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Fundamental Research in Amplitude Modulation – a Project by RenewableUK

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Abstract

This paper outlines a research project designed to improve our understanding of the phenomenon known as 'amplitude modulation' (AM), and presents key results.

The frequency and severity of AM in the UK is such that there has been no need for a specific planning condition to control its emission. Regardless, there is increasing pressure from planning authorities and local residents for developers to accept such a condition for AM. The problem for the wind power industry is that there is currently insufficient knowledge on which to base a condition without potentially causing unnecessary difficulties in future.

The project aims to improve understanding of the AM phenomenon, so that a suitable condition can be developed, based on an objective method for quantifying levels of AM and a well-defined dose-response relationship for AM.

In parallel with this, fundamental research will be pursued so that the key drivers that cause AM in the first place can be identified. This knowledge will enable developers and manufacturers to predict when AM is likely to occur, and reduce or possibly even avoid entirely the potential for it.

The aim of this project, therefore, is to be highly targeted and to provide clear, definitive recommendations on AM for use by the industry, planners and the public, on a rapid timescale.

1 Introduction

This paper outlines a research project designed to improve our understanding of the phenomenon known as 'amplitude modulation' (AM). There is little peer-reviewed, published research into the causes of AM and, because there is an increasing pressure for controls on such noise in the planning system, it is essential that this lack of knowledge is rapidly remedied.

2 Background

RenewableUK are strongly of the view that the frequency and severity of AM are such that there is no need for a planning condition to control its emission – the University of Salford report 'Research into Aerodynamic Modulation of Wind Turbine Noise' makes precisely this point [1]. Despite this, there is increasing pressure from both local authorities and the public to accept a planning condition designed to control the emission of amplitude modulation. The problem for the industry is that there is currently insufficient knowledge to be able to draft such a condition or, at least, to draft one which does not cause difficulties for the industry in future. This lack of knowledge has not stopped opposition groups from drafting their own condition and, in the absence of an alternative from the industry, Planning Inspectors have, on several recent occasions, adopted an opposition condition. The concern is that this condition is completely untested and may pose a serious barrier to the continued development of onshore wind power in the UK whilst, at the same time, not giving proper protection to nearby residents. The best way to address this is to improve understanding of the phenomenon, so that a condition can be developed, based on an objective method for quantifying levels of AM and a well-defined dose-response relationship for AM.

In parallel with this, it is essential that the industry understands the key drivers that cause AM in the first place. Only with this knowledge will developers & manufacturers be able to predict when AM is likely to occur, and possibly even avoid or reduce the potential for this acoustic feature entirely.

3 Outcomes

Given this background to the situation, there is clearly little benefit in pursuing research which may deliver inconclusive results or simply highlight the need for further research. The aim of this project, therefore, is to be highly targeted and to provide clear, definitive recommendations for use by the industry, planners and the public, on a rapid timescale.

Specifically, the research will deliver the following hard outcomes:

- an improved understanding of the mechanisms causing the phenomenon, specifically an understanding of the key drivers that cause AM in the first place, so that developers & manufacturers are better able to predict when AM is likely to occur
- an objective measurement method for quantifying levels of AM and, associated with it, a well-defined dose-response relationship for AM.

In order to gain maximum credibility for this work, an essential element is widespread dissemination of the results, e.g. at this conference. In addition to ensuring that all individual work packages are publicised as widely as possible, both in the literature and at conferences, it is essential that a final report summarising all the findings of the work are published in a peer reviewed, internationally-respected acoustics journal. This will ensure maximum exposure of the work and should provide a definitive reference in future planning appeals, public inquiries and court cases.

It is anticipated that the project outcomes will allow the creation of model planning conditions for AM, which embody both the objective measurement methodology and the dose-response relationship.

4 Project Overview

The project commenced on 19 January 2011 and is due to report in July 2011. It comprises two phases, within which there are a number of separate work packages, as follows:

Phase 1 Research into Amplitude Modulation

Work Package A	Fundamental Research into the Causes of AM
Work Package B	Development of Objective Amplitude Modulation Measurement Method & Dose-Response Relationship
Work Package C	Collation and Analysis of Existing Acoustic Recordings
Work Package D	Measurement and Analysis of New Acoustic Recordings

Phase 2 Publication and Refinement of Results

Work Package E	Dissemination of Results

Details of each phase and each work plan are detailed below.

