COMPARISON OF DIFFERING AMPLITUDE MODULATION METHODOLOGIES USING TEST CASES AND MEASUREMENTS

Krispian Lowe   RWE Renewables UK Limited, Swindon, Wiltshire, UK

1 ABSTRACT

Amplitude Modulation (AM) Rating can be determined from a variety of methods using time domain (e.g. Tachibana, Den Brook), frequency (e.g. RenewableUK) or a hybrid method (e.g. IOA AM Method, IEC TS 61400-11-2). This paper investigates the different methods using test cases to compare these methods. The test cases investigate the AM frequency range, AM level, spectral range, underlying sound pressure level, introduction of random noise and variation of the AM signal. This analysis will indicate the sensitivity of each method to different introduced effects. The real-world example, in the subsequent presentation, will examine the level of AM from a wind farm and compare the conditions where AM is detected and is not detected.

The Den Brook method can produce a Rating level irrespective if the input signal is modulated or not. Tachibana et al Rating method can produce a value with fewer false positives, but cannot definitively determine if the signal is modulated. The IOA/IEC AM method can determine the modulation frequency and the rating level. When a random signal is introduced a rating level can still be determined, albeit with greater range of AM Ratings over the 10-minute period. The RenewableUK (RUK) method can determine the AM rating level and modulation frequency, but can produce false positives for AM signals from high frequencies (e.g. birds). Both the IOA/IEC and RUK methods produce the lowest level of false positives, however, it is limited for turbines with RPM greater than 5.

2 INTRODUCTION AND METHODOLOGY

A noise complaint from a wind farm can be instigated by one or more of these factors such as, but not limited to, the character of the sound, sound level and/or non-acoustic factors. The character of AM can be described as “swish”, “whoomph” or “thump” [iv], but may only be observed under specific conditions. It is important for a noise log or diary[i] to be kept by the resident, so that the investigating party can determine the weather and wind farm operating conditions[ii] that led to the complaint. Therefore, it is important to have a robust AM Rating method that can determine: (a) if the complaint log matches periods of AM, (b) when AM occurs outside periods of the complaint log, and (c) when AM does not occur.

AM Rating methods range from time domain: Den Brook condition[viii] and Tachibana et al method[iii,ix], frequency domain: RUK condition[iv] based upon the OAM research[v], or a hybrid method for the Institute of Acoustics (IOA) Amplitude Modulation Working Group (AMWG)[ix], which was adapted into IEC TS 61400-11-2:2024[vi]. The Author has not investigated the AM methodology in “Noise Effects of the use of land-based wind energy” report for the German Environment Agency[vii].

This paper uses generated AM signals, and the signal analysis was conducted in MATLAB. The rating method that is calculated is prior to any character correction. The input test signal is based upon the source level with a set amplitude modulation with an addition of background noise. The sound pressure level, $L_{\mathrm{source},i,j}$, for unit time, *i*, and frequency, j, of the source and is dependent on the level of amplitude modulation, A, from peak to trough, R is the rpm of the turbine, $t_i$is the time in seconds, $S_{i,j}$ is the is the general underlying sound pressure level for the source per unit frequency, *j*.

$$L_{\mathrm{source},i,j} = \frac{A}{2}\sin\left[\frac{R\pi t_i}{10}\right] + \mathrm{S}_j \qquad \text{Equation 1}$$

The ambient level, $L_{\mathrm{ambient},i,j}$, per unit time and per frequency is the logarithmic addition of the source level with a with the background level, $L_{\mathrm{background},i,j}$, per unit time and per unit frequency. The relative level is only required, owing to the analysis of the AM signal is the variation in the signal, hence the terms for ground attenuation, atmospheric and geometric divergence are not included.

$$L_{\text{ambient},i,j} = 10\ \log_{10}\left[10^{0.1L_{\text{Source},i,j}} + 10^{0.1L_{\text{background},i,j}}\right] \qquad \text{Equation 2}$$

The resulting $L_{\text{ambient},i,j}$ sound level world be representative level of the signal received at a receptor, and is summed for the respective frequency band, 1 to *n*, per unit time:

$$L_{\text{ambient},i} = 10\ \log_{10}\left[\sum_{j=1}^{n} 10^{0.1L_{\text{ambient},i,j}}\right] \qquad \text{Equation 3}$$

The ambient level per unit time is used in each AM rating method. All results shall be in units of dB.

2.1 AM Rating Methodologies

The AM methodologies used in these analyses and to provide a highlight of the advantages, limitations and interpretations of each method. An AM method can be time domain, frequency domain or a hybrid of both domains. A time domain is the sound pressure level change with time (seconds), whilst frequency domain converts a time domain signal, using a Fast Fourier Transform (FFT), to represent sound pressure level per unit frequency (Hz). A hybrid method converts a time domain signal to a frequency domain signal, then extracts the periodic feature, and converts back to the time domain.

