WIND TURBINE NOISE AMPLITUDE MODULATION PENALTY CONSIDERATIONS

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1 INTRODUCTION

This paper sets out the authors' considerations regarding a penalty for Amplitude Modulation (AM) of noise from wind turbines. It follows the publication from a number of UK authors of a wind farm noise condition in the Acoustic Bulletin [1]. This article incorporated a penalty graph which the authors recommended should be treated as provisional. The penalty graph used was the one set out in the WSP/Parsons Brinckerhoff report "Wind Turbine AM Review Phase 2" (WTAMR) for the UK Government [2], which was produced after a review of the evidence. That penalty graph was similar to the one originally published by RenewableUK [3] at the same time as the outcome of the AM research project [4] they commissioned was published.

The Acoustic Bulletin article referenced above said: "*The conclusion is that the penalty graph needs further research to establish whether it should be amended to take account of rotational speed and the difference between Leq and L90 (which increases as AM increases) and that this should be progressed as soon as possible*". The present article does not present additional research but discusses different factors which the authors consider require additional consideration when considering a potential penalty to be used in combination with the method and planning condition set out in the article.

2 THE ISSUES

There is a series of issues to be considered in relation to the penalty graph which are listed below. These are discussed in more detail in the sections below. These different factors are inter-related and so will be considered each in turn.

- **Metric adjustments (L_{eq}/L_{90}):** should the penalty be adjusted for the difference between L_{eq} and L_{90}? All the quoted research on the subject of annoyance and modulation depth is based on a comparison of annoyance with L_{Aeq}. However, in the UK we measure wind turbine noise in L_{A90} – what effect, if any should this have on the penalty graph?

- **Penalty threshold**: Where should the penalty start? WTAMR proposed a penalty graph which starts at a modulation depth of 3dB. Should a different threshold apply?

- **Zero AM adjustment**: the Salford study results were interpreted differently with a correction in the derived adjustments sometimes applied based on zero modulation depth results.

- **Metric calibration**: which metric is used and how does it relate to that used if the different research papers on which the penalty is based?

- **Modulation rate**: should the penalty vary with the modulation frequency (or rate) and how?

On the last point, it is noted that most of the research results relate to a modulation rate of around 0.8 Hz which represents a period of 1.25 s or a 3-bladed turbine rotating at 16 RPM, which is typical of relatively large turbines in the 2-3 MW category. This will be assumed to be the case in a first instance until this aspect is considered further below in section 7.

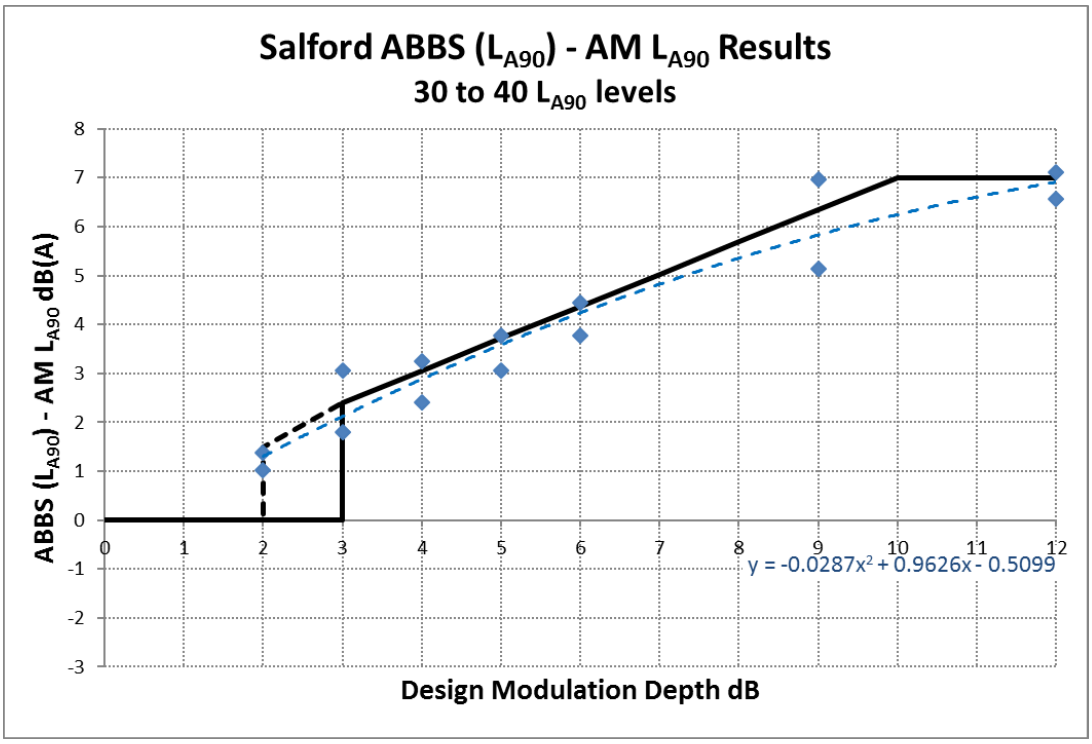
3 METRIC ADJUSTMENTS (L_{EQ}/L_{90})

