RMS level.

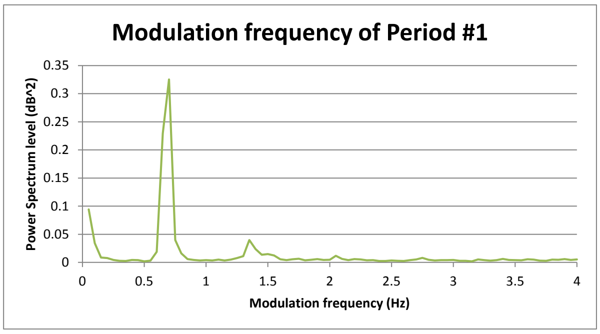

Figure 2. Power spectrum result of the 100 ms data presented in Figure 1, which shows the blade pass modulation frequency to be 0.65 Hz.

As the turbine noise in all frequency bands is due to the rotation of the turbine blades, the modulation frequency in all frequency bands will be the same. It is therefore not necessary to correctly identify the blade pass frequency in every individual frequency band, but rather is possible to identify the blade pass frequency on results in all the other frequency bands in the same 2 minute period. The blade pass frequency for a 2 minute period could then be identified by taking the most commonly detected modulation frequency in all frequency bands during the 2 minute period.

Review of the blade pass frequency selected from power spectrums of all third octave bands between 0.8 Hz and 20 kHz octaves indicated that under conditions when the turbine noise was controlling the noise level at the residence, the blade pass frequency could occasionally be detected in all third octaves between approximately 50 Hz and 2500 Hz, and also in the A- and C-weighted levels. However, reliable detection of the blade pass frequency was rare, and was not immediately obvious from the inspection of the power spectrums of all the frequency bands in about 90% of the 2 minute assessment periods at the residence.

During the initial stages of development of the blade pass frequency detection algorithm the third octave bands between 200 Hz and 1250 Hz, and the C-weighted level were used to try and identify the blade pass frequency, as under good conditions the blade pass frequency was more obvious in these frequency bands. It was suspected that the use of a broad range of frequency bands would reduce the chance of an extraneous modulating noise source controlling noise levels in the majority of the bands, and therefore improve detection of blade pass modulation during periods of extraneous noise. However, it was later found the most reliable detection of blade pass frequency was achieved using only the 250 Hz to 1000 Hz third octave bands.

The power spectrum of the 100 ms A-weighted level was not a particularly reliable indicator of the blade pass frequency for the majority of the measurements at the residence due to its sensitivity to noise in the 1000 Hz to 4000 Hz frequency range; where modulated bird, insect and other animal calls (such as frogs) are frequent.

To demonstrate the influence of extraneous noise on the power spectrum, Figure 3 provides an example where wind turbine noise is modulated at blade pass frequency for the majority of the measurement, but there are two higher level short-term extraneous events near the end of the measurement. Figure 4 shows the power spectrum of the measurement presented in Figure 3.

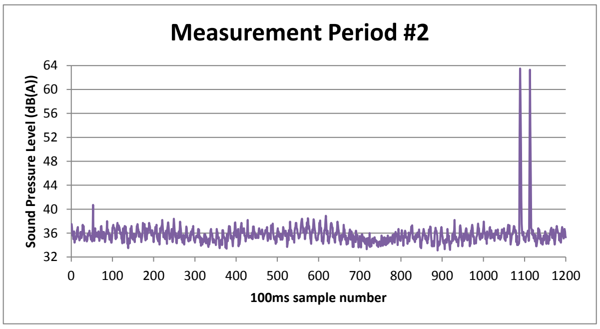

Figure 3. Blade pass modulation visible in A-weighted 100 ms measurements over a 2 minute period, with two high level extraneous events at the end of the measurement.

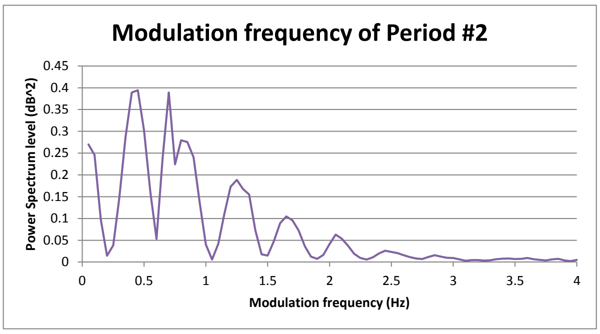

Figure 4. Power Spectrum of the 100 ms data presented in Figure 3, with modulation due to the two high level extraneous events apparent, along with multiple harmonics.

Figure 4 provides a less clear indication of the modulation frequency than the power spectrum in Figure 2, as the two extraneous events spaced 2.4 seconds apart have resulted in the power spectrum showing amplitude modulation at approximately 0.4 Hz (1 / 2.4 seconds). Multiple high level harmonics of the 0.4 Hz peak are also visible, along with the peak due to the actual modulation of the wind farm noise at 0.65 Hz. The possible wind turbine operational speeds included 0.4 Hz, and so selection of the highest peak in the operational range of the turbine would have resulted in mistaken identification of the blade pass frequency.

From review of a large number of turbine and non-turbine controlled measurements, it was apparent that modulation due to the wind turbine did not show harmonics at nearly the same high level as the harmonics due to two (or more) closely spaced extraneous events. On this basis a test was implemented to sort through the peaks showing possible blade pass frequency, and discard peaks with high level second or third harmonics until a likely turbine blade pass frequency was found. Where no possible peak passed the second and third harmonic level test, a tone passing only the second harmonic test was selected. Where no peak passed either test, the highest level peak was selected.

Further improvements in finding the blade pass frequency

A number of additional improvements in the identification of the blade pass frequency were implemented. The first and most significant improvement was to identify the modulation frequency in each individual FFT window of each third octave band, rather than using the average 2 minute power spectrum for each third octave band. The relationship between frequency resolution (filter bandwidth, B (Hz)) and length of the individual window (sample time, T (seconds)) is given by Equation (1).

$$B = 1 / T \tag{1}$$

As a compromise between maintaining reasonable frequency resolution while trying to maximise the number of individual windows in a 2 minute period, a sample time for each individual window of 24 seconds was selected. This gives a blade pass frequency resolution of about 0.042 Hz, and with a 50% window overlap allows nine individual 24 second long power spectrums to be calculated in each 2-minute period for each of the third octave bands.

