PRACTICAL INVESTIGATIONS OF AM MITIGATION

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1 INTRODUCTION

The issue of amplitude modulated noise (often referred to as ‘blade swish’ or ‘AM’) arising from the operation of wind turbines is presently receiving a high focus of attention. Whilst the acceptability of audible noise from wind turbines continues to be the subject of considerable debate, the specific issue of AM has been specifically considered in a number of studies which have reported disturbance from this feature of the wind turbine noise. In some cases, the observed characteristics of the AM could not be explained by existing, validated theoretical models of ’blade swish’. This has led to speculation as to the potential existence of quite different source generation mechanisms, and/or propagation effects, which could explain the observed differences between the well understood and quite ‘normal’ blade swish noise and this other manifestation of AM noise. It was also identified that there was no generally accepted metric for describing and quantifying AM noise in general, and that the knowledge of the subjective response to it was limited compared to, for example, tonal noise which has been the subject of extensive work.

To progress these issues a research project comprising theoretical and experimental investigations into the amplitude modulation of noise from wind turbines was commissioned by RenewableUK, and headed by the authors of this paper, with the results published[1] in late 2013. This paper will briefly summarise some of the key results from this project in terms of the causal mechanisms identified for different types of amplitude modulation noise from wind turbines, and consider the objective method developed to rate the modulation. The paper will mainly focus on more recent investigations which provide further support for the results of these previous investigations and point towards the development of practical mitigation measures for an atypical feature of wind turbine noise.

2 RENEWABLEUK RESEARCH

2.1 Normal Blade Swish

The aerodynamic self-noise generated by the interaction of flow turbulence and the surfaces of a wind turbine’s rotor blades is said to be amplitude modulated when its level exhibits periodic fluctuations; for a fixed observer this will be at a rate corresponding to the frequency at which each rotor blade passes a fixed point (the ‘blade-passing frequency’). This amplitude modulation (AM) is always detected close to a rotating wind turbine, and is commonly described as ‘swish’. The principal source of audible noise from the blades is “trailing-edge noise”: caused by the interaction of turbulence in the boundary layer with the trailing (thinner) edges of the rotor blades (Figure 1). Because this noise source has particular directional radiation characteristics, even in a smooth laminar flow, an observer close to the wind turbine would experience periodically varying levels of noise related to the passage of each blade.

This characteristic blade swish had been explained by theoretical models[2] validated in the field through measurements prior to the above-mentioned RenewableUK research. AM resulting from this trailing edge noise directivity effect was therefore termed ‘Normal AM’ (NAM), it being an inherent and therefore ‘normal’ feature of wind turbine noise.

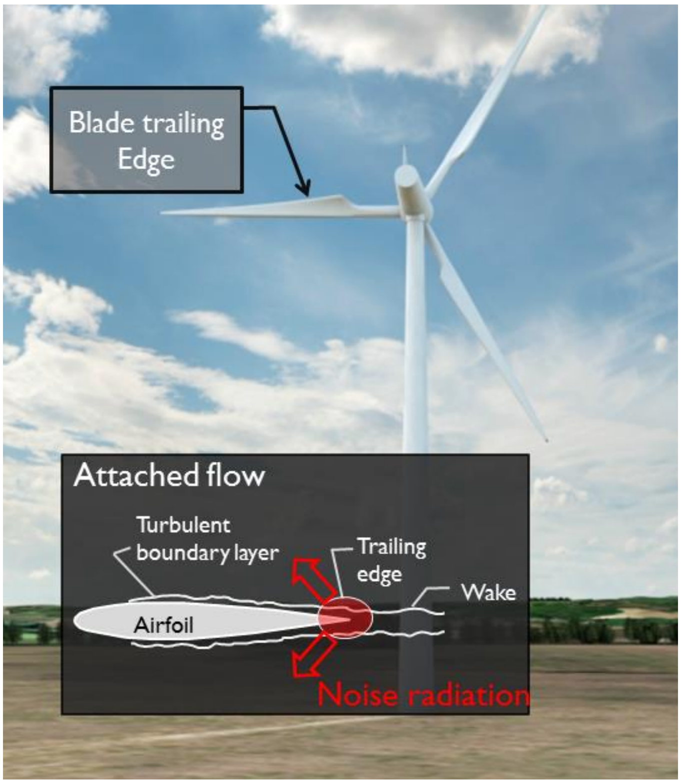

Figure 1 – illustration of a turbine blade trailing edge in normal operation and the preferential noise radiation of the noise generated

2.2 "Other" AM and causal explanations

Observations made by several authors[3,4,5,6,7] reported AM in the far-field, particularly in downwind directions, with variations in noise levels of a magnitude sometimes higher than that predicted for NAM (5 to 10 dB), the noise being described as more impulsive in character, more of a 'whoosh' or 'thump' rather than a 'swish', with increased dominance of frequencies in the 200-400 Hz region. For example, a review of such evidence was published[8] in 2011.

