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Wind turbine amplitude modulation: research to improve understanding as to its cause & effect

M. M. Cand[a], A. J. Bullmore[a], M. Smith[b], S. Von-Hunerbein[c] and R. Davis[d]

[a]Hoare Lea Acoustics, 140 Aztec West Business Park, Almondsbury, BS32 4TX Bristol, UK
[b]Institute of Sound and Vibration Research, University of Southampton, University Road, S017 1B Southampton, UK
[c]Acoustics Research Centre, University of Salford, Salford, M5 4WT Greater Manchester, UK
[d]Robert Davis Associates, The Holt, Upper Timsbury, SO51 0NU Romsey, UK
matthewcand@hoarelea.com

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 come to the fore in recent years. The issue of AM is not a new one, having been the subject of a previous study undertaken on behalf of the UK Government by the University of Salford in 2007. That study was initiated following complaints of what was believed to be problematic levels of low frequency noise arising from a limited number of operational wind farms. A research project has been underway to improve understanding of the phenomenon, and develop an objective method for quantifying levels of AM and provide a well-defined dose-response relationship. This paper will discuss the results of this research. The project is 100 % funded by RenewableUK.

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, following the publication of a number of studies claiming that the existence of such noise may result in an enhanced possibility of adverse effects.

Residual confusion is still often encountered as to what aspect of wind farm noise people are actually complaining of, particularly as the term 'low frequency sound' is often used to refer to broadband amplitude modulated aerodynamic sound. With specific regard to low frequency sound and infrasound, repeated studies have confirmed the lack of sufficient energy in these low frequency and/or infrasonic frequency bands to result in the claimed direct adverse health or even subjective effects from operational wind farms. Hence the possible existence of enhanced levels of AM provided a possible causal link between a physically measurable and subjectively perceptible effect and some instances of reported adverse responses. It should be noted here that what constitutes 'normal' levels of AM is still the subject of some debate. In this respect it is noted here that aerodynamic noise from wind turbines is always amplitude-modulated at source at the blade-passing frequency.

Work by Oerlemans described below confirms that the dominant noise source for typical wind turbine operating conditions is the outer section of blade, near the tip. The directivity of noise radiated from this area of blade, which varies in time for rotor position, explains the generally-observed 'normal' level of amplitude modulation (swish) at locations close to the turbine. This 'normal' AM is expected to reduce with distance; however there is evidence of reported instances of 'other' AM, distinctly audible at distances in excess of 500 metres, sometimes impulsive in nature (described as 'thump') and occurring intermittently rather than being an inherent feature of the radiated noise.

The authors are part of a consortium which was commissioned by the RenewableUK association to undertake further research to improve the understanding of wind turbine Amplitude Modulation (AM). Specifically, the aim of this study was to obtain a better understanding of the causes of AM (and therefore its likelihood of occurrence), develop a reproducible means of objectively quantifying AM, and obtain an associated dose-response relationship based on this objective metric.

The main project work has now completed and results are being collated, and will be published on completion. The present paper outlines the different elements of the project, and presents a review of the knowledge and experience of AM (mainly in the UK). The conference presentation will aim to set out key results obtained by the team.

2 Project elements (work packages)

In order to best fulfil the research objectives, the delivery of the project brought together a project team with strong combined expertise in both the aero-acoustic mechanisms of wind turbine noise and the environmental impact assessment and planning issues associated with wind farm noise.

The project was divided into a number of separate work packages (WP), with one of the project team members generally leading the technical input in each project area but with Hoare Lea Acoustics (HLA, based in the UK) providing a general technical and project management role. The various work packages, and the lead project team organisation responsible for their delivery, comprised:

- **WPA**: Fundamental Research into Possible Causes of Amplitude Modulation: Institute of Sound and Vibration Research, University of Southampton (ISVR), UK.
- **WPA(SO):** Source generation effects modelling, Stefan Oerlemans, National Aerospace Laboratory (NLR), Netherlands.
- **WPB1:** Development of Objective AM Measurement Methodology, ISVR.
- **WPB2**: Development of an AM Dose-Response Relationship, Acoustics Research Centre, University of Salford, UK.
- **WPC**: Collation and Analysis of Existing Acoustic Recordings, HLA.
- **WPD**: Measurement and Analysis of New Acoustic Recordings, HLA
- **WPE**: Wider Dissemination of Results, HLA and others.
- **WPF**: Collation of Work Package Reports and Final Reporting, HLA.

