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Measurements demonstrating mitigation of far-field AM from wind turbines

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Summary

The presence of amplitude modulated (AM) aerodynamic noise has been identified as potentially increasing the perception of operational wind turbine noise at typical neighbouring residential property distances. Work led by the authors was undertaken on the subject in the UK on behalf of RenewableUK. The paper will first summarise this work which identified in particular two distinct forms of AM: 'blade swish', which is an inherent feature of the operation of all wind turbines and which the research therefore labelled as 'Normal' AM (NAM), and a quite different form of AM which the research labelled as 'Other' AM (OAM).

NAM is caused by the flow of air over the trailing edge of the blades, and the acoustical characteristics of NAM (blade swish) are therefore defined by the source characteristics of such noise. OAM, however, was identified as most likely being related to localised transient stall effects occurring over restricted portions of the blade surfaces and for part of the rotational paths, which could be caused by a range of conditions, including meteorological effects and site and turbine design factors. Hence OAM is an intermittent and not inherent feature of wind turbine noise, with different acoustical characteristics to those of NAM.

The present paper presents results of a dedicated series of both near and far field measurements at two separate wind farms comprising 2MW+ wind turbines. Given the identified source mechanism for OAM, the paper reports measurements undertaken both pre- and post- the modification of the turbines' blades and/or operational characteristics. These modifications were aimed at reducing the potential occurrence of transient blade stall. Comparisons of these measurements are then presented which reveal potentially significant reductions in the occurrence of OAM, providing further confirmation of the source mechanism identified.

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 (considered below) 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’ (sometimes called Normal AM or NAM). This has led to different mechanisms being proposed to explain the observed differences between the well understood and quite ‘normal’ blade swish noise and this other manifestation of AM noise (“Other” AM or OAM).

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. The results of this research program were published [1] in December 2013.

In a series of novel and detailed experimental measurements [2], the work determined that instances of atypical or ’Other’ AM (OAM) were consistent with the predictions of the ‘transient stall’ theoretical model developed at the project outset[3]. In the far-field, instances of OAM were associated with propagation in the downwind direction and were reduced cross-wind, with increased peak to trough modulation depths of sometimes more than 5 dB(A) and increased acoustic energy typically in the 200 to 400 Hz frequency range. These characteristics would not be expected from NAM, but could be explained by the occurrence of stall on the turbine blades during part of the rotation: this source of blade noise has lower frequency characteristics and a directivity which is such that it may be perceived upwind or downwind of the source turbine, and so in the latter case in particular may propagate more effectively to the far-field.

In the absence of techniques such as actual blade surface measurements it was not possible to positively identify the occurrence of stall during these measurements, but further work by Madsen [4] (2013) provided support to the above hypothesis through the analysis of detailed on-blade measurements and additional theoretical modelling. This work discussed factors which may influence the onset of partial or transient blade stall, and noted that it would depend on blade design and turbine operational characteristics, in addition to meteorological factors. The report also identified potential technical mitigation measures, such as dynamic pitch control, which could reduce the incidence of stall and therefore also OAM in the far-field.

The present paper sets out results of further measurements subsequent to the above referenced research project, which set out the results of measurements at two sites at which OAM was found to be present and the source of complaints. At each site, mitigation measures were put in place and the prevalence of AM was compared before and after the mitigation measures were put in place.

2. Site A

2.1 Measurement description and survey setup

The first of the two sites comprised more than 5 turbines with a generating capacity of more than 2 MW each, situated on moderately elevated position surrounded by rolling terrain. On one of the turbines at the site, a “kit” was installed on the blades of the turbine, comprising several specific blade additions designed to improve or modify the flow of the air on the blades, and which was understood to likely reduce the potential incidence of stall on the blades. Based on the above theory regarding the underlying source mechanism for OAM, this was therefore likely to reduce the incidence of AM which had been observed in some instances in the far-field (approximately 1 km) from the turbines in some downwind and upwind conditions.

The survey comprised a combination of near- and far-field measurements undertaken simultaneously at four locations, over a duration of several months. The near-field locations (1 and 3) comprised ground-board based noise measurement systems which complied with the requirements of IEC 61400-11, and were situated at a distance from the turbine tower equal to its tip height (as required by the standard). The azimuthal location was varied throughout the survey in order to maximise the amount of data captured in downwind conditions (within +/- 15 degrees) as required by the standard.

