APPLICATION OF THE AM METRICS – CASE STUDIES

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1 INTRODUCTION

This paper gives some examples of a potential amplitude modulation (AM) assessment using the three metrics proposed in the IOA AM discussion document[1]. Results are presented, discussing the analysis of noise measurements undertaken at a residential receptor location near a wind turbine site where operational and background noise periods were measured. Some of the issues involved are discussed. The objective of these metrics is a consistent quantification of the modulating character of the wind turbine related component of the noise, which can be implemented in a practical way.

Analysis was performed upon free-field noise measurements made in a garden area located approximately 500m from a single multi-megawatt wind turbine. Analysis was undertaken on the evening to night-time periods of 18:00 – 06:00 for twenty one consecutive nights. Every evening, the turbine was periodically shut-down from approximately 22:10 – 01:20, thereby providing some background noise periods.

The three methods used are as described in the IOA AM discussion document. Method 1 is a time-domain method based upon the approach first proposed in Fukushima et al[2], where here the $L_{Aeq,100ms}$ parameter is used in place of the L_{AFast} parameter, and results are obtained for each 10s period. Method 2 is a frequency domain method based upon the results from power spectral density functions of band-limited $L_{Aeq,100ms}$ data. Method 3 is a hybrid approach utilising audio filters centred around the fundamental and harmonics applied on the band-limited $L_{Aeq,100ms}$ data.

2 METHOD 2/3 ANALYSIS SETTINGS

2.1 Determining appropriate modulation frequency range

For the calculation of the Method 2 result (and Method 3 result), it is required that a suitable modulation frequency range is determined. The appropriate modulation frequency range should be related to the rotor speed range of the installed turbines. For example, if the turbines under analysis have an RPM range of 5 – 25 rpm, and are three-bladed, then it would be appropriate for the user to consider modulation frequency results within the approximate range 0.25 – 1.25 Hz. Experience suggests that it may be prudent to examine a slightly wider range than the exact rotor speed range, due to the integration step. Also, it is preferable to have slightly more false positive results that subsequently may need to be discarded following manual interrogation, rather than erroneously reject valid results. If it was desired to take account of turbines that are operating out-of-sync (where there may be blade passing from different turbines occurring out of phase), then the valid modulation frequency range could be expanded to take account of higher frequencies, e.g. up to the second harmonic frequency. Obviously, having access to the SCADA operational data is useful, and the acquisition of the RPM data for the noise survey is encouraged. In addition to the 10 minute average values, it may also be useful to acquire the rotor speed standard deviation for each 10 minute period, to allow further understanding of the potential variation within a 10 minute period. By concentrating on the modulation frequency range that sensibly relates to the blade passing frequency of the wind turbines under analysis, valid results of the modulation attributable to the wind farm can be determined.

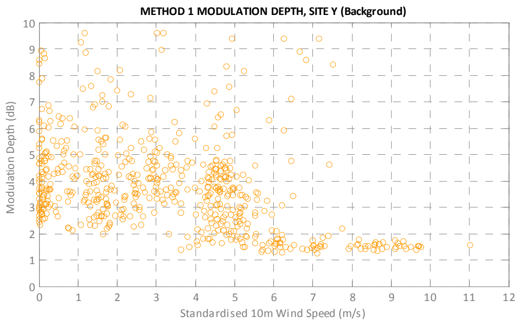
2.2 Determining appropriate analysis frequency range

For the purposes of Method 2 and Method 3, the appropriate acoustic frequency range should be determined. The default acoustic frequency range to examine is 100 – 400 Hz. Experience suggests 100 – 400 Hz is usually the range where the modulation from the wind farm is greatest. Nevertheless there may be scenarios where another range is more appropriate, e.g. turbines with particularly high rotational speeds or particularly close measurement locations. Within the IOA AM discussion document, an alternative option was to use the 200 – 800 Hz range. Here, both these frequency ranges are examined.

3 RESULTS

3.1 Before manual interrogation for spurious sources

Figure 1 below shows the modulation depth results from Method 1, for the background and operational periods of the evening and night-time periods of the three week survey. The results shown here are simply the results of the method being applied on the raw data, before any manual interrogation for the potential influence of spurious sources. The results are plotted against standardised 10m wind speed.



