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Affective Response to Amplitude Modulated Wind Turbine Noise

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Summary

Residents living adjacent to wind farms are exposed to a combination of turbine noise and background noise with all its environmental and local constituents. As the amplitude modulation character in turbine sounds is thought to specifically contribute to the annoyance response listening tests were conducted in a controlled laboratory environment with the aim to find annoyance ratings as a response to modulated wind turbine sounds.
The stimuli were 20 s noise samples systematically changing in L_{Aeq} level and estimated modulation depth. They were presented to 20 participants in random order. The participants rated the annoyance of the noise samples on an absolute scale and adjusted an unmodulated reference sound in volume to be equally annoying as the noise samples.
In agreement with a previous study by Lee et al. (2011) annoyance rating trends are shown to increase significantly with sound level and not statistically significantly with modulation depth. A clear on-set of annoyance at a modulation depth threshold was not observed. The results are interpreted in the context of the study limitations and comparisons between the LAeq and LA90 metric are drawn.
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1. Introduction

The presented work is part of the project “Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect”. The project comprised a total of six separate work packages most of which were concerned with the mechanism and categorisation of amplitude modulation sound from wind turbines. The results were obtained within Work Package WPB2: ‘Development of an AM Dose-Response Relationship’.

The work was motivated by findings of Janssen *et al.* (2011) and others that WT noise is more annoying than other environmental noise at the same noise level. As a contributing factor sound characteristics have been suggested; in particular the amplitude modulated (AM) character as well as its irregular sound level variation.

A previous study (Lee *et al.,* 2011) investigated the affective response to synthesised WT sounds based on recordings with the aim of finding a dose-response relation between modulation and annoyance ratings. According to this study AM modulation depth increases annoyance ratings. However, annoyance scaled more strongly with overall sound level than AM strength. Given the small number of stimuli used results were not sufficiently consistent to derive a dose-response relation. The study showed that more research needs to be done to understand average affective response to broadband sounds with AM characteristics.

This is one reason noise regulations on AM are still the exception. A limited number of countries and provinces such as New Zealand, Victoria, AU and New South Wales, AU have special AM conditions in their standards (NZS 6808:2010). The cited standard concedes that "No appropriate objective test for amplitude modulation has been standardised."

A second reason for this is the uncertainty of the prevalence of AM at typical receiver locations. Moorhouse *et al.* (2007) made an early attempt of estimating prevalence in the United Kingdom through investigating the number of complaints. However, because of the difficulty to identify AM, the number of complaints is not directly comparable to the prevalence of occurrence and the number of complainants was quite low a large uncertainty remained.

Another difficulty relates to reliably and objectively distinguishing AM WT sound from background noise (e.g. Bass, 2011 and Bass, 2012). And even if separation is possible there are many ways to quantify the strength of modulation in different metrics based on various physical measures such as intensity and power or on perception measures such as loudness and fluctuation strength.

Loudness is well established for steady sounds but first attempts of application to wind turbine stimuli have shown strong disagreement of loudness results from the German and American standard methods (King, 2012). Fluctuation strength as defined by Fastl & Zwicker has the advantage of being directly related to human perception but is somewhat cumbersome to calculate with software that is not readily available to most local authorities and noise consultants. In the policy context it is therefore useful to look at metrics that are widely used in environmental noise assessment, which is why this paper focuses on a very simple definition of modulation depth and categorises the signal strength in terms of L_{Aeq} and L_{A90}.

Following Lee *et al.* (2011) listening tests on synthesised stimuli are presented with the intention of investigating the affective response of listeners to modulated wind turbine sounds as a function of modulation depth and $L_{Aeq.}$ The effect of using L_{Aeq} and L_{90} metrics on the interpretation of annoyance response was also explored.

2. Study design

2.1 Stimuli

A typical schematic of a sound comprising of steady amplitude modulation (blue) and background noise (black) is shown in Fig. 1. It can be seen how modulation is masked with increasing background noise levels.