2.1.1 Den Brook (Time Domain)

The Den Brook planning consent[viii], condition 20. The following steps are indicated for determining a *"greater than expected Amplitude Modulation"*:

a) log $L_{Aeq,125ms}$, and if that level changes more than 3 dB within a 2 second period;
b) if this change (a) occurs 5 or more times in 1 minute, and if the $L_{Aeq,1minute}$ is greater than or equal to 28 dB L_{Aeq}, and
c) if the changes (a) and (b) above occur for 6 minutes or more in an hour period.

In this paper the 28 dB L_{Aeq} threshold is ignored, assumed non-consecutive time periods for (b) and (c), the assessment period is 60 minutes, assumed that the rating level is the arithmetic average of the largest peak-to-trough value for the top 6 1-minute values, and the variation of the Rating level is the standard deviation of the top 6 1-minute values.

2.1.2 Tachibana (Time Domain)

The Tachibana et al method, has been taken from the proceedings for internoise[iii] and methodology described in the IOA AMWG AM report[ix].

This method requires:

a) the measurement of instantaneous sound pressure levels with fast and slow weighting with a sample rate of 100 ms,
b) The difference in sound pressure levels is calculated by subtracting slow-weighting levels from the fast-weighting levels,
c) The difference levels for each 10 second period is determined[1].
d) The calculation of the modulation is from the subtraction of the 95th percent level from the 5th percentile level.

The assumed a total assessment period of 10 minutes with the final rating level as the 90th percentile from each 10 second period, and the variation of the Rating level is the 90th percentile minus the 10th percentile level.

2.1.3 RenewablesUK (Frequency Domain)

The method to determine the amplitude modulation is described in the RenewablesUK research on Other Amplitude modulation (OAM)[v]. The method given in the example planning conditions is as follows[iv]:

a) Measure $L_{Aeq,100ms}$ for each consecutive 10 second period.
b) Fit a 5th order polynomial to (a) and subtract from (a)
c) Perform an FFT and calculate the Power Special Density (PSD).

---

[1] The authors of Tachibana et al[iii] used an average period of 3 minutes, however, it is suggested to use 10 seconds in the IOA Rating Method Report[ix].

d) Determine if a peak within the spectrum. If no peak, set the amplitude to 0.
e) Calculate the energy of the peak, E_c, for the following band of 0.9 to 1.1 of the BPF.
f) Determine the amplitude by $2\sqrt{2\,\Delta f\,E_c}$.
g) For the 10-minute period, determine the arithmetic mean of the 12 highest levels of amplitude[2].
h) If the 10-minute amplitude value is greater than 0 dB, the modulation frequency matches the BPF of the turbine, and there are no extraneous sources of noise, the values is kept and used to correlate with wind speed.

It is assumed that the standard deviation of the 12 highest levels is the variation in the rating level.

2.1.4 IOA AM Rating Method (Hybrid)

The Institute of Acoustics (IOA) Amplitude Modulation Working Group (AMWG) further developed in defining an AM metric[ix]. The method is:

a) Measure $L_{Aeq,100ms}$ for each consecutive 10 second period in 1/3 octaves,
b) Determine three bands, 50 Hz to 200 Hz, 100 Hz to 400 Hz and 200 Hz to 800 Hz, and for each band:
c) Fit a 3rd order polynomial to (b) and subtract it from (b) for each band,
d) Perform an FFT and calculate the power spectrum for each band,
e) Identify the maximum peak in the valid BPF range, and if it has a prominence value greater than 4. If does not discard the 10 second period.
f) Determine if the 2nd and 3rd harmonic should be included, if the amplitude, filtered for the fundamental frequency, of the inverse-FFT is >1.5 dB, and if the amplitude of each of the 2nd and 3rd harmonics is >1.5 dB.
g) Perform the inverse-FFT for the fundamental and include harmonics, if appropriate, and calculate the 95th percentile minus the 5th percentile.
h) Aggregate the 10 second results for the 10-minute period. If there are 30 or greater valid values, calculate the 90th percentile value from the 10-second periods. If there are less than 30 valid values, discard the 10-minute period.
i) Plot the 100 to 400 Hz band against the 50 to 200 Hz, 100 to 400 Hz and 200 to 800 Hz bands.

In this paper we have assumed that the 90th percentile minus the 10th percentile of the aggregated results indicates the variation of the rating level for that 10-minute people.

2.1.5 IEC 61400-11-2 (Hybrid)

The method is similar to the IOA AM rating method, but with the following changes:

a) the greatest AM Rating from the 3 bands is chosen,
b) this value is binned into wind speed and wind direction bins, and
c) the arithmetic mean and uncertainty determined.

2.2 Test Signals

2.2.1 Simple Test

To test each AM Methodologies the following example signals are used and shown in Figure 2-1:

1. No variation with time, $A = 0$, e.g. flat.
2. Simple Amplitude Modulation of a $A = 4$ with an RPM of 10.
3. Random variation in the source level between $-2 \leq S_j \leq 2$, with respect to time, between with $A = 0$
4. Random variation in the source level between $-2 \leq S_j \leq 2$, with respect to time, between with $A = 4$ with an RPM of 10.