The far-field measurement locations (2 and 4) were both situated at a distance of between 300 and 400 m from the test turbine in two different directions (approximately 90 degrees apart), in order to obtain measurements in a range of wind directions. These locations were placed to evaluate the noise at a further distance from the test turbine due to the expectation that modulation was considered more likely to be present at these locations more distant from the test turbine. The locations were chosen with consideration of the local terrain and the fact that further separation distance would have introduced potential ground screening between the turbine and the measurement location. The different locations are represented schematically in Figure 1.

The noise measurement systems used were capable of monitoring overall noise levels and, in addition, could also provide periodic audio recording for subsequent off-line analysis. The chosen noise measurement systems comprised individual Rion NL 52 units. These systems accord with the requirements of a Type 1 sound level meter. The sound level meters were each housed in an environmental enclosure and were battery powered. The clocks on all noise equipment were synchronised with Greenwich Mean Time (GMT or UTC) using a global positioning system receiver. This time synchronisation method was used to allow all noise data to be related to simultaneous data from the wind farm Supervisory Control and Data Acquisition (SCADA) system. All noise measurement systems were regularly acoustically calibrated. All the measurement systems were set to log continuous periodic ten minute periods of a range of parameters, as well as the short-term L_{Aeq} and 1/3 octave band levels

in more detailed resolution (100ms) to enable analysis of wind turbine Amplitude Modulation (AM).

The microphones at the far-field locations were mounted at a height of between 1.2 m and 1.5 m above local ground level and equipped with a proprietary RION enhanced windshield system used to reduce wind induced noise on the microphone and designed to maintain the required response of the measurement system. At the near-field locations the microphones were installed flush to the surface of 1.2 m diameter circular boards which were laid directly on the ground in order to control ground reflection effects. Each ground board based measurement system was additionally equipped with a two layer large windshield in accordance with the IEC 61400-11 standard. A rain logging system was also setup on the ground next to location 1.

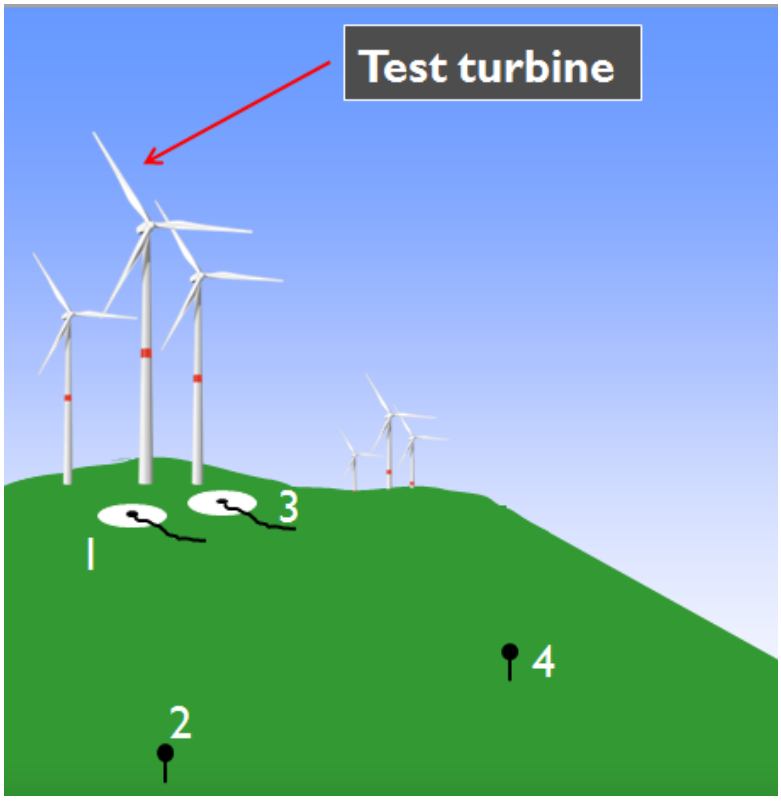

Figure 1 – schematic representation of the installed noise measurement locations (not to scale)

The nearest turbines to the one tested were shut down between 21:00 and 01:00 every night (in the wind directions of interest) in order to obtain a suitable signal-to-noise ratio in the measurements of noise emanating from the test turbine. The operation of the test turbine was also curtailed for limited periods at these times in order to obtain background measurements for the turbine sound power analysis.