Taking the measurement in Figure 3 as an example, the modulation frequency calculated from the first eight windows would have correctly identified the blade pass frequency, while the ninth window (on the last 24 seconds in the measurement period) will identify the modulation frequency based on the spacing between the two extraneous peaks.

The algorithm uses the result from nine FFT windows in each of the seven frequency bands (the number of third octave bands between 250 Hz and 1000 Hz inclusive), so that 63 power spectrums are used to identify the modulation frequency in every 2-minute period. Falsely identified modulation frequencies due to extraneous noise are typically randomly distributed throughout the possible frequency range, while the blade pass frequency is correctly identified during quieter periods in any of the third octave bands.

The modulation frequency results from the 63 individual power spectrums were binned to count the number of results at each frequency over the range of operational frequencies of the turbine. Figure 5 shows the count of the number of the individual power spectrums with maximum level at each possible blade pass frequency in each 2 minute period, over a time interval of 40 minutes at the residence. During the first 16 minutes of the measurement the majority of the 63 power spectrums in the 2-minute measurements showed a blade pass frequency of 0.54 Hz. 20 minutes into the measurement a blade pass frequency of 0.5 Hz was more commonly detected, and the most commonly detected frequency then gradually increased to 0.67 Hz up to the 36 minute mark of the measurement.

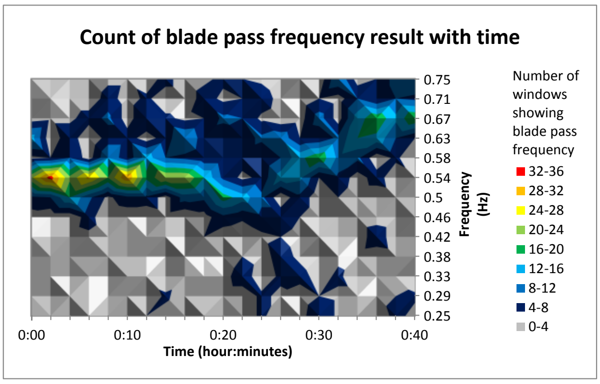

Figure 5. Count of the number of power spectrums showing various blade pass frequencies with time, from which the blade pass frequency of the turbine can be followed.

To account for the possible variation in frequency and improve the correct identification of the blade pass frequency, the sum of the number of detections in each frequency bin and the bins both immediately below and above in frequency was calculated. The bin with greatest sum of detections of the modulation frequency was selected as the blade pass frequency in each 2-minute period. While there is a chance that the blade pass frequency will vary slightly during the 2 minute measurement, an analysis of frequency variation showed it was relatively rare for this to be more than the frequency resolution (0.0417 Hz) and never more than twice the frequency resolution (0.0833 Hz). Any variation in blade pass will therefore be captured in a sum of three adjacent bands.

The 40 minute period presented in Figure 5 shows the number of detections of each frequency during a time with relatively little extraneous noise, particularly during the first 20 minutes of that measurement. The influence of extraneous noise made identification of the blade pass frequency more difficult than the example presented for the majority of the measurements.

The lack of large variation in blade pass frequency with time was able to be used to improve the accuracy of the blade pass frequency detection in periods of significant extraneous noise, by preferentially weighting the counts in frequency bins nearer to the blade pass frequency in the previous 2-minute period. Counts in the frequency bin matching the blade pass of the previous 2 minute period were assigned a weighting of 1, with the weighting applied to every other bin calculated as per Equation 2, where W is the weighting applied to the count in that frequency bin and N is the number of frequency bins between the previous blade pass frequency bin and the frequency of that band.

$$W = 1 - 0.1*N \qquad (2)$$

Figure 6 provides the count of the number of individual power spectrums indicating blade pass at each possible frequency, over a 40 minute period with significant extraneous masking noise at the residence. Figure 7 shows the same 40 minute period, but with preferential weighting to the blade pass frequency in the previous 2 minute period applied. From a comparison of Figures 6 and 7, the blade pass frequency is more easily identified with the preferential weighting applied.

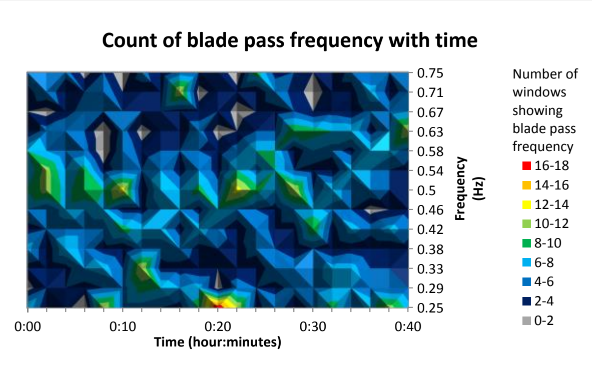

Figure 6. Count of the number of power spectrums showing blade pass frequency during a period of significant extraneous noise.

The improvements to the blade pass frequency analysis provided significantly more reliable detection of the blade pass frequency than provided from a single power spectrum of the 2 minute period. However, there were periods when the frequency of the blade pass was unable to be determined due to the significant extraneous noise present for that period.

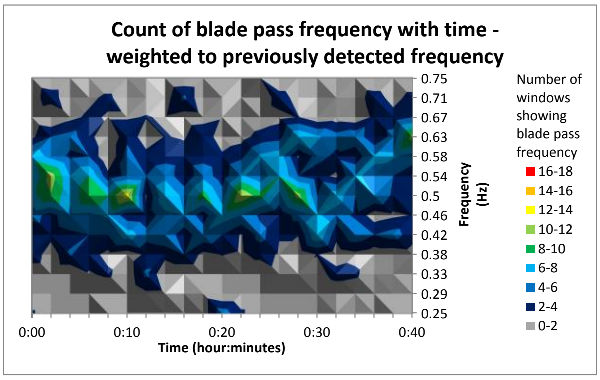

Figure 7. Count of the number of power spectrums showing blade pass frequency during a period of significant extraneous noise, but with weighting applied to favour the blade pass frequency identified in the previous 2 minute period.