5 Project Phases

5.1 Phase 1: Research into Amplitude Modulation

Work Package A - Fundamental Research into the Causes of AM

Although there is little peer-reviewed, published research into the causes of amplitude modulation (AM), some of the work that has been published is convincing, e.g. that based on detailed aero-acoustic analysis which identifies possible mechanisms by which AM may be caused. Measurements using microphone arrays, for example, have shown that these predictions agree well with measured levels of AM [2,3].

To date this modelling has been developed assuming a wind turbine operating in rather unrealistic wind conditions, i.e. zero wind shear. It is intended to extend this work to consider the effects of other atmospheric conditions by explicitly including wind shear, since this may be an exacerbating factor to AM. The driver for this is anecdotal evidence which suggests that AM is particularly prevalent during stable atmospheric conditions – characterised by high shear, low turbulence and low levels of background noise – something that existing modelling does not yet include.

The goal of this work is to gain a more fundamental understanding of what causes AM at the source, i.e. at the wind turbine blades. This may give insight into what measures, if any, manufacturers may take to reduce or avoid such noise emission in future or, at the very least, may make AM a more 'predictable' phenomenon. Such measures may relate to the blade geometry and manufacture, the conditions in which the blade operates or some 'retrofit' option, e.g. serrated leading or trailing edges.

In addition to considering the source of this acoustic feature, guidance will also be provided to developers & manufacturers on other factors which may affect the levels of AM emitted, including, for example:

- 'stumpy' towers, i.e. towers which are relatively 'short' in relation to the rotor diameter
- high levels of turbulence
- yaw error
- closely spaced turbines, e.g. in a linear array.

Whilst there are relatively few researchers working in this field, there are several that are making important contributions. Efforts will be made to review the literature, locate those doing promising work and to identify the potential for this to make a significant contribution to understanding the underlying physics of AM in future.

The deliverables for this work package are as follows:

- an aero-acoustic model capable of predicting levels of AM in both 'near' and 'far' field from a modern wind turbine, to include a wide range of atmospheric conditions, e.g. wind shear, turbulence etc
- through analysis of this model and its results, a description of the fundamental causes of AM at the source, i.e. at the wind turbine blades
- identification of the key drivers of amplitude modulation, and hence guidance into measures manufacturers may take to reduce or avoid such noise emission at source. This may relate to blade geometries, construction, finish or retrofit options
- guidance into measures developers may take to reduce or avoid such noise emission. This may relate to turbine layout, hub height choice and the effects of a site's wind regime
- the identification of others working in the area who are pursuing promising lines of research and assessment of their potential for future contributions to the area.