Whilst the authors agree that some allowance has to be made for the difference between L_{90} and L_{eq}, there are several ways in which that allowance might be made. Two arguments are set out in the sub-sections below. This analysis initially focuses on the data presented in the Salford study for RenewableUK [5] of subjective response to AM.

3.1 Argument 1

The first approach or argument is based on a direct analysis of the Adaptive BroadBand Stimuli levels (ABBS) in the Salford tests but related to L_{90} levels for the samples: see Figure 22.2 of [5]. This results in larger corrections which increase more clearly with modulation depth. The penalty graph of Figure 1 is based on the average ABBS adjustments ("ABBS-AM" levels) in the Salford data plotted against the test metric (modulation depth MD) for L_{90} values between 30 and 40dB – the range of levels arguably most likely to be present in the event of complaints and excluding the extremes for which less data was available.

Figure 1 - Salford ABBS-AM L_{90} level adjustment data plotted against the modulation depth, for stimuli level values between 30 and 40 dB – showing corrections starting both at 2 or 3 dB (see section 4)



The argument goes as follows: WTAMR says "*the ETSU-R-97 methodology uses $L_{90,10min}$ as a proxy for $L_{eq,10min}$*" but that is arguably not the case. The aim is to derive a penalty scheme for incorporation in a planning condition. Compliance with such a condition requires that we measure the sound levels as L_{A90}, because the limits are defined as L_{A90}. We are not using L_{A90} as a proxy. The only time L_{A90} was ever used as a proxy was in ETSU-R-97 when the arguments for the derived limits were put forward. From that point on everything is L_{A90}. According to this argument, a penalty must be derived by comparing in a dose response test a modulated sample of noise with an unmodulated sample so that they are equally annoying and then finding the difference between the levels as L_{A90} not as L_{Aeq}. This can quite simply be done in the case of the RUK research – and, indeed, was done in the Salford report.

3.2 Argument 2

The WSP authors of WTAMR, in a subsequent article [6] in the IOA Bulletin, dispute the direct use of the charts plotted as a function of the L_{90} level in the RenewableUK research. Although these charts appear to show a clearer result as a function of modulation depth, they argue it is in large part a bias introduced "*by the physical parameters employed to derive*" the results, i.e. the L_{eq}/L_{90} difference present in the samples. Therefore, whilst the Salford study concluded that more research on this aspect would be of interest, they "*concluded that equivalent adjustments from the L_{90} results 'cannot be identified'*". On this basis, it would arguably not be correct to use this alternative correction as suggested, but consider the potential adjustment for L_{eq} normalised samples as done mainly in the UK, Japanese and Korean studies referenced in the WSP report for DBEIS.

In addition, the characteristics and L_{eq}/L_{90} differences of the short and relatively constant AM stimuli used use in the research by Salford may be very different to real AM in the field, which is often highly variable.