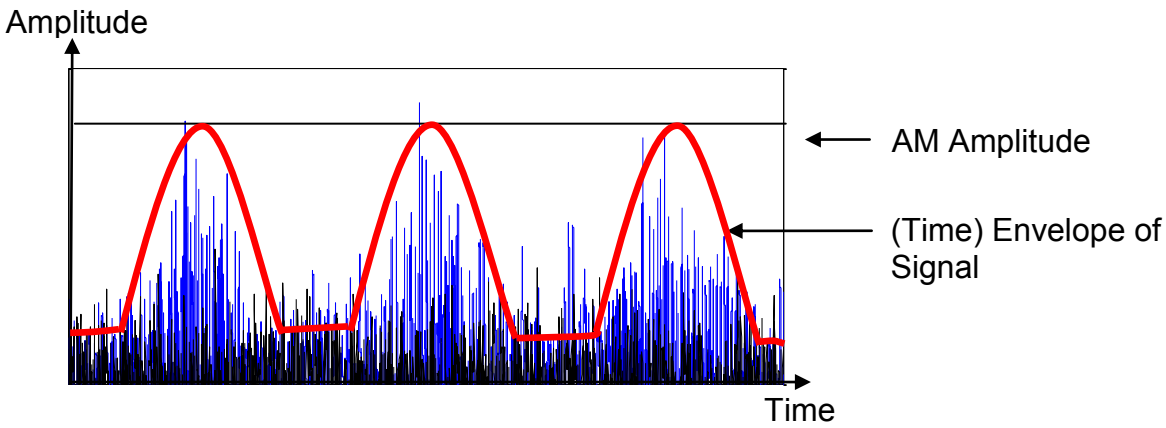

Figure 1 – Schematic representation of AM sound.

The Modulation Depth (MD) used in this study is therefore defined as the difference between the mean peak level and the mean trough level in the A-weighted RMS time series for any consecutive group of pulses over the length of the test stimulus and derived from 100 ms averages of L_{Aeq} according to Fig. 2.

The MD value was mainly used for stimuli design purposes. The term 'modulation depth' has currently no accepted definition and the exact value depends on the protocol adopted for analysing the modulated signal. This factor highlighted the central importance of relating any specific response to measured AM levels in a consistent way.

As part of the broader project, more robust metrics were investigated and that results were considered against these metrics, but for simplicity the present paper presents all results as a function of the MD parameter determined as shown in Figure 2.

The stimuli were created by overlaying a steady masking noise of typical wind turbine spectral characteristics with AM pulses to achieve a stimulus with a target L_{Aeq} and MD. The masking noise was designed as in von Hünerbein *et al.* (2010). In summary:

- A typical spectrum was derived from 47 recordings in accordance with IEC 61400-11 (2006)
- Propagation effects were simulated using the NORD2000 propagation model (Plovsing & Kragh, 2006)
- A random white noise of constant amplitude was filtered using the spectrum and the phase randomised to produce the unmodulated WTN sound

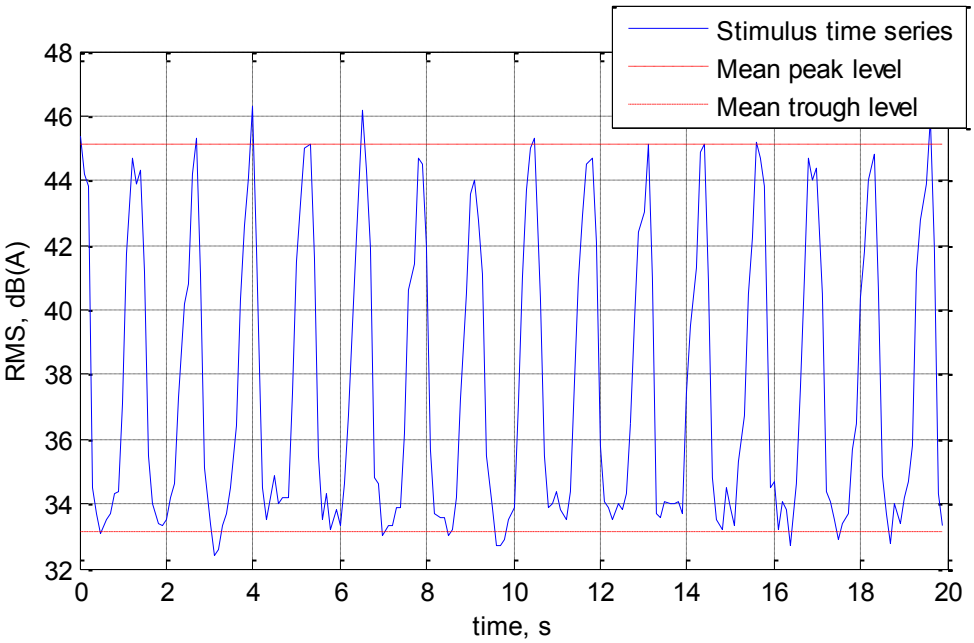

Figure 2 – Measured time series for a typical stimulus containing a 12±0.25 dB(A) modulation depth with an L_{Aeq} of 40±0.15 dB(A).