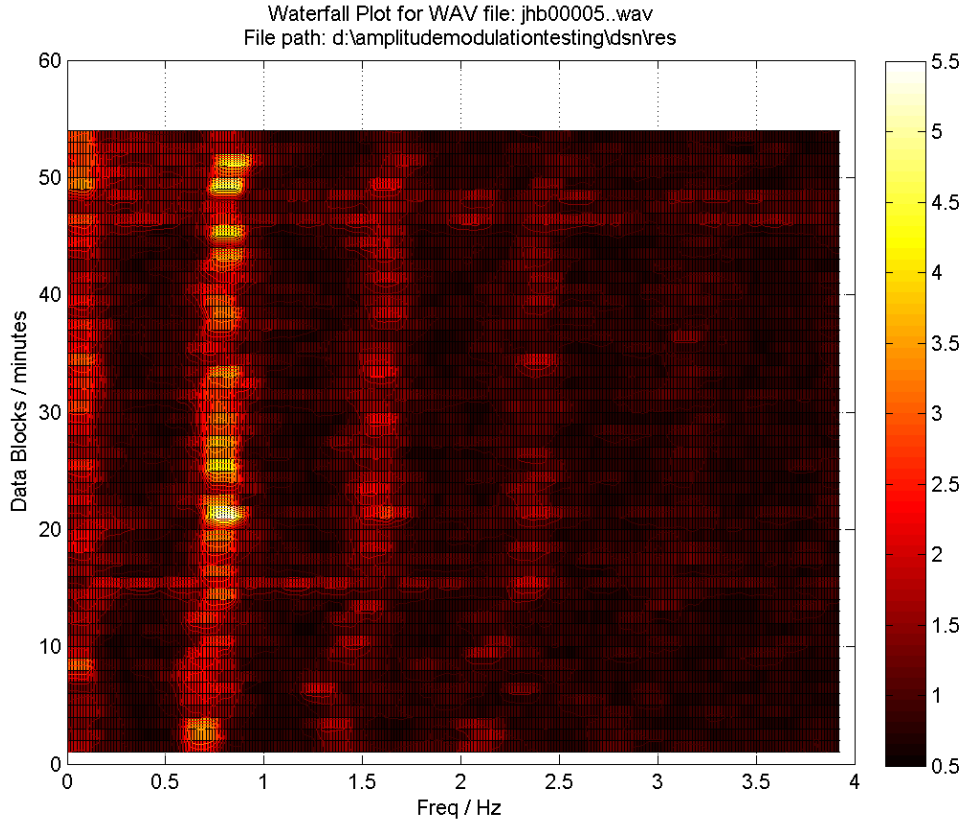
Work Package B - Development of Objective Amplitude Modulation Measurement Methodology & Development of a Dose – Response Investigation

A fundamental requirement for understanding AM is having a methodology available able to provide an objective, repeatable measure of the level of AM present in a

sample of acoustic data. If the wind industry is to understand the levels of AM residents are being exposed to, then such an objective method for measuring it absolutely essential.

Renewable Energy Systems Ltd (RES) has already developed a candidate methodology which serves as an objective measurement method for AM: this has been widely circulated among the acoustics section of the UK wind energy community. The methodology has been extensively tested on both artificially created test data and on around 60 hours of measured acoustics recordings from wind farms. As a result, the method should be regarded as a 'good, working model' that has received a reasonable degree of validation.

Figure 1: Typical Results from RES Analytical Software



However, this candidate methodology is clearly only a starting point and it will receive considerably more critical attention that it has done to date. This means detailed review by those experienced in the area of noise analysis and, particularly, frequency-based noise analysis. To achieve this, RES have provided the existing code base, and accompanying documentation, to this project for further development in this fashion.

In addition, the RES methodology needs to be tested on real-world data, hence Work Packages C & D, which will provide the raw material to allow this development.

The ability to quantify objectively the level of AM present in an acoustic recording is one thing, but for the number obtained to have any meaning it must be considered within a wider context, i.e. what is the psycho-acoustic (subjective) response of a typical listener to this level of AM?

To obtain this essential 'context' a series of detailed listening tests will be conducted in an audiometry chamber (or 'listening' room). A large number of listeners, drawn from as wide pool of the general public as possible, will be exposed to noises with varying degrees of amplitude modulation, of varying waveforms, and asked to rate them in terms of annoyance. Careful controls will be used to ensure that relative annoyance can be precisely determined using well-defined and accepted statistical methods.

As it is entirely possible that the results of such listening tests may highlight that the objective method, identified above, for quantifying AM does not provide a 'useful' measure, 'useful' in the sense that it does not correlate with the subjective responses, the listening tests will be conducted in two phases. The first phase will be a relatively quick, simple and cheap test to verify that the objective measurement methodology provides a useful index of subjective response. If it does, then a second phase of listening tests will be pursued, this similar to the first phase in content but considerably more detailed and lengthy, and aim to arriving at the best possible definition, in statistical terms, of the dose-response relationship. If it does not, then alternative objective metrics should be investigated, until some index can be isolated that correlates well with the subjective response. The second phase of listening tests will then be redesigned from the first phase, to take this new index into account, but be considerably more detailed and lengthy than the first phase. Again, the aim is to arrive at the best possible definition, in statistical terms, of the dose-response relationship.

To ensure the widest possible acceptance of the results of such tests, the following are essential:

- the experimental design will be peer-reviewed before commencement
- the tests will be conducted by an independent body whose reputation is impeccable and who have experience in the area of audiometry
- the statistical analysis of the results, leading to a dose-response relationship, will be peer-reviewed following analysis.

