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Addressing the Issue of Amplitude Modulation: A Developer's Perspective

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Summary

When a noise complaint arises it is the duty of the wind farm operator to deal with the issue, thereby maintaining a good relationship with the local residents as well as verifying that they comply with planning conditions. Many instances of complaint are as a result of activity on a wind farm site, or a fault with a turbine, but on rare occasion a problem with noise may in fact result from the normal operation of the wind turbines.

One such instance arose recently, but there was already a good relationship with local residents in the area, and as a consequence it was immediately recognised that their noise complaint was genuine. The residents first approached the construction team when the wind farm became operational and described the noise as excessive. Following detailed conversations and the creation of a noise diary, it was determined that measurements were required.

The wind turbine manufacturer typically supplies a warranty that guarantees that their turbines must not exceed specific sound power levels. For this site the warranty also included a guarantee on specific noise character. Following noise measurements by an independent acoustic consultant, amplitude modulation was identified.

The process involved in remedying the AM noise issue was a trial and error procedure based on turbine adjustments, in conjunction with the turbine manufacturer, to produce a viable solution that significantly reduced the level and frequency of occurrence of AM, but limited the energy loss.

Based on experience with this occurrence, this paper provides inside knowledge on how we, as a wind farm operator, have successfully dealt with AM.

1.0 Introduction

The purpose of this paper is to present an example of successful mitigation of AM from a wind farm developer's perspective, following a genuine noise complaint. The paper describes the process that was involved in resolving the noise complaint, and details the history of complaint for this specific site and the actions taken to resolve the issue.

The wind farm became operational in late 2012 and a noise complaint was received shortly thereafter. In January 2013 discussions took place with the local residents that had the noise issue and noise measurements commenced in February 2013, made by an independent acoustic consultancy.

Periods of other amplitude modulation (OAM) were identified in the measurements based on the criteria considered by the independent consultant as an acceptable measure of AM. As this was unreasonable to the residents, and given it was also in breach of the turbine supplier's warranty, the wind farm was immediately put into a curtailment regime involving turning the turbines off in the conditions that had previously given rise to complaint, but the noise measurements continued whilst an acceptable mitigation scheme was developed.

Successful mitigation was verified following confirmation from both measurements and the residents that the noise issue was effectively resolved and no longer causing complaint.

This paper commences with a background on AM and the latest guidance on this subject, particularly how it is identified. The literature review also examines examples of AM complaints and other known solutions.

A methodology section outlines typical practice for dealing with complaints and how people are protected by the wind farm planning conditions and the turbine supplier's warranty. An in depth analysis follows and includes a background on the site layout and locations of the complainants. There is also a complaints history together with the actions taken to resolve the problem.

Analysis of the data includes both meteorological data and acoustic data which were used to identify specific periods that caused complaint, and so enabled appropriate mitigation to be identified. The analysis also includes the steps taken to verify that the mitigation was working and, therefore, to identify a permanent solution that would both be advantageous in resolving the AM whilst limiting operational energy loss.

The results section summarises the findings of the analysis as proof the AM control strategy works and includes indicative details of the production loss with this solution.

Following the conclusions of the paper there is a section on future work that is suggested as a follow up to enable future issues to be resolved more quickly and to limit operational losses.

The key points that are addressed in this paper are:

- A high level overview of AM
- Dealing with a wind turbine noise complaint
- Measures for protecting residents form noise
- Identifying AM at a specific site
- Implementing mitigation/solutions for AM
- Verification of AM noise issue resolution.

2.0 Literature Review

This section provides a background on the phenomenon known as 'Amplitude Modulation' in the context of noise problems associated with wind farms, and includes the latest best practice in identifying this phenomenon. The literature review also includes specific details relating to known occurrences of AM causing noise complaint. There is also mention of solutions, i.e. mitigation measures that have been proven to resolve AM.

