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The Development of a Penalty Scheme for Amplitude Modulated Wind Farm Noise

Description and Justification

December 2013

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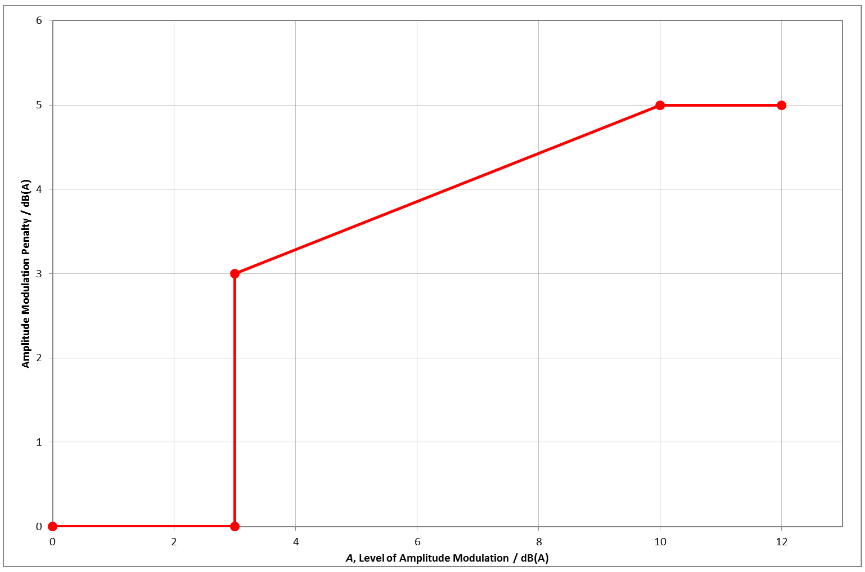
1 Introduction

This report contains a description, and a justification, of the penalty scheme presented within the template planning condition for amplitude modulation (AM) recently published by RenewableUK [1].

To assist with the uptake of the new AM planning condition, it has been published in a form which shows how it can be easily integrated into the 'Example Planning Conditions' published within the Institute of Acoustic's 'Good Practice Guide' [2]. With a small amount of editorial work, it could also be integrated into other 'standard' forms of wind farm noise planning condition in a similar fashion.

The AM penalty scheme appears in Guidance Note 4 of the scheme and is reproduced in Fig 1 below:

Fig 1 *The Penalty Scheme Contained in the RenewableUK Planning Condition for AM*



The interpretation of this penalty scheme is as follows:

- *for AM with a peak to trough level of < 3 dB there is no AM penalty*
- *for AM with a peak to trough level of 3 – 10 dB there is a sliding scale of penalties ranging from 3 – 5 dB*
- *for AM with a peak to trough level of ≥ 10 dB there is 5 dB penalty.*

This scheme is the analogue of the penalty scheme used to control tonal noise in ETSU-R-97, 'The Assessment and Rating of Wind Farm Noise' [3], also present in the Institute of Acoustic's 'Good Practice Guide'.

2 Background

The basis for this penalty scheme are listening tests performed by the University of Salford and published in [4,5]. In particular the results published in section 9 and Fig 9.4 of [4].

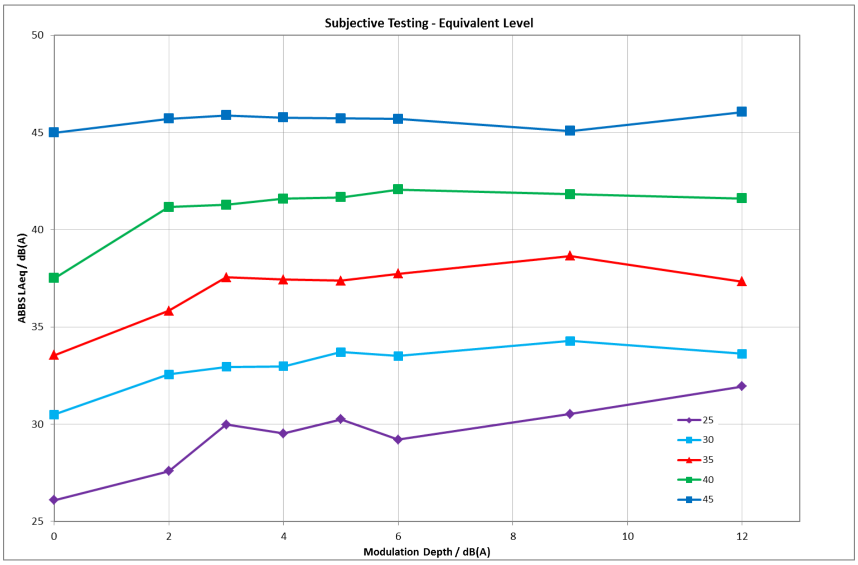
To determine the psycho-acoustic, or subjective, response of humans to amplitude modulated sound, auditory experiments were performed in a specially designed test facility. A number of test subjects were exposed to modulated wind farm noise and asked to adjust the level of an un-modulated noise, having identical frequency characteristics, to have an equivalent level of 'noisiness' or 'annoyance'. Several different overall noise levels, i.e. 25, 30, 35, 40 45 dB(A) were investigated and several different modulation depths[3], i.e. 0, 2, 3, 4, 5, 6, 9 & 12 dB.