The final measure implemented to allow the blade pass frequency to be determined at the residence was to restrict the allowable change in blade pass frequency between adjacent 2 minute periods. In the case that the change in frequency was less than or equal to one frequency bin, the change was followed. If the change was greater than one frequency bin but less than or equal to 2 frequency bins, it was more likely that this change was due to extraneous noise, and the adopted change was $1/3^{rd}$ of the difference. When the change in frequency was greater than two frequency bins, it was clearly not due to actual blade pass noise and a change of $1/3^{rd}$ of the frequency resolution was applied. The approach adopted meant that a realistic change in frequency was followed, but the change due to an extraneous source would not significantly alter the blade pass frequency, and would be recovered by the next correct frequency detection. Blade pass frequencies very different to the frequency of the previous 2 minute period were not ignored, so that the blade pass frequency would be automatically re-acquired by the algorithm if lost due to long term extraneous amplitude modulation or the shutdown of the turbines.

A review of the results of the blade pass detection against a number of manually calculated periods throughout the assessment period at the house indicated the blade pass frequency was being correctly identified whenever turbine blade pass noise was audible. The blade pass frequency was able to be correctly identified whenever modulation was identified through visible inspection of the 100 ms measurement series.

The review of the results also found that the modulation frequency of the wind turbine noise was being calculated significantly more reliably using the above method than the approach of adopting the operational speed of one or more of the nearest turbines to the residence.

Calculation of level of modulation

It was relatively easy to automatically calculate the average peak to trough level once the blade pass frequency had been determined.

The blade pass frequency determined for each 2-minute period was first used to calculate the expected number of 100 ms samples between each blade pass. As an example, for a 0.5 Hz blade pass frequency, the local maxima would be expected to be spaced 1/0.5 = 2 seconds, or twenty 100 ms samples apart.

It was noted that while the spacing between each broad peak due to blade pass was relatively regular, the 100 ms levels did not follow a perfect sine wave and the broad peaks and troughs were irregularly shaped. For this reason the spacing between the 100 ms samples containing maxima and minima was somewhat irregular.

Figure 8 provides an example illustrating the relatively regular blade pass spacing in the 315 Hz third octave band, but irregular spacing of the local minima and maxima due to the irregular shape of the peaks. The blade pass frequency detected during this period was 0.5 Hz, providing an expected spacing between individual maxima and minima of 2.0 seconds. However, local maxima are spaced at between 1.5 and 2.5 seconds, with the spacing between minima being between 1.3 and 2.8 seconds.

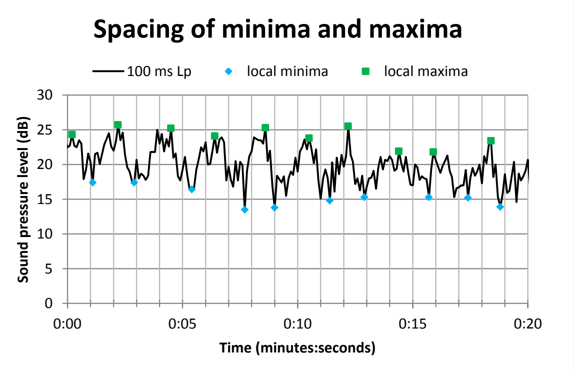

Figure 8. Relatively regular spacing of broad peaks and troughs due to blade pass, but irregular spacing of the lines of individual maxima (green squares) and minima (blue diamonds) due to the irregular shapes of the peaks.

Local maxima in the time traces were identified using sliding windows, which for each 100 ms sample checked to see if that sample was the highest level within approximately half a blade pass in either direction (for 0.5 Hz, the highest value out of the 10 samples before and also the 10 samples after). If the 100 ms sample was the highest sample within half a blade pass, that sample was marked as a local maximum. The same process was repeated to find the local minima, although a slightly smaller search window was found to yield the best results when identifying the minima. Cases where more than one 100 ms sample shared the same value were identified and the average sample number of the multiple samples assigned.

The local minima and maxima in the time series were then sorted to find alternating minima and maxima, and the spacing of the local maxima from the minima checked to make sure it was reasonable (that they were no further than blade pass apart).

A review of the time periods where wind turbine amplitude modulation was greatest found no individual peak to trough differences greater than 13 dB, and on this basis a test of peak to trough differences was included to exclude high level extraneous peaks with greater peak to trough differences than 13 dB. The key advantage of an amplitude modulation assessment method identifying the individual peaks and troughs is the ability to exclude high level extraneous peaks. An RMS assessment would either include the peaks as blade pass noise or alternatively require exclusion of the whole 2-minute period, both undesirable results.

Finally, the spacing between the adjacent maxima where checked to establish whether the local maxima were spaced at blade pass frequency. For the purposes of this test, the modulation was only considered to be possible wind turbine modulation when there were three or more appropriately spaced local maxima. Two local maxima spaced at approximately blade pass in the absence of any other adjacent potential blade passes were considerably more likely to be the result of extraneous noise than turbine noise, and were therefore excluded.

Due to the variability of spacing of the lines of local minima and maxima as shown in Figure 8, it was necessary to set some relatively lenient limits on the allowable spacing of wind turbine noise modulation. Based on the review of the spacing between a large number of modulated turbine noise maxima these limits were initially placed at 0.5 to 1.3 times the spacing expected based on the blade pass frequency in that 2 minute period. These limits could however be altered if review of a 2 minute period indicated that a blade pass had been missed. The selection of these limits is a trade-off between ensuring that the all turbine noise modulation is captured (requires more widely spaced limits), while trying at the same time to minimise the detection of modulation due to extraneous noise (requires more narrowly spaced limits).

To minimise the exclusion of wind turbine noise modulation, the limits selected for spacing of the individual peaks were leniently set. This resulted in a relatively large number of extraneous noise events being characterised as being modulated at the blade pass frequency for which the audio data then needed to be reviewed. However, in the 10 day assessment period at the residence there were only 82 2-minute periods in which the 2 minute averaged level of modulation falsely exceeded the 6 dB third octave band criterion due to extraneous noise. Only two 2-minute periods falsely exceeded the 5 dB criterion for A-weighted noise as a result of extraneous noise. Many of these periods where extraneous noise was identified to be modulating were the result of noise from frogs, which was modulated continuously during the measurement at a similar frequency to the blade pass, but at a higher noise level.