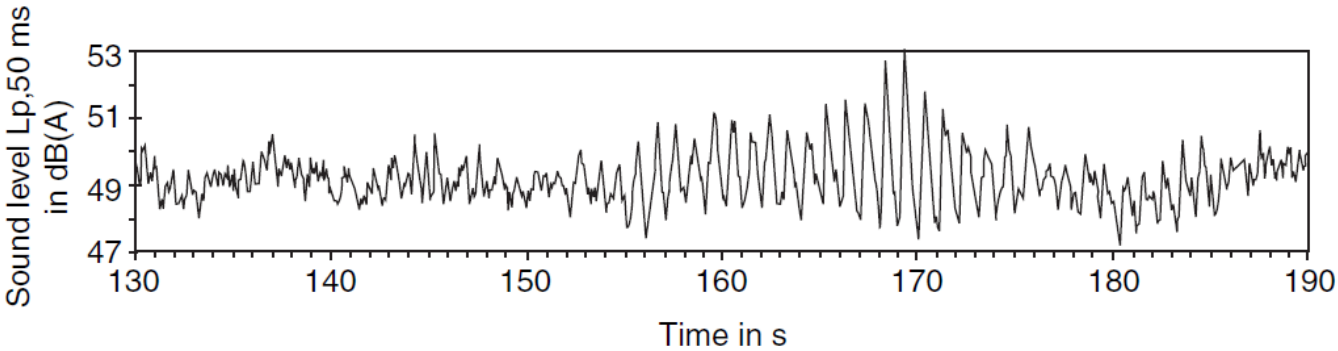
2.1 Background

Amplitude modulation is defined as the modulation of a wave by varying its amplitude, used especially as a means of broadcasting an audio signal by combining it with a radio carrier wave (Oxford, 2010). The term is simply a means of describing the amplitude or strength of the oscillations: for example in AM radio communication, a continuous wave radio-frequency signal has its amplitude modulated by an audio waveform before transmission.

Wind turbines noise is characterised by two sources: mechanical and aerodynamic. Mechanical noise is that associated with moving components, such as the gearbox, whereas aerodynamic noise is produced by the rotating wind turbine blades. Aerodynamic noise contains a periodically fluctuating, or amplitude modulated (AM), component and this form of AM is an inherent feature of the operation of all wind turbines (commonly referred to as 'blade swish') and is noise produced at blade passing frequency (the frequency at which a blade passes a fixed point). This type of AM is explained by known mechanisms and is the result of the directivity characteristics of the noise created by the air flowing over a turbine blade as it rotates. Because this type of AM is fundamental to all wind turbines it is typically described by the term 'normal amplitude modulation' (NAM).

In a Department of Trade and Industry (DTI) report (Hayes, 2006) researching low frequency noise emitted by wind turbines, it was noted that a related phenomenon known as 'Amplitude Modulation' (AM) was, in some isolated circumstances, occurring in ways not anticipated by ETSU-R-97 (ETSU, 1996). This is sometimes referred to as other amplitude modulation (OAM) or excessive/enhanced amplitude modulation (EAM), however it is defined in this paper simply as AM. An example of AM is presented in Figure 1 (Van den Berg, 2005).

Figure 1 Broadband A-weighted noise showing evidence of AM



To investigate whether or not AM was an issue which might require attention in the context of the rating advice in ETSU-R-97, the Government subsequently commissioned the University of Salford to undertake further research in the area (DTI, 2006).

In August 2007 the Government issued a statement regarding the findings of the University of Salford's report into AM of wind turbine noise (Salford, 2007), which found that, of 133 operational wind farms in the UK at the time of the report, there were only four cases where AM may have been a factor (BERR, 2007).

In December 2013 the wind industry trade association RenewableUK published detailed new scientific research into the identification, occurrence and prevention of AM (RenewableUK 2013). This work is an important study and represents a significant step forward in the industry's understanding of the acoustic characteristics associated with AM, its causes and mitigations. This research was carried out by a group of independent experts, including academics from the Universities of Salford and Southampton, and the National Aerospace Laboratory of the Netherlands, Hoare Lea Acoustics, Robert Davies Associates and DTU Riso in Denmark, with a project steering group consisting of RenewableUK, Dick Bowdler and RES. The findings of this research, conducted over a three year period, identify a range of possible solutions for mitigating the occurrence of AM and for minimizing existing issues on those few sites where it is found to occur.

2.2 Identification of AM

The RenewableUK work recognised that some AM exhibited characteristics that fell outside those expected of NAM and that these 'other' AM characteristics were annoying to some

people. The findings of this research, conducted in two phases between 2010 and 2013, identified solutions for resolving any existing issues on sites where it is found to occur.

A methodology for measuring amplitude modulation was defined and listening tests undertaken to determine the subjective response to noise with a modulating characteristic as part of the work funded by RenewableUK.

RenewableUK commissioned this research in 2010. The first phase of research concluded in 2012 and addressed the following areas:

- Investigation into possible causes of amplitude modulation
- The development of an objective measurement method for AM
- The development of an objective method for measuring the annoyance caused by AM
- Collation and analysis of existing acoustic recordings
- Measurement and analysis of new acoustic recordings
- Effects of different weather conditions on blade pitch and sound emissions.

RenewableUK then commissioned a second phase of research in early 2013. The second phase was conducted by the Wind Energy Department of the Technical University of Denmark (DTU). This research further investigated the mechanisms and causes of AM, focussing principally on the impact that changes in wind speed (wind shear), wind direction (wind veer), and inflow turbulence may have on the inflow conditions seen by the blades as they rotate.