The project commenced in March 2011, with an initially targeted duration of 8 months to result in a final report being delivered in November 2011. However, due to reasons largely associated with access complications and logistics associated with certain key areas of the work, the project programme slipped by 4 months, with a revised completion date for the major part of the project in March 2012.

2.1 WPA: Fundamental Research into Possible Causes of Amplitude Modulation

The scope of this project element involved: carrying out a review of published literature relating to aerodynamic noise effects in rotating machinery; examining existing wind turbine noise measurement data available from WPC; producing a number of hypotheses for the origins of AM derived from the literature and current measurement data review and project team meetings, as well as contributions from other researchers in the field and from wind turbine manufacturers; determining what the likely spectral, temporal and spatial features of each of the candidate mechanisms is likely to be; comparing with existing data; and finally inform data gathering required for WPD; use all available data to identify the key drivers and if possible the 'risk factors' for AM and hence establish potential causal mechanisms.

The key to delivering these aims was thought to establish a clear correlation between the characteristics of noise (i.e. spectral, temporal and spatial features) on a few typical installations compared with the expected characteristics of the potential mechanisms. For example, Oerlemans[1] has shown that some degree of AM is inevitable even under ideal environmental conditions because of the inherent directivity of noise sources on a moving aerofoil, but this does not explain the observed variability of the phenomenon. Initially the research under WPA has been based on an analysis of the existing data which is available immediately under WPC, thus limiting lead times for this element of the work, but an important output from WPA was to inform the gathering of additional corroborative data of a specific and targeted nature to be carried out in WPD.

2.2 WPA(SO): Source generation effects modeling

This element was directly commissioned by RenewableUK to NLR on a separate basis, and used to inform the work undertaken as part of the project. This involved an extension of the work by Oerlemans [1] to a wider range of non-uniform flow conditions.

2.3 WPB1: Development of Objective AM Measurement Methodology

Fundamental to developing any dose-response relationship is the use of a metric which represents the characteristics of the stimulus (the amplitude-modulated noise) and weights these characteristics to generate (ideally) a single number value that can be shown to correlate with subjective response.

Any such objective measurement methodology may need to be modified to take account of the findings of the subjective testing (e.g. the auditory model that best represents the response) which will determine what parameters are important in controlling the dose-response relationship. However, in the first instance, such a metric would be expected to take account of such factors as:

- level and frequency content of the modulated sound;
- depth of modulation;
- waveform of modulation
- temporal variation of modulation.

Signal-to-noise ratio may also be a factor: in the presence of background noise levels close to the mean level of a modulated superimposed sound, the superimposed sound will be partially masked and the modulation depth reduced, depending on the frequency content of both components.

Such a metric cannot be developed in isolation of the associated subjective response. The necessary approach is therefore:

- to develop a candidate metric (or metrics) which would ideally address all variables that are likely to be subjectively detectable, in an objective manner;
- to design the subjective tests in such a way that the range of stimuli presented to subjects represents all variables included in the metric(s) and that the range of stimuli presented corresponds with the range observed on wind farm sites (with input from WPC);
- to refine and develop the metric based on the subjective response.

2.4 WPB2: Development of an AM Dose-Response Relationship

This work element was based on a series of listening tests, with a two-fold purpose:

1. to validate AM metric(s) as a measure of AM which correlates with subjective response;
2. to investigate the relationship between AM values and annoyance scores.

This may determine a threshold of onset of annoyance, when modulated sound becomes more annoying than steady sound of the same mean level, and the relationship between AM value and mean annoyance score at AM values above the threshold.

Test signals were generated from both 'real' noise data and simulated data to represent the range of characteristics of AM noise generated by wind turbines (based on input from WPC). Pilot tests were first carried out to validate and develop the experimental method. This involved presenting test sounds and asking subjects to record an annoyance score on the basis that they were relaxing. Sounds were presented for short durations of at least 20 seconds in a random sequence and included background noise representing different environments and test 'wind turbine' noise at different levels and varying AM characteristics. Further listening tests were then carried out with a larger number of subjects selected from the general population, after refining the test procedure and set of stimuli.

