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A METHOD TO CONTROL AMPLITUDE MODULATION IN WIND TURBINE NOISE WITHIN THE UK PLANNING REGIME

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WSP | Parsons Brinckerhoff was commissioned by the then UK Government Department of Energy and Climate Change (DECC) in 2015 to undertake a review of research into the effects of and response to the acoustic character of wind turbine noise known as Amplitude Modulation (AM), or more specifically an increased level of modulation of aerodynamic noise as perceived at neighbouring residential dwellings, with a view to providing protection where it is justified within the planning regime. This paper summarises the key findings from the review of those papers on the state of knowledge of AM, its effect on people, and the dose response relationships that exist. The paper will describe the potential methods proposed to control AM, the recommended factors for a method suggested to DECC, how that condition may be written in accordance with UK Planning Policy, and the feedback received to date follow publication of the research report by DECC.
Keywords: wind turbine noise; amplitude modulation; exposure-response; planning control

1. Introduction

Community response to wind turbine noise (WTN) remains a sensitive topic in the UK, and amplitude modulation (AM) is one issue that has been the subject of much debate. The fluctuating level of the amplitude envelope in WTN can be audible and when sensed can increase the annoyance people report upon hearing it [1]. When compared with other sources of environmental noise at the same exposure level, this AM characteristic is believed to be one of the factors contributing to heightened negative response to WTN [2, 3].

Recent research, funded and published by the UK Government, reviewed evidence on human perception and response to AM in WTN, with the aim of recommending an AM control for wind farm planning. Full details of the project aims, methodology and team structure are available in existing publications, including the Govt report deliverables [4, 5]; the recommendations include the use of the objective method for detecting and rating AM in real WTN signals devised by the Institute of Acoustics (IOA) AM Working Group (AMWG) [6][1].

2. AM exposure-response review

Following search and sifting phases, 71 publications on AM were examined in detail [4]. Further studies have been reviewed subsequently to consider ongoing research developments. A review of epidemiological field studies into WTN showed that to date these have examined only time-

[1] Use of this method has been made in the presentation of results in this paper, which have been re-scaled where possible from the original AM measures used, to enable wider comparisons using the AMWG metric, which utilises the level differences within a third-octave band-pass filtered range of the A-weighted L_{eq} signal envelope sampled at 0.1s intervals, denoted here as $\Delta L_{Aeq,100ms(BP)}$, with 'BP' signifying the filtered frequency range.

averaged noise level-based exposure-response relationships; the subjective effect of varying AM in the signals has not been directly quantified. The primary adverse health effect consistently identified by these studies in relation to exposure to WTN is annoyance; sleep disturbance and stress are also highlighted by some authors, but the evidence in many cases suggests these effects are more closely related to the annoyance experienced than to the noise exposure. Evidence for a direct relationship between WTN exposure at typical levels (eg 25-45 dB $L_{\mathrm{Aeq,T}}$ outdoors) and disturbed sleep is not consistent, and use of objective measures of sleep disruption (rather than self-reporting) do not support a direct association [7, 8]. Meanwhile, a significant relationship between self-reported annoyance and sleep disturbance has been consistently observed [9, 10]. This finding suggests that it would be sufficient to develop a control for AM from the evidence base for annoyance; by reducing annoyance, the associated indirect pathway effects would be expected to be similarly reduced.

The experimental evidence reviewed also indicates that, of the acoustic factors contributing to the annoyance response to AM in WTN, the time-averaged overall level and the depth of modulation appear to be most important in determining response. Results from lab experiments reported in refs [11, 12] are shown[2] in Figures 1 and 2a (N = 30 and 20 respectively). The results for $L_{\mathrm{Aeq,T}}$ show statistically significant ($p < 0.05$) relationships with annoyance; the results for modulation depth (MD) are weaker, with significance typically found when comparing high and low depth values from the ranges.