Nonetheless, the WSP report states that the adjustments should be applied to the "*the overall time-averaged level*", meaning the 10-minute L_{eq} values. ETSU-R-97 explains p.54-57 that the L_{A90} index was chosen to represent L_{Aeq} values without the corruption experienced in rural areas, and that the limits were derived from L_{Aeq} values (p.61 for example). ETSU-R-97 also states that the 10-minute L_{90} of the wind farm is likely to be "*about 1.5-2.5dB(A)*" less than the L_{Aeq} measured over the same period. A value of 2dB is usually used to this effect in common practice (as specified for example in the IOA GPG, Summary Box 20).

The above-referenced IOA Bulletin article [6] explains that the proposed penalty was effectively based on the L_{90} being a proxy for L_{eq} and the typical differences between the two metrics of around 2 dB set out in ETSU-R-97. Therefore, the authors of that article explain that:

> *"the real question is whether or not the L_{eq}-L_{90} relationship for a WTN signal, assumed in ETSU-R-97 to be 1.5-2.5 dB, continues to hold over typical 10-minute periods under real, variable AM conditions"*

It follows that, if this relationship is not valid in practice, it may be necessary to consider additional adjustments.

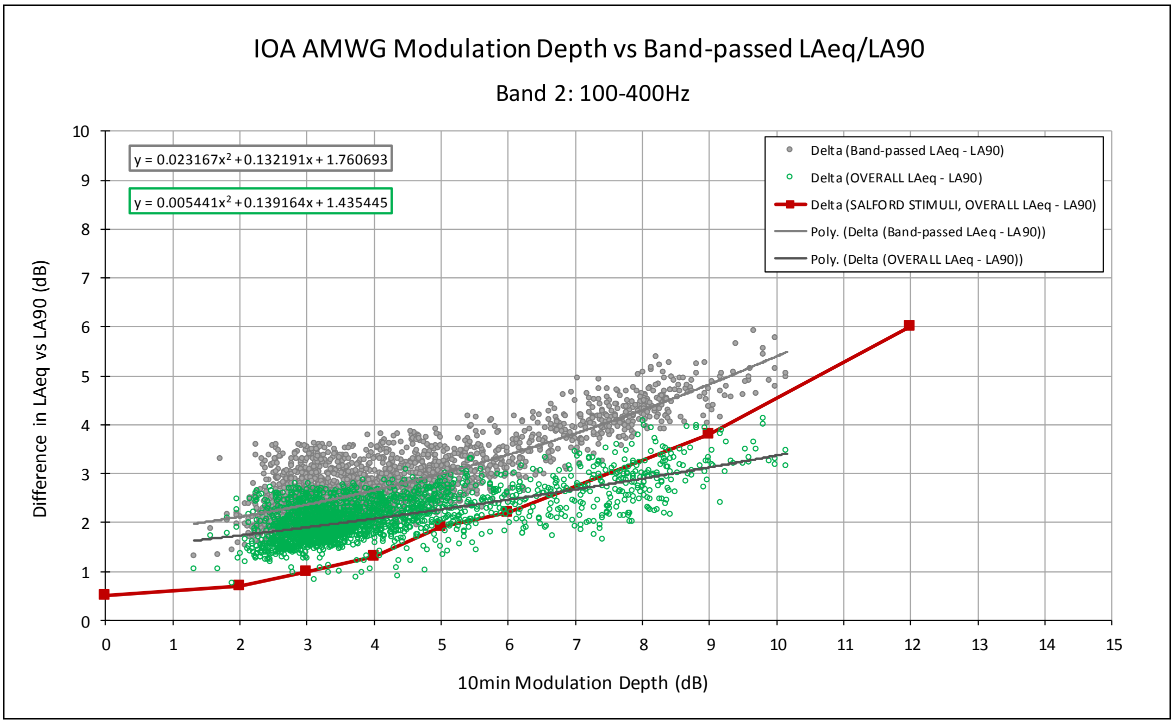
In the experience of the present authors, elevated AM values can be detected for short periods without the L_{eq}-L_{90} difference over 10 minutes increasing much beyond the range assumed in ETSU-R-97 (excluding corruption from other sources), which can sometimes be counter-intuitive. There is also limited data available for the highest end of the range of AM values considered (more than 6dB) occurring for sustained periods. Nonetheless, evidence is emerging that if the 10-minute AM value (as determined by the IOA AM reference methodology) goes beyond about 6dB, meaning persistently high occurrence of elevated AM, then higher L_{eq}-L_{90} differences may in fact arise in practice.

