An Approach to Compare Amplitude Modulation Depth and Penalty Schemes for Wind Farms

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Abstract - There is agreement among relevant wind farm standards and government guidelines that Amplitude Modulation (AM) from wind farms beyond a normal degree of fluctuation typical for horizontal axis wind turbines should have a special audible characteristic penalty applied. However, more than one method exists for establishing the level of AM depth and for determining the applied penalty. This presents a commonly occurring challenge, when methods of calculating AM depth and incompatible penalty schemes make their way into consent conditions and testing plans. The two schemes compared in this study were 1) New Zealand Standard NZS 6808:2010 (NZS6808), which provides an interim method to identify periods of excessive amplitude modulation depth and a fixed +5 dB penalty, if discovered; and 2) The UK Institute of Acoustics (IoA) Amplitude Modulation Working Group (AMWG) method described in *Final Report – A Method for Rating Amplitude Modulation in Wind Turbine Noise Version 1* (2016).

A novel method to compare the schemes was developed where the analytically superior AMWG algorithm was run over the reference noise metrics described in NZS6808 interim method (one-third octave bands and overall level) and then a linear regression of these results compared against the AM depth results from a strict AMWG interpretation using the relevant frequency band (100 Hz - 400 Hz).

Analysis of monitoring data of an operating wind farm for the purposes of this study found that an AMWG method AM depth of approximately 4.4 dB was equivalent to the interim method and penalty described in NZS 6808. The methodology of the assessment and obtained outcomes, along with implications on wind farm projects is detailed in this study.

1 INTRODUCTION

Amplitude modulation (AM) from wind farms refers to the regularly fluctuating sound level generated by the wind turbines. The modulation occurs due to the periodic changes in the intensity of the noise (loudness), typically occurring at the blade pass frequency. All horizontal axis wind turbines exhibit normal AM blade ‘swish’. There are times when the AM is more pronounced typically due to the blade entering transient stall conditions during high wind shear atmospheres. This is often referred to as ‘Other AM’ (OAM) (Renewable UK, 2016) or ‘Excessive AM’ (EAM).

The transition point between normal AM and OAM is generally considered the point at which annoyance from the special noise character is significant enough to warrant an AM penalty to be applied.

New Zealand Standard NZS 6808:2010 *Acoustics – Wind farm noise*, provides an ‘interim test method’ in Appendix B3.1 to evaluate AM (Standards New Zealand, 2010). The interim method relies on reviewing 1/3rd octave and overall time series noise data and if the peak to trough (analogous to AM depth) criteria are regularly met, a fixed penalty of 5 dB is applied. In practice, this is not a practical approach for large datasets. This is particularly the case as post-construction measurements of wind farms typically require months' worth of continuous monitoring which can generate significant datasets.

The UK Institute of Acoustics (IOA) Amplitude Modulation Working Group (AMWG) released "*A Method for Rating Amplitude Modulation in Wind Turbine Noise*" (AMWG report) (AMWG, 2016). It provides a robust analytical method and executable code to determine the blade pass associated AM depth of large sets of recorded data. The AMWG method has been broadly adopted as the industry best practice method to determine wind farm related AM depth levels. Whilst it is an effective (albeit sensitive) method for determining the depth of wind farm related AM for large datasets, the AMWG report does not provide any guidance on which penalties should apply.

In the UK an AM penalty scheme was developed and documented in the 2016 report *"Wind Turbine AM Review - Phase 2 Report"* (UK Phase 2 report) (DECC, 2016). The report outlines a sliding scale penalty scheme, in which the penalty is scaled with increasing level of AM rating (modulation depth).

The AMWG method has been widely adopted as best practice with many consent conditions or Noise Compliance Test Plans (NCTP) adopting it to determine AM depth. However, a conflict often occurs where the conditions or NCTP require the use of an objective method to determine the AM penalty, whilst referencing the AMWG method and the UK Phase 2 report as well as specifying a fixed +5 dB penalty be applied to be consistent with NZS6808 . The conflict arises due to the NZS6808 fixed +5 dB penalty and the sliding scale penalty scheme of the UK Phase 2 report. Furthermore, since the AM analysis methods of the AMWG and NZS6808 are different, they are not directly comparable.