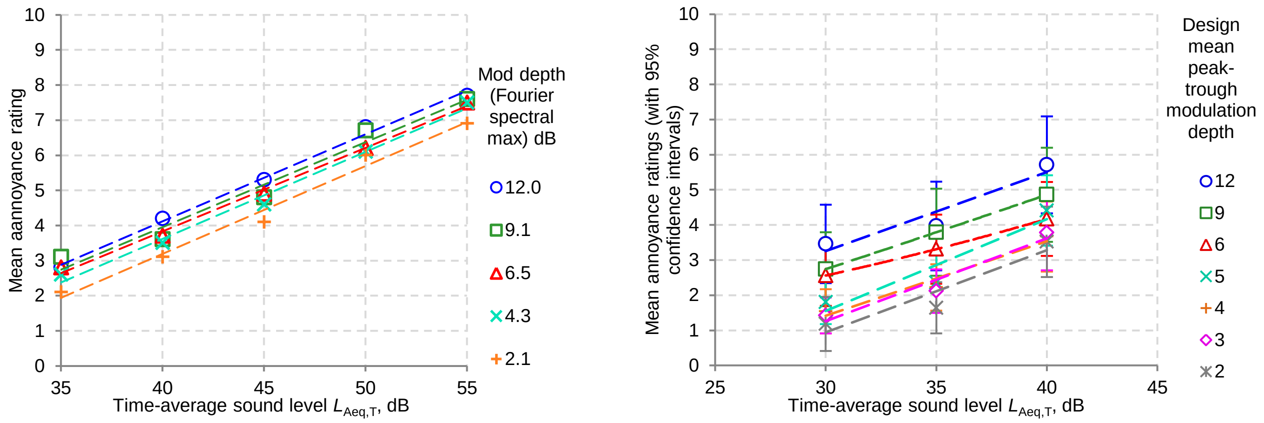

Figure 1: AM WTN time-average sound level exposure-response relationships identified by (a, left) Lee et al, 2011 [11]; (b, right) von Hünerbein et al, 2013 [12]

Further evidence for the influence of MD has been reported in lab study results in ref [13], shown in Figure 2b (in which the MD for each stimulus is shown relative to its maximum value), which shows a significant effect of relative modulation strength on rated annoyance (N = 19). Results from a field-based case-study at a site with historical noise complaints also indicated a significant relationship between the degree of AM within measured WTN and the reported annoyance [14]. In general across these studies, differences in individual subjective ratings and associated uncertainty tend to expand with increasing MD.

A threshold for perception of the fluctuations in a modulating WTN-like sound has been studied by Yokoyama et al [15]; the lab results shown in Figure 3, indicate that around 40-50% of participants (N = 17) perceived fluctuation at MDs of 2 dB $\Delta L_{\mathrm{Aeq,100ms(50\text{-}200Hz)}}$, increasing to 95-100% at 3 dB. This suggests that fluctuation in broadband WTN-like sounds is likely to be sensed by most people with normal hearing at approximately 2 to 3 dB $\Delta L_{\mathrm{Aeq,100ms(BP)}}$, with around 3 dB being approximately the certain detection threshold. Overall $L_{\mathrm{Aeq,T}}$ also appears somewhat related to the likelihood of AM detection, in agreement with other psychoacoustic results [16].

[2] Linear regression lines in the figures are shown only to aid visibility of broad trends and potential relationships, not as tested parametric models.