See for example Figure 2, which is based on real site data in the far-field of an operating wind farm. Figure 2 details the differences in L_{eq}-L_{90} level, of both the broadband overall level, and that of the band-passed 100-400 Hz range, plotted against the modulation depth results (IOA method). It can be seen that a trend for increasing L_{eq}-L_{90} differences appears for ratings broadly above 6 dB. The measured differences between the metrics appears similar in magnitude to that observed in the shorter stimuli used in the RenewableUK research, which are set out in Table 1 below and plotted in red in Figure 2. There is also a greater difference seen in the 100-400 Hz band-passed results compared to the broadband results. This is not unexpected given that the broadband results are more likely to be corrupted by non-wind farm sources in the local environment, and that the 100-400 Hz range exhibits a more consistent modulation-related trend. These results suggest that in certain circumstances actual sustained modulation in the field can result in comparable L_{eq}-L_{90} differences to that of the stimuli used in the RenewableUK research.

Table 1 – Comparison between L_{eq}/L_{90} in RenewableUK stimuli (from Ref. [5] Appendix X, Table 22.1) and derived adjustment

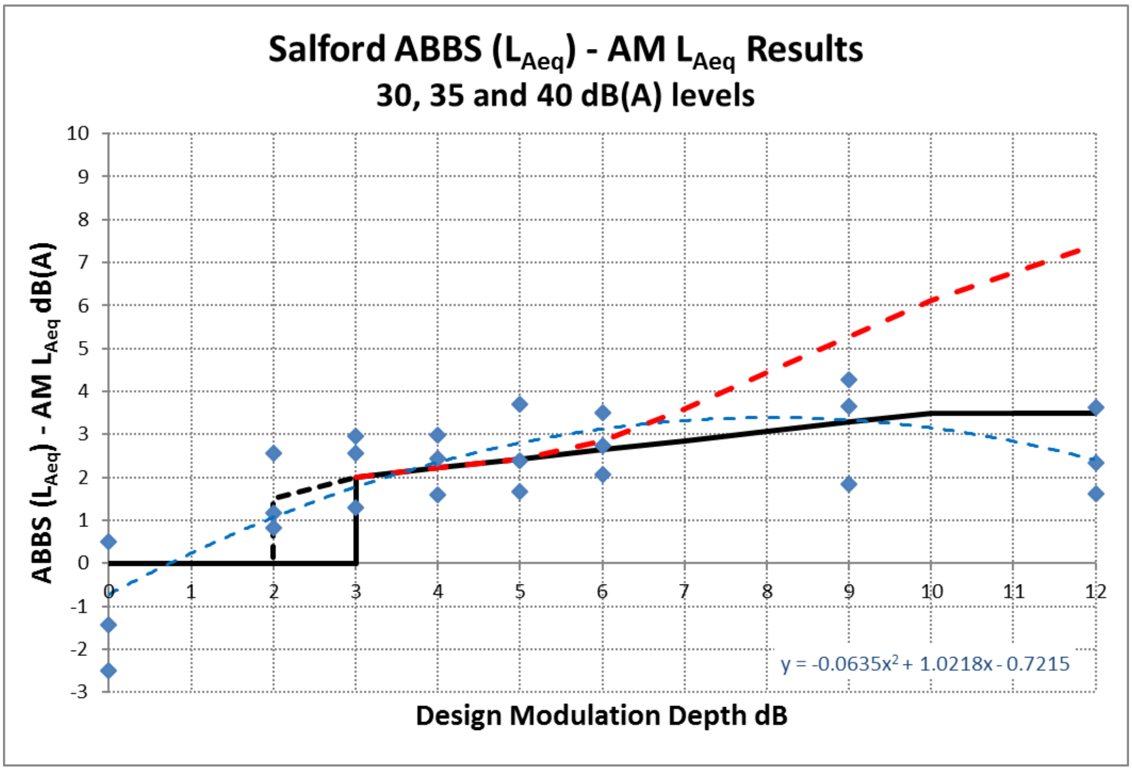
AM depth	L_{eq}-L_{90}	Increase above 2dB
0	0.5	
2	0.7	
3	1.0	
4	1.3	
5	1.9	
6	2.2	0.2
9	3.8	1.8
12	6.0	4.0