This study presents an approach that is compatible with both the AMWG method and NZS6808 penalty scheme and provides an equivalency threshold for the penalty. Data collected from a wind farm in Victoria has been used to determine the equivalency for this particular case.

2 AMPLITUDE MODULATION DEPTH ANALYSIS PROCEDURE

2.1 New Zealand NZS 6808:2010

Appendix B3.1 of NZS6808:2010 Standard (NZS) outlines that some amplitude modulation character is typical of all wind farm operations, although not always present at greater distances from the wind farm. However, where amplitude modulation is significant, being a 'greater than the normal degree of fluctuation as a function of blade passing frequency', then a special audible characteristic penalty should be applicable for the conditions under which it occurs. In order to facilitate such an assessment, the Standard includes an interim test method (ITM) as reproduced below:

> In making an assessment under B3.1, 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.

The proposed NZS6808 ITM relies on evaluating time series sound pressure data to evaluate the regularly varying peak to trough noise levels (which is analogous to modulation depth) as attributed to blade pass frequency.

Where either of the conditions are applicable, a penalty should be applied as per Appendix B4 of the Standard which defines the penalty adjustment applicable for amplitude modulation to be +5 dB.In practice it is not possible to deploy the ITM to screen large datasets as:

1. The terminology '*regularly varying basis'* is too subjective and provides no context or statistical means of determination;

2. The ambient environment alone (in the absence of wind farm noise) can often cause greater variance in noise levels than the test requires; and

3. There is no reliable means of identifying blade pass associated modulation.

2.2 United Kingdom

The IOA AMWG developed an analysis reference method which offers a robust way to identify periods of AM within any 10-minute timeframe, allowing for a specific AM rating level to be calculated for that period. The reference method enables the detection of wind turbine AM while minimizing the influence of non-wind turbine sources by focusing on modulation frequencies corresponding to the blade passing frequencies of the turbines being studied and in the relevant frequency bands.

The reference method utilises a frequency domain signal analysis technique because of the ability of such a method to discriminate more objectively between fluctuations in noise levels resulting from wind turbine AM (which has a periodic characteristic related to the turbine rotational speed) and fluctuations resulting from other variable environmental noise sources (such as birdsong).

Section 4.3 - *Input Data* of the reference method notes the analysis should be conducted on A-weighted, band-filtered 100 ms Leq values. The analysis should be done for the following frequency bands:

- 50 to 200 Hz
- 100 to 400 Hz
- 200 to 800 Hz

The specific range chosen is the one which tends to give the highest modulation values of a representative range of valid data. This is evaluated by plotting a sample of the valid data as a scatter plot with the reference 100-400 Hz range values as the x-axis. This was conducted on one month’s data at a sample location of the subject wind farm and shown in Figure 1.