2.5 WPC: Collation and Analysis of Existing Acoustic Recordings

Third party sources that may hold relevant acoustics and/or audio data relating to AM were approached and access to their data requested on the basis of its confidential use. Relevant data on the sites such as topography, turbine types etc was also queried. The resulting data was analysed as much as practicable within the available budget, timescale and confidentiality constraints. This formed the basis of a compilation of audio recordings suitable for the testing of candidate AM assessment methodologies under other work packages, in particular WPB1&2.

The aim was also to try, at least as far as is of the available information, possible factors (if any) positively contributing to the occurrence of enhanced levels of AM.

2.6 WPD: Measurement and Analysis of New Acoustic Recordings

Based largely on the outcome of other Work Packages, a programme of measurements was derived in order to collect supplementary acoustic and audio data, in addition to the database developed under Work Package C, as well as detailed supporting information.

It has been the experience of the project team that, even at those wind farm sites where AM has been reported to be an issue, its occurrence may be relatively infrequent. Thus, the capture of time periods when subjectively significant AM occurs may involve elapsed periods of several weeks or even months. It was also identified at the project outset that rather than only acquire more examples of AM audio recordings, more detailed supporting information, such as better defined meteorological and turbine operational data was crucial to an improved understanding of the subject. This was because recordings acquired to date were not sufficient to prove or disprove the different mechanisms identified.

It was therefore necessary to consider a focused measurement programme to make best use of the project resources, with particular regards to the observations of WPA. New measurements were designed to assess the key drivers and characteristics identified in the theory, and involved a close collaboration with turbine manufacturers. The aim of the subsequent analysis of the data acquired was to enable results to be correlated against the potential controlling factors identified in other work packages.

2.7 WPE and WPF: reporting and further dissemination

The final element of this project involves the collation of the conclusions and results from the different work packages into an overarching report, and the peer review and dissemination of this work throughout the acoustic community.

3 Review of available evidence

This section comprises a brief review of current knowledge and experience of AM: relevant and available studies in the scientific and technical literature, as well as relevant reports of disturbance or complaints from wind turbines, focusing mainly on the UK.

3.1 ETSU-R-97

The ETSU-R-97 report [2] noted that blade swish, defined as a rhythmic modulation of the aerodynamic noise of the turbines, can be audible in some circumstances by wind farm neighbours at typical separation distances. It suggested that it might be due to directivity of trailing edge noise, dependent on blade profile and tip speed, and it was described as being dominated by high frequencies: 800 – 1000 Hz and above. It will be more apparent closer to the turbines, with typical variations of 2-3 dB(A) in A-weighted levels, but with stronger variations in some frequency bands. But with increasing observer distance, because of atmospheric absorption, this modulation becomes less pronounced. As the relative contribution of background noise will also generally increase, this would reduce the prominence of the “swish”. The document reports variations in swish levels between different turbines, as well as site-specific variations for the same turbine type. ETSU-R-97 on page 68 contains further descriptions of AM:

“This modulation of blade noise may result in a variation of the overall A-weighted noise level by as much as 3dB(A) (peak to trough) when measured close to a wind turbine. As distance from the wind farm increases, this depth of modulation would be expected to decrease because of atmospheric absorption […]. However, it has been found that positions close to reflective surfaces may result in an increase in the modulation depth […]. If there are more than two hard, reflective surfaces, then the increase in modulation depth may be as much as +/- 6dB(A) (peak to trough).”

The noise limits defined within ETSU-R-97 were established on the basis that they took account of the noise from wind turbines containing a certain level of AM, but the report also suggested that it would be useful to undertake further work to understand and assess this feature of wind turbine noise.

3.2 Additional UK research

A report for ETSU in the UK in 1999 [3] monitored turbine noise at close range of what would currently be considered a relatively small turbine (32 m to the hub). It concluded that “*the experimentally observed modulation [measured close to the turbine] is due to a combination of tower shadow effects as the blades pass the tower plus the preferential radiation of noise into some directions in preference to others*.” It should be noted that that this “shadow effect” was a predominantly a shielding mechanism rather than a blade-tower interaction effect, the test turbine being of the upwind type.

The modulation observed above 1 kHz, which was more marked than at 500 Hz and below, was found to be strongly correlated to yaw error, but not with wind shear or turbulence intensity, and only weakly correlated with wind speed.