Two different 1/3 octave spectra are used for signals 1 through 4 and are shown in Figure 2-2:

a. 100 dB(A) signal with each band with the same acoustic energy of 85.5 dB(A), or

[2] Equivalent to 2 minutes

b. An average spectrum normalised to 100 dB(A) for a total of 18 turbines with rotor diameter of 150 m or greater. For signal 3 and 4, instead of ±2 dB, the random variation is equal to $\sqrt{\sigma_p^2 + 2^2}$, where σ_p is the standard deviation for the 1/3 octave from the 18 turbines, and 2 dB is the standard uncertainty.

The expected outcome for tests 1 and 3 is that the AM rating should be close to 0, and for tests 2 and 4 shall be close to 4. Deviations from the expected value of 4 dB, for tests 1 and 2, may indicate the methodology alters value of the peak-to-trough value. If the methodology can detect an AM signal, where the tests include a random variation, the values should be approximately to the expect value of 4 dB. The value of ± X dB is the variation in the rating value and not a reflection of the uncertainty. A full treatment of uncertainty is not covered in this paper. The results of these tests are shown in Table 3-1.

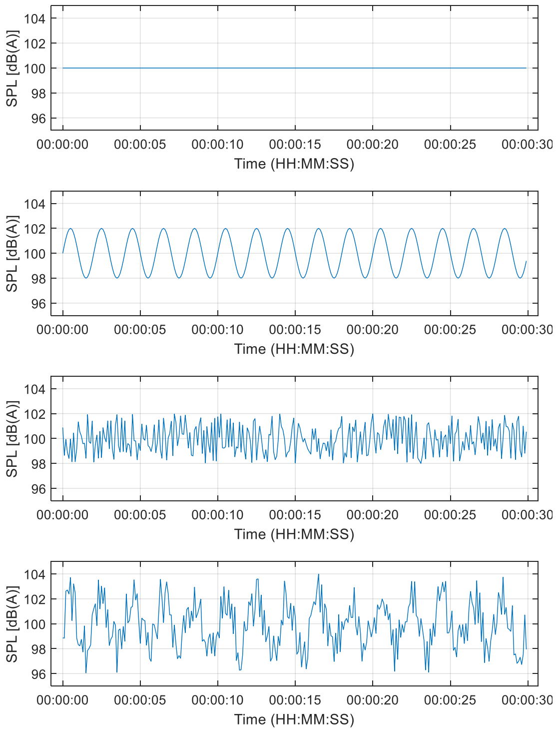

Figure 2-1 shows the example test signals for 0 to 30 seconds for, test 1: A = 0 with no random signal (top panel), test 2: A = 4 with no random signal (2nd from top panel), test 3: A = 0 with ± 2 dB random signal (2nd from bottom panel), and test 4: A = 4 ± 2 dB random signal (bottom panel).

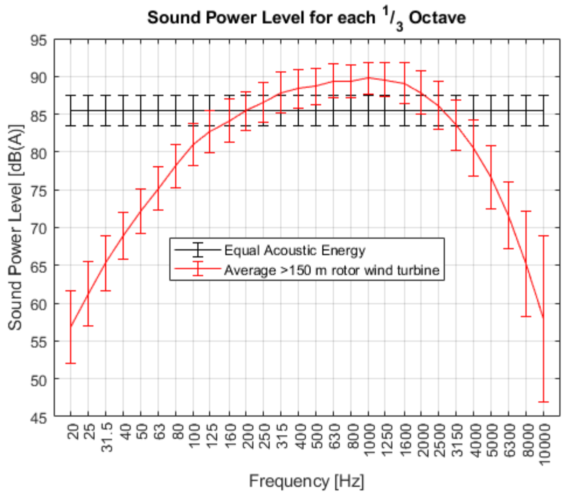

Figure 2-2 shows the two types of input spectrum for the test signals, The black line is for source spectrum (a) where the spectrum has equal energy in each 1/3 octave band, and the red line for source spectrum (b) for the average wind turbine with an rotor diameter of 150 m or greater. The error bars indicate the variation used in test 3 and 4.

2.2.2 Sensitivity Testing

A simple approach to sensitivity testing for each AM rating method uses the parameters stated in Table 2-1. The default value for flat A-weighted spectrum signal with an amplitude of 4 dB, no random variation in the source level, background set to -20 dB(A), no random variation in the background level, an RPM of 10, and no variation in the RPM. The tests alter one of the parameters of the input signal and they are as follows. *Test 1:* the amplitude modulation value, A, is changed from 0 to 10 dB, in steps of 0.1 dB; *test 2*: the random variation in the source, per time step, ranges from 0 to 10 in steps of 0.1 dB; *test 3:* the source level minus the background level ranges from -10 dB to 10 dB in steps of 0.5 dB; *test 4:* the random variation of the background level, per time step, ranges from 0 dB to 10 dB in steps of 0.1 dB, with the sound level minus background of 3dB; *test 5*: the RPM ranges from 0 to 20 RPM with a step of 0.1 RPM, and test 6: the RPM varies by a random value between 0 to 1 RPM every 60 seconds in a step of 0.1 dB.