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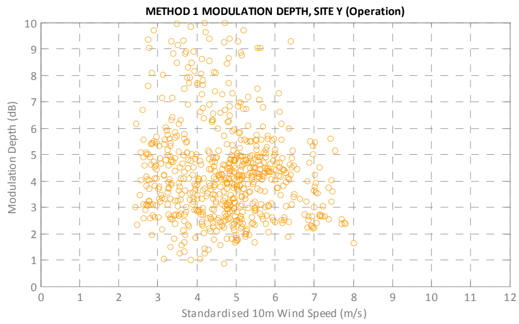

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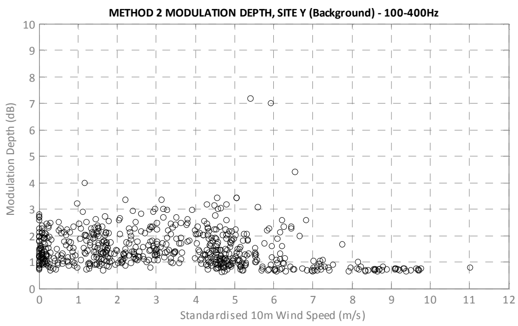
Figure 1: Method 1 – Modulation Depth vs Standardised 10m Wind Speed, a) background, b) operation

Figure 2 below shows the modulation depth results from Method 2 (100 – 400 Hz), for the background and operational periods of the evening and night-time periods of the three week survey, before any manual interrogation.



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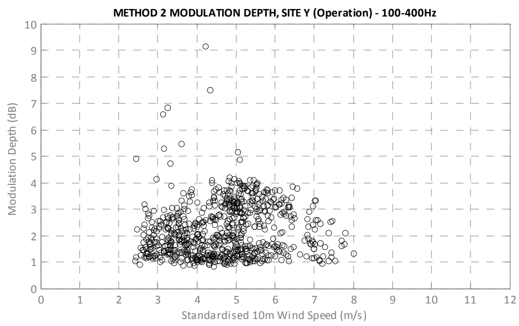

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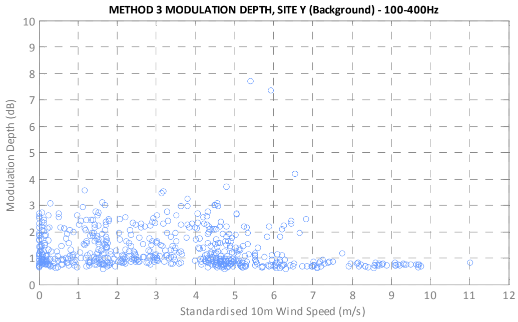
Figure 2: Method 2 (100 – 400 Hz) – Modulation Depth vs Standardised 10m Wind Speed, a) background, b) operation

Figure 3 below shows the modulation depth results from Method 3 (100 – 400 Hz), for the background and operational periods of the evening and night-time periods of the three week survey, before any manual interrogation.



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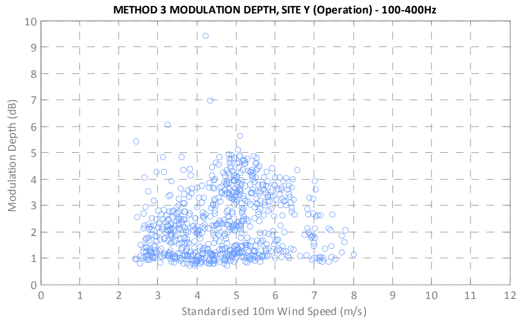

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Figure 3: Method 3 (100 – 400 Hz) – Modulation Depth vs Standardised 10m Wind Speed, a) background, b) operation

Figures 1 indicates that for Method 1, a similar range of raw results is obtained for the background and operational periods. The range present in the background plot indicates that Method 1 (at least without being band-limited) is quite susceptible to being triggered by spurious noise events not related to the wind farm. For Methods 2 and 3, the range for the operational dataset is largely greater than that for the background dataset, with Method 3 having a slightly larger dynamic range. The overlap between the operational and background raw datasets indicates that, although these methods are suitable for a semi-automated assessment, the methods are not flawless (i.e. they don't have 0% false positive rate) and that careful attention is required to ensure any results included in a final assessment are definitely attributable to the wind farm, and were not due to other sources that were present in the environment at the same time.