Due to power issues the system at location 4 did not record data during most of the post-treatment phase. A preliminary analysis showed in any case that the recordings of the first phase at this location 4 were contaminated by the influence

of turbines situated further away, despite the shutdowns implemented. The analysis of far-field effects therefore focused on the measurements at location 2.

2.2 Analysis method

The success of any noise mitigation measures aimed at reducing the level of AM and/or the frequency of occurrence of AM to an acceptable degree needed to be objectively determined. At present no universally accepted objective methodology exists to quantify AM and criteria against which the output result of an objective methodology should be judged remain to be defined in a standard fashion. However, in order to provide some form of objective benchmark for the blade mitigation implemented, an AM identification and quantification methodology previously implemented by the authors as part of the above mentioned research [5] was developed and used. The analysis involved a computer code implementing a signal envelope Fourier analysis technique using the MATLAB software. This algorithm [5] undertakes a frequency analysis of the acoustic A-weighted signal envelope, using a Fast Fourier Technique (FFT), to produce a modulation spectrum.

For the present analysis, the technique was developed further and applied to the envelope of the narrow-band 1/3 octave band signal. 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. This AM analysis was undertaken for each 1/3 octave band between 100 and 500 Hz, as the analysis of sample AM recordings showed that these frequencies dominated the modulated signal observed in the far-field. The average AM “depth” or dB rating for each of the bands in that range was then averaged to provide a single metric. The analysis showed that this reduced the occurrence of false positives which can occur if only one frequency band is considered. The results of the analysis were imported into a database which combined the AM analysis results with turbine SCADA data (including wind speed and turbine power and yaw).

Due to the highly variable nature of the wind turbine modulation in the far-field, even for periods in which this feature is relatively marked, the residual effect of spurious events can still be significant. For this reason a statistical analysis was found to be most useful in understanding the measurements. The analysis is made in terms of the level of AM identified in individual 10 s periods. However, because of the high variability of AM observed in practice it is advantageous to quantify the AM magnitude over standard 10 minute periods over which turbine data is known. As there is currently no generally accepted method for such data reduction, for the purpose of this study the proportion of the data for which the 10 s rating exceeded a certain arbitrary threshold (3 dB) was considered for each 10 minute period. This was expressed as a percentage of the 10 min period for which the short-term AM ratings exceeded the arbitrary threshold set. This provides a measure of the prevalence of AM at the far-field location.

2.3 Analysis results - AM

The analysis focused on periods for which location 2 was downwind of the test turbine and during which the operation of the adjacent turbines was curtailed. The resulting valid dataset represented approximately 10 hours of data for the pre-treatment phase and approximately 30 hours of data for the post-treatment phase.

The analysis results are first shown in terms of overall statistics: see Table 1. This shows a clear reduction in the relative prevalence of AM. For example, the occurrence of periods with 5 % of AM rated above the threshold is reduced by more than half. However, a comparison of the range of wind conditions experienced (Figure 2) shows that both phases did not experience comparable wind speeds: the post-treatment phase experienced more periods of higher wind speeds (13 m/s and above) than were experienced during the pre-treatment measurements. Despite the extensive filtering undertaken, it is still the case that In these higher wind speed conditions more spurious results would be expected. A more meaningful comparison can be obtained by comparing like-for-like wind speed conditions between the pre- and post-treatment measurements. When the higher wind speed periods are excluded from the analysis, in order to provide a more meaningful comparison, then the reduction in the proportion of periods of higher AM becomes even more apparent: a ten-fold reduction from 40% to 3% is obtained in the 10 min periods where 5% of each 10 minute data has modulation ratings above the threshold: Table 1.