These occurrences cannot be accounted for by the established trailing edge noise mechanism of normal blade swish (NAM), and it was therefore concluded that other source generation mechanisms and/or propagation effects must be responsible. AM phenomena with characteristics falling outside those expected of NAM became termed 'Other AM' (OAM). However, whilst the existence of OAM was relatively widely acknowledged at that time, the causal mechanisms of OAM were not understood and, as a consequence, no specific information was available to guide operators or manufacturers towards the likelihood of occurrence of OAM or appropriate remedial actions to mitigate its effects in circumstances where it did occur.

The existing model of NAM referenced above[2] was further developed[9] as part of the RenewableUK project to include the effect of the separation of the flow from the blades for part of their rotation, or *transient blade stall*. Whatever the cause of such localised blade stall, the turbulent air in the stalled region creates an increase in noise generation with a lower frequency content and different directivity characteristics when compared to trailing edge noise. Thus a momentary and periodic increase in noise level is created when such flow separation occurs over a small area of each turbine blade in one part of the blade's rotation only (for example as it passes over the top of its path: see Figure 2). This results in modulation with significantly different characteristics to NAM; in particular, the change in directivity of stall noise is predicted in the model to result in significant modulation levels in upwind and downwind directions. These characteristics were observed experimentally using detailed measurements[10] as part of the project.

Figure 2: Illustration of detached flow over part of the rotation (partial stall)

In the absence of techniques such as actual blade surface measurements, it was not possible to positively identify the occurrence of stall as part of the RenewableUK research project referenced above. However, additional work[11] undertaken independently of the above described project, provided further support to this hypothesis through the analysis of detailed on-blade measurements and additional theoretical modelling. This research also outlined potential mitigation measures which would in theory reduce the potential onset of blade stall and therefore potentially reduce or prevent the incidence of OAM.

3 INVESTIGATING AM MITIGATION MEASURES

3.1 Approach taken

The authors undertook additional investigation at sites at which OAM was found to be present and mitigation measures based on the above studies were investigated. The prevalence of AM in the noise was compared before and after the mitigation measures were put in place. This paper describes results at one of these sites: a large scale modern wind farm consisting of more than 5 turbines with a generating capacity of more than 2 MW each, situated in relatively flat terrain. Instances of OAM were observed at the site, particularly in conditions of increased wind shear, at two locations both situated approximately 1 km away from the nearest turbines at which measurements were undertaken following complaints. No physical modifications to the turbine blades were made, and mitigation took the form of a modification to the operation of the turbine via changes to the turbine control software, developed in consultation with the turbine manufacturer. The standard operating pitch angle, describing the rotation of the blade around its axis, was modified with the specific aim of reducing the angle of attack of the flow on the blades (and therefore the potential for stall) for the wind speed region over which OAM had been detected.

A 01dB Duo sound level meter was installed at each location. The sound level meter equipment is certified Class 1 under IEC 61672 and weatherproof, with connection to a battery supply to supplement its internal battery and allow for extended periods of operation. The microphone was mounted at a height of approximately 1.2 m to 1.5 m above ground using a tripod mounting, and fitted with a primary and secondary windshield system used to reduce wind-induced noise on the microphone. The A-weighted Leq and 1/3 octave band noise data was recorded continuously in 100 ms resolution for the period of the measurements.

3.2 AM detection and rating

Defining the magnitude of amplitude modulation ideally requires a robust and objective method that is applicable in a repeatable manner to real measured data. The key feature of AM that assists in its detection and analysis is the fact that the noise has a periodic character. Fourier-transform analysis techniques of the signal envelope (this signal envelope typically being provided by the $L_{eq,100ms}$ or similar) can be used to objectively identify the modulation frequency and then rate the magnitude of the modulation at this frequency.