The research concluded with an assessment of how these variable inflow conditions relate to the pitch of the blades and the possible link of these interactions with partial blade stall and the potential for this to result in AM.

The research found that significant wind shear and wind turbulence can cause changes in the angle at which a wind turbine blade comes into contact with the wind (the angle of attack of the flow over the blades) as they rotate through each 360 degree cycle. In extreme cases, these changes can push the blades into partial stall over part of their rotation. In such conditions of partial blade stall, AM can occur. This AM is likely to be experienced in the far field but not necessarily in the immediate vicinity of the turbine (RenewableUK, 2013).

RenewableUK subsequently developed a planning condition with acoustics specialists which, if required, can be applied to projects when they receive planning permission (RenewableUK, 2013). This condition differs from previous conditions that have tried to address AM as it relies on an objective and repeatable method for identifying and rating AM. This method, unlike other methods, recognises that all amplitude modulation is a periodic phenomenon directly related to the rotational speed of the wind turbine. The template planning condition takes the form of a penalty scheme which sits within in the normal compliance process, with the magnitude of the penalty dependent upon the level of amplitude modulation.

The Institute of Acoustics (IoA) have not endorsed the AM condition published by RenewableUK, but in 2014 set up a working group to deal specifically with addressing AM given a number of concerns raised about the inadequacy of the proposed planning condition in protecting residents. The aim of the AM Working Group is to review the available evidence, and to produce guidance on the technical elements for the assessment of AM in wind turbine noise.

To achieve this, the assessment method will need to contain a means of characterising a sample of amplitude modulated wind turbine noise data, with an agreed format and length, by means of a single metric uniquely defining the level of AM within it. The value of that level is outside the scope of the working group.

It is recognised that there is therefore no endorsed guidance for the identification of AM, and it is anticipated this will happen following publication of the IoA AM Working Group findings, therefore until such time latest published work from the RenewableUK research remains 'best practice' in the identification of AM.

2.3 Noise Complaints

Since the University of Salford study in 2007, a number of wind farm sites have been identified as causing AM. A list of wind farm sites across the UK has been compiled by MAS Environmental on their website (MAS, 2014). There are over 30 wind farms identified, and it is stated that many of the references derive from a study by the University of Salford in 2007. However it is evident from this list there are some wind farm sites claimed to cause AM that have not been verified as actually causing it or, indeed, whether the noise complaint has been proven to be genuine.

One of the earliest examples of such a noise complaint is the Deeping St. Nicholas wind farm, known with regard to the problems apparently experienced from AM at Grays Farm, approximately 1 km from the nearest wind turbines. However, due to a settlement during High Court proceedings, there is limited information on what was discussed but some data is in the public domain, from prior to the settlement, showing fluctuation of the noise indicative of AM.

Without a definitive measure of the level of AM, there is an issue about determining whether a wind farm site is causing AM or if it is a noise complaint due to a turbine fault or other noise source on the wind farm. Until there is a nationally, or internationally, endorsed method for identifying and quantifying AM, the issue of proving or disproving the existence of problematic AM will remain. However, given the latest research from RenewableUK, identifying if a noise complaint is due to AM is certainly possible, and despite the method not being endorsed by a nationally/internationally recognised acoustic organisation, it is agreed by many acoustic experts that this method works well at identifying and measuring AM.

2.4 AM Solutions

There are 'off-the-shelf' solutions to AM provided by wind turbine manufacturers, but these are commercially sensitive and may involve additional attachments to the wind turbine blades or modified control algorithms which adjust the way the turbines operate. It is recognised that such measures may reduce the power output from the wind turbines slightly, however this loss is far less significant compared to switching the wind turbines off due an AM noise issue.

One of the presentations at the EWEA Wind Turbine Noise Workshop in Malmo discussed two anonymous wind farm sites having AM which were resolved successfully with mitigation solutions (Cand, 2014).

The first solution that was presented was flow improvement additions installed on all three blades by the manufacturer. Both near field and far field measurements were made for a period of approximately 3 months, though the far field distance was only 300 m from the nearest turbine. A modified version of the RenewableUK methodology was used, focussing on 1/3 octave bands between 100 Hz and 500 Hz, as the modulation of the wind turbine noise dominates at these frequencies and it excludes most other 'extraneous' noise sources. The percentage of 10 minute periods where the AM rating exceeded a threshold of 3 dB were identified and statistically analysed to show that the flow improvements dramatically reduced the AM noise issue.

The second AM wind farm site that was presented used an operational strategy, where the turbine was modified such that the pitch of the wind turbines was adjusted with the aim of reducing the angle of attack over the range of wind speeds for which AM disturbance was noted.