3.2 Interrogation of results – what to include/exclude?

3.2.1 Methods 2 and 3

Examination of the background periods shown within Figures 1a), 2a), 3b) suggest that the true noise floor of the methods, i.e. when nothing but vegetation noise (or constant noise of another source, e.g. distant road noise 'drone') is in the environment, is approximately 0.5 – 1.5 dB. For all results above approximately 1.5 dB, there were spurious noise events that were slightly triggering the methods. For this case study these were in the form of; overhead planes, pass-bys of individual vehicles on nearby roads, pigeons cooing, cows mooing, owls, a bird-scarer, doors shutting, and banging in a nearby workshop. Therefore due care needs to be taken that for the operational dataset, similar false positives are not included, especially if a dose type calculation is to be performed with the intention of quantifying the amount and degree of wind farm related modulation across a prolonged noise survey of several weeks.

It may be useful to undertake a simultaneous, or second-pass, analysis, where the maximum value across the full modulation frequency range of 0 – 5 Hz is calculated. Experience is suggesting that when spurious noise events occur, this usually results in a maximum value that is outside the RPM operational modulation frequency range. Therefore a useful test may be to check whether the valid result within the operational range is also the maximum value across the full spectrum, i.e. when there is turbine related modulation present, there is a peak in the spectrum within the operational range, and this is also the maximum across the full range. But if there is something else present that is modulating or varying to some degree, then the maximum across the full spectrum occurs outside the operational range, and it is likely inappropriate to take the result within the operational range.

However the converse is not always true, as it is possible that other noise sources in the environment may modulate or vary at a similar rate to the operational rotor speed range, and in the same acoustic frequency range. Therefore some interrogation of the results is always required.

Figure 4 below shows an example of a period partially influenced by an overhead plane. The first panel shows the modulation spectra from the band-limited result of Method 2, the second panel shows the modulation depth results from the three methods for each 10s block, the third panel shows the $L_{Aeq,100ms}$ parameter, the fourth panel shows a third octave spectrogram of the period. There is turbine related modulation present, peaking at around Block 10 or 13, but the results for Blocks 26 – 32 are due to the passing of an overhead plane. This is verified by listening to the audio, but is also indicated from the third octave spectrogram in the bottom panel, and is also shown by vertical lines in the modulation spectra waterfall plot in the upper panel, where a departure from the SCADA indicated modulation frequency is also apparent.

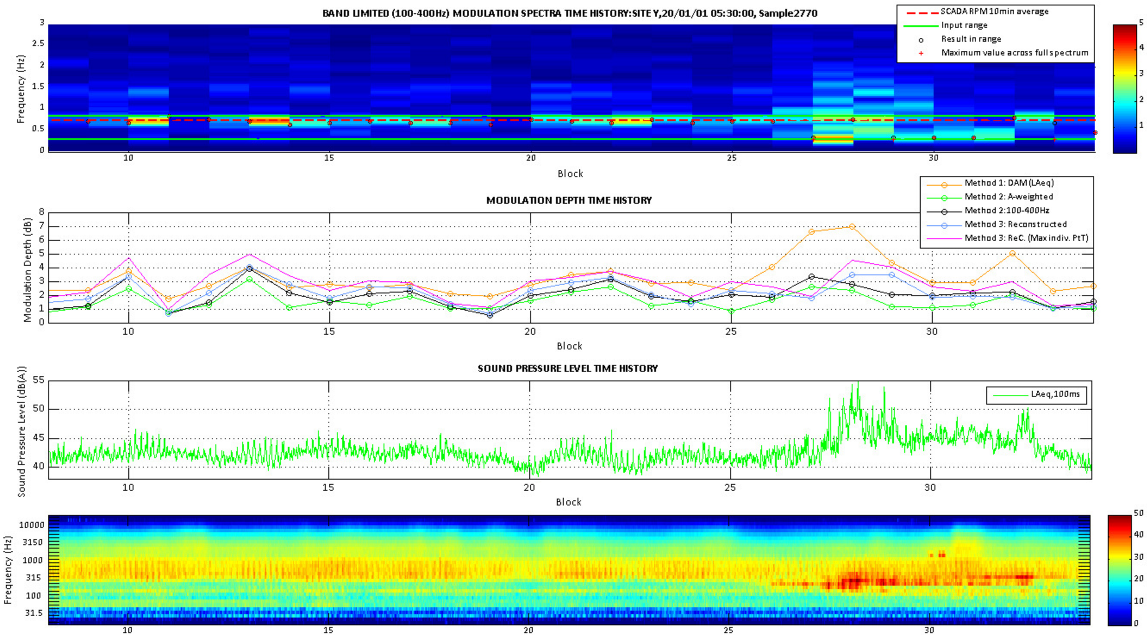


Figure 4: Example of period partially affected by an overhead plane

Figure 5 opposite shows the 10s modulation frequency spectrum from Method 2 of Block 13 in comparison to that from Block 27. This shows how the turbine related period has a peak in the spectrum that sensibly corresponds to the rotor speed indicated from the SCADA data for this 10 minute period. Whereas in comparison, the block affected by the plane is more broadband and has a peak that is almost outside the potential rotor speed range of the turbine under analysis.