We believe that one alternative to setting lenient limits for the spacing of lines of individual maxima would be the application of a low pass filter to the 100 ms results to find the broad peaks and troughs, which for blade pass noise should be more regularly spaced. If the spacing of the broad peaks and troughs was found to match blade pass frequency then the line of the local maxima and minima near each broad peak or trough could be located, and used to calculate the modulation depth. This approach was not trialled in our assessment due to time constraints, but we suggest could provide better rejection of extraneous noise.

As an example of the effectiveness of the implemented method for detecting local minima and maxima and calculating the level of modulation, the results from the automated amplitude modulation detection is provided in Figure 9. It shows the measured noise level for the minute of the 2-minute period in which the highest level of amplitude modulation was detected during the 10 days of measurements. Note that the 100 ms sound pressure level is the level in the 800 Hz third octave band. Overlayed are the local minima and maxima automatically detected by the algorithm, and the level of modulation (against the secondary axis), for each maxima which has been automatically classified as being of blade pass origin.

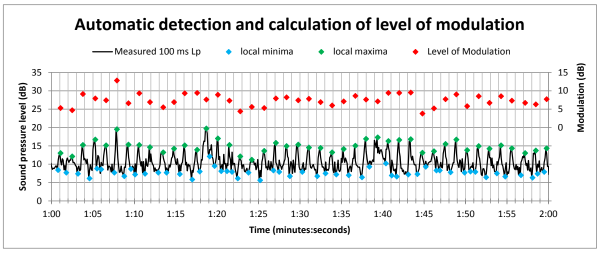

Figure 9. Automatically detected local maxima (green squares), minima (blue diamonds) and the resulting peak to trough level (red on the secondary axis), from the 2-minute period at the residence in which the highest average level of amplitude modulation was measured. Results are in the 800 Hz third octave band.

Once the peak to trough differences had been calculated, they were linearly averaged to calculate the average level difference during that two-minute period in that one-third octave band or for the overall A-weighted levels. Where modulation was anticipated based on the regular blade pass spacing but did not occur a value of 0 dB was used for that missing blade pass when calculating the average blade pass level for the 2-minute period. This results in the calculation of a lower level of amplitude modulation in 2-minute periods where modulation only occurred for a small percentage of the time, when compared to those 2-minute periods where blade pass modulation at the same level occurred continuously.

RESULTS AT A RESIDENCE

The residence selected for the assessment was at a distance of approximately 1.5 km from the nearest turbine of a relatively large wind farm (turbines rated to 3 MW, hub height of approximately 80 m). The topography at the wind farm site is relatively flat. Noise levels at the residence due to the wind turbines alone was approximately 35 dB(A) at maximum sound power output, but lower at times of low wind speeds. The detection of the blade pass frequency was relatively difficult at this residence at times, due to the ambient environment being controlled by extraneous noise. However, a review of the accuracy of the blade pass frequency during periods that the wind turbines were clearly audible showed excellent agreement between the automatically detected and manually counted blade pass frequency.

The assessment of amplitude modulation at the residence identified 114 2-minute periods where the average peak to trough modulation exceeded 6 dB in one or more one-third octave bands. Two of the same periods also had modulation of the A-weighted level exceeding the 5 dB A-weighted criterion. However as previously stated, a number of the periods identified to contain excessive modulation were the result of modulating extraneous noise (often frog noise), rather than wind turbine blade pass noise. This assessment took the conservative approach of considering a level 0.01 dB above criteria to be excessive modulation.

Through listening to the recorded audio for each of the periods where modulation exceeded the 5 and 6 dB criteria, the periods where modulation was due to an extraneous source were discarded. Modulation due to wind turbine blade pass noise caused the 6 dB third octave band criterion to be exceeded in only 32 of the 7083 2 minute periods (0.45% or the total measurement period).

In all of these periods, the amplitude modulation in the relevant one-third octave band was between 6 and 6.5 dB. The highest level of amplitude modulation due to wind turbine noise had average blade pass modulation of 6.5 dB. Neither of the two periods where an exceedance of 5 dB A-weighted criterion was detected were a result of wind turbine noise, with one a result of bird and the other a result of frog noise.

To investigate the conditions resulting in the excessive amplitude modulation due to wind turbine noise, the occurrence of excessive amplitude modulation was examined against wind speed, wind direction and time of day. Figure 10 shows the occurrence of exceedances of the 6 dB one-third octave band criterion with hub height wind speed and wind direction, and Figure 11 shows excessive modulation occurrence with wind speed and time of day. Note that occurrence is the percentage of measurements in that particular wind speed and direction/time bin in which the 6 dB criterion was exceeded. Results are presented as the occurrence rather than a count of the number of events exceeding criteria so that results are not skewed to the bins that contained the greatest number of raw 2-minute periods for assessment.

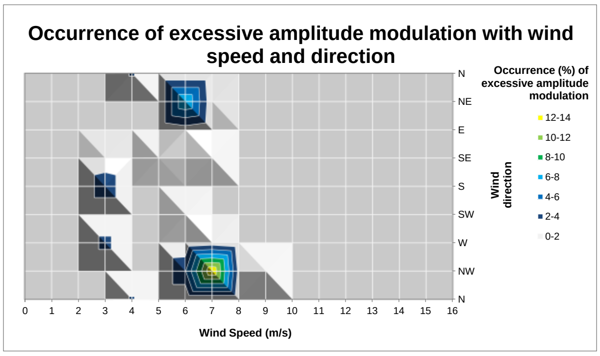

Figure 10. Frequency of detection of one-third octave amplitude modulation greater than 6 dB at the residence, with hub height wind speed and wind direction.

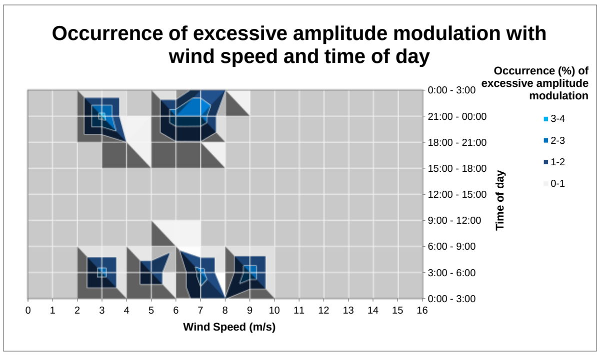

Figure 11. Frequency of detection of third octave amplitude modulation greater than 6 dB at the residence, with hub height wind speed and time of day.