It is recognised that, as yet, there are very few examples of mitigation solutions for AM in the public domain, primarily due to commercial sensitivity. It is therefore difficult to utilise a known solution for controlling AM, hence the need to undertake extensive data analysis and a trial process of controlling the wind turbines to eliminate/reduce the level of AM as described in this paper.

3.0 Methodology

This section discusses how noise complaints are dealt with and how residents are protected from noise. A general description of how a typical noise complaint is dealt with by Environmental Health is included along with details of typical wind farm planning conditions which should provide confidence that a development will not cause an adverse impact on local residents.

3.1 Dealing with Complaints

The standard methodology for addressing a noise complaint is for it to be dealt with by the Environmental Health department of the local council in the area where the wind farm is located.

Upon receipt of a complaint, Environmental Health request information which typically includes where the noise is coming from, the name of the person/operator causing the noise and the address if known, the nature of the problem (specifically describing the character of the noise and the times when it occurs), and the name, address, and contact details for the complainant. Letters are sent to the address where the noise causing the alleged nuisance is occurring, and the person who made the complaint would receive a nuisance diary to record details of any further nuisance.

Should the noise continue and result in further complaints, the next step is for the Environmental Health to visit the complainant at the times of the noise issue, or set up some noise monitoring equipment, to gain evidence about it.

It would then be the decision of the Environmental Health department whether further action was required, by determining if the noise is unacceptable or in breach of planning conditions (see section 3.2 on how planning conditions protect residents from noise).

It should be noted that the complainant may instead report the noise issue directly to the wind farm operator and in this instance the complaint is dealt with in the same professional manner, and this is typical of the approach RES would follow. The complainant is contacted and details of the specific complaint are established in order to resolve it as soon as possible, with the complainant asked to complete a noise diary so that any problem periods can be identified. The complainant can take the route of contacting Environmental Health at any time if they believe a satisfactory solution has not found or progress is too slow.

3.2 Protecting Residents

The purpose of planning conditions is to enhance the quality of development and enable development proposals to proceed where it would otherwise have been necessary to refuse the granting of planning permission, by mitigating the adverse effects of the development. The objectives of planning are best served when the power to attach conditions to a planning permission is exercised in a way that is clearly seen to be fair, reasonable and practicable. It is important to ensure that conditions are tailored to tackle specific problems, rather than standardised or used to impose broad, unnecessary controls (NPPF, 2014).

Conditions should help to deliver development plan policy and accord with the requirements of the National Planning Policy Framework, including satisfying the six tests for conditions: necessary; relevant to planning and to the development to be permitted; enforceable; precise

and reasonable in all other respects. The six tests must all be satisfied each time a decision to grant planning permission subject to conditions is made.

In addition to planning conditions an Environmental Health Officer may decide that the noise amounts to a 'Statutory Nuisance' therefore an 'Abatement Notice' would be served on the operator of the wind farm responsible for the noise nuisance. The abatement notice would prohibit the recurrence of further noise nuisance or, if necessary, specify a time limit for remedial work to be done. The noise would be monitored and if a statutory nuisance still existed this would normally result in prosecuting the company that received the abatement notice in the Magistrates Court.

Aside from planning conditions and statutory nuisance a developer typically signs a turbine supply agreement (effectively a noise warranty) with the supplier of the turbines for the wind farm site as a measure that not only protects the developer and operator of the wind farm from contractual issues relating to noise as well as other potential defects, but also the local residents because the manufacturer must meet specified criteria. Such criteria include warranted sound power data specific for the turbine type and wind farm site, and how this is measured. Increasingly such warranties now make explicit reference to AM.

4.0 Analysis

The purpose of this paper is to describe an example on the resolution of an identified AM issue at an operational wind farm, and this section provides the details of the site, the noise complaint history with actions taken to resolve the issue.

4.1 Site & Complaint Details

Due to commercial sensitivity, specific details of the wind farm cannot be disclosed. However the important information is provided and this should not limit in any way the relevance of this paper. The wind farm site is of medium size, between 8 - 12 turbines, and the distance to the two complainants' properties (which are the closest to the wind farm in the predominant wind direction) are approximately 875 m & 950 m respectively.

The location type is a flat rural agricultural area not close to any major roads or other dominant noise sources. It is also noted the number of properties in the area with predicted noise levels greater than 35 dB(A) is approximately 7, which is relatively few.

Noise complaints were received following the operation of the wind farm at the end on 2012, and a meeting was held with the residents that complained at the start of 2013 to identify the noise issue. There was already a good relationship between the residents and RES, from the construction phase of the wind farm when the local residents were regularly updated on construction activities, and in particular the complainants since they are the closest properties, so it was understood immediately that there was a genuine issue.