Table 2-1 shows parameters for each sensitivity test, numbered 1 through 6.

Test	**A (dB)**	**±ΔS (dB)**	**L_{source} - $L_{background}$ (dB)**	**±$\Delta L_{background}$ (dB)**	**RPM**	**±RPM**
1) **Varying Amplitude modulation**	0 to 10	0	N/A	N/A	10	0
2) Variation in source level	4	±0 to ±10	N/A	N/A	10	0
3) Background Level	4	0	-10 to 10	0	10	0
4) Variation in background level	4	0	3	±0 to ±10	10	0
5) RPM	4	0	N/A	N/A	0 to 20	0
6) Variation in RPM	4	0	N/A	N/A	10	±0 to ±1

3 RESULTS

3.1 Test Results

Table 3-1 shows the results from the test signals 1 through 4 for the flat spectrum (a) and example turbine spectrum (b) for each AM Rating methodology. The input amplitude and variation in the Test column, with the resulting AM rating (A), determined BPF (F_{BPF}) and the percentage that AM was detected (t_{AM}). The variation in the AM rating and BPF is given after the "±", where no value is stated, it is 0 dB or 0 Hz to 1 decimal place. The results highlighted in **bold** are false positives.

Test	**Input Signal**	**AM Rating**				
		Den Brook	**Tachibana**	**IOA AM**	**IEC 61400-11-2**	**RUK**
1) A = 0	Equal Energy (a)	A = 0 dB F_{BPF} = ? Hz t_{AM} = 0%	A = 0 dB F_{BPF} =? Hz t_{AM} = 0%	A = 0 dB F_{BPF} =? Hz t_{AM} = 0%	A = 0 dB F_{BPF} =? Hz t_{AM} = 0%	A = 0 dB F_{BPF} =? Hz t_{AM} = 0%
	Average Turbine (b)	A = 0 dB F_{BPF} =? Hz t_{AM} = 0%	A = 0 dB F_{BPF} =? Hz t_{AM} = 0%	A = 0 dB F_{BPF} =? Hz t_{AM} = 0%	A = 0 dB F_{BPF} =? Hz t_{AM} = 0%	A = 0 dB F_{BPF} =? Hz t_{AM} = 0%
2) A = 4	Equal Energy (a)	A = 4.0 ± 0.0 dB F_{BPF} =? Hz t_{AM} = 100%	A = 3.0 ± 0.0 dB F_{BPF} =? Hz t_{AM} = 100%	A = 3.9 ± 0.0 dB F_{BPF} = 0.5 Hz t_{AM} = 100%	A = 3.9 ± 0.0 dB F_{BPF} = 0.5 Hz t_{AM} = 100%	A = 3.6 ± 0.0 dB F_{BPF} = 0.5 Hz t_{AM} = 100%
	Average Turbine (b)	A = 4.0 ± 0.0 dB ? Hz t_{AM} = 100%	A = 3.0 ± 0.0 dB F_{BPF} = ? Hz t_{AM} = 100%	A = 3.9 ± 0.0 dB F_{BPF} = 0.5 Hz t_{AM} = 100%	A = 3.9 ± 0.0 dB F_{BPF} = 0.5 Hz t_{AM} = 100%	A = 3.6 ± 0.0 dB F_{BPF} = 0.5 Hz t_{AM} = 100%
3) A = 0 ± 2 dB	Equal Energy (a)	**A = 4.0 ± 0.0 dB** **? Hz** **t_{AM} = 100%**	**A = 0.7 ± 0.2 dB** **F_{BPF} = ? Hz** **t_{AM} = 100%**	A = 0 dB F_{BPF} = ? Hz t_{AM} = 0%	A = 0 dB F_{BPF} = ? Hz t_{AM} = 0%	A = 0 dB F_{BPF} = ? Hz t_{AM} = 0%
	Average Turbine (b)	**A = 5.1 ± 0.0 dB** **F_{BPF} = ? Hz** **t_{AM} = 100%**	**A = 0.9 ± 0.2 dB** **F_{BPF} = ? Hz** **t_{AM} = 100%**	A = 0 dB F_{BPF} = ? Hz t_{AM} = 0%	A = 0 dB F_{BPF} = ? Hz t_{AM} = 0%	A = 0 dB F_{BPF} = ? Hz t_{AM} = 0%
4) A = 4 ± 2 dB	Equal Energy (a)	A = 7.9 ± 0.0 dB F_{BPF} = ? Hz t_{AM} = 100%	A = 3.3 ± 0.3 dB F_{BPF} = ? Hz t_{AM} = 100%	A = 4.7 ± 1.1 dB[1] A = 4.7 ± 1.0 dB[2] A = 4.7 ± 1.2 dB[3] F_{BPF} = 0.5 Hz t_{AM} = 100%	A = 4.7 ± 1.2 dB F_{BPF} = 0.5 Hz t_{AM} = 100%	A = 4.0 ± 0.1 dB F_{BPF} = 0.5 Hz t_{AM} = 92%
	Average Turbine (b)	A = 9.0 ± 0.0 dB F_{BPF} = ? Hz t_{AM} = 100%	A = 3.4 ± 0.3 dB F_{BPF} = ? Hz t_{AM} = 100%	A = 5.2 ± 1.2 dB[1] A = 5.2 ± 1.6 dB[2] A = 4.9 ± 1.5 dB[3] F_{BPF} = 0.5 Hz t_{AM} = 100%	A = 5.2 ± 1.6 dB F_{BPF} = 0.5 Hz t_{AM} = 100%	A = 4.3 ± 0.2 dB F_{BPF} = 0.5 Hz t_{AM} = 100%