The outcome of this phase will be an objective measurement methodology for AM, a dose – response relationship for AM and, based on this, a meaningful noise penalty scheme for AM.

The deliverables for this work package are as follows:

- an objective, repeatable methodology for quantifying the level of amplitude modulation present in a sample of acoustic data
- a demonstration, by means of the real-world data obtained through Work Packages C & D, that this methodology can provide meaningful results

- the identity of a high-profile, independent body capable and willing to undertake AM listening tests who have experience in the area of audiometry.
- an initial experimental plan for deriving a dose - response relationship and details of a peer-review of this obtained prior to commencement
- a highly-credible listening test in an audiometry chamber, with a sample of listeners from the general population, and a rigorous statistical analysis of the results, this also to be peer-reviewed
- details of any refinement of the objective measure required depending on the results of the preliminary listening test
- developing a second, and final, experimental plan for deriving a dose - response relationship and details of a peer-review of this obtained prior to commencement
- a highly-credible listening test in an audiometry chamber, with a large sample of listeners from the general population, and a rigorous statistical analysis of the results, this also to be peer-reviewed
- a dose – response relationship for the amplitude modulation of wind turbine noise and, based on this, a penalty scheme for AM suitable for inclusion in noise planning conditions.

Work Package C - Collation and Analysis of Existing Acoustic Recordings

The most effective way to make rapid progress with the development of the objective AM assessment method, as described in Phase 1: Work Package B, is to test it on real-world data. This process can be greatly accelerated by making use of data that already exists within the wind energy community, i.e. acoustic data that has been collected for other purposes. Indeed, RES have already used 60 hours of such data in their development of the methodology.

To achieve this, developers, consultants and others with appropriate data will be approached with a view to compiling a database of wind farm acoustic recordings. It is likely that this database will feature data measured in both near and far fields, and from a wide variety of wind turbines. The benefits of doing this will be twofold:

- assuming the available data is representative of all UK wind farms, it will enable a ‘broad’ estimate of the frequency and severity of the AM problem to be determined
- it will enable the details of the analysis methodology (Phase 1: Work Package B) to be refined.

The acoustic data obtained should, as far as possible, consist of mono, or stereo, audio (WAV) recordings at high frequency (e.g. 48 kHz). Ideally this would be accompanied by information on:

- the site’s topography/turbine model/hub height/rotor diameter/blade geometry etc...
- whether the site has any reported AM issues

- how the measurements were made, i.e. in free-field conditions, on a façade or by use of a parabolic microphone.
- meteorological data, such as wind speed, direction etc, up to tip height
- turbine operational data, if available from site operator.

If there are problems relating to commercial confidentiality, these could be addressed by either removing any meta-data enabling identification of the data source, or by asking the data owner to analyse the data themselves using a 'standard' version of the methodology.

The deliverables for this work package are as follows:

- a compilation of wind farm noise audio recordings suitable for testing using the AM assessment methodology, this to be accompanied by a description of the measurement circumstances, i.e. 'near' or 'far' field; turbine type & hub height, for each data file, as above
- an indication of the frequency and severity of the AM from UK wind farms, based on analysis of the above data, and those data directly assessed by the data owners
- identification of any common factors to low/high levels of AM etc, based on analysis of the above data, and those data directly assessed by the data owners
- insight into conditions where AM may be observed, and the effect of measurement conditions, i.e. free-field, façade or internal.

Work Package D - Measurement and Analysis of New Acoustic Recordings

Whilst existing data may prove useful to the understanding the frequency and severity of AM, as well as in the development of an objective AM assessment method, as described in Phase 1: Work Package B, the very fact that these data have been collected for other purposes may compromise its usefulness.

To gain real insight into these areas, and to optimise development of the methodology described in Phase 1: Work Package B, the ideal approach is to collect highly targeted acoustic data from the current fleet of UK wind farms. This would involve making acoustic measurements:

- at approximately 7 sites, and possibly more
- at least one measurement location per site, and possibly more
- as mono, or stereo, audio (WAV) recordings at high frequency (i.e. 48 kHz)
- at sites with varying topography/turbine models/hub heights/rotor diameters/blade geometries etc
- at sites both with, and without, reported AM issues

- in both free-field conditions, on a façade and possibly using a parabolic microphone.