The RenewableUK research[1] describes such a Fourier-transform technique, which was implemented in the MATLAB software. The sequence of the $L_{Aeq100ms}$ values represents the signal envelope; it is separated in sample blocks of 10s length (with a rectangular window) and de-trended using a polynomial function. The power spectrum of the envelope was then calculated, normalised by calculating twice the square root of twice the spectrum, and integrated over a moving window of 10% of the modulation frequency considered (typically around 0.15 Hz). The value of the local peak in the integrated modulation spectrum at the modulation frequency, which equates to the blade passing frequency of the turbine for samples containing wind turbine AM noise, results in a representative measure of the modulation magnitude: see example in Figure 3.

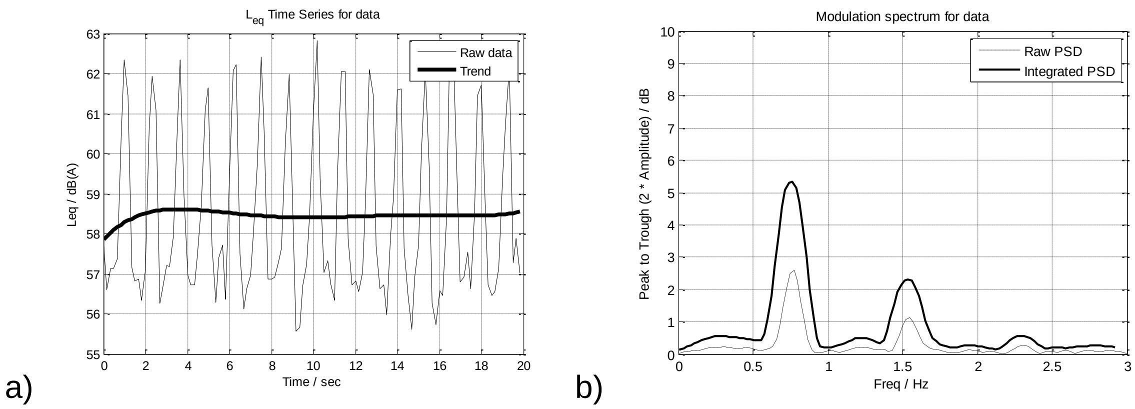

Figure 3 – a) Time history ($L_{Aeq100ms}$, arbitrary scale, as a function of time) and b) resulting modulation spectra (as a function of modulation frequency), both raw and integrated, for an artificial AM signal. A clear peak at the modulation frequency of 0.8Hz is visible in b).

The same method was applied to the measurements described, but applied to each of the 100 ms resolution 1/3 octave band levels between 100 and 500 Hz, instead of the A-weighted $L_{Aeq,100ms}$ values. Experience has shown that the analysis of the short-term evolution of the variations in certain 1/3 octave bands can provide a better characterisation of the modulation in many circumstances. This approach also filters out spurious noise sources that occur at higher or lower frequencies than those which dominate the wind turbine noise. The average AM "depth" or dB rating for each of the bands in that range was then averaged to provide a single metric.

Due to the highly variable nature of the wind turbine modulation in the far-field, a statistical analysis was found to be most useful in understanding the measurements. The distribution and variation of the calculated 10s AM metric magnitude values was analysed over each 10 minute period, and then related to the turbine operational data and meteorological data which was available at this resolution. Extended periods which were clearly affected by spurious data were excluded from the analysis: this is appears in the modulation spectrum as high values not "modulating" at a frequency characteristic of the turbines. As an example Figure 4 shows the evolution of the modulation spectrum for a period of 6 hours between 18:00 and 00:00 for a particular period analysed. In this example, the period between 20:30 and 21:00 is affected by spurious sources, which appear as horizontal lines on the plot, with the apparent "modulation" covering a wide band not restricted to a defined frequency related to the turbine(s). In contrast, a fixed vertical trend, around 0.8 Hz, appears in the plot towards the end of the period in question. This represents a frequency characteristic of the wind turbine AM, because for a three-bladed turbine operating at around 15 Rotations Per Minute (RPM), this corresponds to a frequency of f=3*RPM/60=0.8Hz. This can often be verified using RPM data from the wind farm control system. Furthermore, this trend is consistent/persistent in time, over periods of several minutes to several hours, which will be characteristic of wind turbines: they operate and respond to changes of wind speed conditions over these timescales. This differs from other more transient sources which do not have these characteristics. This constitutes objective evidence of the presence and influence of wind turbine noise and AM, and there is generally no need to verify this through audio recordings.