[1]frequency band 50 Hz to 200 Hz; [2]frequency band 100 Hz to 400 Hz; [3]frequency band 200 Hz to 800 Hz.

3.2 Sensitive Range

The results of the test of the sensitivity of each AM method for the values stated in Table 2-1 are shown in Figure 3-1 through to Figure 3-6.

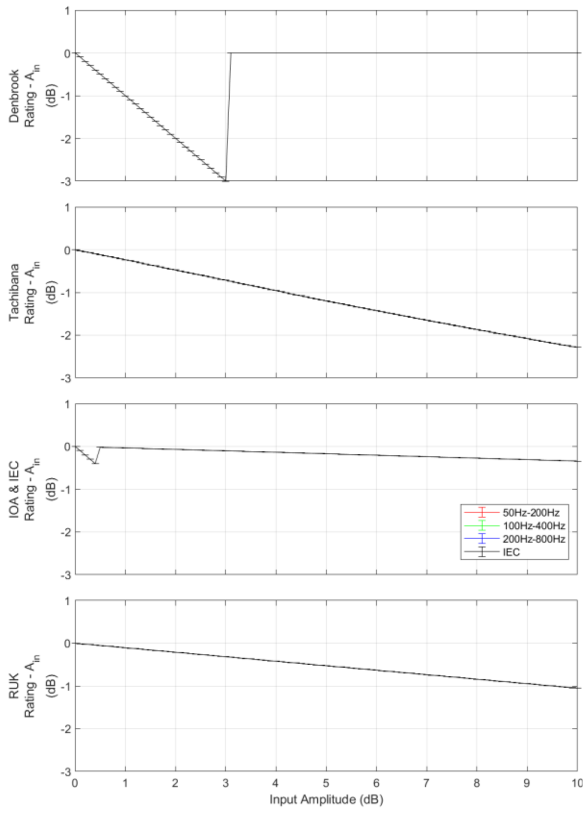

Figure 3-1 shows, test 1, the difference between the Rating level minus the input AM value (*y*-axis), for each AM method for changing input AM value of the test signal from 0 to 10 dB (*x*-axis). The error bars indicate the variation in the Rating level for the assessment period. The top panel is the Denbrook method, 2nd from top panel is the Tachibana method, 2nd from bottom is the IOA method three bands as red, green and blue lines with the IEC 61400-11-2 method as a black line, and the bottom panel is the RenewableUK method.

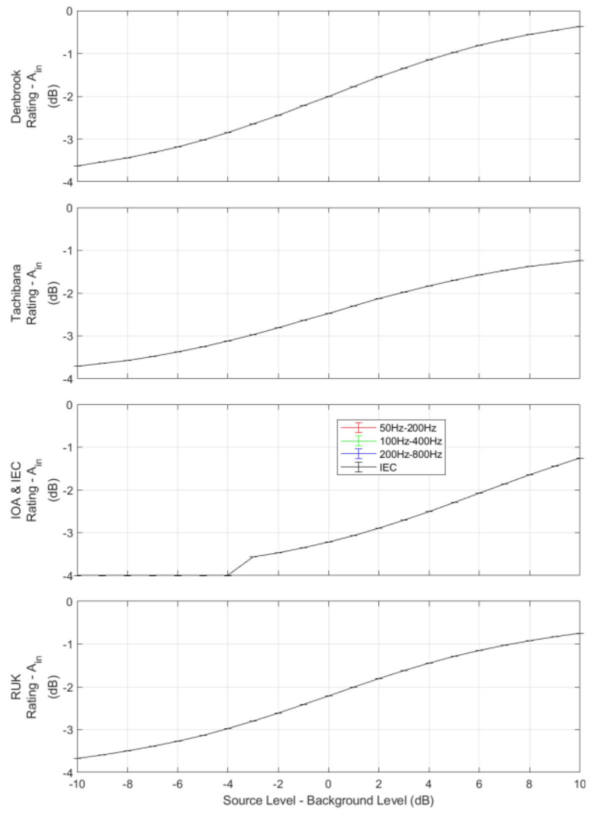

Figure 3-2 shows, test 3, the difference between the Rating level minus the input AM value (*y*-axis), for each AM method for relative difference of the source level minus the background from -10 dB to 10 dB (*x*-axis). The error bars indicate the variation in the Rating level for the assessment period. The top panel is the Denbrook method, 2nd from top panel is the Tachibana method, 2nd from bottom is the IOA method three bands as red, green and blue lines with the IEC 61400-11-2 method as a black line, and the bottom panel is the RenewableUK method.