Note that:

- *a modulation depth of 12 dB(A) was assumed to be beyond the maximum that would commonly be observed in realistic scenarios*
- *the small increments in modulation depth between 2 and 6 dB(A) were chosen to possibly observe an onset of perceptibility of AM*
- *the lower overall L_{Aeq} level, 25 dB(A), was assumed to be the onset of perceptibility in most background noise scenarios*
- *the maximum overall L_{Aeq} level, 45 dB(A), was selected as typical of the upper limit of acceptability.*

Key results are shown in Fig 2 (see original text for further explanation [4]. Note that error bars have been removed for clarity):

Fig 2 *Adjusted, Un-modulated Noise Levels Corresponding to Different Levels of Modulated Noise*



This, and the original research by Salford University, shows that:

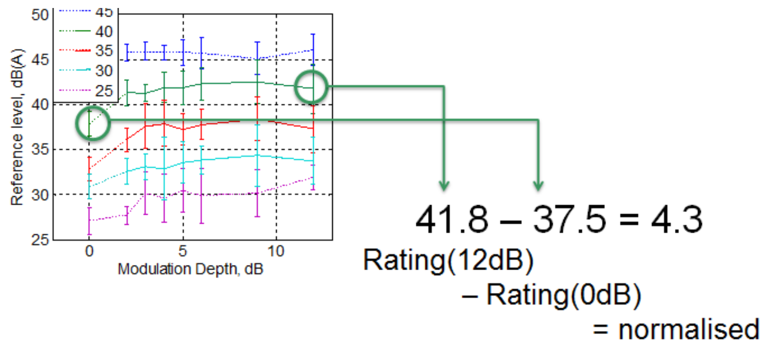
- *the noise level adjusted for 'annoyance', i.e. the 'ABBS Level[2]', is expressed in decibel (dB) terms*
- *annoyance is primarily determined by the overall, A-weighted level*
- *the effect on annoyance of modulation depth is secondary*
- *a clear 'onset of annoyance' with modulation depth is not apparent*
- *the shape of the annoyance versus modulation depth curves are broadly similar, irrespective of overall level.*

[1] *'Modulation depth' was defined, in the context of these tests, as the difference between the mean peak level and the mean trough level in the A-weighted, RMS time series over the length of the test stimulus.*
[2] *ABBS: Adapted Broadband Stimulus – see [4] for further details*

This last point suggests that it is possible to separate out the annoyance due to the overall level of noise from that due to modulation depth, and this may be achieved by 'normalising' (or differencing) the results for a particular overall level to the results corresponding to zero dB(A) modulation depth.

At zero dB(A) modulation depth the adjustments were expected to be ~ 0 dB(A) as the two stimuli were identical. This was, however, not the case. Quieter stimuli were adjusted to higher levels, for example ~ 2 dB(A) higher for the 25 dB(A) AM stimulus. For louder stimuli the level adjustment was ~ 2 dB(A) lower than the AM stimulus L_{Aeq}*. This confirms a participant observation 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. To account for this effect we can normalise the average adjusted level for a certain modulation value by the average value determined without modulation: this process is explained in Fig 3:*