In contrast, Figure 5 shows examples of the time history of the raw $L_{Aeq,100ms}$ levels for extracts of the same period covered by Figure 4. The direct analysis of short-terms levels in this way, recommended different stakeholders[8], is problematic as it relies on a more subjective assessment of the variations, and their consistency, in what is often a very noisy signal. Figure 5a) shows a period of strong modulation in noise levels, but this is caused by bird noise, as could be determined from audio recordings or frequency analysis or subjectively from experience. Figure 5b) however shows a more complex example where instantaneous fluctuations are caused by a wide variety of sources, some of which are turbine noise and very difficult to identify directly. Even in the clearer example of Figure 5c) in which wind turbine AM dominates, the influence of other sources introduces corruption. Furthermore wind turbine AM may not always be apparent in the A-weighted signal as it occurs at frequencies which can be masked by other sources. This can be revealed in the analysis of more restricted bands of frequencies, where the Fourier techniques described assist greatly. Finally as wind turbine AM is known to vary greatly over the long-term due to its dependence on changing wind conditions (i.e. speed, direction or shear) over periods of weeks or months, the direct analysis of raw 100ms data is not realistically practical.

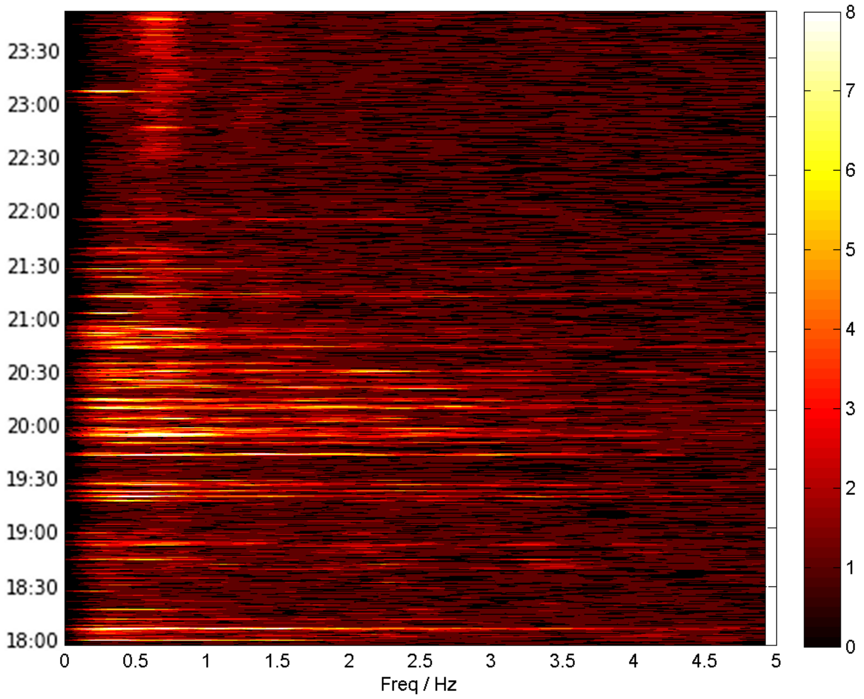

Figure 4 - "Waterfall" Plot showing the evolution of the modulation spectrum for the measured $L_{315Hz,100ms}$. The vertical axis the time in 10s blocks, and the horizontal axis the calculated modulation frequencies (0 to 5 Hz).