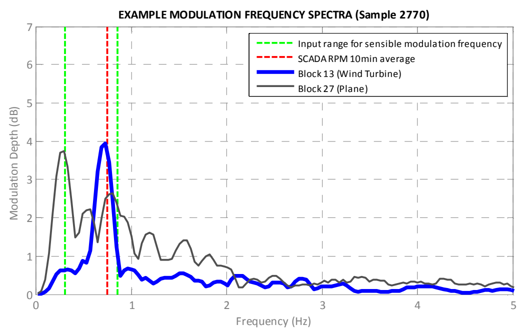


Figure 5: Modulation frequency spectra of a turbine affected period in comparison to a period affected by a plane

Figure 6 below shows a particularly complex example. This shows noise data over a 10 minute period, with the 10s modulation results from the three methods shown in the second panel. Blocks 1 – 12 are turbine related (indicated by the sensible peak modulation frequency and the harmonic content). Blocks 13 – 22 are influenced by a plane (indicated by the slightly non-sensible peak modulation frequency and the spectrogram). Blocks 23 – 33 are turbine related again. Blocks 34 – 43 are influenced by someone opening and shutting doors then driving off in a car (indicated by the vertical lines in the modulation spectra waterfall and the third octave spectrogram). Then Blocks 44 onwards are turbine related again.

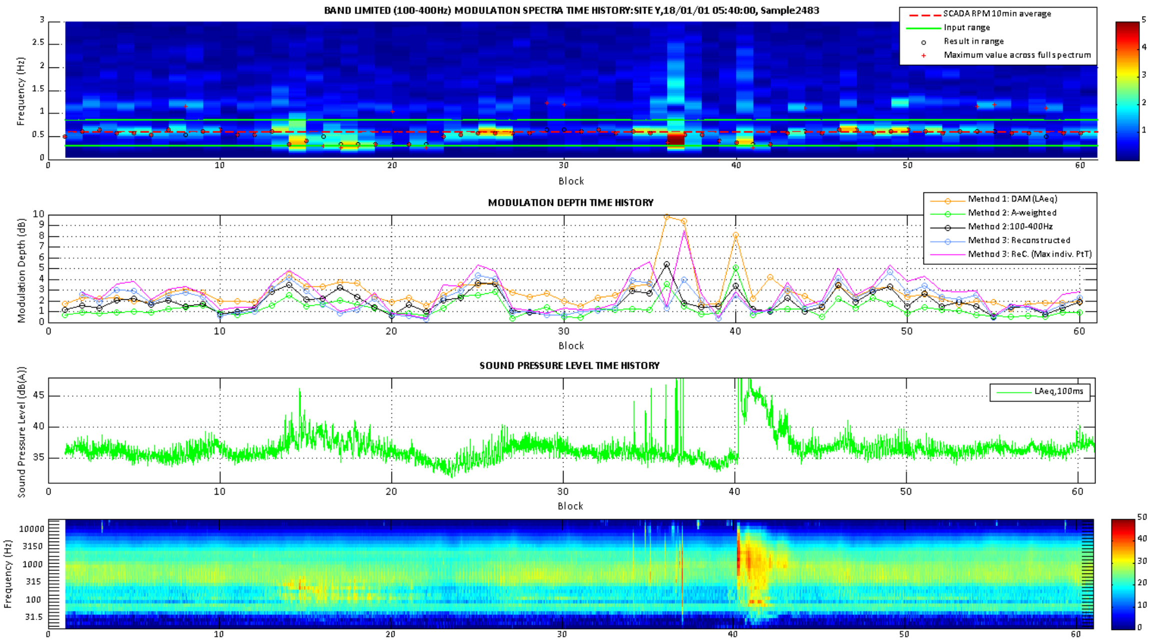


Figure 6: Example of 10s modulation results over a period of 10 minutes, with various noise sources influencing the results.