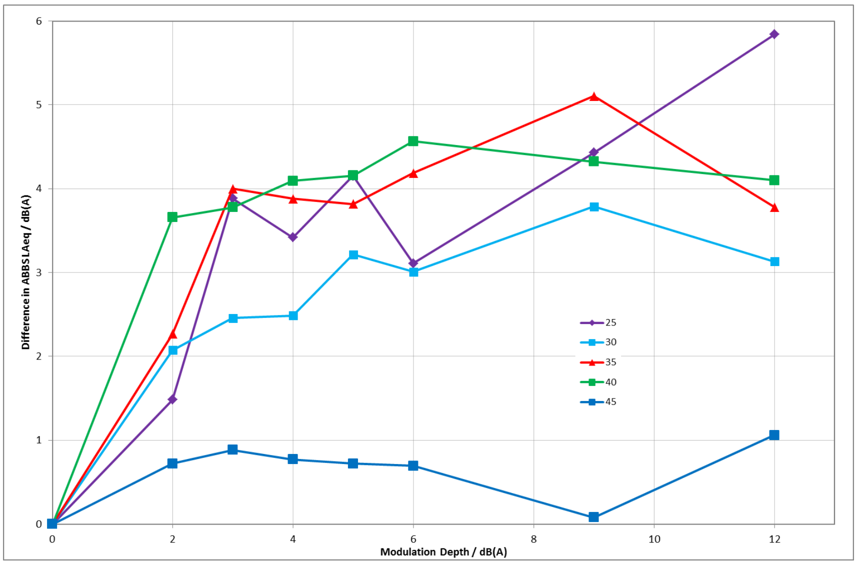
Fig 3 *Normalising the Adjusted Level Results*



Consider the annoyance curve for test samples with a nominal overall level of 40 dB(A) – the green line. In this example, the annoyance for the sample with zero dB(A) modulation depth is 37.5 dB(A), slightly below the 40 dB(A) nominal level. For the sample with a 12 dB(A) modulation depth, the annoyance is 41.8 dB(A), suggesting that the marginal annoyance solely due to the 12 dB(A) of AM, compared to an un-modulated noise with the same spectrum and overall level, is 4.3 dB(A).

This process can be repeated for each one of data points on the 40 dB(A) nominal level curve, to determine the marginal annoyance for varying modulation depths. It can also be repeated for the 25, 30, 35 and 45 dB(A) nominal level curves, and the results of this are shown in Fig 4:

Fig 4 *Marginal Annoyance Resulting from Modulation Depth*



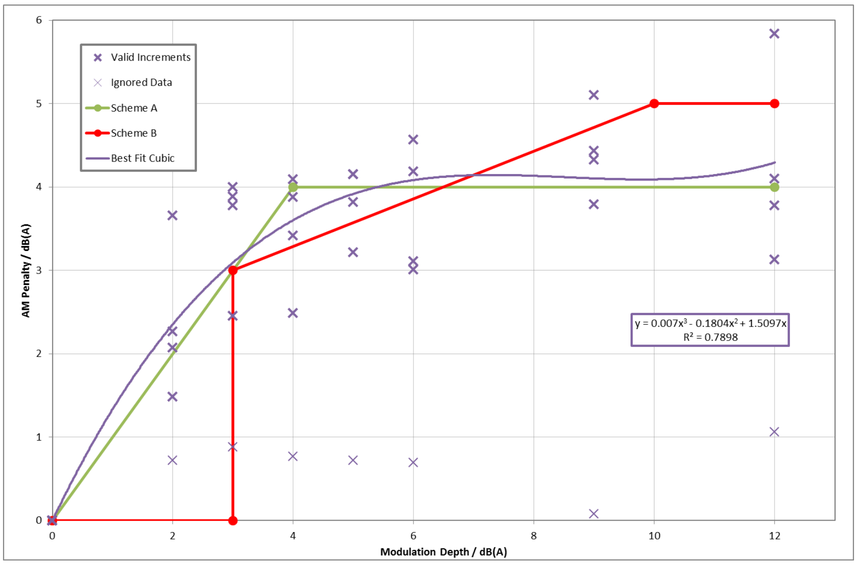
Inspection of Fig 4 indicates that:

- *the index for ‘ marginal annoyance’, i.e. the ‘Difference in ABBS Level’, can be expressed in decibel (dB) terms*
- *apart from the 45 dB(A) results (dark blue line)[3], the marginal annoyance appears to have little obvious dependence on overall level, and the normalised data are fairly well grouped*
- *this supports the normalisation approach adopted and indicates that it is indeed possible to separate out annoyance due to the overall level from that due to the modulation depth, suggesting a possible penalty scheme.*

Fig 4 gives a slightly misleading impression, in that the results for individual data points have been joined by straight lines. If these are removed – see Fig 5 – it gives a clearer picture of the underlying data and suggests ways in which this data can be effectively modelled.