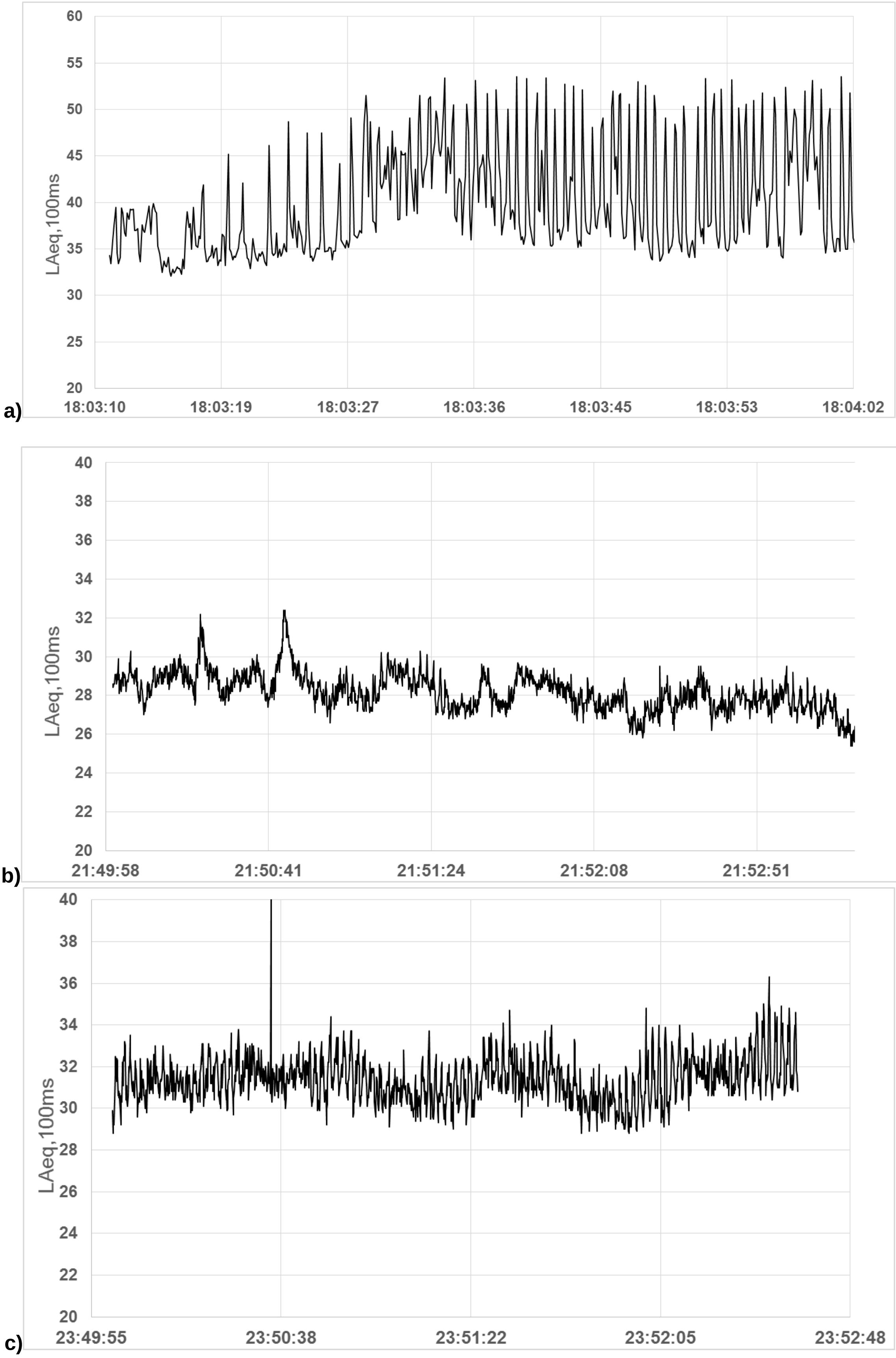

Figure 5 – example of time history evolution of the $L_{Aeq,100ms}$ from the period of Figure 4

In order to further minimise the influence of spurious sources, the analysis was restricted to late evening or night-time periods only (after 21:00 and before 06:00), and when the monitoring locations were downwind of the wind farm. The dataset was then sorted into 1 m/s wide wind speed bins. In each bin of the filtered dataset, the average and standard deviation of the variation of the dB modulation metric were calculated.

Figure 6 shows the results of the analysis at the one of the measurement locations (similar results were obtained at the second location). It can be seen that a significant reduction in the average modulation rating is apparent in the data following mitigation over the range of 4 to 7 m/s. It was over this range that disturbance was previously noted: the change in the blade pitch angle was therefore designed to be highest in these conditions. The reduction is such that the average + 1 standard deviation results over this range are lower than the pre-mitigation average results, which is evidence of a significant reduction.