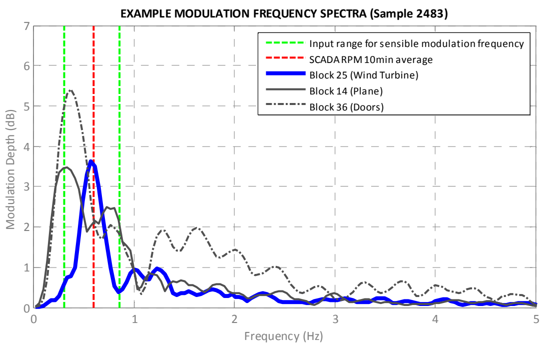


Figure 7 opposite shows the 10s modulation frequency spectrum from Method 2 of Block 25 (turbine) in comparison to that from Blocks 14 and 36. In a similar fashion to the example above, the blocks affected by sources other than the turbine are slightly more broadband, and have peak frequencies that do not correspond with the rotor speed indicated by the SCADA data.

Figure 7: Modulation frequency spectra of periods affected by various noise sources

Figure 8 below shows a relatively clean period of turbine related modulation. All the methods generally react sensibly to the different modulation depths apparent in the noise data shown in the bottom two panels (note that the 10s modulation depth values shown in the second panel are plotted at the beginning of the 10s period).

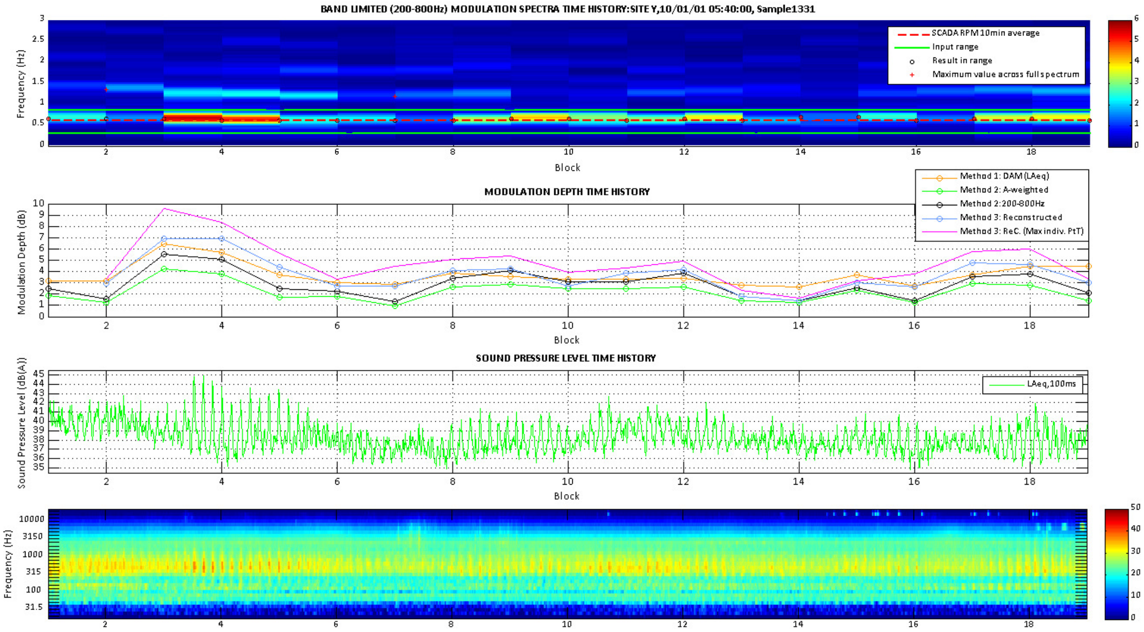


Figure 8: Example of 10s modulation results over a period of approximately 3 minutes, with relatively clear turbine related modulation of varying degree.

Figure 9 below shows the modulation depth results over a 3 hour period from the same morning. The second panel shows the 10 minute modulation depth values from the three methods. The turbine is not operating initially, but starts operating at about 01:20. This figure shows that Methods 2 and 3 have a relatively low noise floor when there is no turbine related modulation present (and in this instance when there are few other spurious noise sources), but do react when there is turbine related modulation present.