The AM pulses had a frequency and time characteristics as shown in Fig. 3, based on an asymmetric Gaussian profile, properties which were derived from different AM recordings. These pulses were overlaid on the un-modulated steady masking noise to create the modulated sound (see Figure 2 for example).

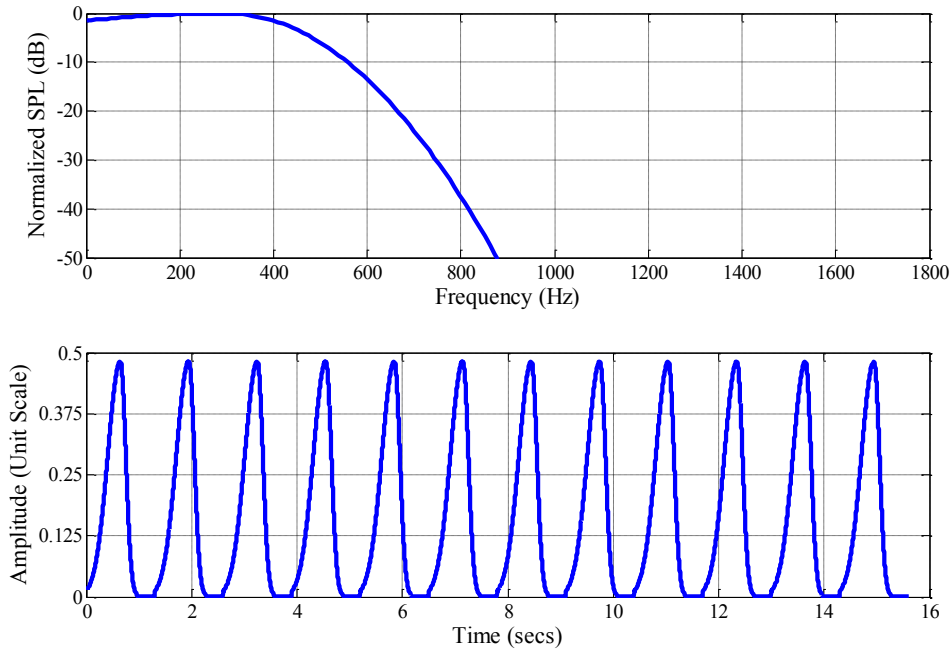

Figure 3 – AM stimulus properties a) frequency envelope with peak at 350 Hz, and bandwidth of 400 Hz. b) time envelope with a rise time of 70% and a drop time of 30%.

The different modulation parameters are tabulated in Tab.1. The modulation depth of 12 dB(A) was assumed to be beyond the maximum that would commonly be observed in realistic scenarios. The small increments between 2 and 6 dB(A) were chosen to possibly observe an onset of perceptibility. The L_{Aeq} ranged from 25 - 45 dB(A). The lower limit was assumed to be the onset of perceptibility in most background noise scenarios. The maximum L_{Aeq} was selected as a typical upper limit of acceptability. Values in bold denote stimuli that were rated by all participants, whereas values in normal font were stimuli that were rated for validation purposes by a subset of participants.

Key parameters (main test in **bold**)		
Modulation depth MD, dB(A)	8 different values	0**, 2, 3, 4, 5, 6, 9, 12**
Sound level of total stimulus L_{Aeq} dB(A)	3 values plus 2 for validation	**30, 35, 40** 25 and 45

Table 1 – Stimuli design parameters

2.2 Test setting

To reproduce wind turbine sound as accurately as possible the tests were conducted in the listening room whose setup, sound reproduction and sound quality control procedures can be found in von Hünerbein *et al.* (2011) and von Hünerbein *et al.* (2010).

The test results presented here stem from the sliding scale ratings which participants adjusted as shown in the top half of the Graphical User Interface (GUI) in Figure 4. Results from comparative tests will be presented elsewhere.