Figure 3 illustrates this reduction more clearly by showing the results of the AM analysis as a function of wind speed. The chart shows the calculated statistics (average and standard deviation) of AM prevalence for all the 10 minute periods analysed for each 1 m/s wide wind speed bin. The results demonstrate that the observed reduction in AM due to the blade treatments was indeed significant. Indeed, the average values of the selected AM metric determined from the post-treatment measurements are consistently and significantly lower than those experienced during the pre-treatment measurements, to the extent that the post-treatment results lie below the range of variability observed during the pre-treatment measurements. This observation is despite the significantly larger dataset obtained post-mitigation on which the analysis has been performed.

The results also show that, pre-treatment, the AM prevalence was highest for moderate wind speeds. This is consistent with previous observations at this site. Post-treatment there is no apparent influence of wind speed which suggests that the residual ’modulation’ likely represents spurious results or the effects of residual ‘noise’ in the analysis method rather than actual wind turbine modulation.

It is also apparent from the charts that a low persistence and strong variability in modulation levels can be observed in the results even when the data is filtered extensively and the analysis is made for the quietest periods. This variability remains a challenging aspect of the study of wind turbine AM noise. Although no standard methods are available, some are emerging. The method used in the

present paper is similar to other FFT methods [6] which have been used successfully in comparable studies [7]. In the present case, it was found necessary to analyse short periods (10s) in order to capture short-term modulation periods, and then to analyse the variability and prevalence of the AM across the multiple 10s periods analysed using statistical methods. This approach has proved efficient to implement, despite the large dataset studied, and effective in its ability to discriminate periods of higher AM. The resultant output has provided meaningful results demonstrating a reduction which appears to be rather significant.

Test turbine operating and upwind of location 2, neighbouring turbines curtailed…	**Pre-treatment**		**Post-treatment**			
			All wind speeds		**Excluding wind speeds ≥ 13m/s**	
	Periods	**%**	**Periods**	**%**	**Periods**	**%**
	63	100%	172	100%	141	100%
..and AM ≥3dB for >5% of 10 min	25	**40%**	27	**16%**	4	**3%**
..and AM ≥3dB for >10% of 10 min	6	10%	11	6%	1	<1%
..and AM ≥3dB for >20% of 10 min	0	0%	0	0%	-	-