From Figures 10 and 11, excessive amplitude modulation was limited to hub height wind speeds of between 3 and 9 m/s, although detection at speeds above 7 m/s was rare. This was despite the maximum sound power output of the turbines, and therefore maximum turbine noise level at the residence, occurring at a wind speed of above 9 m/s. No trend in detection of excessive amplitude modulation with wind direction is apparent. Excessive amplitude modulation was limited to the evening and night time periods, with review of the data indicating no detection of modulation greater than 6 dB during the daytime between 6:30 am and 7:00 pm.

There were two obvious potential causes for the detection of excessive amplitude modulation during the night time period. The first is that there is less extraneous noise during the night time, and so less masking noise to hide the wind turbine noise. The second reason could have been the anticipated increased wind shear during the night, which has previously been suggested to increase the strength of the modulation at the source, and will also reduce masking noise from wind through vegetation. Figure 12 shows the periods during which the excessive amplitude modulation was detected on a graph of noise level v's wind speed, and Figure 13 shows points with excessive modulation on a graph of the wind shear v's wind speed. Wind shear was determined from wind speed measurements conducted at a number of heights using a wake-free meteorological mast at the site.

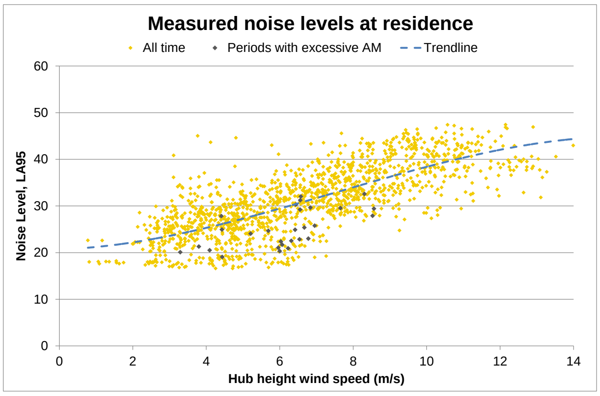

Figure 12. Periods with excessive modulation with measured noise level and wind speed.

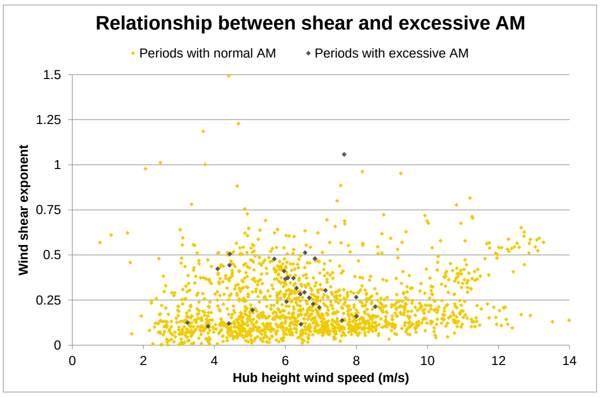

Figure 13. Periods with excessive modulation with wind shear and wind speed.

Figure 12 indicates that excessive amplitude modulation only occurs during the quieter periods at any given speed, with no excessive modulation detected at a noise level above 33 dB(A). Figure 13 shows a less clear trend in modulation with wind shear. While there is a larger proportion of high shear measurements in which excessive amplitude modulation was detected, excessive modulation occurs over a wide range of wind shears. From the results in Figure 12 it would be expected that the reduced masking that results from increased wind shear would alone have been enough to skew detection towards periods of higher shear. It does not therefore appear that excessive amplitude modulation at the house is a result of an increased level of modulation at the source during times of high wind shear. Noise levels at the receiver location appear to be the most important factor for the detection of what the NZS 6808:2010 Standard deems to be excessive modulation.

RESULTS AT A TURBINE

Previous measurements of amplitude modulation at a turbine have indicated that, while the L_{Aeq} is greater upwind and downwind of the turbine, the amplitude modulation is greatest at the sides of a wind turbine (Oerlemans, 2009). It has also been previously suggested that excessive amplitude modulation is a result of high wind shear, which results in uneven flow speeds over the rotor of the turbine.

Measurements conducted simultaneously at one of the nearest turbines to those previously described at the residence allowed an analysis of the influence of wind conditions on the generation of amplitude modulation at the source.

The measurements at the turbine were conducted as per the requirements of IEC 61400-11 *Wind turbines – Part 11: Acoustic noise measurement techniques* (IEC, 2012), which uses a microphone positioned on a ground board to minimise wind induced microphone noise. Audio data was stored for the complete measurement period and was used to calculate an overall A-weighted 100 ms time series over only the 63 Hz to 1250 Hz third octave bands. This range of frequencies was selected for analysis as lower frequencies are typically borderline inaudible at residential distances from wind turbines, and higher frequencies are heavily attenuated with distance to the receiver and were frequently dominated by bird noise at the turbine location.

The average level of amplitude modulation was calculated in every 2-minute period at the turbine. A total of 4,794 2-minute periods were available for analysis at the turbine once periods due to rainfall and non-operation due to both wind speed below turbine cut in and shutdown for service were excluded.

Figure 14 presents the distribution of levels of modulation measured at the turbine, where each bin is 0.5 dB wind and centred on the half dB level. It shows that the average modulation depth at the turbine was typically in between 3 and 6 dB. The highest level of modulation measured in any 2-minute period was 8.7 dB, which occurred at a wind speed of 9 m/s when the measurement location was to one side of the turbine. The maximum level of amplitude modulation at the turbine was therefore higher than the level of modulation at the residence. A reduction in modulation appears to occur between the turbine and residence, perhaps due to the interaction of multiple sources on a site, and the greater background noise at the residence.

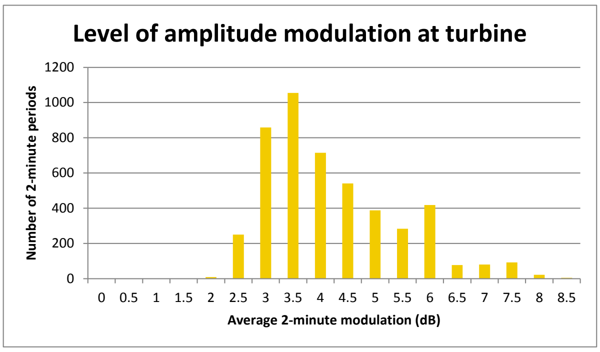

Figure 14. Distribution of level of amplitude modulation at the turbine.