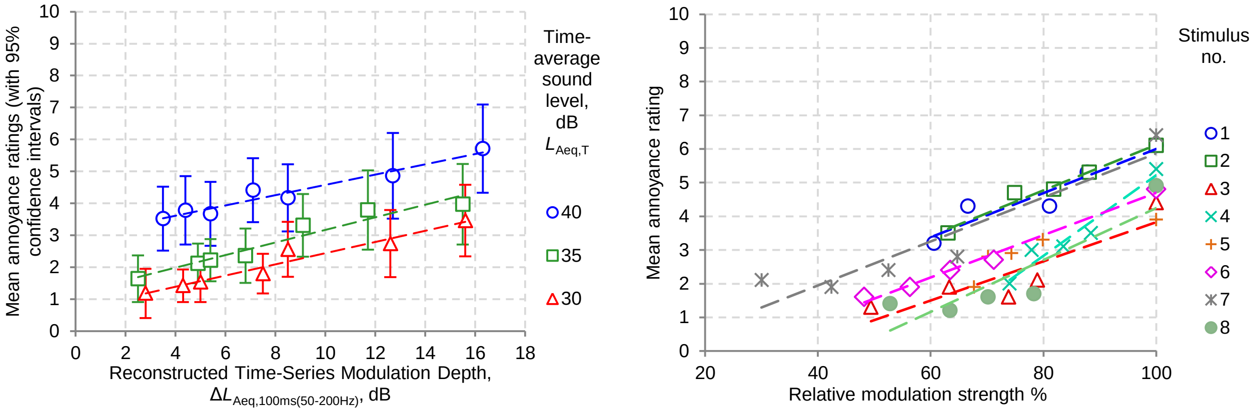

Figure 2: AM WTN modulation depth exposure-response relationships identified by (a, left) [adjusted from] von Hünerbein et al, 2013 [12]; (b, right) Ioannidou et al, 2016 [13]

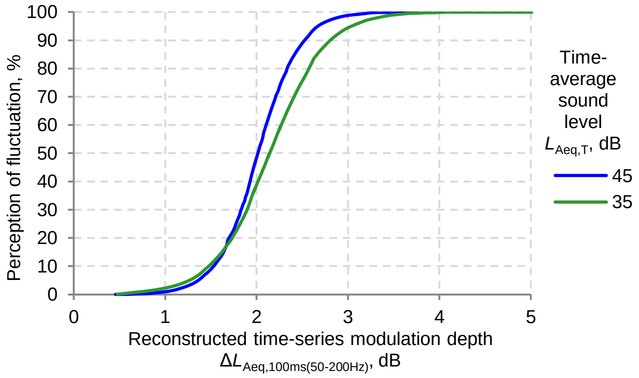

Figure 3: WTN AM detection threshold identified by [and adjusted from] Yokoyama et al, 2015 [15]

Some studies have examined the subjective equivalence of a modulating WTN sound compared with its steady-amplitude counterpart. This has been examined using a method of paired comparison adjustment, in which one of the signals is modified in level until the participant judges both sounds to be equivalent. In the results of ref [12], the steady signal was adjusted relative to the AM, and the target response for equalisation was ‘annoyance’, while in those of ref [15], the AM signal was adjusted, and the judgement prompted was of perceived ‘noisiness’. Nonetheless the experiments were very similar, and the results are shown together in Figure 4a. On average, the equivalence between the AM and negligible-AM WTN sounds used is approximately in the range 0-4 dB. The results of an experiment with a larger sample (N = 60) have been used to develop a logistic regression model for the probability of high annoyance associated with WTN sounds exhibiting i) no significant AM and ii) periodic AM with a varying MD in the range of around 6 to 9 dB [17]. This model, as shown in Figure 4b, indicates an equivalent annoyance for periodic AM of around 1-3 dB for time-average levels in the range 35-55 dB $L_{Aeq,T}$.

Human sensitivity to periodic AM in broadband noise has been shown to peak over the modulation frequency (f_m) range 2-8 Hz [16, 18, 19]. The f_m of WTN AM has likewise been shown to have some effect on lab ratings of annoyance. The results reported in ref [13] and shown in Figure 5a indicate a visible (but not significant) trend of increases in annoyance over the f_m range 0.5-2.0 Hz.

Sensitivity test results presented in ref [12] also indicate an increase in annoyance when comparing f_m of 1.5 Hz with 0.8 Hz (the difference was not tested statistically due to the small sample size: N = 11). The results are shown in Figure 5b, which, for the sake of comparability, have been subject to adjustments to account for differences in $L_{Aeq,T}$ and MD between stimuli, and so should be interpreted with caution (the adjustments are detailed in ref [20]). In both cases (Figure 5a and b), it can be seen that differences between the stimuli, such as spectral content, can have a larger influence on ratings than f_m over the ranges considered.