4.2 Data Analysis & Mitigation Steps

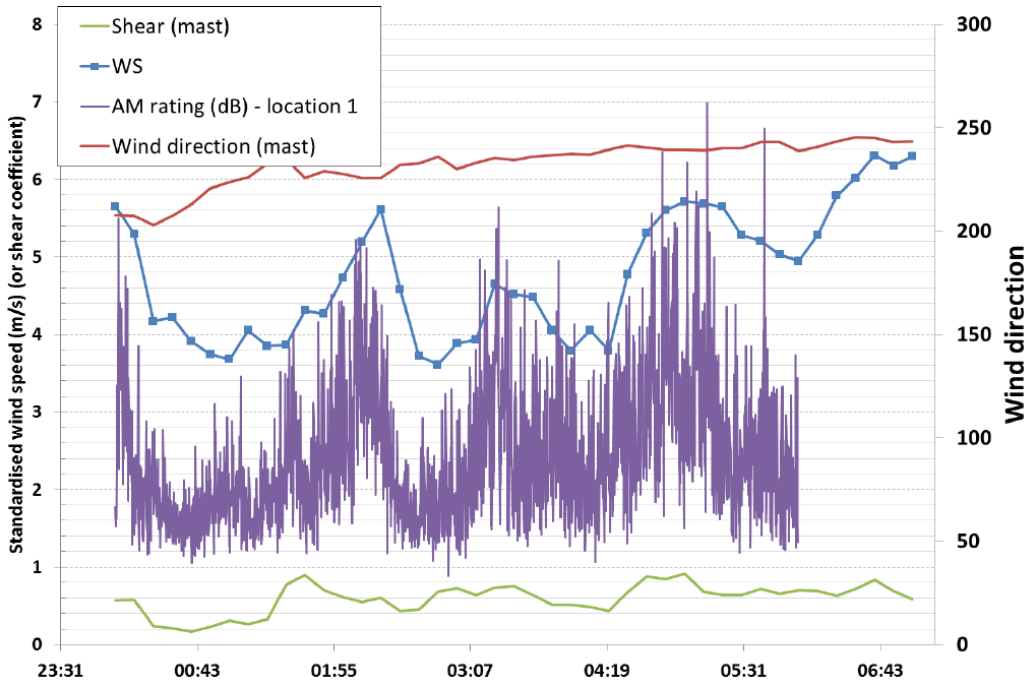
Following the noise complaints, acoustic testing was carried out in accordance with the wind turbine supply warranty between the wind turbine supplier and RES. An independent consultant was employed to carry out the relevant tests as specified in the turbine warranty.

The independent consultant determined that the modulating noise, which was the source of the complaints, breached the wind farm warranty which had a 'subjective criteria'. Subsequently, different noise mitigation measures were implemented on the site.

Following initial results from the independent consultant, a temporary noise mitigation curtailment strategy was implemented in June 2013 which consisted of shutting down the three wind turbines closest to the affected properties, in certain weather conditions. The results of

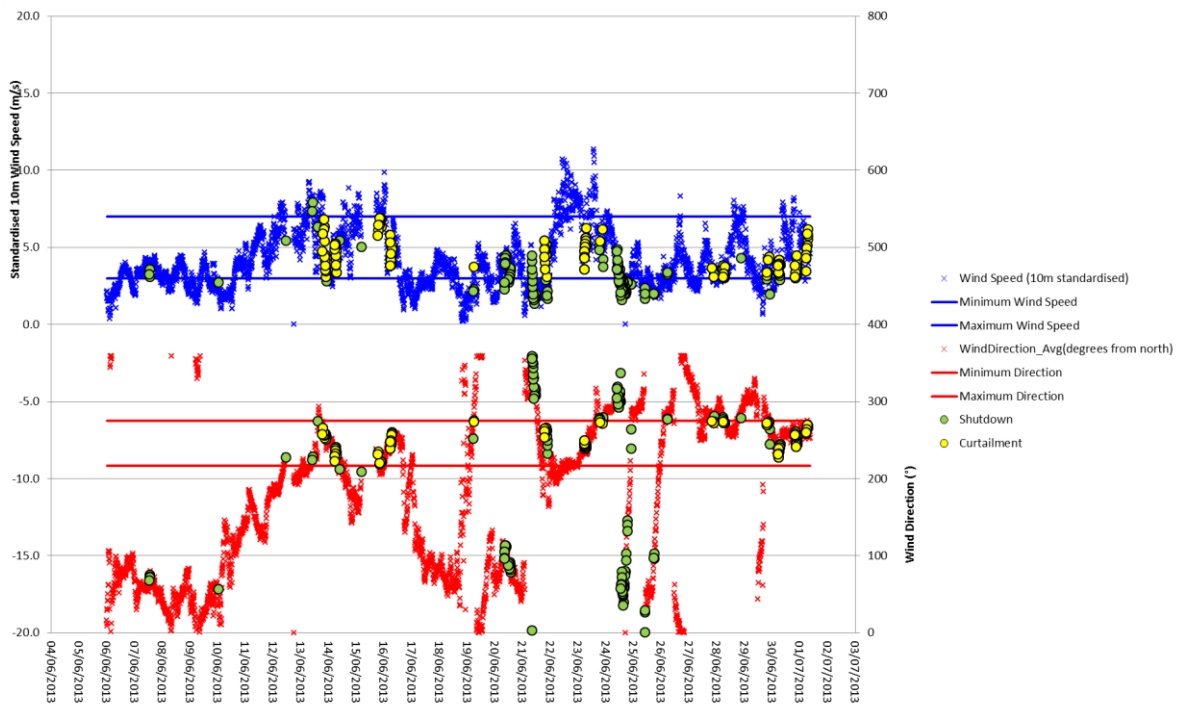
the specific periods analysed were based on complaint periods to identify the AM and recommend the mitigation/curtailment strategy. The AM periods were found to occur when the residents were downwind of the turbines and for wind speeds in the range 4 – 7 m/s. Figure 2 shows an example of the weather conditions for a periods identified as causing AM.