Figure 2 – example of differences between 10-minute L_{Aeq} and L_{A90} ratings measured at a residential location neighbouring a wind farm; green: broadband A-weighted metrics (as per ETSU-R-97), grey: 100-400Hz band-passed L_{Aeq}/L_{A90} metrics; red: Salford stimuli differences for comparison (Table 1).



Because of the above, for rated 10-minute modulation values above 6 dB, increases above the 2dB adjustment usually assumed should arguably be added to a derived penalty curve. Figure 3 shows the Salford results for (ABBS – AM) level adjustments for the L_{Aeq} metric, for stimuli L_{Aeq} levels of 30 to 40 dB(A), along with a simplified curve going through this data (thick black line) as in Figure 1. This results in adjustments of 1.5 to 3.5 dB, as described in WTAMR, which were determined for modulation at 0.8 Hz. A red dotted line in Figure 3 shows an alternative penalty curve with adjustments derived from Table 1 applied with some interpolation.

Figure 3 – Salford ABBS-AM L_{eq} level adjustment data plotted against the modulation depth, for stimuli level values between 30 and 40 dB – additional correction based on Table 1: red line - showing corrections starting both at 2 or 3 dB (see section 4)



3.3 Comparison

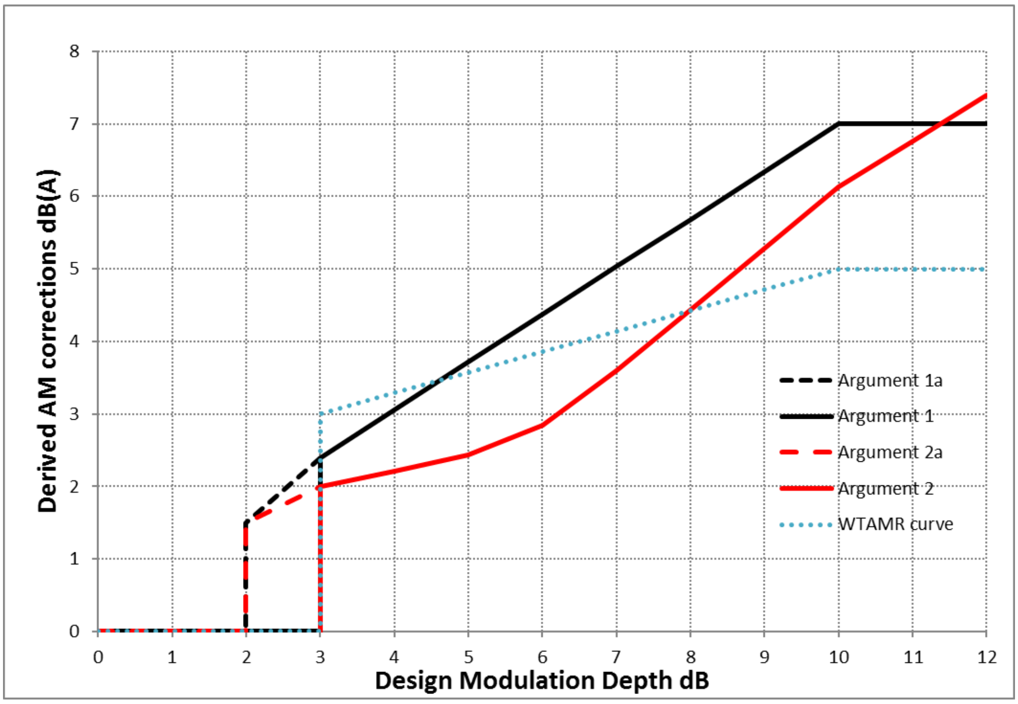
The authors could not reach a consensus on these alternative interpretations of the Salford test results. For comparison, Figure 4 and Table 2 set out both of the penalty curves (based on data at for AM at 0.8 Hz) and the WTAMR curve (AM up to 1.6 Hz, see Section 7). The penalty curve is shown for illustration starting at 2 dB or 3 dB in relation to the discussion in the following section.