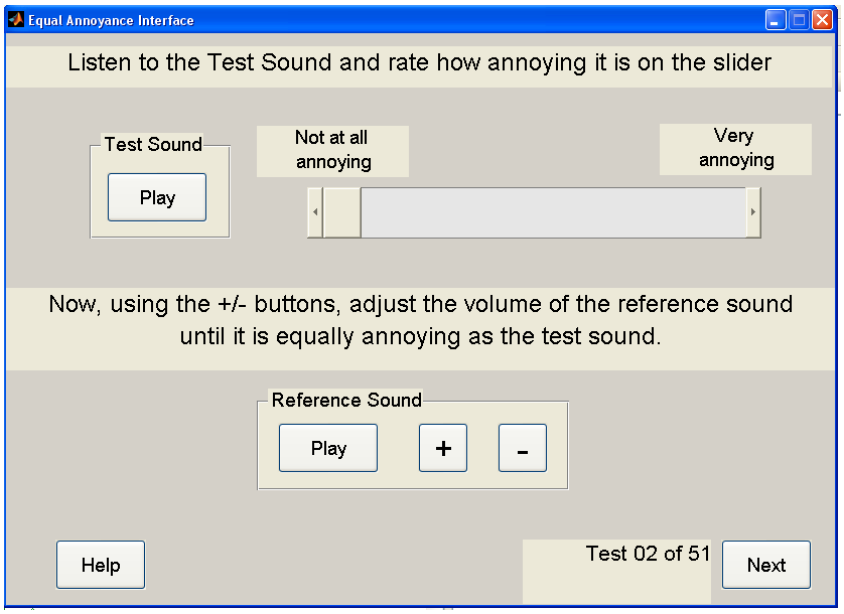

Figure 4 – Graphical user interface to measure equal annoyance and annoyance on a sliding scale.

2.3 Participants

20 listeners, 8 female and 12 male of normal hearing participated in the tests. The age distribution is centred between 20 and 30 with 6 participants in their mid-thirties and beyond.

3.0 Results

Using the 11 point scale for absolute annoyance ratings in the final listening tests allowed plotting the annoyance ratings as a function of L_{Aeq} in groups of MD (Figure 5a).