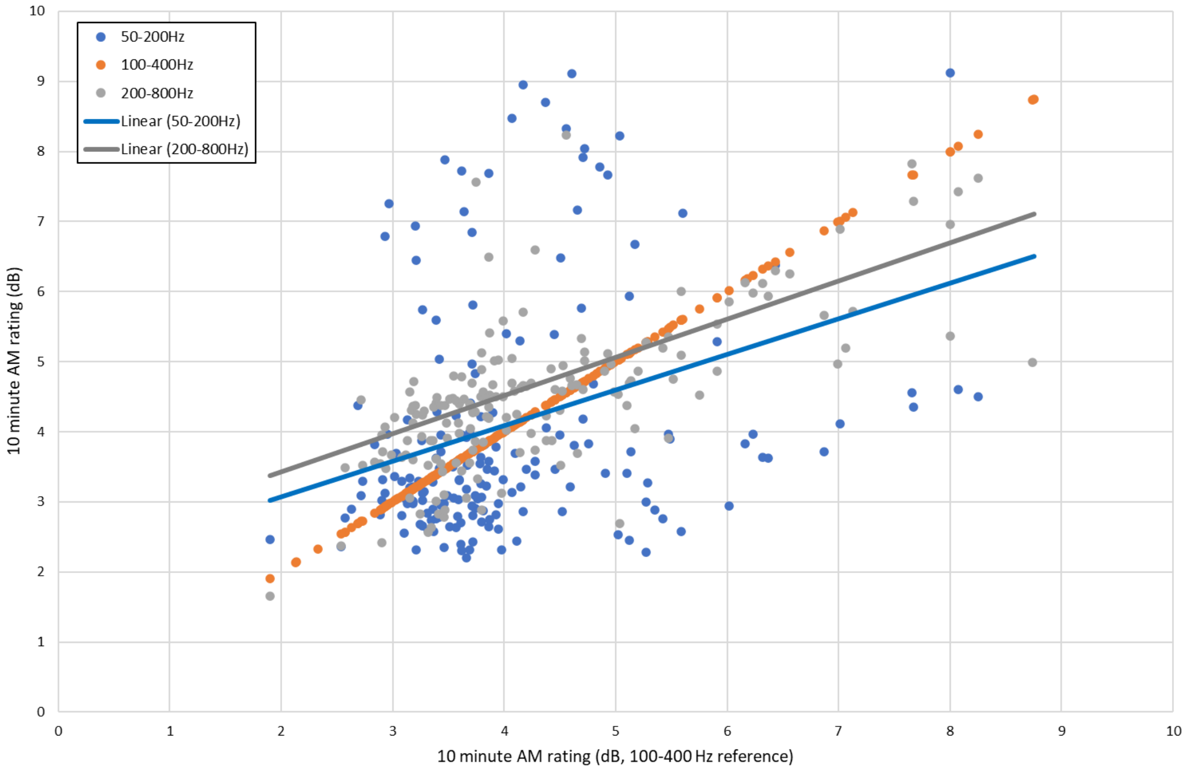

Figure 1 – Scatter plot of modulation values of three frequency ranges to evaluate highest representative range

Figure 1 did not show as clear a result as the example provided in the AMWG report, but it was deemed that the 100 - 400 Hz was the most appropriate for analysis, especially considering the limitations of the lower and higher frequency ranges.

The reference AWMG method and its accompanying programming code is used to establish an AM rating for each 10-minute interval of data. The AMWG report does not provide any AM rating of acceptability or assessment penalty scheme recommendations.

In the UK an AM penalty scheme was developed and documented in the 2016 report *"Wind Turbine AM Review - Phase 2 Report".* The report outlines a sliding scale penalty scheme, in which the penalty is scaled between a value of 3 dB and 5 dB with increasing level of AM rating (modulation depth), starting at modulation depth of 3 dB and extending to a modulation depth of 10 dB, refer to the extract from the Phase 2 report in Figure 2.