Table 1 - Analysis of 10 minute periods AM statistics at location 2

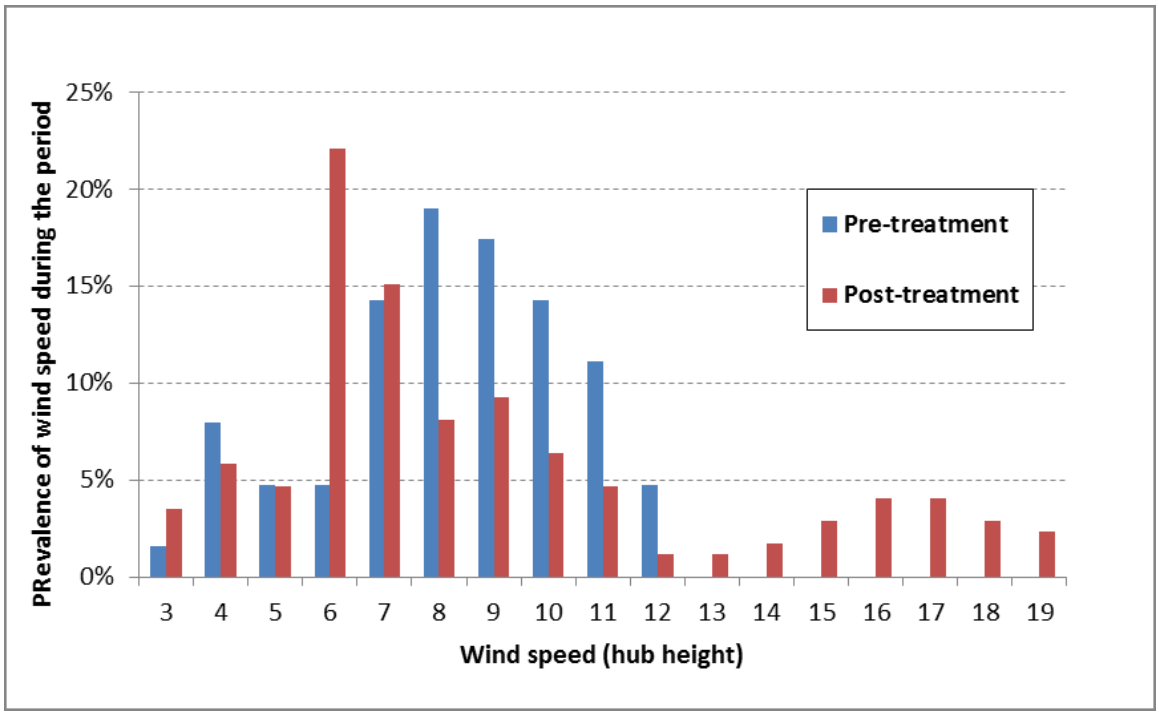

Figure 2 – range of wind speeds experienced during the periods analysed

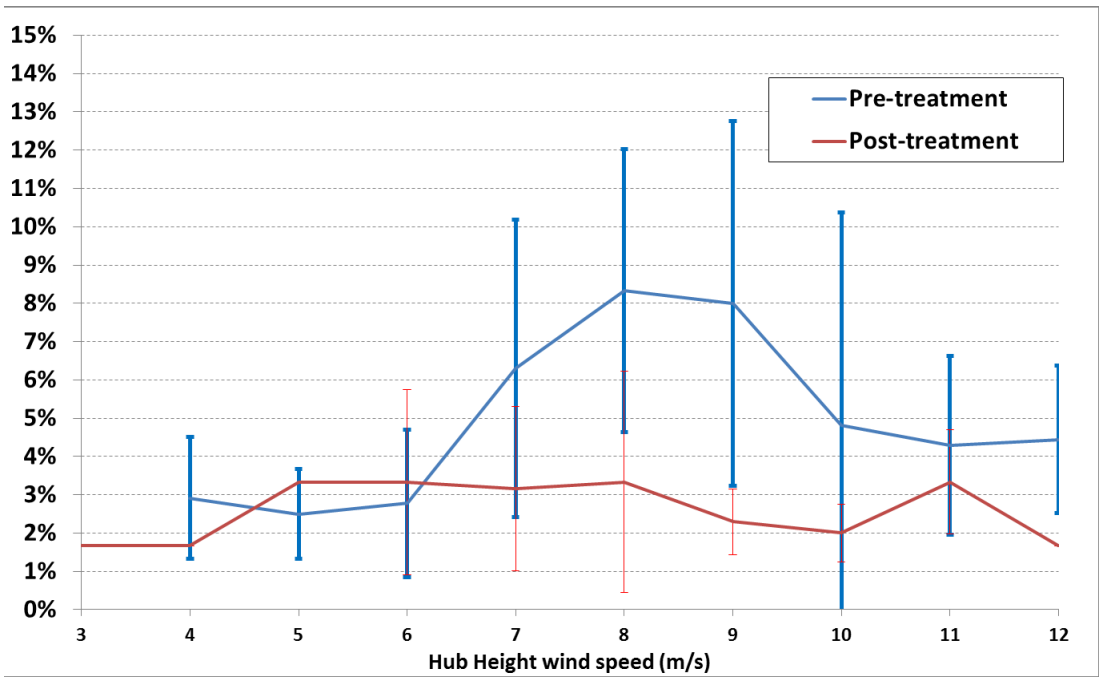

Figure 3 – Statistical analysis of prevalence of rated modulation above the threshold for all 10 minute periods as a function of wind speed (hub height) – the error bars represent the standard deviation in the data

2.4 Analysis results – Sound power

Noise levels measured at the near-field locations were analysed using the methodology of IEC 61400-11. A suitable range of wind speeds for this purpose was obtained for both the pre- and post-treatment phases. The analysis of the sound power showed that the overall A-weighted sound power levels measured before and after the treatment were similar, within the expected uncertainty for such measurements. However, examining the sound power spectra derived for each phase revealed a clearer effect of the blade treatment. Figure 4 illustrates that the treatments led to a reduction of the sound power between 50 and 400 Hz and, conversely, an increase above 600 Hz of the order of 3 to 4 dB(A). Despite this increase, because of the relatively enhanced attenuation of the higher frequencies due to atmospheric absorption, such a frequency shift in the near field of the turbines would correspond to a reduction of 1 to 2 dB(A) over a propagation distance of 1 km when calculated in accordance with the ISO 9613-2 method.