Figure 2 Sample Modulation Levels with Meteorological Data



A comparison was made to verify the curtailments were working correctly for the defined wind speeds and wind directions, as shown in Figure 3. It is noted that there were periods of shutdown due to maintenance and standard operational requirements. This figure is useful in showing how often the turbines needed to be curtailed to prevent the generation of AM.

Figure 3 Curtailment Check June 2013

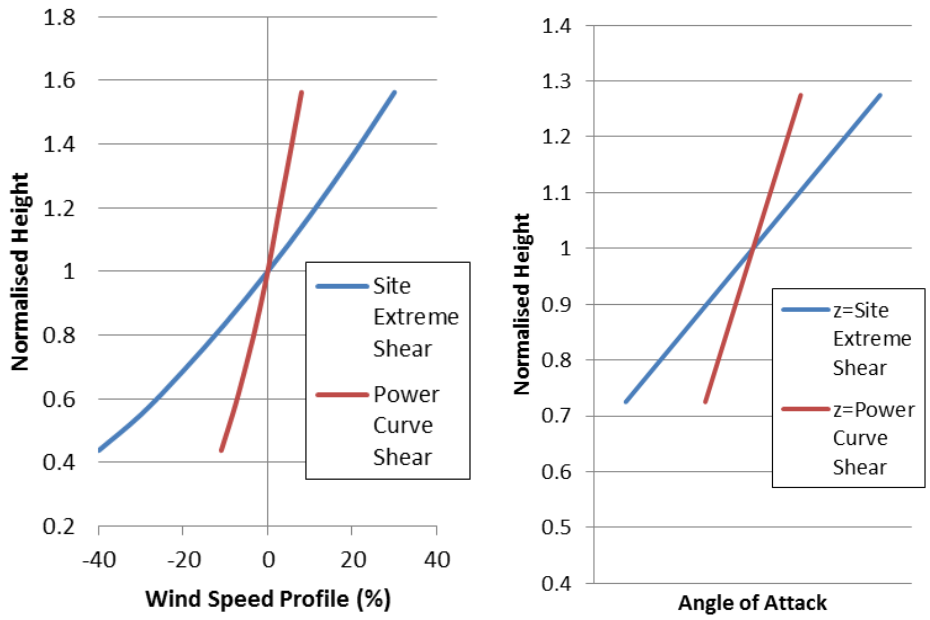


The independent consultant later analysed similar periods and concluded that the mitigation was effective at reducing levels of AM at the affected residences. However, this curtailment

represented a significant constraint on the operation of the wind farm. Further consultation then took place with the wind turbine supplier to come up with a more practical, permanent solution that would limit the production loss but still resolve the AM noise issue.

Measurements continued to further identify the AM noise issue so that an appropriate curtailment could be established. It was suggested that the AM noise due to the wind farm was caused by rotor blades periodically operating in partial stall, at blade passing frequency, as discussed earlier. The most probable causes for periodic stall was established as being the high levels of wind shear, which caused increased angle of attack peak, leading to stall. Figure 4 shows an example of the wind shear influence on blade angle of attack for this wind farm site.