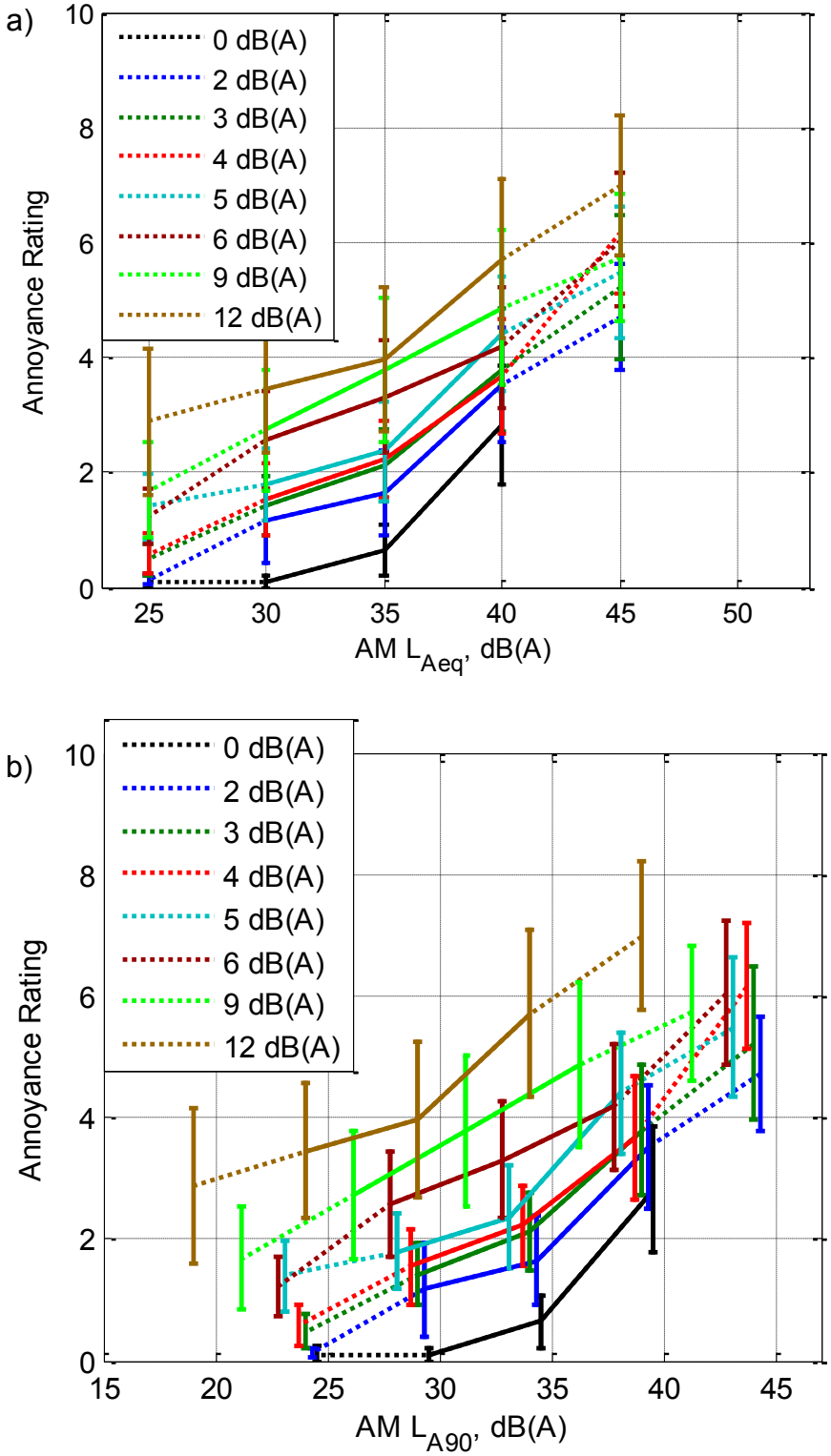

Figure 5 – Mean annoyance rating of AM test stimuli as a function of modulation depth and L90 b) in comparison to ratings as a function of L_{Aeq}.a). Solid lines are results from final test, dotted lines from the validation tests with reduced participant numbers. The legend specifies MD, error bars denote 95% confidence intervals. See data in Table 1.

This presentation is in a similar form to published results by Lee *et al.* (2011). Figure 5a shows that mean annoyance ratings consistently increase with the L_{Aeq} of the AM stimuli. Un-modulated stimuli were clearly rated as less annoying than modulated stimuli. A systematic increase with modulation depth is also apparent although some of the ratings overlap especially at higher L_{Aeq} values. This can be explained by results from Legarth (2007) who found that it was difficult for listeners to correctly identify the change in modulation depth in a signal. Therefore when perception of these changes is difficult it is not surprising that annoyance ratings show similar inconsistency. The error bars denote 95% confidence intervals (CI). They are smaller than one point on the annoyance rating scale for low L_{Aeq} and low MD. At high L_{Aeq} and MD the error bars span up to 2.2 points (25%) of the rating scale which is a large value but not unexpected for an attitudinal parameter like annoyance. The statistical significance of the result in the presence of large error bars is further discussed in the context of **Figure** .

A similar study (Lee *et al.*, 2011) showed results with similar general features like the strong increase in annoyance ratings with L_{Aeq} and less pronounced and sometimes overlapping ratings with increasing modulation factor.
Because Lee *et al.* used a different metric for modulation depth their results cannot be directly compared. Lee *et al.* used the standard 11 point scale according to ISO15666 (2003). They found minimum annoyance ratings of 1.5/2.5 and maximum annoyance ratings around 7/8 for two different tests, respectively. The minimum values in the current study are lower because stimuli with lower L_{Aeq} values were included. The maximum values are similar to results in Figure 5 which is surprising because Lee *et al*. included L_{Aeq} values of up to 55 dB(A) in comparison to the 45 dB(A) used in the current study. This can possibly be explained by the descriptors used for the maximum annoyance rating was "very annoyed" in the current study and "extremely annoyed" for the study by Lee *et al.*

Figure 5a) shows sound levels as L_{Aeq} values. Another common measure is L_{A90}. In Figure 5b) the same annoyance ratings have been plotted as a function of the respective L_{A90} equivalents. The increase in annoyance ratings with increasing MD is clearly visible in both representations. The difference between the two measures only becomes significant at MD $\geq$ 9 dB(A) when L_{A90} suggests that the contribution of AM to annoyance might be larger than suggested by the L_{Aeq} measure. This is because L_{A90} is lower by up to 7 dB(A) at MD = 12 dB(A). It should be noted though that MD has rarely been observed to exceed 10 dB(A).