Table 2 – Comparison of the derived correction or penalty curves obtained in Figures 1 and 3.

AM Rating	0	1	2	3	4	5	6	7	8	9	10	11	12
Argument 1	0	0	1.5*	2.4	3.1	3.7	4.4	5.0	5.7	6.3	7.0	7.0	7.0
Argument 2	0	0	1.5*	2.0	2.2	2.4	2.8	3.6	4.4	5.3	6.1	6.8	7.4
WTAMR	0	0	0	3.0	3.3	3.6	3.9	4.1	4.4	4.7	5.0	5.0	5.0

**If the penalty starts at 2dB.*

Figure 4 – Comparison of the derived correction or penalty curves obtained in Figures 1 and 3 for a modulation rate of 0.8 Hz (black and red) and the proposed penalty in WTAMR (blue).



4 PENALTY THRESHOLD

The proposed penalty in WTAMR starts at 3dB, the reasoning being that this was "*the level of AM currently considered to be 'normal', and representative of the approximate onset of fluctuation perception for the majority of people*".

WTAMR presents in Fig 4 (p.20) results from research from Yokoyama et. al. [7] that suggest that the onset for perception of AM is around 2dB: the chart shows that 60% of people perceive modulation at a depth of 2dB, increasing to almost 100 % at 3dB. This is consistent with previous research, but should be interpreted with caution as it relates to perceptive rather than affective response. This means it should not be conflated with other research studies (such as the Salford study) which studied the annoyance response to AM rather than its detection.

The research undertaken by Salford University for RenewableUK [5] is an example of such affective research. But the results of such studies are inherently more complex and with increased variability/uncertainty. The charts showing level adjustments of participants to broadband noise could appear to suggest an apparently clear increase in average adjustments with modulation around 2 to 3 dB, with a response "flattening" at higher AM levels, but the statistical analysis made shows that this was not statistically significant and that "*[a] clear onset of annoyance at a particular modulation depth could not be found.*"

A further study of paired comparison tests by Yokoyama et. al. [7] (Figure 3 in WTAMR) can offer further guidance. In the first set of tests (35 dB L_{Aeq}), average adjustments remain close to zero or negative until 3 dB, however in the second set of tests (45 dB L_{Aeq}), this started at 2 dB. As in the Salford study, the level of variability in the results means that it is unlikely such differences can be statistically resolved from the results.

It is acknowledged that, as part of any robust metric, such as the one proposed by the IOA [8], there is some degree of averaging of the modulation, which may reduce some instances of increased AM (such as very short bursts). On the other hand, in common with any numerical method, there is a "noise floor", or a minimum level which may be returned by the method even in the absence of clear or marked AM. Current practice suggests that values of 1 to 2 dB may be obtained in this case with the IOA method. Both of these aspects were minimised as far as practicable in the IOA method but these factors should be recognised when considering the onset of any penalty.

5 ZERO AM ADJUSTMENT

Setting aside the issue of L_{90}/L_{eq} metric, it can be observed that the adjustments based on the Salford results (black curve in Figure 3), are of the order of 1.5 to 3.5 dB, as noted in WTAMR (4.5.24). These are clearly lower than the penalty curve initially derived by RenewableUK in [3]. The difference is mainly due to the interpretation of the Salford test results at zero modulation.