Relationship to wind speed and direction

The average levels of modulation in every 2-minute period were sorted into wind speed and direction bins and the average modulation for each wind speed and direction combination calculated. Figure 15 shows the relationship between the level of modulation and wind speed and direction. Bins with no data due to prevailing conditions during the 10 days of measurements are in grey. Wind speed is measured at hub height of the test turbine, and measurement angle is the location of the measurement location with respect to the heading of the turbine nacelle. An angle of 0 degrees is directly upwind of the turbine and +/-180 degrees directly downwind. When viewed from behind (downwind of) the turbine, positive angles are measurement locations to the right of the turbine and negative angles to the left. The direction of rotation of the turbine blades is such that the blades move downwards at the measurement angle of -90 degrees.

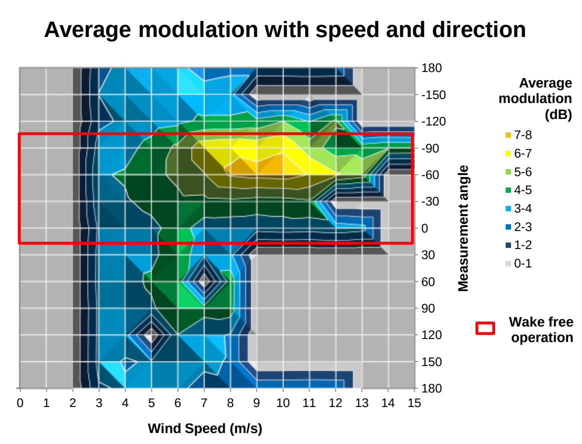

Figure 15. Average level of amplitude modulation at the turbine with wind speed and direction.

Note that the turbine selected for the analysis was amongst other turbines. For this reason only measurements upwind and to one side of the turbine occurred when test turbine was free of the wake of other turbines. These periods are marked as “Wake free operation” in Figure 15 and all subsequent figures.

The analysis with wind speed and wind direction shows no change in modulation with direction around the turbine at wind speeds of 3 to 4 m/s. However, at higher wind speeds, a significant difference in modulation is observed with direction. At 8 m/s, the average level of modulation directly up and downwind of the turbine was approximately 3 dB(A), and to the side was about 7 dB(A). Interestingly, the level of modulation directly upwind and downwind are similar across all speeds between 3 and 12 m/s, despite the upwind measurements being free from turbine wake and the downwind measurements occurring while the test turbine was in the wake of another turbine. This suggests turbulence resulting from other turbines is not a significant contributor to A-weighted amplitude modulation over the frequency range of 63 Hz to 1250 Hz.

Relationship to wind shear

The data gathered at the turbine was reviewed to determine whether there was any relationship between wind shear and amplitude modulation as has been previously suggested. The wind shear exponents used in this analysis were calculated from wind speeds measured at multiple heights between 20 metres and hub height, from wake free met masts at the site.

It is demonstrated above that there is a relationship between both wind speed and wind direction on the level of amplitude modulation from the turbine. The analysis of the influence of wind shear therefore needs to consider periods with matching wind speed and directions, but differing wind shear. Figures 16 to 19 are provided to allow comparison of the same wind speeds and directions but for differing wind shear. The data with lowest wind shear (exponent of 0 – 0.2) is presented first in Figure 16, with results for increasing shear through to the highest shear (0.6 and greater) last in Figure 19. Note that any differences with wind shear would be expected to be most obvious for the wake free measurements, as wind shear was taken from a wake free met mast, such that shear would be reduced at the location of the turbine due to the wake of other turbines.

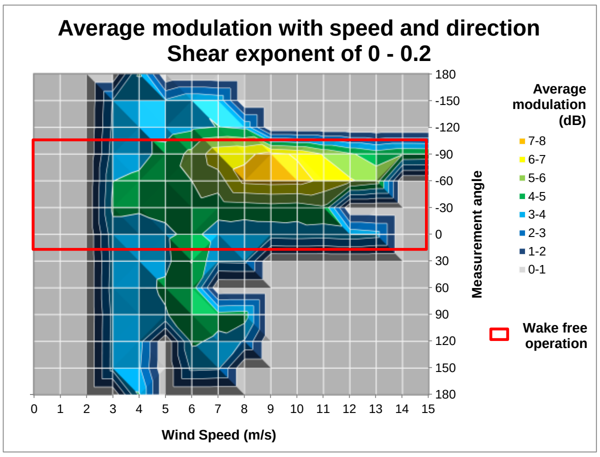

Figure 16. Average level of amplitude modulation at the turbine with wind speed and direction for wind shear exponent of 0 to 0.2.

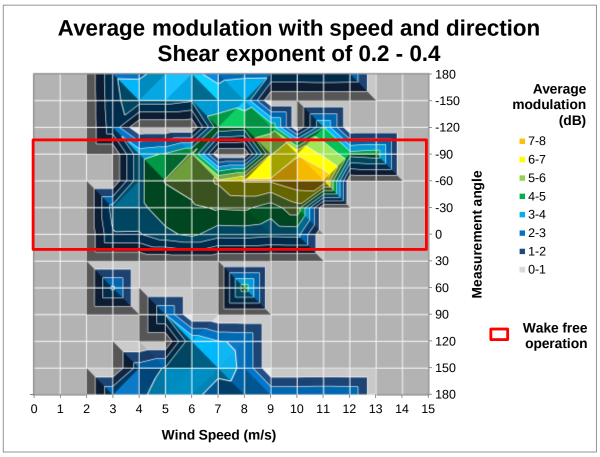

Figure 17. Average level of amplitude modulation at the turbine with wind speed and direction for wind shear exponent of 0.2 to 0.4.