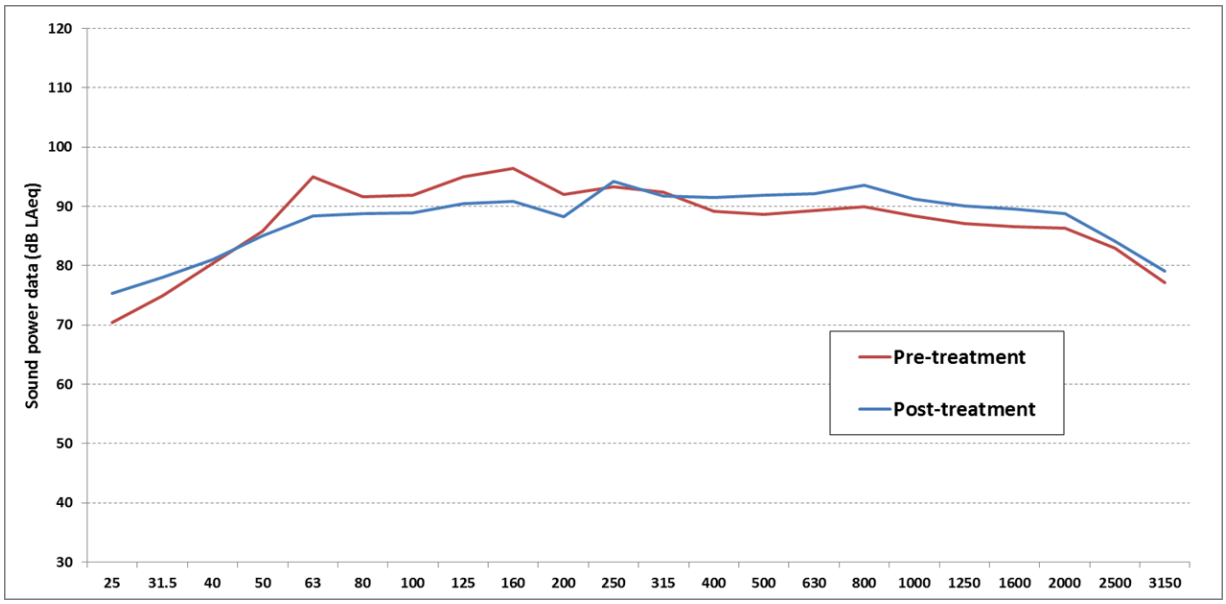

Figure 4 - Sound power spectrum of the test turbine measured both before and after the blade modifications were installed, at a wind speed of 8 m/s.

2.5 Site A – conclusions

The blade treatments implemented have been identified to successfully reduce the incidence of OAM observed in downwind conditions in the far-field region of the turbine. The treatments have additionally been measured to reduce the sound power emitted by the turbine in the 50-500 Hz frequency region. These results are consistent with the transient stall theory being the underlying mechanism for the generation of OAM.

3. Site B

3.1 Introduction

The second site considered in the present paper was a similarly large scale modern wind farm to the first site considered, consisting of more than 5 turbines with a generating capacity of more than 2 MW each, but 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. In the case of this second site no physical modifications to the turbine blades were made, but mitigation instead took the form of a modification to the operation of the turbine via changes to the turbine control software. The algorithm which sets the turbine blade pitch angle was modified with the specific aim of reducing the angle of attack of the flow on the blades (by several degrees) for the wind speed region over which OAM had been detected and associated complaints had been received.

3.2 Measurement description and survey setup

The chosen noise measurement system comprised a 01dB Duo unit at each location. This system accords with the requirements of a Type 1 sound level meter. The sound level meter equipment was 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 measured noise data and analysis methods were similar to those of site A, with 100 ms data being recorded continuously for the period of the measurements.

However, due to the extensive dataset acquired, the acquired dataset was not analysed in totality. Instead, periods of data were identified prior to the aforementioned mitigation being put in place during which AM was deemed to be prevalent. These selected periods were mostly based on complaints received, with data corresponding to these complaint periods being analysed in greater detail to confirm the presence of higher levels of AM. Similar periods during the post-treatment measurement phase were then collated and analysed. These periods were then supplemented by additional periods which were analysed in order to obtain comparable wind speed and direction conditions in both datasets. As for site A, the post-mitigation dataset was more extensive, thereby reducing the risk of missing potential residual modulation periods.