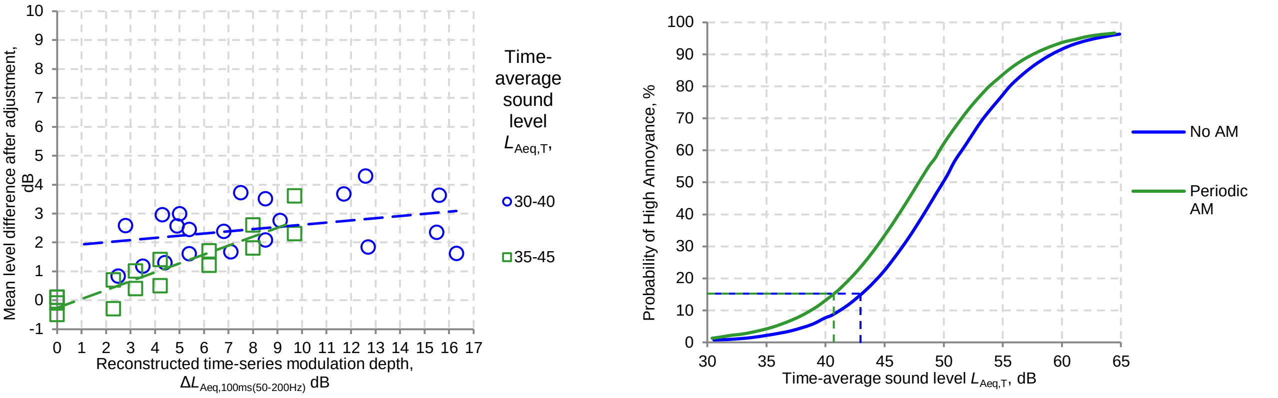

Figure 4: AM WTN equivalent response exposure-response relationships (a, left) identified by [adjusted from] (○) von Hünerbein et al, 2013 [12] and (□) Yokoyama et al, 2015 [15]; (b, right) Schäffer et al, 2016 [17]

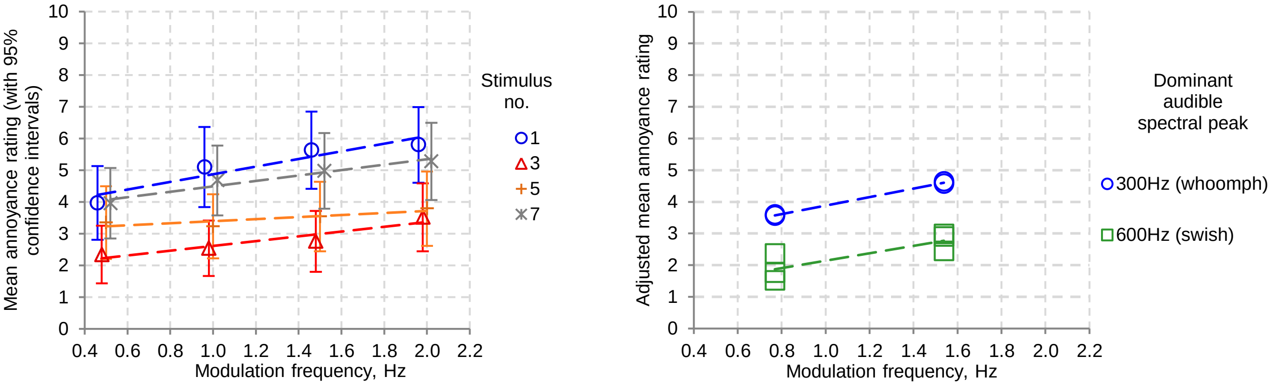

Figure 5: AM modulation frequency exposure-response relationships identified by (a, left) Ioannidou et al, 2016) [13]; (b, right) [adjusted from] von Hünerbein et al, 2013 [12]