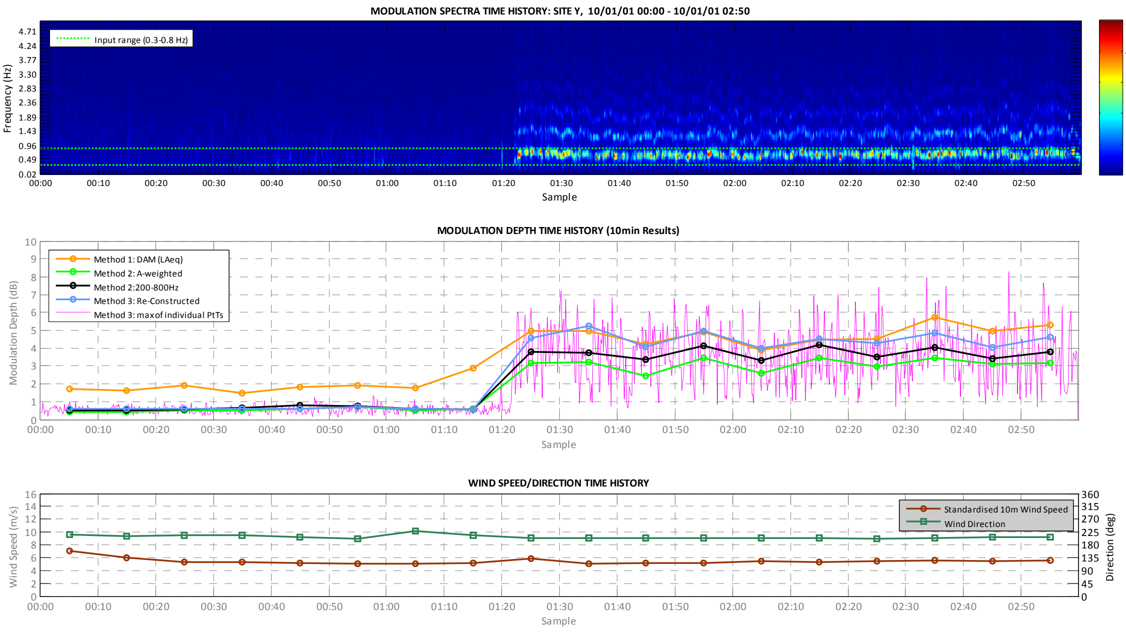


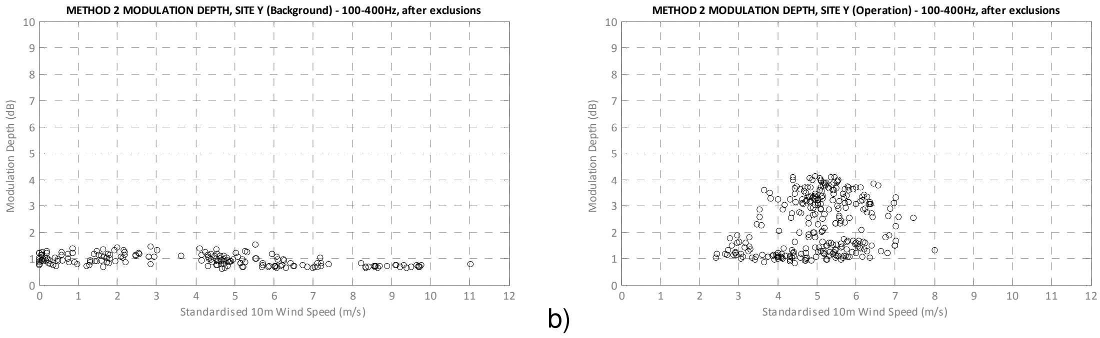
Figure 9: Modulation results over a period of 3 hours, during which the turbine begins to operate.

4 FINAL RESULTS

Results are shown below for Methods 2 and 3, after excluding periods where spurious noise sources were resulting in false positive results.

4.1 Method 2

Figure 11 below shows the 10 minute results for Method 2 as a function of standardised 10m wind speed, for the background and operational datasets. This figure shows Method 2 applied on the default frequency range of 100 – 400 Hz.

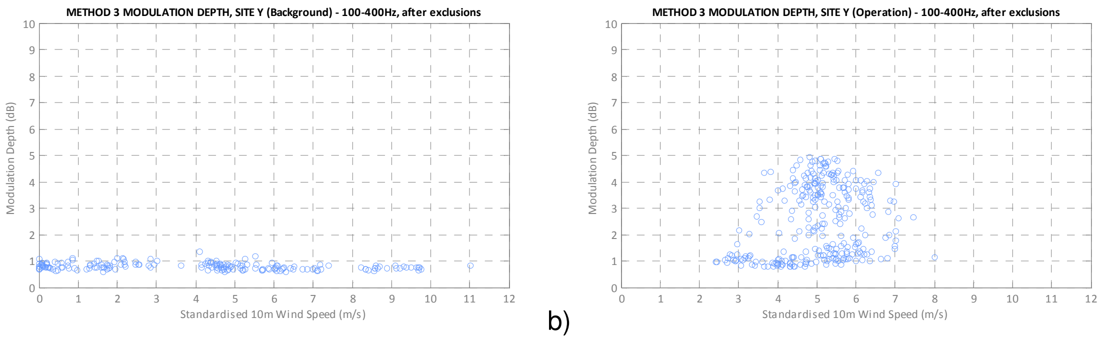


a) b)