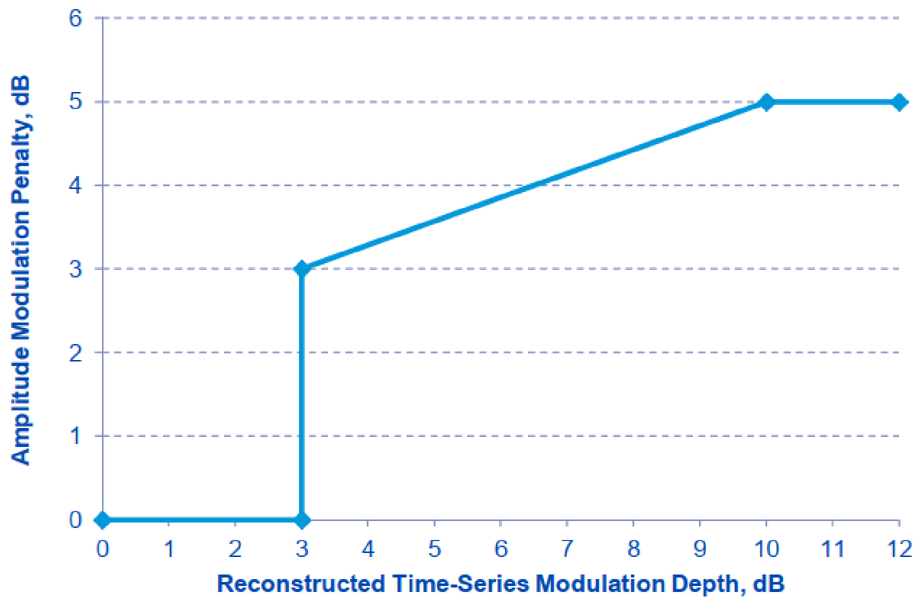

Figure 2 - Phase 2 report – AM Penalty Scheme

3 APPROPRIATE IOA AMWG DEPTH

The objective of this investigation was to determine an UK IOA AMWG reference method AM modulation depth that is equivalent to the NZS6808 ITM metrics. This is necessary as even as both methodologies are broadly similar (evaluating peak to trough or modulation depth), they use slightly different metrics (NZS6808 uses the overall dBA level as well as individual 1/3 octave levels, whereas AMWG reference method uses a low frequency band e.g. 100-400 Hz).

The investigation is summarised as follows:

- Select site where more significant time periods have had an identifiable AM rating using UK IOA AMWG reference method (100-400 Hz band).
- Use "valid data" periods only (e.g. all relevant WTGs operating, no insects/frogs etc).
- Modify UK IOA AMWG reference method inputs (100ms SPL trace) to separately evaluate:
    - AM of the Overall Leq level,
    - AM of each individual 1/3 Octave band (between 100 to 400 Hz), select the 1/3 octave band that yields the maximum modulation depth,
- Pair data points, plot and evaluate a best fit linear regression to compare the following:
    - Modified UK IOA AMWG overall Leq level with standard UK IOA AMWG reference method inputs (100-400 Hz band),
    - Modified UK IOA AMWG maximum 1/3rd octave band level with standard UK IOA AMWG reference method inputs (100-400 Hz band)
- Determine what value of UK IOA AMWG reference method (100-400 Hz band) AM depth provides 'equivalent' NZS6808 metrics.

The paired data for the NZS6808 ITM Overall Level against the UK IOA AMWG reference method (100-400Hz) is presented in Figure 3.

The paired data for the NZS6808 ITM maximum 1/3 Octave band against the UK IOA AMWG reference method (100-400Hz) is presented in Figure 4.

The regression analysis of the data sets provides for the UK IOA AMWG reference method equivalent values as shown in Table 1.

Table 1 Modulation Depth Equivalency - NZS6808 ITM vs UK AMWG Modified Method

Metric	Modulation Depth, dB	
	NZS6808:2010	UK IOA AMWG Modified Method with NZS6808:2010 Inputs
Overall Leq Level	5	5.1
Maximum 1/3rd Octave Level	6	4.4

Based on extensive audio listening tests of the results, the maximum 1/3rd octave metric is less susceptible than the overall noise level to extraneous noise such as birds, sheep bleating, successive cars passing and wind on microphone. Likewise, the maximum 1/3rd octave is more similar to the 100-400Hz band noise level than the overall noise level which comprises noise from 12.5 Hz to 20kHz. Given the NZS6808 method provides the option to choose either the 1/3rd octave noise level or the overall noise level, the maximum 1/3rd metric is considered superior and therefore used for assessing the equivalency.