The study reported in ref [17] found that AM WTN was rated more annoying at the same $L_{\text{Aeq,T}}$ than AM road traffic noise (RTN) and equivalence in annoyance translates to a level difference of roughly 5 dB, in broad agreement with the field-study analysis of ref [2] and related observations in ref [3]. This was considered potentially attributable to the f_{m} range of the WTN AM stimuli, and the closer proximity of this range to that of peak fluctuation sensitivity (in contrast with the lower f_{m} of the RTN stimuli used). Accordingly, it is surmised that f_{m} has an effect on response, but, within the context of modern large-scale commercial wind turbines, with f_{m} in the range 0.5 to 1.5 Hz (and typically around 1 Hz), this can be expected to be relatively slight.

The spectral content of AM has been highlighted in the negative experiences that have sometimes been reported by affected residents [21], with low-frequency character (‘whoomph’) raising particular concern [22, 23]. The indicative results in Figure 5b (in which the influence of MD has been adjusted for) suggest the lower frequency range AM (‘whoomph’) is rated more annoying than the upper range (‘swish’). Counterintuitively, the tests in ref [13] did not show any significant modification of annoyance by intermittent ‘whoomph’-like AM; responses instead appeared to be determined by the AM character of the ‘swish’-like AM periods – the stimuli used were short in duration however. Further work would be beneficial to more fully understand the influence of the spectrum of AM WTN on responses.

As summarised in refs [4, 5], there have been several studies, both field and lab-based, which have highlighted a wide range of non-acoustic factors with a significant influence on the annoyance that people attribute to the WTN they are exposed to, including: noise sensitivity, turbine visibility, colour and flicker, attitude to wind energy and turbine aesthetics, exposure to wind energy-related media, neighbourhood land-use, economic involvements with wind turbines, association of sound with wind turbines, and general health. These factors present real difficulties for analysts in isolating and identifying the effects associated with acoustic parameters and characteristics, such as AM.

The effects of diurnal variation in AM (ie time of day, occurrence intermittency and prolongation) are not well documented in the evidence reviewed, although there are field reports of increased impacts occurring at evening, night or early morning [24, 25]. Van den Berg [24] has shown how atmospheric and wind conditions more frequently encountered at night are likely to increase risk and severity of AM occurrence. Further probable factors are increased sensitivity and sense of intrusion during the night-time, and lower levels of other background sounds [26]. The influence of AM exposure variation on expected responses has not yet been studied in sufficient detail to draw useful conclusions, but should be expected to be an important factor in determining responses.

In general, the results from laboratory-based exposure-response studies are limited by small samples typically recruited from somewhat unrepresentative populations (eg urban-dwellers, university students and staff); one exception is the sample recruited by Schäffer et al [17], which was larger and with a broader representation, including a wide age group (range 18-60, median 35) and a majority of rural residents (52%), however none of the participants were already living near turbines. The lab exposures used are also relatively brief, between 10s and 30s; while this may not significantly affect the short-term response ratings expected within the experimental setup, this cannot be expected to be closely representative of the responses that might be expected from those exposed within sensitive settings, for longer durations, and in which the expectation of cessation of the exposure (ie respite) may be uncertain. The advantages afforded by these studies include the ability to accurately control and quantify (short-term) exposure-response and isolate the acoustic parameters without the influence of the many potential confounding factors and risk of subject preconceptions that may accompany field research around existing wind turbine sites.

The field studies on the other hand examine real long-term exposure, and involve WTN-exposed populations – however, this raises the risk of selection bias, especially if problematic situations involving WTN (or other contentious issues, such as visual impacts and intrusion) have arisen. Many of the studies do not feature control cases for comparison. All the field studies identified are cross-sectional, preventing examination of changes in the measured responses over time (and establishment of causal relationships). Very few field studies identified directly compared quantifiable AM with scaled responses, which limited their value against the aims of the project.