Figure 11: Method 2 (100 – 400 Hz) – Modulation Depth vs Standardised 10m Wind Speed, after exclusions, a) background, b) operation

4.2 Method 3

Figure 12 below shows the 10 minute results for Method 3 as a function of standardised 10m wind speed, for the background and operational datasets. This figure shows Method 3 applied on the default frequency range of 100 – 400 Hz.



a) b)

Figure 12: Method 3 (100 – 400 Hz) – Modulation Depth vs Standardised 10m Wind Speed, after exclusions, a) background, b) operation

4.3 Other Analyses

It is notable that some scatter is seen within Figures 11b) and 12b) above. Upon examination of the data, it is apparent that some of the variation coincides with different wind directions. Figure 13 below plots the modulation depth of Method 3 with respect to wind direction.

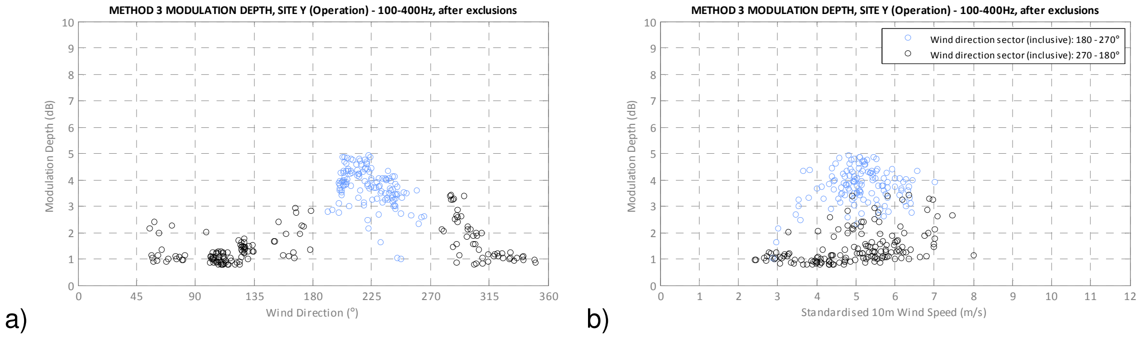


Figure 13: Method 3 (100 – 400 Hz) – Modulation Depth, a) vs Wind Direction, b) vs Standardised 10m Wind Speed for different Wind Direction Sectors

Figure 13 indicates that for this survey period and site, the higher periods of modulation were measured when the wind direction was in the sector 180 – 270 degrees. This is a wind direction where the receptor location is approximately upwind of the wind turbine (a wind direction of 56° would be directly downwind). This is also a direction when the measurement location is upwind of the nearby main roads. For an upwind wind direction there was less masking provided by road noise, and the modulation from the turbine was more observable.

One output from the Method 3 procedure is a 'cleaned' version of the time series, with reduced influence of extraneous noise whilst retaining the energy from the first three harmonics of the modulation frequency. This enables quantification of individual peak-to-trough values throughout a 10 minute period, and subsequent statistical measures of how such values are distributed. Figure 14 below shows the 10 minute results for Method 2 and 3 versus various statistical measures. The results are shown against; i) the maximum individual peak-to-trough value in a 10 minute period, ii) the 90th percentile of the peak-to-trough values in a 10 minute period, iii) the 50th percentile of the peak-to-trough values in a 10 minute period. The correlation coefficient value (R^2) is calculated between these statistical parameters and the standard 10 minute result proposed in the IOA AM discussion document.