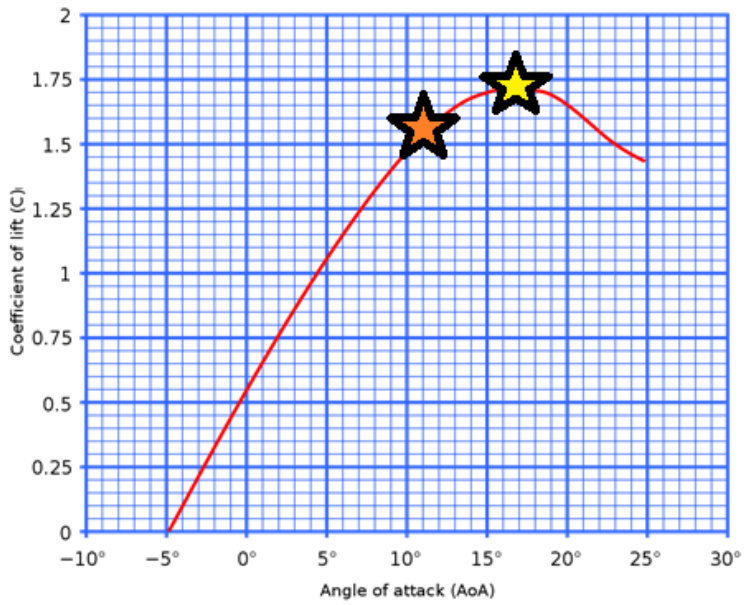
Figure 4 High Wind Shear Influence on Blade Angle of Attack



A corrective measure was developed, known in this paper as the AM curtailment strategy, and this was to increase the pitch angle by several degrees in the 4 – 7 m/s wind speed range. Figure 5 shows this AM curtailment strategy and how the pitch varies to control the AM noise in comparison to the standard optimum pitch angle.

Figure 5 AM Control Strategy

Yellow star indicates optimum for energy production, orange star indicates solution for AM (for indication purposes only)



The AM curtailment strategy was tested by the turbine supplier and verified as suitable for the site specific conditions. This took some time to verify due to the need to be certain there would be no structural issue caused as a result. Monitoring of the wind turbine status is continuous and any such issue would be identified very rapidly.

Since January 2014 the AM curtailment strategy, which modifies the operation of the turbines in certain wind and time based conditions, has been operational at the site. An analysis of this scheme then followed, and a detailed review of the noise measurements taken at the site demonstrated that the modified operation created a significant reduction in the level of frequency of occurrence of modulation measured at the residences, in the conditions which were previously associated with complaints and in which previous breaches of the turbine supplier warranty criteria had been identified.

Following is a summary of the process involved in resolving the AM noise issue at this specific wind farm.

Date	Action
February 2013	Commenced monitoring at the two complainants properties
May 2013	Independent consultant determined the noise breached the wind farm warranty
June 2013	A temporary noise curtailment mitigation strategy was implemented (the three closest turbines were shut down under specific conditions)
July & August 2013	Further noise complaints
August 2013	Periods and controls adjusted
January 2014	AM control strategy implemented
July 2014	Final independent consultant report issued describing effective mitigation of AM
September 2014	Residents officially notified of noise issue resolved. No complaints received subsequently.

5.0 Results

This section shows the effectiveness of the mitigation in resolving the AM noise issue, and also provides details of the resulting energy loss in comparison to the loss that resulted from switching off the turbines.