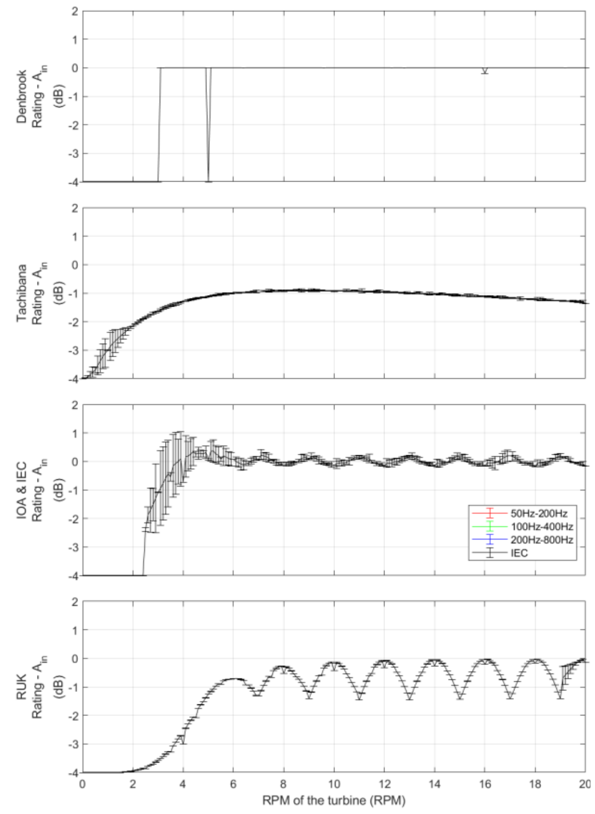

Figure 3-3 shows, test 5, the difference between the Rating level minus the input AM value (*y*-axis), for each AM method for the variation of RPM from 0 RPM to 20 RPM (*x*-axis). The error bars indicate the variation in the Rating level for the assessment period. The top panel is the Denbrook method, 2nd from top panel is the Tachibana method, 2nd from bottom is the IOA method three bands as red, green and blue lines with the IEC 61400-11-2 method as a black line, and the bottom panel is the RenewableUK method.

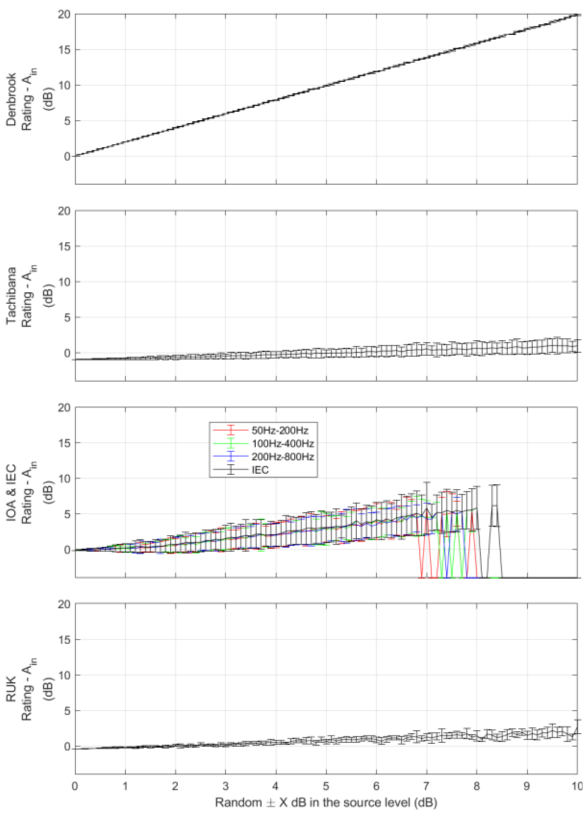

Figure 3-4 shows, test 2, the difference between the Rating level minus the input AM value (*y*-axis), for each AM method for random value in the source level within a set range denoted on the *x*-axis. The error bars indicate the variation in the Rating level for the assessment period. The top panel is the Denbrook method, 2nd from top panel is the Tachibana method, 2nd from bottom is the IOA method three bands as red, green and blue lines with the IEC 61400-11-2 method as a black line, and the bottom panel is the RenewableUK method.