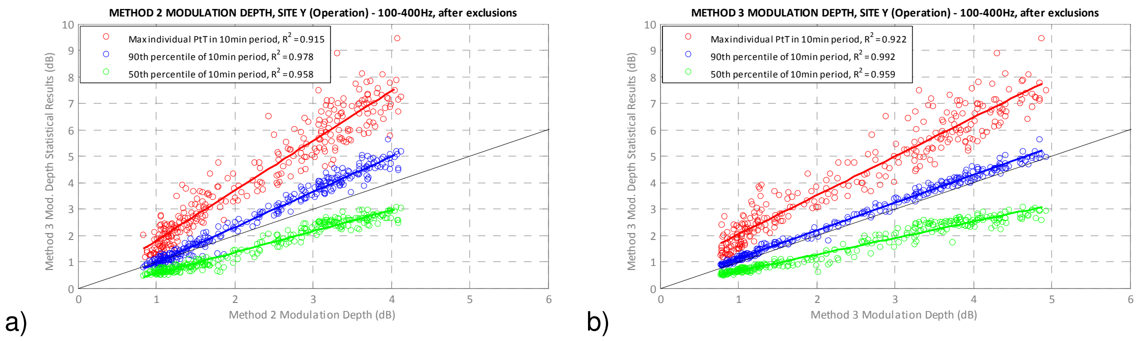
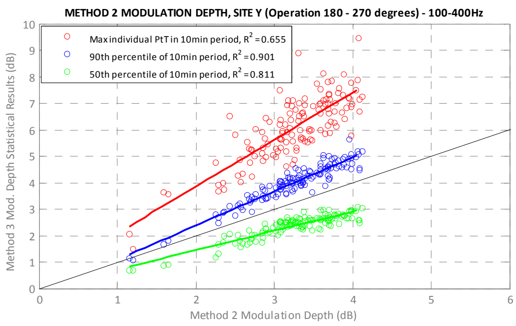


Figure 14: Method 2 & 3 (100 – 400 Hz) – Modulation Depth vs Method 3 Statistical Measures, a) Method 2, b) Method 3

These figures indicate that the proposed 10 minute measure for both methods is broadly correlated with the maximum individual peak-to-trough value within a 10 minute period. The correlation coefficient R^2 is greater than 0.9 for both methods, indicating that the methods' results would be related to, and broadly representative of, the worst periods of modulation, assuming that the acoustic frequency range is chosen appropriately. For instance, for this dataset a result of 4 – 5 dB for Method 3 is broadly representative of maximum individual peak-to-trough values of 5 – 10 dB, whereas a result of 2 – 3 dB is broadly representative of maximum individual peak-to-trough values of 3 – 7 dB. As expected, the methods are most correlated with the 90th percentile value.

Figure 15 below shows the 10 minute results for Method 2 and 3 versus the various statistical measures, for the wind direction sector 180 – 270 degrees, which is more dominated by turbine related noise. A similar relationship to that shown in Figure 14 is evident. The correlation coefficient reduces in this instance due to the omission of the majority of lower values, but a similar relationship is apparent. Some scatter is shown between the methods' results and the worst individual peak-to-trough value. However evidence towards the psycho-acoustic response to intermittent and non-constant modulation is somewhat lacking, and the question remains as to whether people respond specifically to the worst individual peak-to-trough event within a longer period. Nevertheless Methods 2 and 3 are broadly representative of the very worst values in a 10 minute period, and are correlated well with the worst 10% of each 10 minute period.



a)

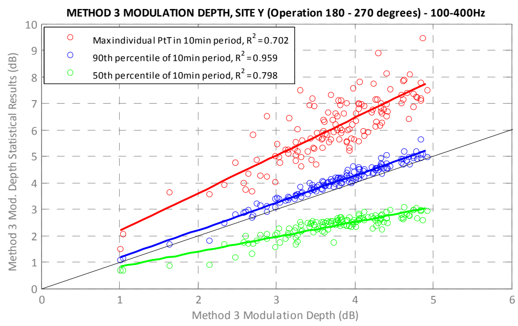


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Figure 15: Method 2 & 3 (100 – 400 Hz) – Modulation Depth vs Method 3 Statistical Measures (wind directions 180 – 270 degrees), a) Method 2, b) Method 3

5 CONCLUSIONS

Some examples of applying the proposed AM metrics on noise measurements taken at a residential receptor location near a wind turbine site have been undertaken. Analysis of both operational and background noise periods has been carried out.

Careful attention is required in ensuring that results are attributable to the wind farm development under analysis. This can be achieved by consideration of the modulation frequency spectra, the acoustic spectrogram, and listening to audio recordings.

Examination of the statistical measures resulting from the Method 3 time series gives broad indication that Methods 2 and 3 generally react to the worst periods of modulation present in a noise survey.

6 REFERENCES

1. Institute of Acoustics IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group Discussion Document. Methods for Rating Amplitude Modulation in Wind Turbine Noise: 22nd April 2015.

2. Fukushima, A., et al. 2013. "Study on the amplitude modulation of wind turbine noise: Part 1 – Physical investigation". Proceedings of Internoise 2013, Innsbruck.