The above issues aside, one of the main knowledge gaps identified in the review is the effect of variation in AM exposure: occurrence, intermittency and prolongation.

3. AM planning control

The evidence reviewed above indicates that AM increases annoyance, and that the expected response to occurrences can be quantified relative to an equivalent period of non-AM WTN. This supports the proposal for a character penalty scheme control (similar in concept to standardised methods, such as BS 4142:2014 and ISO 1996-1:2016), which can be imposed at planning stages, to be activated in reaction to complaints about possible AM occurrences.

Based on the studies considered, it is proposed that a combination of the time-averaged level and MD parameters is a reasonable objective expression for the expected annoyance response to AM WTN. A more detailed expression could include spectral content and modulation frequency, but the current evidence appears to be less clear on the strength of these parameters. One approach to addressing the issue of spectral content is inherent within the AMWG method [6], which employs filtering to ensure the signal is evaluated for the frequency range that produces the maximum AM rating; this metric is believed to be a robust and effective approach to detecting and evaluating real AM in WTN. A proposed threshold for the penalty is 3 dB $\Delta L_{\mathrm{Aeq,100ms(BP)}}$; this is the MD at which detection can be confidently expected, and adverse responses may start to increase significantly. Based on the equivalent response evidence, the magnitude for the penalty is a variable 3 to 5 dB against a MD range of 3 to 10 dB (and 5 dB thereafter). The AM character penalty scheme as proposed is shown in Figure 6a, with relevant data from the supporting evidence. The result of application of this penalty scheme to the absolute response data shown in Figure 1b is illustrated in Figure

6b – it should be noted that this is a separate response dataset from the equivalent response data used to inform the penalty shown in Figure 6a. As would be expected, the average responses are significantly (p<0.01) correlated with the rated level $L_{Ar,T}$ dB, with Pearson r-value of 0.872 (compared with r-values for the separated parameters of 0.684 for $L_{Aeq,T}$ dB and 0.693 for $\Delta L_{Aeq,100ms(50-200Hz)}$ dB).

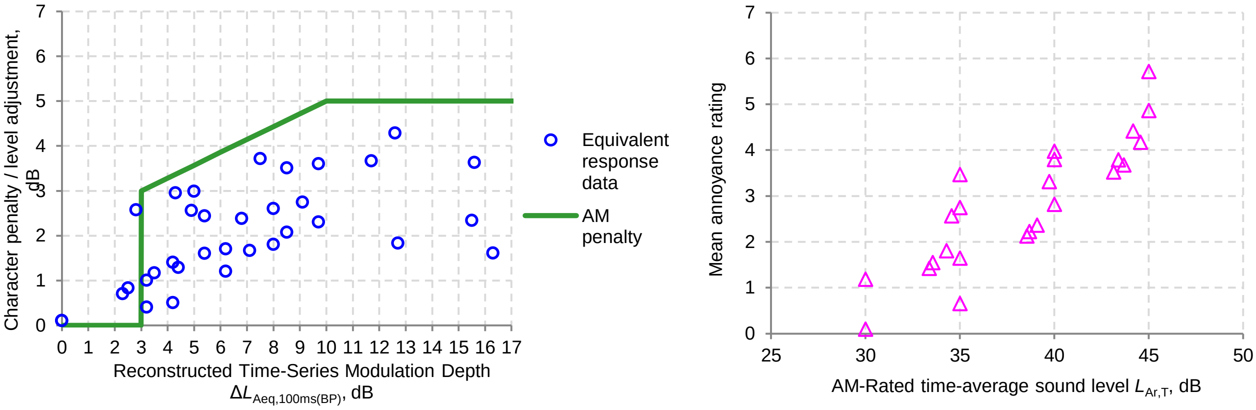

Figure 6: AM penalty scheme (a, left) value to be applied and equivalent response datasets [adjusted from] von Hünerbein et al, 2013 [12] and Yokoyama et al, 2015 [15]; (b, right) application to absolute annoyance response dataset from von Hünerbein et al (2013)

A further feature of the scheme proposed is the control for night time AM: if a higher limit has been imposed for night-time WTN in the planning consent at any given wind speed, the difference between the day and night limits at that wind speed would be added to any AM penalty assigned to the same wind speed. This should afford sufficient protection against AM at night, when it appears it could otherwise cause the greatest disturbance.