As noted by Bowdler [4], the general descriptions of AM in refs [2] and [3] are consistent with the subsequent work of Oerlemans and Scheper [1], which showed that the directivity of the trailing edge noise from the blade, combined with the Doppler amplification effect of the blade movement, would explain the ‘normal’ swishing noise of a turbine. These results, validated using detailed measurements, showed that “*for both cross-wind directions, the average level is lower than in the up- and downwind directions, but the variation in level is larger.”*

3.3 Government-funded UK studies

In 2006, the results of a study specifically commissioned by the UK Department of Trade and Industry (DTI) to look at the effects of infrasound and low frequency noise (LFN) arising from the operation of wind farms were published [5]: referred to as the “DTI LFN Report”. This study was based on measurements at 3 U.K. sites where LFN had been reported to be an issue.

This report was actually commissioned as a direct result of the claims made in the press concerning problems associated with LFN from wind turbines, including the potential effects of “infrasound”. In this respect, the DTI LFN Report is quite categorical in its findings: infrasound is not the perceived health threat suggested by some observers, nor should it even be considered a potential source of disturbance. Whilst it is known that infrasound can have an adverse effect on people, these effects can only come into play when the infrasound reaches a sufficiently high level.

In respect of low frequency sound as opposed to infrasound, the DTI LFN Report identified that wind farm noise levels at the studied properties were, under certain conditions, measured at a level just above the threshold of audibility. The report therefore concluded that "*for a low-frequency sensitive person, this may mean that low frequency sound associated with the operation of the three wind farms could be audible within a dwelling*". This conclusion was, however, placed into some context with the qualifying statement that "*at all measurement sites, low frequency sound associated with traffic movements along local roads has been found to be greater than that from the neighbouring wind farm*". In particular it was concluded that, although measurable and, under some conditions, audible, levels of low frequency sound were below permitted night time low frequency sound criteria. It was only when woken by other sources of a higher level (such as local road traffic) that there were self-reported difficulties in returning to sleep, the report commented: *"it is not uncommon for a wind farm to be identified as a cause of the awakenings although noise levels and the measurements/recordings indicate to the contrary"*.

The DTI LFN Report went on to suggest that, where complaints of noise at night had occurred, these had most likely resulted from an increased level of amplitude modulation of the blade passing noise more prominent than normal.

It should be noted that the effect had only been reported as a problem at a very limited number of sites: 3 out of the 5 U.K. sites where it had been reported to be an issue out of 126 onshore wind farms reported to be operational at the time. In addition, these effects occurred only under certain conditions at these sites, which involved long delays to capture the appropriate conditions.

Following publication of these findings, the Government commissioned an independent research project to further investigate the findings of the report. The scope of this research project included a more wide-ranging investigation into the prevalence of the impact of enhanced levels of amplitude modulation across UK wind farms. This research work was awarded to the University of Salford who reported on their findings in July 2007 [6].

In the questionnaire sent out by the University of Salford, AM was defined as "*Wind turbine blade noise which is modulated at blade passing frequency (typically once per second) with a sharper attack and a more clearly defined character than usual blade swoosh. It is sometimes described as being like a distant train or distant piling operation.*" This description would be more consistent with 'other' rather than 'normal' AM.

A total of 133 windfarm sites were operational across the UK at the time of the survey. Based on responses from local authorities with wind-farms in their areas, the report concluded that: "*AM was considered to be a factor in four of the sites, and a possible factor in another eight. Regarding the four sites, analysis of meteorological data suggests that the conditions for AM would prevail between about 7% and 15% of the time. AM would not therefore be present most days, although it could occur for several days running over some periods. Complaints have subsided for three out of these four sites, in one case as a result of remedial treatment in the form of a wind turbine control system. In the remaining case, which is a recent installation, investigations are ongoing.*"

The reported noted that "*the causes of AM are not fully understood and that AM cannot be fully predicted at current state of the art*". But it does suggest that "*[a]erodynamic noise generation depends primarily on the rotor tip speed, but there is also some dependence on wind speed. Therefore, if wind speed is not even across the rotor plane then some fluctuation in level can be expected as the blade turns.*"

3.4 Van den Berg work

Van den Berg [7] has described measurements at a 30MW, 17-turbine wind farm located on the Dutch-German border. One of the main findings of this research was that measured sound levels were higher than predicted at set 10 m height wind speeds because of wind shear effects, which are now well-recognised and incorporated in the study of wind farms in the UK according to best practice.