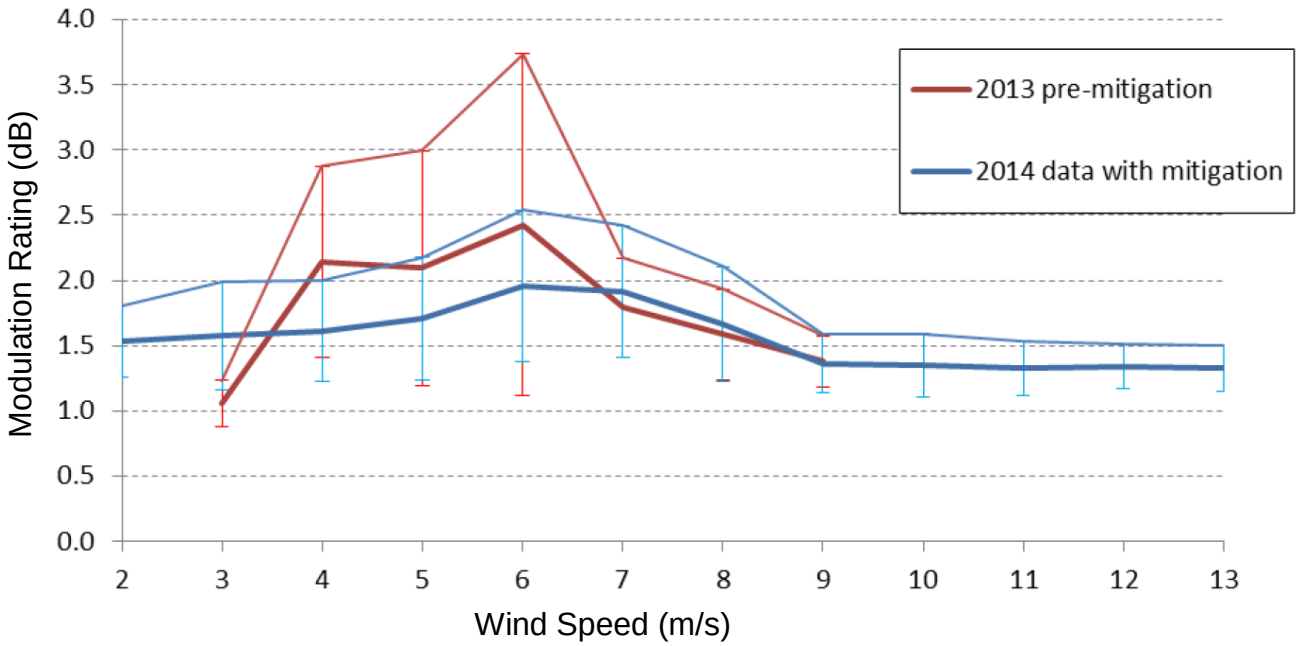
5.1 Effective Mitigation

This was an innovative and effective measure to address the issue of AM, through control of the turbine blades, in order to provide a practical solution that resulted in limited loss of production for the wind farm, whilst resolving the noise issue.

The effectiveness of the solution has been assessed through noise monitoring at both complainants properties and through comparison of data before and after the mitigation, under similar meteorological conditions. This can be observed in Figure 6 which shows a modulation analysis comparing pre-mitigation periods in 2013 with 2014 periods with the mitigation in operation. The figure shows periods with all turbines operating, including average and standard deviation of the rated modulation for the filtered dataset (thick line is the average, thin line is the average + 1 standard deviation).

It can be seen from this figure that there is a reduction in AM between the wind speeds of 4 – 7 m/s, which is where complaints were originally identified. It is also observed that, despite the reduction in AM, there is a slight increase in noise at the higher wind speeds between 7 – 8 m/s, though this increase is not believed to be significant.

Figure 6 Comparison of Modulation Analysis



It should be noted that even though the figure demonstrates effective control of AM, the residents that complained have stated the noise has significantly reduced, with one individual going so far as to say it's as different as night and day.

5.2 Energy Loss

The purpose of the AM curtailment strategy is to provide a more practical solution to the AM noise issue rather than shutting down wind turbines. It is estimated that the energy loss due to shutting down the wind turbines compared to operating them using the AM control strategy is approximately a 50% difference, i.e. a significant improvement whilst still addressing the AM noise.

6.0 Conclusions

This paper has provided a high level overview of AM which helps understand where the industry is at in identifying and resolving this phenomenon. The background on AM and the latest guidance on this subject have been included in the literature review along with examples of AM complaints and other known solutions.

The methodology section has outlined typical practice for dealing with complaints and how people are protected by planning conditions, statutory nuisance and turbine supplier warranty.

The specific analysis of AM for the noise complaint at a wind farm site has been analysed in this paper. Periods of AM were identified in noise measurements, and analysis of data, including both meteorological and acoustic data, has been used to identify specific periods that caused complaint and enabled appropriate mitigation to be identified.

Furthermore, steps taken to verify that the mitigation is working, and that it represents a permanent solution that is both effective in resolving the AM whilst at the same time limiting operational losses, have also been presented.

This analysis has proved that the AM control strategy works, and it is clear from discussions with the local residents that the mitigation solution to control AM is effective. This, after all, is the main purpose of this work: to resolve the noise issue and maintain a good relationship with the nearby residents.

7.0 Further Work

This paper has presented one solution to AM and it would be useful to carry out tests at residential distances on other potential solutions, such as the flow control attachments mentioned in the literature review. It is likely that wind turbine manufacturers will progress rapidly in identifying appropriate solution for AM, particularly once a recognised method of identifying and quantifying AM is available.

The key solution to AM will be one that does not increase operating losses and eventually one that is a standard feature on all wind turbines. However, the phenomenon of AM is still quite rare and very site specific, so a permanent, standard solution is unlikely to be available in the near future.

It is evident that an international standard on identifying AM would be useful for all parties involved in the wind industry, so that this phenomenon can be addressed as soon as possible, hopefully resulting in the simpler and quicker resolution of AM noise issues.

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