The steps to be taken in applying the proposed scheme are outlined in Table 1:

Table 1: Application steps for the AM penalty control scheme

Stage	**Action**
Instatement	Added within a planning condition attached to new development consent for wind turbines falling inside the scope of the method. Monitoring of WTN would be required under the scheme, including the specification of equipment suitable for obtaining measurements to produce ratings of AM in accordance with the AMWG Reference Method.
Activation / monitoring	Triggered in reaction to complaints about AM in WTN received by the local authority. Monitoring of WTN would be conducted.
Rating	The ratings produced would be considered against the penalty scale shown in Figure 6a. The corresponding penalty values would be added to the WTN levels measured using existing methodologies for compliance testing as set out in ETSU-R-97 and the IOA Good Practice Guide [27, 28] for integer wind speeds to derive a rated equivalent level $L_{Ar,T}$.
Assessment	The rated levels, including the additional night-time protection affordance, would be compared with the overall noise limits set out in the planning consent.
Enforcement	Limit exceedances demonstrating a breach of the condition could be enforceable by the local authority, in which case the specific wind speeds in which limits are breached should frame the mitigation requirements – this may be formalised by a ‘mitigation scheme to be agreed and implemented’ clause, or similar, in the condition.
Mitigation	This should address a reduction so that the overall rated level consistently meets the limits; there are two pathways to achieve this: i) reduce AM in the WTN; ii) reduce the time-average level of WTN.

Practical implementation of the above application remains an area that requires further technical development. In particular, an issue highlighted within refs [4, 5, 21, 29] is how to apply the penalty to the derived WTN levels for compliance assessment – the current UK good practice set out in refs [27, 28] is to derive averaged WTN levels for each wind speed, subtract averaged background sound and compare with the limits. The penalties for AM should be calculated from the AM ratings for individual 10-minute periods, not from a rating averaged over a longer period. For compatibility with current practice, one approach would be to then average the penalties over the assessment period, and apply this to the average level (in effect this is the same approach taken to tonal character penalisation).

The control is underpinned by the assumption of f_m similar to those in the research supporting the scheme, and the range that forms the basis for the practical application of the AMWG rating metric, ie up to 1.6 Hz. Where higher f_m are expected, such as with small domestic turbines, it is possible the scheme could underestimate the AM character impact. Further research could extend this applicability.

The review has highlighted a lack of evidence on which to determine the effect of prolongation of exposure on expected responses. This is an area that has not been well explored, yet is relevant in determining the application of the penalty scheme. It does not seem reasonable to suggest that brief, sporadic or occasional occurrences of 10-minute periods of AM ≥ 3 dB MD constitutes justifiable grounds for imposing corrective measures, yet it seems clear that frequent and prolonged exposure to AM ≥ 3dB (where the sound is audible) should be avoided; in between these extremes an effective, practical, sustainable and legally sound approach must be established.

4. Conclusions

The research review has concluded that i) WTN contributes to annoyance, ii) AM increases that contribution, and iii) that existing annoyance effect evidence provides a reasonable basis for an objective control framework for AM based on a principle of 'equivalent response' with negligible-AM WTN. A suitable character penalty control incorporating the main acoustic exposure factors thought to affect response has been recommended for application in planning wind farm developments. However, significant questions remain regarding the extent and prolongation of impacts, and how this can be addressed within a practical, effective and lawful implementation of the proposed scheme.

It is hoped that the proposed control will lead to the development of more proactive approaches to prediction and mitigation of AM on the part of wind farm operators and developers.

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