[3] *It is possible that the 45 dB(A) results indicate that, at high overall noise levels, the impact of a given level of modulation is reduced, although more experiments would be needed to verify this.*

Fig 5 Developing a Model for Marginal Annoyance



Ignoring the 45 dB(A) overall level results, a third order, 'cubic' polynomial has been fitted to the remaining data points – see purple line. A simple piece-wise, continuous linear model can be developed - Scheme A (green line) - which is broadly equivalent to this, defined as follows:

- *a sloped line running from (0, 0) to (4, 4)*
- *a flat line at 4 dB from (4, 4) to (12, 4).*

This suggests a maximum level of penalty, for modulation depths of up to 12 dB peak to trough, of 4 dB.

However, in forming a penalty scheme, there are a number of practical considerations which should be considered:

- *according to ETSU-R-97, 'This modulation of blade noise may result in variation of the overall A-weighted noise level by as much as 3 dB(A) (peak to trough)… …The noise levels recommended in this report take into account the character of noise described in Chapter3 as blade swish. Given that all wind turbines exhibit blade swish to a certain extent we feel this is a more common-sense approach given the current level of knowledge' [3]. This suggests that there should no AM penalty for modulation depths of less than 3 dB*
- *according to BS 4142:1997 'Certain acoustic features can increase the likelihood of complaint over that expected… …such features are taken into account by adding 5 dB to the specific noise level to obtain the rating level' [6].This suggests that the maximum AM penalty for modulation should be 5 dB, not 4 dB.*
- *according to ETSU-R-97, the maximum penalty for tonal noise is 5 dB [3].*

Given these constraints, an alternative penalty scheme can be conceived – Scheme B - as the red line shown on Fig 5.This is defined as follows:

- *a flat line at 0 dB from (0, 0) to (3, 0)*
- *a vertical line at 3 dB running from (3,0) to (3, 3)*
- *a sloped line running from (3, 3) to (10, 5)*
- *a flat line at 5 dB from (10, 5) to (12, 5).*

It is this model which has been adopted as the penalty scheme in RenewableUK's proposed template planning condition for AM.

2.1 Comparison with Results from Recent Japanese Research

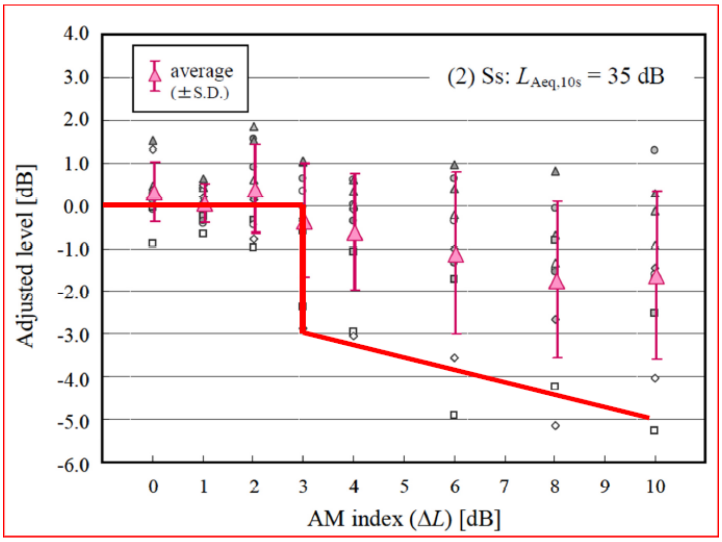
performed very similar experiments to those at the University of Salford [7,8].

As before, a number of test subjects were placed in a specially designed listening room and asked to adjust the level of a realistic, modulated wind farm noise to have the same level of 'noisiness' as an identical un-modulated sound.

Several different depths of peak to trough modulation were investigated, i.e. 0, 1, 2, 3, 4, 5, 6, 8 & 10 dB. Also two different overall noise levels were considered, i.e. 35 & 45 dB(A).

Keys results from this research are shown in Figs 6 & 7, where the 'AM index ΔL [dB]' is equivalent to the peak-to-trough modulation depth referred to earlier, and the 'Adjusted level [dB]' is equivalent to a 'penalty' for the degree of modulation[4]. Results for individual test subjects are shown, as well as the mean values (pink triangles) and error bars (± 1 standard deviation unit).