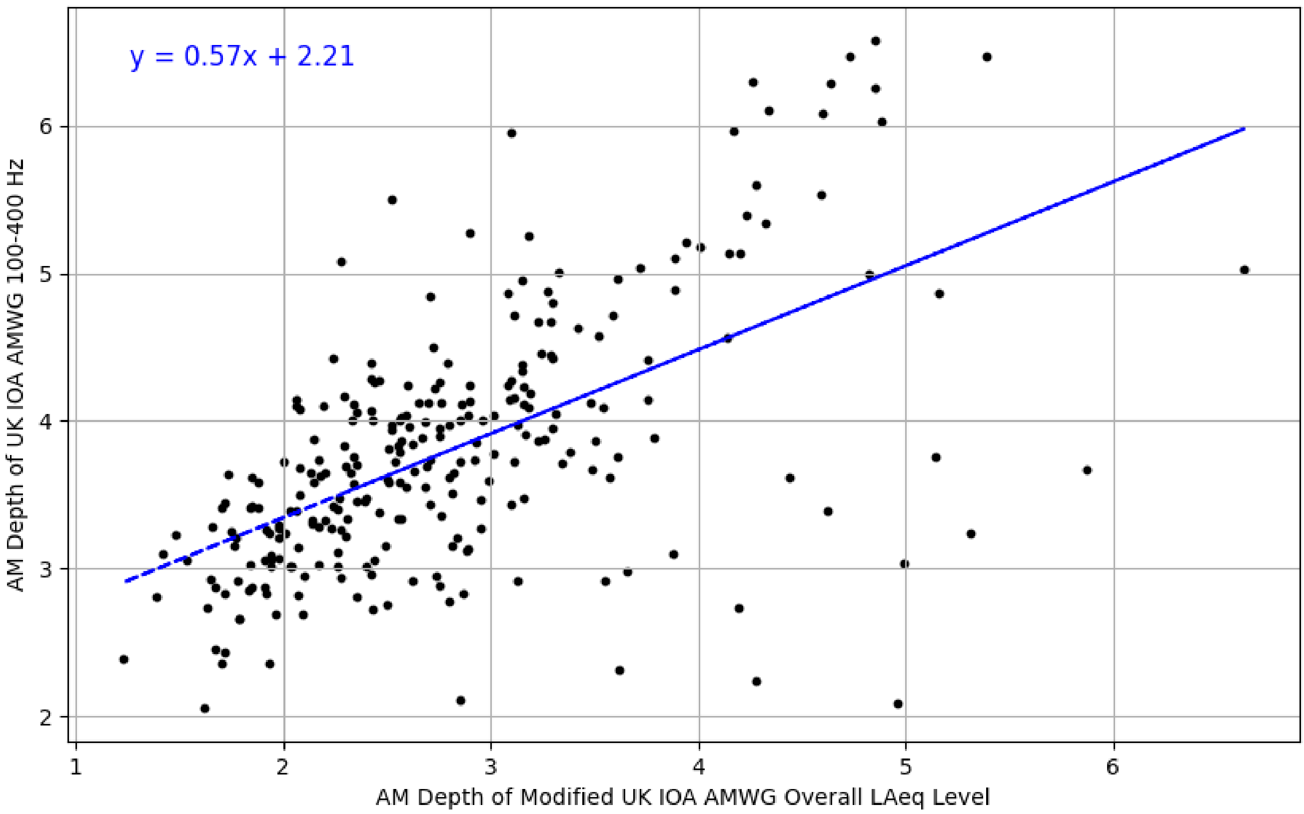

Figure 3 –NZS6808 ITM Overall Level versus UK IOA AMWG reference method (100-400Hz)