A similar AM analysis technique as above was applied to the 100 ms 1/3 octave band data measured. In this case a statistical analysis was also undertaken but a different data reduction approach was taken. The statistical distribution of the AM ratings obtained for each 10 s periods were considered, rather than the proportion of a rating obtained above a specific threshold. The results of the AM analysis were imported in a database and linked to wind farm SCADA data for

each corresponding 10 minute period. This allowed checking that the wind farm was operating during the periods analysed.

Extended periods which were clearly affected by spurious data, i.e. with elevated values which were not dominated by a component in the modulation spectrum around 0.8 Hz (corresponding to the blade passing frequency of the turbines), were excluded from the analysis. In order to minimise the influence of spurious sources, the analysis was further 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 (as a function of the turbine hub height wind speed standardised to 10 m height, in accordance with the IEC 61400-11 methodology). In each bin for the filtered dataset the average and standard deviation of the variation of the dB modulation metric were calculated.

3.3 Measurement description and survey setup

Figure 5 shows the results of the analysis at the first location. Similar results were obtained at the second location: Figure 6. 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 and that the change in the blade pitch angle was therefore designed to be highest. The reduction is such that the average + 1 standard deviation results over this range are lower than the pre-mitigation average results.

The present 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 present analysis provides objective evidence to support this observation of reduced occurrence of complaints.

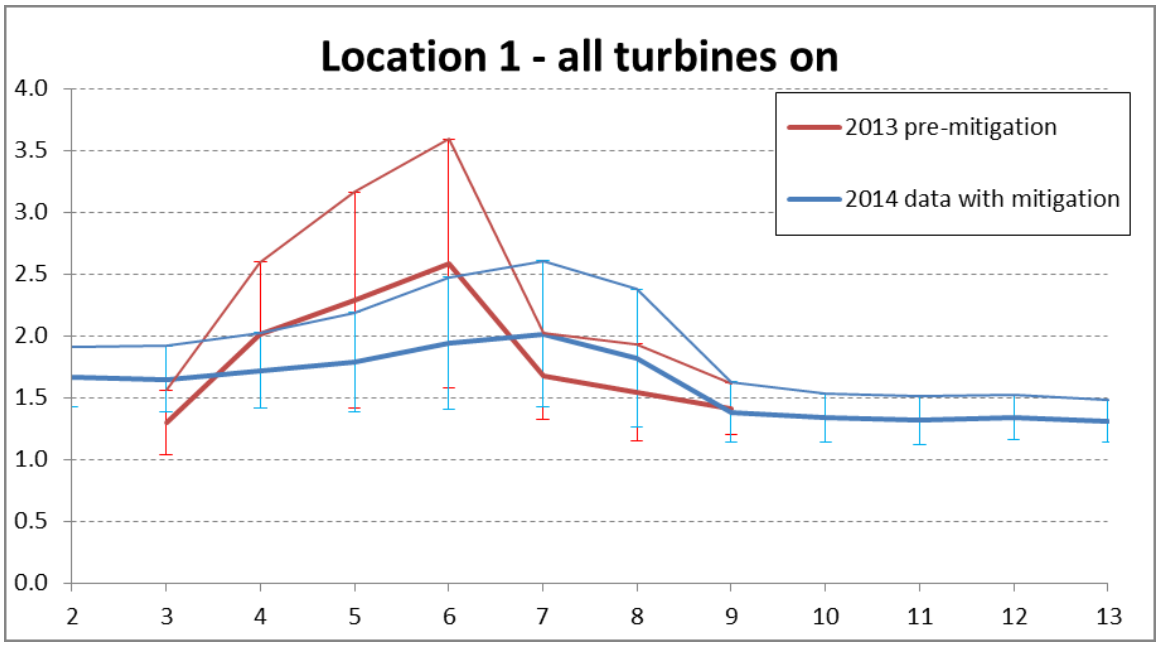

Figure 5 – Location 1 - statistical analysis of rated AM magnitude (dB, vertical axis) for the periods analysed both pre- and post-mitigation, as a function of standardised wind speed (m/s, horizontal axis). Error bars represent one standard deviation (average + 1 deviation noted by thinner line).