Figure 6 shows the mean annoyance ratings as a function of modulation depth with isolines of L_{Aeq} to bring out any MD related trends more clearly. Like in Figure 5 it can be seen that L_{Aeq} levels clearly change the average annoyance ratings and at the lowest L_{Aeq} the stimuli are the least annoying. In comparison modulation depth increased the mean ratings only slightly which given the large error bars is statistically insignificant. A clear onset of annoyance with modulation depth is not apparent from the Figure. 95% CI are large as expected for an attitudinal parameter like annoyance.

To assess the significance of increased annoyance ratings, statistical analysis using a GLM ANOVA has been performed using SPSS™. The results suggest that L_{Aeq} increases annoyance significantly whereas the modulation depth does not with current numbers of participants. Given the consistent increase of annoyance ratings with MD it seems likely that a small but significant effect would be found with a larger number of participants. Beyond 6 dB(A) the curves seem to flatten off for L_{Aeq} of 25, 30 and 35 dB(A). A similar decrease albeit with much less data has been observed Vos *et al.* (2010) for low frequency AM broadband noise.

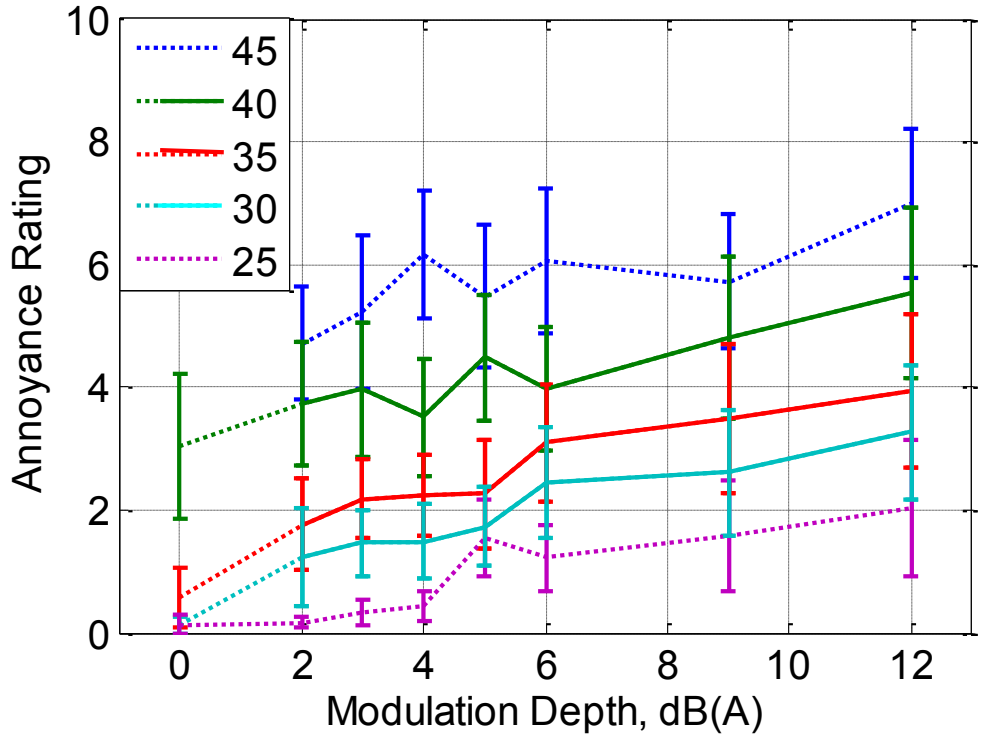

Figure 6 – Absolute annoyance ratings of AM stimuli as a function of modulation depth. Solid lines are results from final test, dotted lines from the validation tests with reduced participant numbers. The legend specifies the L_{Aeq} of the test stimuli in dB(A). See data in Table 1.

4.0 Conclusions

Listening tests have been conducted with the aim to find annoyance ratings as a response to modulated wind turbine sounds. The test stimuli were grouped by estimated modulation depth and LAeq. The term 'modulation depth' has currently no accepted definition and the exact value would depend on the adopted metric. LAeq was then replaced LA90 to find whether the interpretation of annoyance ratings would change.

Sound pressure level was shown to dominate the annoyance response. In contrast the increase in modulation depth did show small but not statistically significant increase in annoyance ratings. The comparison between L_{Aeq} and L_{A90} measures was not designed to evaluate best correlation with human response. However, it was seen that significant differences between the measures would only occur at the very highest naturally occurring modulation depths. The full project report is available under Cand (2013).

5.0 Acknowledgements

The presented work is part of the project "Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect". It was funded by RenewableUK.

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