The results of the broadband level adjustment test in the Salford study: Figs 8 in WTAMR [2] or Figure 9.5 in the original report [5] show cases of negative average adjustments when the modulation depth (MD) is zero. This means that the test subjects sometimes tended to adjust reference broadband levels down even in the absence of modulation in the test stimuli. The Salford report noted in this respect that "*This confirms a participant observation from Section 19.1 stating that levels were hard to judge. Also participants might have felt the need to always make adjustments in the belief that the AM stimuli must be different from the ABBS*." The question is therefore: is there a bias/error which only occur with MD=0 or does it equally affect results at other, positive modulation depths?

RenewableUK, in deriving their proposed condition in [3], "normalised" the average ABBS results by correcting for the value at zero MD, on the basis that this was real bias affecting all results, and that the resulting values (with some exceptions) did appear broadly more consistent. The RenewableUK document then determined a penalty curve from a trendline analysis of this "normalised" data which was then smoothed.

Such an adjustment was not proposed by the authors of the Salford report. More generally, caution should be used in analysing *average* values only and disregarding the relatively large variability in the results in the study and the associated uncertainty. There was no negative average adjustment for non-zero MD values, and adjusting all these values because of one result would be associated with a high level of uncertainty. A nominal adjustment could nevertheless be considered.

The effect at zero modulation depth is dismissed as an "anomalous result" in the WSP report. To support this, a comparison is made with additional results such as those of Yokoyama et. al. [7]: Figure 3 in WTAMR. This represents a similar study involving adjusting broadband levels to account for the AM character which usefully supplements the Salford study. There was no similar strong bias in the average results at zero modulation, bearing in mind the high variability in the results, and the average adjustments are closer to 1.5-3.5 dB in the range of 3 to 10 dB modulation depth, and therefore similar to the Salford results without applying the adjustment for 0 MD.

The WTAMR report does end up recommending a penalty identical to that of in [3], but this is to account in WSP's view with the issue of modulation rate, which is considered below in Section 7.

6 METRIC CALIBRATION

The authors and the WTAMR report propose the use of the IOA metric because this seems to be the most comprehensive and robust one available.

WTAMR notes that the IOA metric can "*effectively be substituted for the metrics used in the laboratory studies reported [in [5] and [7]] with relatively small differences*". This refers to charts 8.2.1 and 8.3.1 in the IOA report [8] which demonstrate the results of analysing the stimuli used in both of these key research studies using the IOA metric, and obtaining close to 1:1 relationship between the different metrics used, effectively demonstrating the "calibration" of the dose-response curves obtained. The data shown in Figures 1 and 3 was plotted against the IOA metric results and a similar outcome was obtained, which supports the use of this metric in relation to the derived penalty curves.