Fig 6 *Results from Japanese Research at 35 dB with RenewableUK Penalty Scheme*

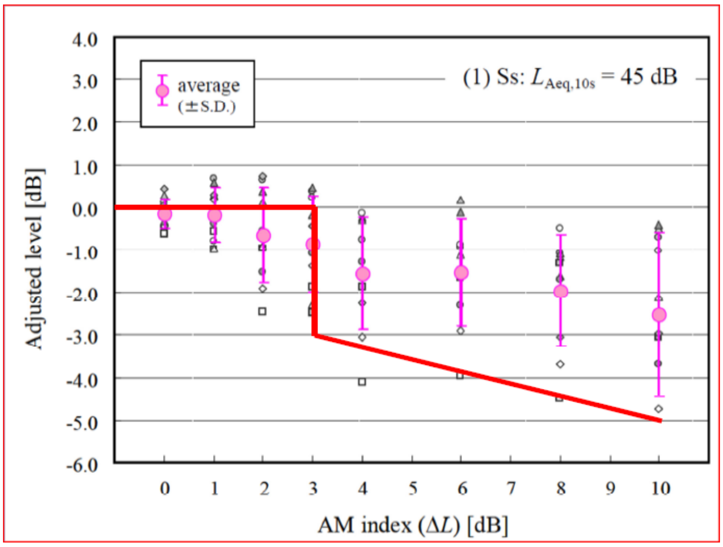


Inspection of Fig 6 - 35 dB(A) - indicates that:

- *AM with a peak to trough level of < 3 dB appears to have little impact on overall annoyance*
- *above 3 dB, average annoyance increases gradually, with increasing AM depth, up to a maximum of ~ 2 dB, for 10 dB of AM.*

[4] *Note sign difference due to the design of the experiment.*

Fig 7 *Results from Japanese Research at 45 dB with RenewableUK Penalty Scheme*



Inspection of Fig 7 - 45 dB(A) - indicates that:

- *results are broadly similar to those for 35 dB(A)*
- *AM with a peak to trough level of < 2 dB appears to have little impact on overall annoyance*
- *above 2 dB, average annoyance gradually increases, with increasing AM depth, up to a maximum of ~ 3 dB, for 10 dB of AM.*

Also shown on Figs 6 & 7 is the penalty scheme derived from the University of Salford data presented in Section 2 earlier. This is clearly considerably more conservative than an equivalent penalty scheme which might be derived solely from the Japanese results. Indeed, it is clear that the proposed penalty scheme provides an envelope which includes not only the average responses to the tests, but also the majority of the individual test results from test subjects.

Based on this, it can be concluded that the proposed penalty scheme is consistent with the latest Japanese results and, indeed, is conservative in this context.

3 Questions and Answers

Discussions during the development phase of this scheme threw up a number of questions relating to the AM planning condition and, because they are likely to be of interest to a wider readership, they are reproduced here:

Q1 *Why place a 5 dB limit on the amplitude modulation penalty?*

A1 *This 5 dB limit derives from British Standard 4142 (1997), which relates to rating industrial noise in mixed residential and industrial areas [6]. This seems to be the most relevant guidance currently extant in the UK.*

Q2 *The procedure is (necessarily) complex and requires computationally intensive analysis. As it will be difficult for most individuals to implement, are there any plans to provide a freely-available software analysis tool? Such a tool would have the benefit of providing a level playing field for all parties.*

A2 *The proposed methodology is not especially cumbersome, particularly when compared to the tonal analysis process in ETSU-R-97. However, such software is currently being developed and will be made available in the near future.*

4 Conclusion

This brief document provides an explanation and a justification for the penalty scheme presented within the template planning condition for amplitude modulation (AM) recently published by RenewableUK [1].

To assist with uptake, the new AM condition has been published in a form which shows how it can be easily integrated into the 'Example Planning Conditions' published within the Institute of Acoustic's 'Good Practice Guide' [2]

It is also shown that the penalty scheme proposed has been derived from fundamental research performed by the University of Salford and is entirely consistent with recent AM research performed in Japan.

5 References

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4. *von Hünerbein S, King A, Piper B & Cand M (2012) Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect. Work Package B2: Development of an AM Dose-Response Relationship, Final Report to RenewableUK*
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6. *BS (1997), Method for rating industrial noise affecting mixed residential and industrial areas, BS 4142:1997, ISBN 0 580 28300 3*
7. *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, Proceedings of the Internoise 2013 conference, Innsbruck, Austria, 15 – 18 September 2013*
8. *Yokoyama S, Sakamoto S & Tachibana H (2013), Study on the amplitude modulation of wind turbine noise: Part 2 – Auditory experiments, Proceedings of the Internoise 2013 conference, Innsbruck, Austria, 15 – 18 September 2013*
9. *Lee S, Kim K, Lee S Kim H & Lee S (2009), An estimation of the amplitude modulation in wind turbine noise for community response assessment, Proceedings of the Third International Meeting on Wind Turbine Noise (WTN2009), Aalborg, Denmark, 17 – 19 June 2009*

Note to Table 3: The geographical coordinate references are provided for the purpose of identifying the general location of dwellings to which a given set of noise limits applies.

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