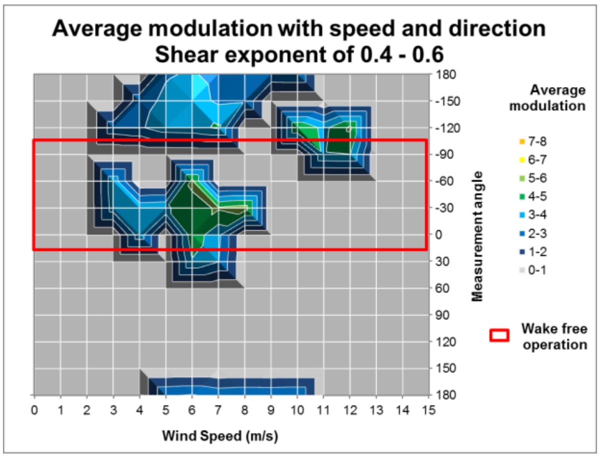

Figure 18. Average level of amplitude modulation at the turbine with wind speed and direction for wind shear exponent of 0.4 to 0.6.

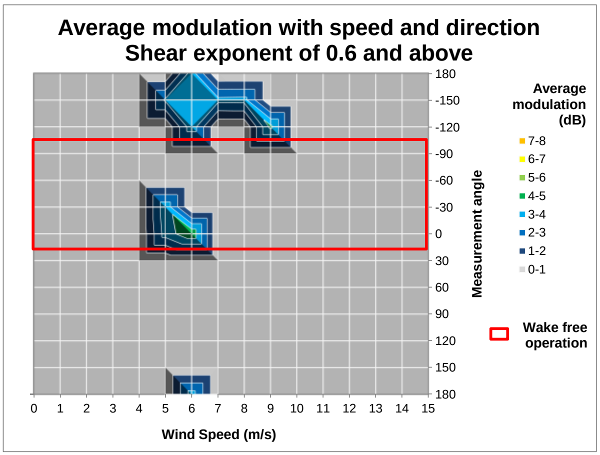

Figure 19. Average level of amplitude modulation at the turbine with wind speed and direction for wind shear exponent of 0.6 and above.

The only combination of wind speed and direction which has wake free data for all four wind shear cases is directly in front of the turbine (0 degrees) at 6 m/s. For this wind speed and direction combination 200 minutes of data was available for shear of 0 – 0.2, 20 minutes for 0.2 -0.4, 90 minutes with shear 0.4 -0.6, and 30 minutes for wind shear of 0.6 and above. A slight increase in modulation is observed between the lowest shear (average modulation of 4.2 dB(A) for both 0 -0.2 and 0.2 – 0.4) and the highest shear cases (4.7 dB(A) at 0.4 – 0.6, and 4.8 dB(A) at 0.6 and above). However, the difference is relatively insignificant when compared to differences resulting from a change of wind speed or direction.

Looking across the data available at other wind speed and direction combinations there does not appear to be any significant trend in the level of modulation of the source and wind shear. It would be interesting to analyse several months of measurements on multiple sides of the turbine to confirm the wake free modulation with wind shear at all directions around the turbine to see if these initial results are repeated in a much larger data set.

DISCUSSION

The biggest challenge in the implementation of an automated assessment tool for amplitude modulation was the identification of the blade pass frequency at the residence, which on this site was not able to be accurately determined from the rotational speed data from the turbines. The turbines on this particular site had a large range of operational speeds, and noise levels at the receiver were influenced by a large number of turbines, rather than being controlled by one or two turbines. It may be the case the rotational speed data provides a more accurate measure of the blade pass frequency at other sites, but we caution against relying on the rotational speed data from the nearest turbine, without due consideration that others may contribute to the noise at a residence.

The detection of excessive amplitude modulation results in a 5 dB(A) penalty being added to the measured wind turbine noise level. For assessment of wind turbine noise at a receiver, there is limited value in assessing modulation if the wind turbine noise level is more than 5 dB(A) below criteria (as the application of a 5 dB(A) penalty will be of no consequence for compliance). Wind turbine noise levels at this receiver were approximately 5 dB(A) below criteria, and we doubt that it will be practical to acoustically identify the blade pass frequency with a lower level of turbine noise. It will however become easier to acoustically identify the blade pass frequency at sites where turbine noise levels are approaching 40 dB(A).

We note that in the current form, it would not be possible to use the algorithm to assess compliance at this residence with a third octave modulation criterion of less than 6 dB, due to the extraneous noise which is classed as being of turbine in origin as a result of the loose limits applied on the spacing of adjacent peaks. However, we believe that a further refinement of detection of individual peaks is practical, such that assessment against a lower third octave modulation limit should in the future be a possibility. This would most likely be through the use of low pass filtering to find broad peaks and troughs, checks on the spacing of the much more equally spaced broad peaks and troughs, and finally identification of the maxima and minima near these broad peaks and troughs.

Additionally, we note the wind turbine noise level was about 5 dB(A) below criteria at this site, such that wind turbine noise was not often the dominant noise source. Assessment against a lower third octave band criterion would be more practical at sites with a greater contribution of turbine noise levels to the total measured level.

The assessment of amplitude modulation at the house indicated that the most significant contributor to the level of amplitude modulation was the level of ambient noise. This finding was subjectively supported by a review of the audio at the residence, which suggested amplitude modulation was greater at time of lower ambient and extraneous noise. Excessive amplitude modulation was not detected at high wind speeds at the house, a result which we suggest was related to increased masking at these high speeds. No trend in amplitude modulation with wind direction was noted at the residence.

In contrast, at the turbine the amplitude modulation increased with wind speed and appeared to be strongly related to wind direction. There are two possible reasons why the trend in modulation with wind direction at the turbine may not have been observed at the residence. The first is that the residence is never at the same relative direction from every turbine at the site. When the residence is to the side of one turbine it is upwind or downwind from other more distance turbines. The second possible explanation is that while the level of modulation is greater to the side of the turbine, a lower level of noise is radiated to the sides when compared to directly in front and behind the turbine. Therefore, while the amplitude modulation is greater at the side, it may not be loud enough to be above the level of background noise at the residence.

Measurements at the house suggested that there was not a particularly strong relationship between wind shear and the level of amplitude modulation. While there were a larger proportion of measurements at the house with excessive modulation at higher levels of wind shear, this could have been expected given the reduced masking from extraneous noise during these periods. A number of periods with excessive modulation were also detected at the house during periods of low shear, suggesting shear was not a dominant cause. The measurements at the turbine confirmed the lack of strong relationship between wind shear and amplitude modulation radiated from the source. The findings at the house are in contrast to the findings of other authors (McCabe, 2011; Larson 2012), and at the turbine contrast with currently popularly accepted theory as to one cause of excessive modulation being increased modulation at the source under conditions of high shear (Smith, 2012).