But another of the reported main findings is that "*wind turbines can produce sound with an impulsive character.*" The "thumping" nature of the wind turbine sound was observed in some occasions, and the author suggested that this must have contributed to the annoyance of the residents. The example illustrated in the article shows a modulation of up to +/-5 dB (peak to trough), measured at 750 m from the nearest turbine, 2 m away from a reflective surface, in the middle of the night. Pulses of depth 3-4 dB occurred for dozen of seconds with the worst cases impulses for no more than ~3s; they are also described as more "pronounced and annoying" at higher rotational speeds. The noise level graph shown exhibits an impulsive shape. The frequency and conditions of occurrence are not described.

Van den Berg distinguishes the normal "swish", which can be heard during most conditions and other types, such as the more pronounced "thump" described in this article. The varying depth of modulation in the latter was attributed by the author to short periods of synchronisation in phase of the rotation of the dominant turbines (closest to the measurement location). He speculated that this emission of pulses would not be apparent in measurements of single turbines, because of his proposed synchronisation effect. The author also suggests that the interaction of the blade passing the tower influences the character of the noise.

Bowdler in [4] casts some doubt on this analysis as the modulation depth would not increase if turbines become in phase. Examining this hypothesis in his review, Bowdler notes that: "*it is perhaps more correct to suggest not that, when turbine noises are in phase the level increases, but rather that when they are out of phase the modulation is reduced because they average each other out*". Bowdler also notes that in modern upwind turbine configurations, blade-tower interaction effects have been shown [1] to be marginal acoustically.

3.5 Finland – Di Napoli

In 2009, Di Napoli presented [8] measurements made at single, isolated 1 MW turbine, located approximately 750 m from holiday houses in Finland. Measurement made at a point 530 m from the turbine showed some modulation, with levels generally varying with wind speed but some periods of clear, apparently impulsive peaks at blade passing frequency, with worst-case amplitude of 5 dB peak-to-trough for at least a few seconds.

The author describes this as generally occurring as wind speed decreased or stopped accelerating, and reports observing it to a certain degree during most of the recording on the day of the measurements. Some "notches" or double-pulses were apparent at times. These results indicate that whilst turbine-turbine interaction may be a contributory factor in some cases, it is not the only potential cause of AM effects.

In 2011, the same author reported [9] measurement at a further site in Finland, at different distances from a wind farm consisting of 5 stall-regulated 600kW turbines. He reports levels of modulation in the far-field, most notably in downwind directions, at distances of 500m to more than 1km. The results appear to show the modulation increasing and then decreasing as the measurement location moved from the near-field to the far-field. Some example periods of modulation are illustrated by the time-evolution of A-weighted levels with time.

4 Conclusion

The mechanisms causing non-normal 'other' AM need to be understood so that the risk of its occurring on a particular site can be minimised by design, and effective remedial action can be taken on sites where it is found to occur after installation. One possible source mechanism is off-design conditions caused by non-uniform inlet flow across the rotor disc, possibly resulting from wind shear, yaw error or large-scale atmospheric turbulence. At a distant receptor, the perception of AM may also be influenced by propagation effects resulting from atmospheric factors, changes in background noise levels or interaction between modulated noise from a number of turbines. These are explored in further detail in the paper by Smith presented at this conference. It seems likely that the phenomenon will eventually be linked to a combination of factors, including but not necessarily limited to this list.

The current RenewableUK sponsored research project aims to improve the understanding of this phenomenon through further fundamental research into the causes of AM, using a combination of data available to date, further study of wind turbine aerodynamic design and control systems, theoretical models and additional targeted measurements on wind turbine sites where the presence of enhanced levels of AM has been reported.

A robust objective metric for the rating of AM effects is required which would relate directly to the subjective impact of AM where it occurs. It would represent the characteristics of the stimulus (the amplitude-modulated noise) and weigh these characteristics to generate (ideally) a single number value that can be shown to correlate with subjective response. Carefully controlled listening tests were undertaken to assess and develop such metrics, and could provide a robust basis for an AM 'correction factor' or 'penalty' to be added to a measured noise level to reflect the increased subjective response to amplitude-modulated noise.

All results of this work will be published on completion and it is planned that key results will be outlined at the present conference in Nantes.

Acknowledgments

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