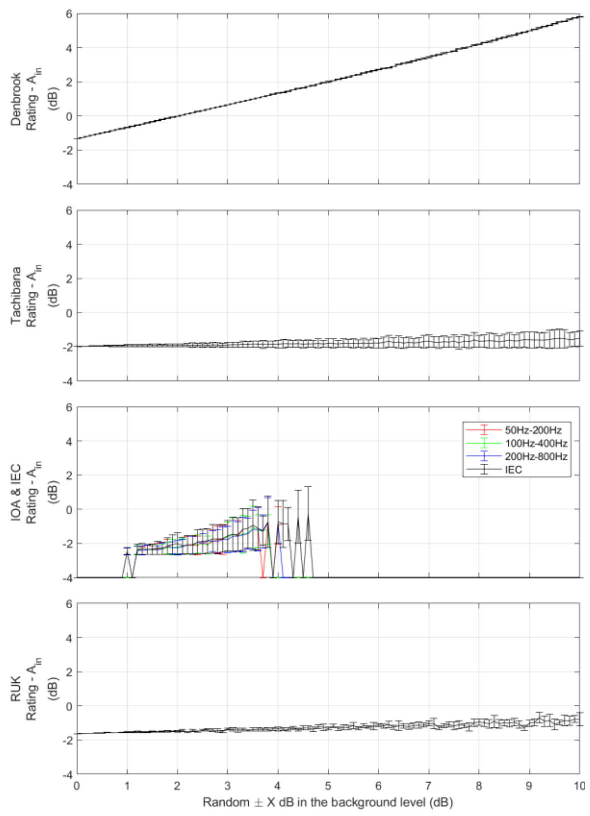

Figure 3-5 shows, test 4, the difference between the Rating level minus the input AM value (*y*-axis), for each AM method for relative difference of the source level minus the background of 3 dB, with a random value with a set range denoted on the *x*-axis. The error bars indicate the variation in the Rating level for the assessment period. The top panel is the Denbrook method, 2nd from top panel is the Tachibana method, 2nd from bottom is the IOA method three bands as red, green and blue lines with the IEC 61400-11-2 method as a black line, and the bottom panel is the RenewableUK method.

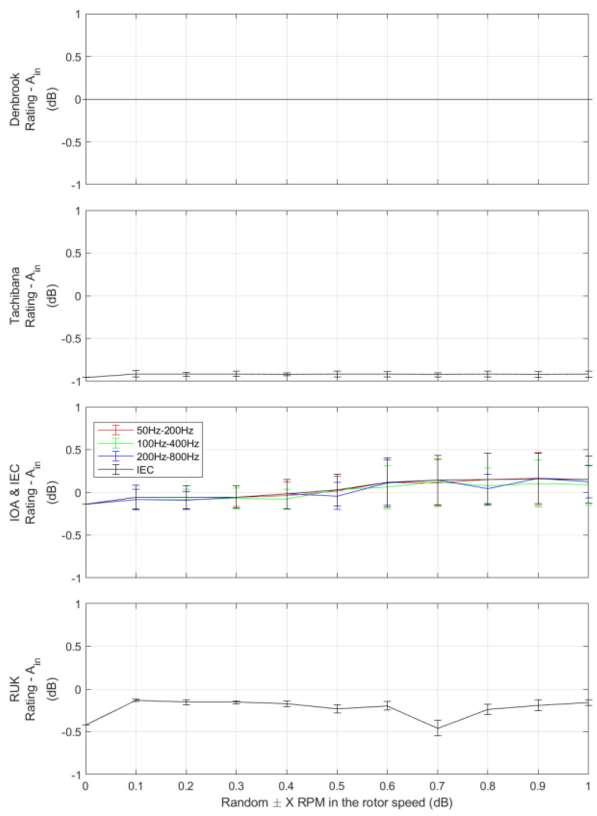

Figure 3-6 shows, test 6, the difference between the Rating level minus the input AM value (*y*-axis), for each AM method for an RPM of 10, with a random value with a set range denoted on the *x*-axis. The error bars indicate the variation in the Rating level for the assessment period. The top panel is the Denbrook method, 2nd from top panel is the Tachibana method, 2nd from bottom is the IOA method three bands as red, green and blue lines with the IEC 61400-11-2 method as a black line, and the bottom panel is the RenewableUK method.

4 DISCUSSION AND CONCLUSION

The *Denbrook* method is simple to implement with tools such as a spreadsheet. However, the method is a time domain method that only assesses the variation of sound pressure level and has no mechanism for discriminating modulating and non-modulating sources. The level of unexpected AM is not defined if it is for consecutive 6 minutes or any 6 minutes, and if it is for a rolling 1 hour period or consecutive 1 hour period, The AM rating reflects the input AM level, but only if there are no random variations in the signal (Figure 3-1). The AM rating is directly proportional to maximum difference in the random variation in the source level (Figure 3-4) and the background level (Figure 3-5). The method cannot determine the BPF of the turbine. The Rating level is 0 dB if the RPM is 5 (BPF of 0.25 Hz), which is twice of the 2 second criteria (Figure 3-3). The only identification of the source of the AM would be to listen to a sound recording, and this method is not suitable for moderate to large datasets. The level of false positives generated by this method is significant.