It would be interesting to review modulation at the house and turbine for a period of several months to see if this initial finding is upheld. However, the explanation for the difference at the house may be as suggested by McCabe, that the increase in modulation at distance during periods of higher shear in his measurements was more a result of reduced masking at the receiver than an increase in modulation at the source. This explanation is supported by Søndergaard (2012), who found similar levels of modulation under unstable conditions during daytime as under stable conditions at night.

The lack of a significant increase in modulation at the source may have been the result of insufficient wind shear during the measurement period to cause stall, although there were several periods with shear exponent of greater than 1. It may also be that modern turbines are less susceptible to excessive modulation due to periods of high shear than the previous generation of stall regulated turbines that were common when excessive amplitude modulation was first reported.

The lack of a relationship between stall and modulation at the turbine might indicate that modulation judged to be ‘excessive’ at this residence under the 6 dB third octave test included in NZS 6808:2010 was actually just ‘normal’ modulation. The audio captured at the residence during these periods of ‘excessive’ modulation did not subjectively sound significantly different in character.

One final issue that needs to be addressed in the assessment of amplitude modulation at residence is the development of dose response relationships, to provide sound justification of the criterion levels currently adopted by the various standards and guidelines used globally. In recognition of the lack of information around the subjective response of listeners to amplitude modulation, one part of the research currently being funded by RenewableUK focuses on the subjective response of listeners to amplitude modulation. From publically available information it appears that work is focusing on an RMS criterion level (Cand, 2012), which may not be directly applicable to the peak to trough assessment criteria like that currently suggested by NZS 6808:2010.

CONCLUSION

This paper has provided a summary of the development of an algorithm for the assessment of amplitude modulation against the requirements of Appendix B of NZS 6808:2010. Additionally, the findings of an assessment at a residence have been provided, along with the results of an analysis of modulation at an adjacent turbine.

On the balance of the available data at the residence it would appear that the ambient noise level at the residence is a more important factor in the detection of excessive amplitude than the influence of wind shear. Periods judged to be ‘excessive’ modulation using the 6 dB third octave test in NZS 6808:2010 occurred at the residence under periods of both low and high wind shear. Measurements at the turbine suggested a negligible influence from wind shear on the generation of amplitude modulation at the source. Review of modulation at the source also indicated no significant increase in modulation from turbulence, which occurs when the turbine is operating in the wake of another.

The lack of increase in modulation at the source during periods of wind shear suggests the modulation at the site might be best described as ‘normal’ wind turbine noise modulation with a ‘swish’ character, rather than ‘excessive’ modulation with a ‘thumping’ nature. This finding was supported by a review of audio at both the residence and turbine, which did not find any obvious change in the character of the sound.

Further work is required to determine whether the 6 dB criterion level for modulation depth of third octave noise provides a suitable test of ‘excessive’ modulation, and to determine a dose response against which the level of increased annoyance can be determined. This 6 dB criterion was regularly exceeded close to the turbine when measuring at high wind speeds to the side of the turbine. The findings at this residence suggest this criterion may also be occasionally exceeded at residential distances during periods of ‘normal’ modulation.

REFERENCES

Bowdler D, Papers and publications, viewed 12 August 2013 http://www.dickbowdler.co.uk/content/publications/

Cand MM, Bullmore AJ, Smith M, Von-Hunerbein S & Davis R, ‘Wind turbine amplitude modulation: research to improve understanding as to its cause & effect’, *Proceedings of Acoustics 2012*, Nantes, 23-27 April 2012

Bass J, Bowdler D, McCaffery M and Grimes G, ‘Fundamental Research in Amplitude Modulation – a Project by RenewableUK’, *Procedings of Wind Turbine Noise 2011*, Rome, 12 – 14 April 2011.

Flow Solutions Ltd, Hoare Lea & Partners Acoustics: Renewable Energy Systems Ltd. “Wind Turbine Measurements for Noise Source Identification: ETSU W/13/00391/REP, 1999

IEC 2012, *Wind turbines – Part 11: Acoustic noise measurement techniques*, IEC 61400-11 Edition 3.0, International Electrotechnical Commission, Geneva.

Larsson C & Öhlund O, ‘Variations of sound from wind turbines during different weather Conditions’, *Proceedings of Internoise 2012*, New York, 19-22 August 2012.

Lee S, Kim K, Lee S, Kim H & Lee S, ‘An estimation method of the amplitude modulation in wind turbine noise for community response assessment’, *Procedings of Wind Turbine Noise 2009*, Denmark, 17 – 19 June 2009.

Lee S, Kim K, Choi W & Lee S, "Annoyance caused by amplitude modulation of wind turbine noise," *Noise Control Engineering Journal*, Vol 59, 38-46, 2011.

Moorhouse A, Hayes M, von Hünerbein S, Piper B & Adams M, ‘Research into Aerodynamic Modulation of Wind Turbine Noise: Final report’, University of Salford, July 2007.

McCabe JN ‘Detection and Quantification of Amplitude Modulation in Wind Turbine Noise’, *Proceedings of Wind Turbine Noise 2011*, Rome, 12 – 14 April 2011.

Oerlemans S, Sijtsma P & Méndez López B, ‘Location and quantification of noise sources on a wind turbine’, *Journal of Sound and Vibration*, Vol 299, 869-883, 2007.

Oerlemans S & Schepers G, ‘Prediction of wind turbine noise directivity and swish’, *Proceedings of Wind Turbine Noise 2009*, Denmark, 17 – 19 June 2009.

SA EPA 2009, *Wind farms environmental noise guidelines*, Environment Protection Authority, Adelaide.

Smith M, Bullmore AJ, Cand MM & Davis R, ‘Mechanisms of amplitude modulation in wind turbine noise’, *Proceedings of Acoustics 2012*, Nantes, 23-27 April 2012

Søndergaard LS, ‘Noise from wind turbines under non-standard conditions’, *Proceedings of Internoise 2012*, New York, 19-22 August 2012.

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

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