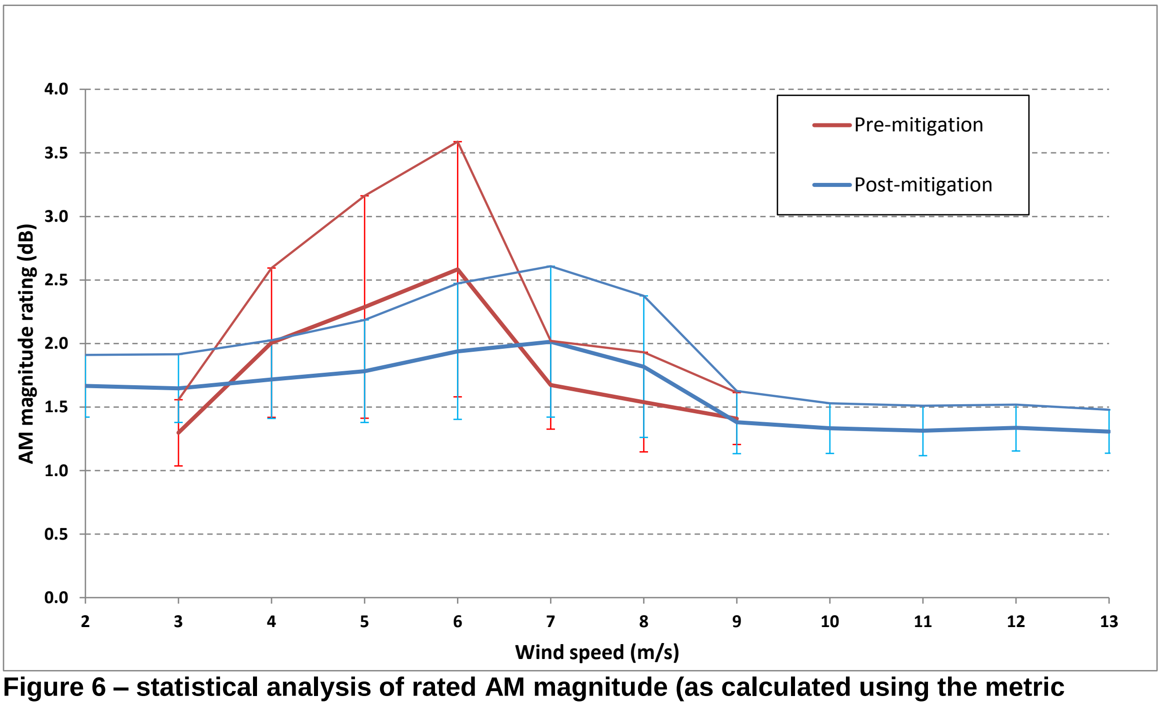

Figure 6 – statistical analysis of rated AM magnitude (as calculated using the metric described) for the periods analysed both pre- and post-mitigation, as a function of wind speed. Mitigation was applied in the range of 4 to 7 m/s. *Error bars represent one standard deviation (average + 1 deviation noted by thinner line).*

The foregoing analysis shows how appropriately modified turbine operation can create an appreciable and systematic reduction in the modulation measured at typical residential neighbour distances when compared to data previously acquired during which disturbance was reported. Complaints of noise from the wind farm are understood to have subsided at the site as a result of the turbine operational control changes. The analysis provides objective evidence to support this observation of reduced occurrence of complaints. Further details and additional results are set out in another publication[12].

4 CONCLUSIONS

The research project sponsored by RenewableUK in 2013 identified a likely generation mechanism which would explain specific instances of amplitude modulated (AM) noise which had been observed to occur in some cases at some wind farms in the UK and abroad. This was described as “other AM” as it could not be explained by the standard well-understood mechanism which describes the AM observed as standard in proximity to any wind turbine. Noise modelling showed that the observed characteristics of Other AM could be explained by the flow on the blades stalling for part of their rotation, and this was supported by specific field measurements undertaken as part of the same project.

The identification of this source generation mechanism has led to operational or design measures which would in theory minimise or fully mitigate the incidence of transient stall, and therefore Other AM. The authors undertook specific measurements on operating turbines at a site at which OAM had been observed. The systematic reduction observed when the mitigation was applied demonstrates that such strategies are possible and effective in practice. This also provided further support of the source generation mechanism identified. The analysis techniques used, based on Fourier techniques, were shown to produce meaningful and repeatable results. It is hoped that future turbine designs will aim to minimise the potential for this feature to arise, and that the methods for analysing and rating AM will become standardised[13] in the near future.

5 REFERENCES

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