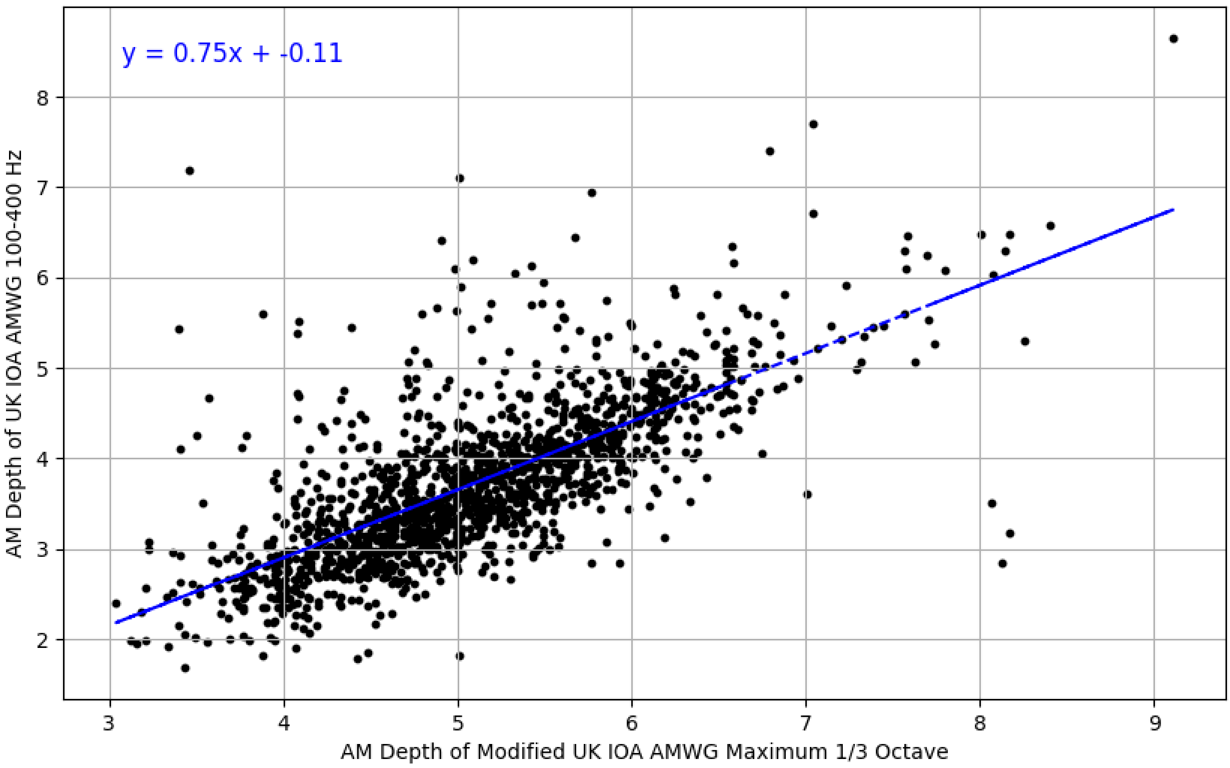

Figure 4 NZS6808 ITM Maximum 1/3 Octave band against the UK IOA AMWG reference method (100-400Hz)

4 AM PENALTY INVESTIGATION EQUIVALENCY SUMMARY

Comparing the UK IOA AMWG reference method (100Hz-400Hz) with the modified AMWG method (incorporating NZS6808 ITM as inputs) shows a modulation depth of 4.4 dB is equivalent to the NZS6808 ITM conditions at which a +5 dB penalty would be applicable as per NZS6808.

This ITM equivalent penalty is compared to the UK Phase 2 report sliding penalty scheme as shown in Figure 5.