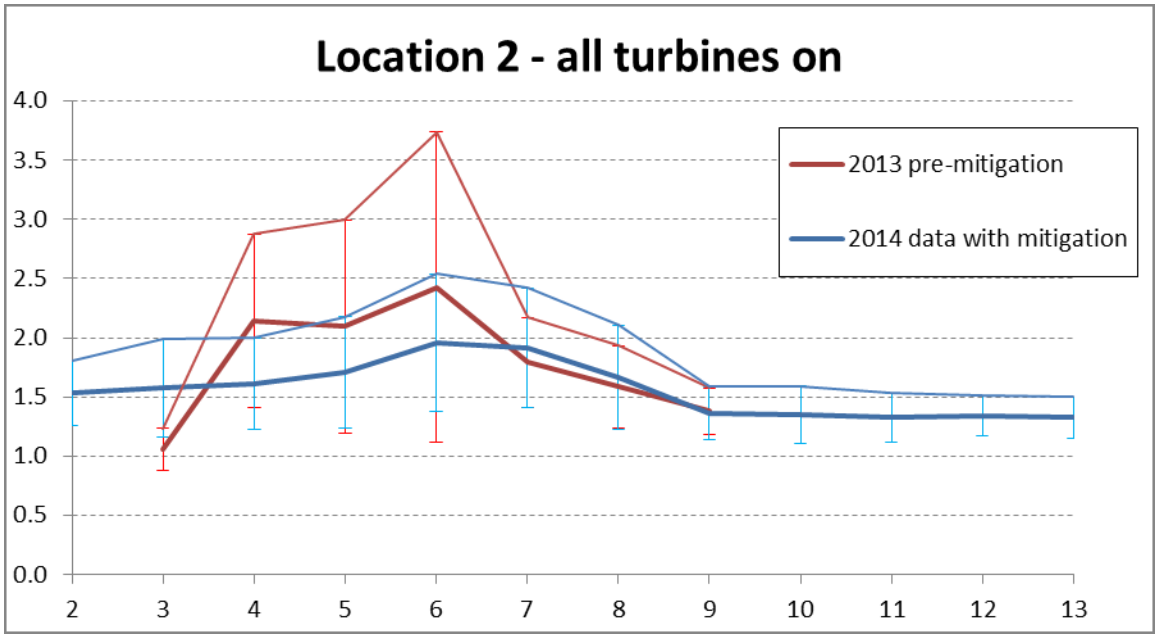

Figure 6 – Location 2 - statistical analysis of rated AM magnitude (dB, vertical axis) for the periods analysed both pre- and post-mitigation, as a function of standardised wind speed (m/s, horizontal axis). Error bars represent one standard deviation (average + 1 deviation noted by thinner line).

4. Conclusions

The experience of the authors is that the variable nature of OAM observed in the far-field, likely due to a combination of an infrequent or variable source mechanism (transient blade stall) and propagation effects, means that a direct analysis in the time domain is rarely meaningful. A statistical analysis of modulation analysed in short periods, taking into account the variation of both wind speed and direction, allows the systematic effects of the mitigation measures studied to be established. This work has also highlighted the worth of emerging AM analysis techniques based on Fourier analysis techniques applied to short-term 1/3 octave band data in analysing the large datasets acquired in a clear way. Such analysis has provided objective evidence in support of subjective reports of reduced impact.

At both sites a significant reduction in the measured modulation prevalence was observed following the implementation of mitigation. These measures were in both cases specifically aimed at reducing the prevalence of blade stall. This therefore provides further evidence supporting the OAM source generation mechanism of transient blade stall which has been identified in previous research. The results also mean that other potential mechanisms identified (such as propagation effects or inflow turbulence), which would not have varied significantly through the periods considered, are considered unlikely to be primary factors at play, although they may be contributing factors influencing the results and their variability.

These measurements also demonstrate that OAM mitigation strategies, previously raised theoretically following identification of the source mechanism, are possible in practice on actual operating turbines. By mitigating the generation of stall at source it should be possible to alleviate this problem if it arises at specific operational wind farm sites. It is also 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 in the near future.

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