The *Tachibana* method can be easily to implement in simple tools, such as a spreadsheet or simple program, but requires a flexible sound level meter and/or post-processing. The limitations of this method are discussed in the IOA AMWG AM report[ix]. It cannot determine the BPF of the turbine (Figure 3-3). The difference between the Rating level and the input AM value increases with increasing input AM values (Figure 3-1). The AM rating is underestimated at RPM less than 5, when AM level is 4 dB (Figure 3-3).

The *IOA AM* rating method has many steps and requires scripting/programming, however; there is example code provided[x]. The Rating value slowly increases for increasing levels of input AM (Figure 3-1). The AM rating can be underestimated at RPM less than 5 (BPF 0.25 Hz), and the sinusoidal variation is owing to the shifting analysis window, between modulation frequency bins (Figure 3-3). The introduction of a random signal of the source or background can lead to an over estimation of the AM rating, when compared to the input AM value (Figure 3-4 and Figure 3-5), until the number of valid data falls below 50 per cent. It should be noted that the error bars are based upon the 90th percentile minus the 10 percentile and is not the standard deviation or level of uncertainty.

The *RenewableUK* rating method does require more complex programming tools. The method can be sensitive to noise sources with similar amplitude modulation frequencies, such as birdsong (not investigated in this paper), owing to the input signal summed over all frequencies. The Rating level slowly increases for increasing levels of input AM (Figure 3-1). The AM rating can be underestimated at RPM less than 5 (BPF 0.25 Hz), and the sinusoidal variation is owing to the shifting analysis window between modulation frequency bins (Figure 3-3). The introduction of random noise in the signal, whether from the source or the background, slowly increases Rating level and increases the standard deviation of the Rating Level (Figure 3-4 and Figure 3-5). This method is less sensitive to random signals than the *Den Brook* condition and *IOA/IEC* method.

For all methods as the general background level increases, the rating level of AM decreases (Figure 3-2). This indicates that the “underlying” level of AM may be the same, but the relative background level reduces the rating. In addition, the variation of RPM does not affect the AM rating level.

In conclusion, the *Den Brook* condition for detecting AM, suffers from false positives and cannot discriminate between a modulated and unmodulated signal. The *Tachibana et al* method can provide information on the variation of the sound pressure level but can return false positives in the absence of a modulated signal. In addition, it cannot determine the modulation frequency or discriminate for high frequency modulated signals. Therefore, for time domain methods, it is only possible to confirm an AM signal from a wind farm with additional recordings.

The *RUK* method can determine the BPF, which can be compared to the turbine operational data to minimise false positives. However, false positives can be generated from other modulated sources such as bird song and dogs barking, since all frequencies are considered. Therefore, additional filtering for specific frequencies can be performed. The method can discriminate a modulated signal from a random signal which is greater than the amplitude of the input signal. However, the energy band to calculate the rating level (step (e)), may need to be expanded to minimise reduction of the AM rating at RPM between frequency bins.

The *IOA/IEC* methodology can determine the BPF which can then be compared with the turbines operational data to minimise the false positives. In addition, the three frequency bands can be used to filter out potential contamination from other modulated sources. However, by performing an inverse-FFT and obtaining percentile levels on the subsequent reformed timeseries, can introduce a greater range of AM rating values, if there is a random variation in the input signal.

5 REFERENCES

[i] DEFRA (2011), Wind Farm Noise Complaint Methodology (NANR 277)

[ii] Noise Working Group (1996), The Assessment and Rating of Noise from Wind Turbines, ETSU-R-97, Department of Trade and Industry.

[iii] Fukushima, A., Yamamoto, K., Uchida, H., Sueoka, S., Kobayashi, T., & Tachibana, H. (2013). Study on the amplitude modulation of wind turbine noise: Part 1 – Physical investigation. *Internoise 2013* (pp. 1-10). Innsbruck: International Institute of Noise Control Engineering.

[iv] RenewableUK. (2013a). Template Planning Condition on Amplitude Modulation: Noise Guidance Notes. London: RenewableUK.

[v] RenewableUK. (2013b, December). *Industry Statement on OAM*. Retrieved from RenewableUK: https://www.renewableuk.com/page/IndustryStatementOAM

[vi] IEC (2024), Wind energy generation systems - Part 11-2: Acoustic noise measurement techniques - Measurement of wind turbine sound characteristics in receptor position, IEC TS 61400-11-2, Geneva

[vii] Schmitter, D., Di Lorlo, A. A., Hemmer, D., Schrechenberg, D., Grossarth, S., Poerchmann, C., Kuehner, T. (2022), Final Report on the Noise effect of the use of land-based wind energy, German Environment Agency (Umweltbundesamt), Dessau-Rosslau.

[viii] Appeal Decision: Land to the south east of North Tawton and the south west of Bow, APP/Q1153/A/06/2017162 (The Planning Inspectorate December 1, 2009)

[ix] Amplitude Modulation Working Group. (2016). *A Method for Rating Amplitude Modulation in Wind Turbine Noise .* St Albans: Institute of Acoustics.

[x] https://sourceforge.net/projects/ioa-am-code/