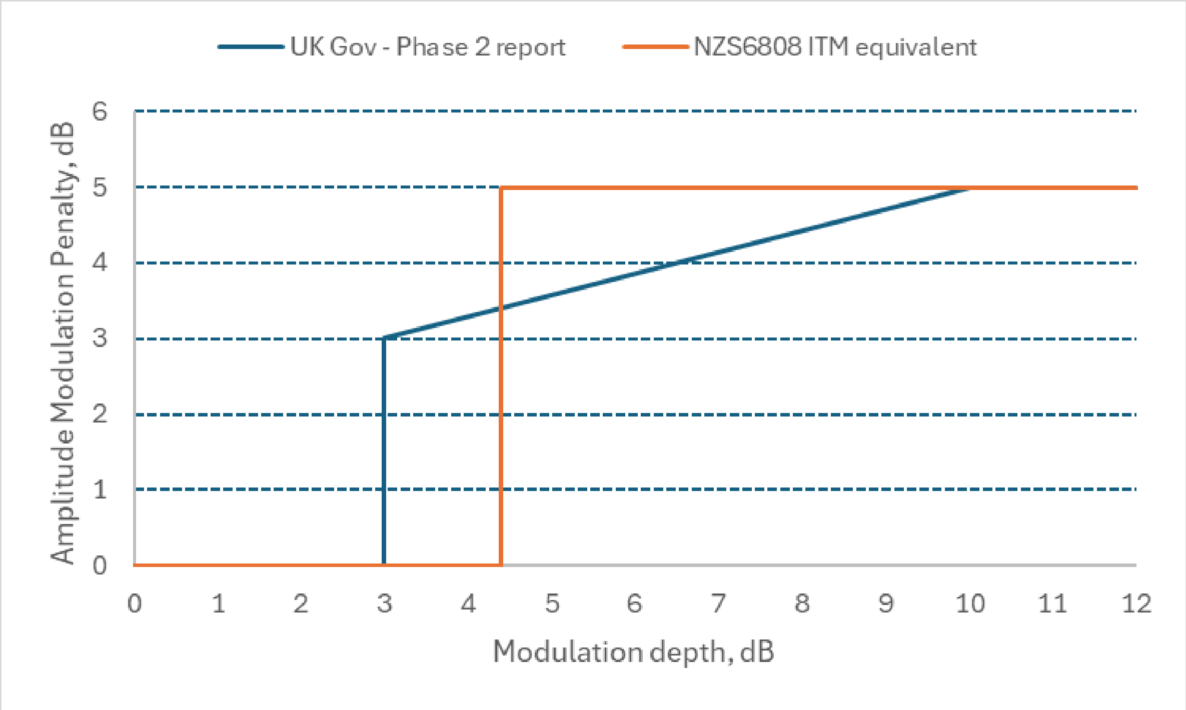

Figure 5 Comparison of AM penalty schemes

In summary, the investigation determined that for monitoring intervals where AM was calculated by the UK IOA AMWG reference method (100Hz-400Hz) with a modulation depth of 4.4 dB or greater, a +5 dB penalty is to apply and is considered to be OAM.

It is important to note that the equivalent modulation depth of 4.4 dB may be specific to the site and the monitoring data collected. It is possible that if this analysis were to be conducted at different location or different monitoring campaigns, then a marginally different equivalency value may result. Further research might analyse additional wind farm monitoring data at multiple locations, times, and multiple different wind farms to assess the variability in AM equivalency values.

5 AM PENALTY FURTHER CONTEXT

5.1 SA EPA Wind Farms

The South Australian EPA Wind farms environmental noise guidelines (released in 2009 and updated in 2021) provides the assessment methodology that is to apply to wind farm regulation in South Australia. Furthermore, the guideline is also adopted for all wind energy projects in NSW (EPA, 2021).

Section 4.7 of the guideline addresses Annoying Characteristics, and provides the following further information in relation to amplitude modulation.

The Institute of Acoustics of UK has published a method for rating amplitude modulation in WTG noise (2016). This method is endorsed by the EPA to assess wind turbine amplitude modulation. At this point no penalty mechanism is associated for this method of assessment. It has been noted that a 3-5dB peak to trough is typically observed for a standard WTG operation. If amplitude modulation depth higher than this is detected, the source of this increased depth should be investigated and rectified.

It essentially endorses the IOA AMWG reference method for the rating of AM, and whilst it doesn't specifically outline a penalty scheme, it states that '3 dB to 5 dB peak to trough is typically observed for standard WTG operation'. Where modulation depth is higher than this, e.g. it is greater than 5 dB, the source of the AM should be investigated and rectified.

This is compatible with the NZS6808 ITM equivalent AM Penalty scheme outlined in Section 3.

5.2 IEC TS 61400-11-2:2024

This recently released international standard '*presents measurement procedures, that enable the sound characteristics of a wind turbine to be determined at receptor (immission) locations. This involves using measurement methods appropriate to sound immission assessment at far-field locations of a wind turbine or wind farm*' (IEC, 2024).

For AM it specifies a detailed analysis method that is analogous to the IOA AMWG reference method. In informative Annex A which addresses the rating of sound characteristics it includes the following.

> A level of modulation depth greater than 5 dB is considered not acceptable and measures should be taken to reduce Amplitude Modulation.

This is compatible with the NZS6808 ITM equivalent AM Penalty scheme outlined in Section 3.

6 CONCLUSION

This study has presented an approach to reconcile the amplitude modulation (AM) penalty methods outlined in New Zealand Standard NZS 6808:2010 ITM and the UK government commissioned Phase 2 report. By conducting an equivalency analysis between the NZS6808 ITM and UK IOA AMWG reference method, it was determined that a modulation depth of 4.4 dB as calculated by the AMWG method is approximately equivalent to the 5 dB penalty threshold outlined in NZS6808. This provides a practical solution for applying both standards when assessing wind turbine noise compliance.

The equivalency established in this study offers a foundation for ensuring consistent regulatory compliance, particularly where consent conditions reference both NZS6808 and UK Phase 2 report methods. However, it is important to acknowledge that the equivalency value may be dataset specific. The modulation depth threshold could vary based on the characteristics of different wind farm locations, the specific conditions during monitoring, and the configuration of the wind turbines.

Further research should focus on analysing additional datasets across a range of wind farms and conditions to validate the robustness of the 4.4 dB threshold. This would enhance the confidence in applying the equivalency method more broadly and provide greater insight into the variability of AM characteristics across different environments.

REFERENCES

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