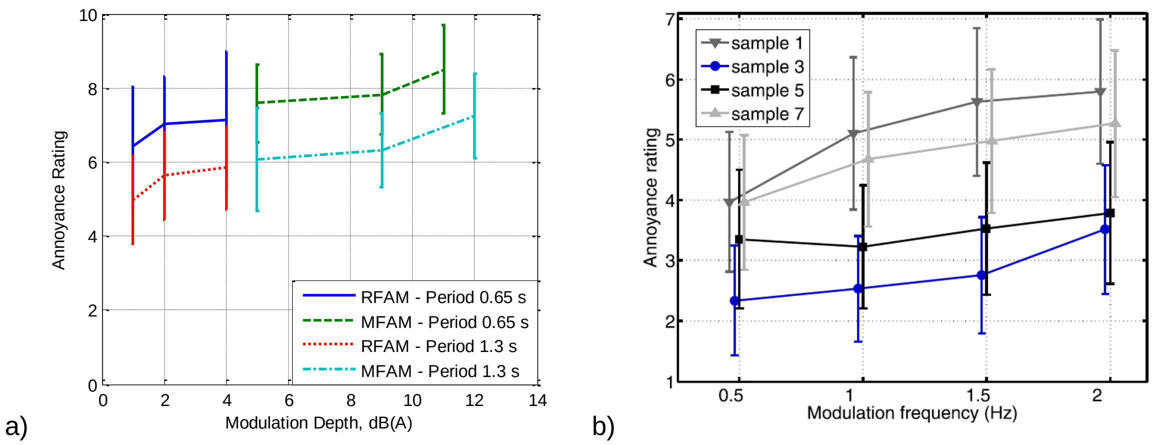
7 MODULATION RATE

As acknowledged in the WTAMR report, and noted above, the evidence on response to AM on which it draws upon was derived based on tests which were mainly undertaken at a modulation rate of 0.8 Hz. The WTAMR authors (ref [2] at 4.5.24) propose a penalty of 3 to 5 dB, higher than the 1.5 to 3.5 dB evidenced in the relevant sources, to account for the potentially increased annoyance that may be associated with modulation faster than 0.8 Hz, up to the upper range of 1.6Hz allowed by the IOA AM method [8]. This adjustment or allowance of +1.5 dB seems to be recommended on a pragmatic basis rather than any specific quantitative reference.

As noted in [2], it is known from general psychoacoustics research [9] that the sensation of fluctuation (described by the fluctuation strength metric) will increase with the modulation rate, reaching a maximum at around 4Hz. This effect was specifically assessed in the Salford study (ref. [5] section 8.1.7). Figure 8.7 in that report (reproduced below as Figure 4(a)) showed that a halving of the modulation period (and therefore almost doubling in the modulation rate from 0.8 Hz to 1.5 Hz) corresponded to a significant increase in annoyance. In fact, this increase was more significant than the effect of increased modulation depth and comparable with the average annoyance increase associated with a 5 dB change in L_{Aeq} noise levels (see Figure 9.3 in [5]).

On the other hand, WTAMR describes in Annex 1 results from Ioannidou [10] which suggest that the effects of modulation rate were apparent although not significant, although this may be due to the specific samples used. The relevant figure is shown in Figure 4(b).

Figure 4 – Evidence on effects of modulation rate on subjective response: a) Figure 8.7 from [5]; b) Figure 7 from [10]



It is recommended that this effect is accounted for and that any penalty considered (such as those shown in Figure 4, based on a 0.8 Hz rate) are corrected to account for modulation rates higher than 0.8Hz. As described above, the Salford University result (Figure 4(a)) imply that doubling the modulation rate is equivalent to a +5 dB increase in noise levels, compared to the +1.5 dB adjustment proposed in WTAMR (more consistent with Figure 4(b).

Fluctuation strength theory [9] of amplitude modulated broad-band noise indicates that a doubling of the modulation frequency will cause a factor of ≈ 1.6 increase in the fluctuation strength up to a maximum frequency of 4 Hz (assuming a “presentation level” of 38 dB). This relationship can be used to derive corrections at other frequencies, based on either a correction of +1.5 dB on a pragmatic basis, as was done in WTAMR, or closer to +5 dB as implied by the Salford data: see

Table 3. The appropriate penalty may lie somewhere between these two proposals. It is acknowledged that at frequencies of more than 1.6 Hz, the IOA reference method cannot be applied in full as it could not capture the upper harmonics of the signal.

Table 3 – Examples of progression of penalty adjustment with modulation rate based on Fluctuation strength theory.

Modulation Frequency (Hz)	**0.8**	**0.9**	**1.2**	**1.6**	**1.8**	**2.1**	**2.4**	**2.7**
Penalty adjustment,+1.5 dB basis	0.0	0.2	0.8	1.5	1.8	2.1	2.3	2.5
Penalty adjustment, +5 dB basis	0.0	0.8	2.8	5.0	5.9	7.0	7.8	8.4

8 CONCLUSIONS

The authors could not reach definitive conclusions in the present paper. As noted in [1], it is considered that further research is required to establish whether the penalty chart proposed in 2016 in the research for the Government should be amended, although the difficulties and limitation of any research on this subject are acknowledged. Based on the existing available research, the authors have nevertheless set out a number of factors for consideration and further discussion in relation to a penalty from wind turbine AM.

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