It would also involve making non-acoustic measurements:

- of meteorological data such as wind speed; direction etc, up to tip height, possibly using remote sensing technology
- of turbine operational data, if available from site operator.

These data should enable the level of AM to be directly correlated with the operating conditions of the wind farms, e.g. wind direction; wind speed and atmospheric stability, to provide a greater understanding of the circumstances in which high levels of AM occur, and hence possible mitigation or prevention/minimisation of effects.

- assuming the available data is representative of all UK wind farms, it would enable a 'broad' estimate of the frequency and severity of the AM problem to be determined
- it would enable the details of the analysis methodology (Phase 1: Work Package B) to be refined.

The deliverables for this work package are as follows:

- a compilation of measured wind farm noise audio recordings suitable for testing using the AM assessment methodology, this to be accompanied by a description of the measurement circumstances, i.e. 'near' or 'far' field; turbine type & hub height, for each data file, as above
- based on analysis of the above data, an indication of the frequency and severity of the AM from UK wind farms
- based on analysis of the above data, identification of any common factors to low/high levels of AM etc
- insight into conditions where AM may be observed, and the effect of measurement conditions, i.e. free-field, façade or internal.

5.2 Phase 2: Publication & Refinement of Results

Work Package E – Dissemination of Results

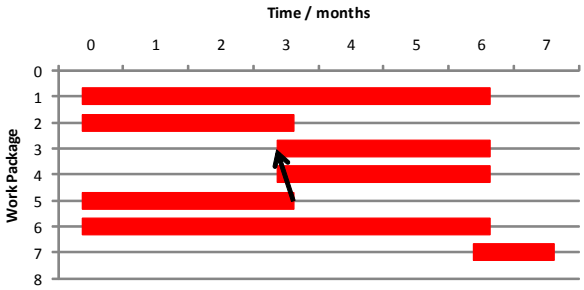
In order to gain maximum credibility for this work, an essential element is widespread dissemination of the results. In addition to ensuring that all individual work packages are publicised as widely as possible, both in the literature and at conferences, it is essential that a final report summarising all the findings of the work are published in a peer reviewed, internationally-respected acoustics journal. This will ensure maximum exposure of the work and should provide a definitive reference in future planning appeals, public inquiries and court cases.

The deliverables for this work package are as follows:

- the identity of an high-profile, international, independent, peer-reviewed journal best placed to receive the results of this work
- a published paper in this journal describing the results of all parts of this project, and publishing as much of the measured data as possible
- the identity of suitable workshops, conferences and seminars which are best placed to receive the results of this work
- a presentation at least 1 of the above events describing the results of this project
- a collation of feedback, comments, and other publications deriving from the above
- suggestions for modifications to the objective measure and AM penalty scheme developed in Work Package B above, based on feedback received following widespread dissemination
- an objective measurement methodology and dose-response relationship that can be used to used to write model planning conditions, in the form of a penalty scheme, capable of surviving inspection at Public Inquiry, and suitable for inclusion in UK noise planning conditions and standards
- a final report detailing the above deliverables.

6 Project Programme

Phase	Work Package	Duration
1	A-Fundamental Research	6 months
1	B-Development of AM Methodology-I	3 months
1	B-Development of AM Methodology-II	3 months
1	B-Dose-Response Investigation	3 months
1	C-Collate Existing Data	3 months
1	D-Obtain New Data	6 months
2	E-Dissemination	1 month



7 Conclusions

This paper outlines a research project designed to improve our understanding of the phenomenon known as AM so that a suitable planning condition can be developed, based on an objective method for quantifying levels of AM and a well-defined dose-response relationship for AM.

In parallel with this, fundamental research will be pursued so that the key drivers that cause AM in the first place can be identified. This knowledge will enable developers and manufacturers to predict when AM is likely to occur, and reduce or possibly even avoid entirely the potential for it.

The aim of this project is to be highly targeted and to provide clear, definitive recommendations on AM for use by the industry, planners and the public, on a rapid timescale.

8 References

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