Fourth International Meeting on Wind Turbine Noise

Rome Italy 12-14 April 2011

Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect

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Abstract

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 following the publication of a number of studies claiming that the existence of such noise may result in an enhanced possibility of adverse effects, both in terms of subjective response and in terms of direct adverse health effects.

The issue of AM is not a new one, having been the subject of a previous study undertaken on behalf of DEFRA in the UK 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 is underway which aims 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 preliminary results and invite contributions from the wind turbine noise research community on the subject. The project is 100 % funded by RenewableUK.

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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 come to the fore following the publication of a number of studies claiming that the existence of such noise may result in an enhanced possibility of adverse effects, both in terms of subjective response and in terms of direct adverse health 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 reported adverse responses. It should be noted here that what constitutes 'normal' and 'enhanced' 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 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 directivity-related effect diminishes as distance from the turbine increases as the 'angle of view' to the extremes of the rotor disk becomes small. However, the reported AM problems concern 'enhanced' levels of AM, where AM is distinctly audible at distances in excess of 500 metres, is sometimes impulsive in nature (described as 'thump') and is observed to occur 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 is 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.

As this research is currently on-going, the present paper presents 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, mainly in the UK. Further developments may be referred to in the presentation, and contributions from the wind turbine noise research community on the subject will be invited.

In the UK

ETSU-R-97

The ETSU-R-97 report [1] 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 and the reduced impact of directivity effects, 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)." Due to standing wave effects from reflection from building structures, the modulation in specific frequency bands can increase significantly.

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.

Additional UK research

A report for ETSU in the UK in 1999 [2] 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.

Jiggins [3] measured turbine swish from several wind farm sites in some detail, both at close range and further away from several wind turbine sites. The turbines studied were also relatively small in size compared to more recent machines.

He noted variations in the time between peaks, which may have been due to the contributions of different turbines. Variations in time in the depth of the modulation (observed in a limited frequency range), similar to "beating", suggested a possible interaction of noise between two or more turbines. The modulation in the high-frequency bands was observed to be reduced further away from the turbines. The document also reported an experimental study of loudness perception of simulated broad-band sounds of increasing modulation depth.

Government-funded studies

In 2006, the results of a study specifically commissioned by the DTI to look at the effects of infrasound and low frequency sound arising from the operation of wind farms were published [4]: referred to as the "DTI LFN Report". This report was actually commissioned primarily to investigate the effects of "infrasound", as a direct result of the claims made in the press concerning health problems arising from noise of such a low frequency 'that it is beyond the audible range, such that you can't hear it but you can feel it as a resonance'. For this reason the results pertaining to infrasound are reported separately from those pertaining to audible low frequency sound above 20 Hz. In respect of infrasound, 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.

Notwithstanding the conclusions and advice presented in the preceding paragraphs concerning both infrasound and low frequency sound, 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, making the 'swish, swish, swish' sound (often referred to as 'blade swish') more prominent than normal. This was referred to in the report as "audible modulation of the aerodynamic noise" or 'AM'. Whilst it was therefore acknowledged that this effect of enhanced amplitude modulation of blade aerodynamic noise may occur, it was also concluded that there were a number of factors that should be borne in mind

when taking into account the importance to be placed on the issue when considering present and proposed wind farm installations:

- it appeared that the effect had only been reported as a problem at a very limited number of sites (the DTI report looked at 3 out of the 5 U.K. sites where it has been reported to be an issue out of 126 onshore wind farms reported to be operational at the time);
- the effect occurred only under certain conditions at these sites (the DTI LFN Report was significantly delayed while those involved in taking the measurements waited for appropriate conditions to occur at each location);
- at one of the sites concerned it had been demonstrated that the effect can be reduced to an acceptable level by the introduction of a Noise Reduction Management System (NRMS) which controls the operation of the turbines as necessary under the relevant wind conditions. This NRMS had to be switched off in order to gain the data necessary to inform the DTI LFN Report;
- the increase in the stability of the atmosphere during evening and night time periods was raised as a potential cause of the increased amplitude modulation; however it was also noted that in at least one case this phenomenon was due to extremely site specific topographical effects: "*[T]he presence of high levels of modulation at Site 1: location 1 is associated with wind direction and the inappropriate aerodynamic conditions seen by the closest three wind turbines to the dwelling*";
- internal noise levels were below all accepted night time criteria limits and insufficient to wake residents, 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 following levels of modulation (peak-through) were reported:

- **Site 1**: 3 to 5 dB(A) at façade level (6-10 dB in individual octave bands) and 5-6 dB internally (1/3 octave bands 315-800 Hz)
- **Site 2**: 3 to 5 dB(A) in free-field (6-10 dB in individual octave bands) and 4-6 dB(A) internally (1/3 octave bands 315-800 Hz); AM described as "thumping and roaring", "whoosh whoosh" etc.
- **Site 3**: 2 to 3 dB(A) internally but modulation depth likely limited by extraneous sources of noise

Following publication of the findings of the DTI LFN report and their provisional advice on how the findings of the report should not be allowed to influence the adoption of ETSU-R-97 as the appropriate methodology, the Government commissioned an independent research project to further investigate the findings of the report. The scope of this research project included a more detailed 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 [5].

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 derives from the observations made in the DTI LFN study.

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*."

The report goes on to finally conclude:-

"*Considering the need for further research, the incidence of AM and the number of people affected is probably too small at present to make a compelling case for further research funding in preference to other types of noise which affect many more people. On the other hand, since AM cannot be fully predicted at present, and its causes are not understood we consider that it might be prudent to carry out further research to improve understanding in this area*."

Following receipt of the report, the UK Government [6] stated that it "*does not consider there to be a compelling case for more work into AM and will not carry out any further research at this time; however it will continue to keep the issue under review.*" The statement then concludes with the advice of the continued support of the ETSU-R-97 methodology.

Following a freedom of information request, the full data used to support the conclusions of the Salford University report was published on the internet [7]. The four sites with noise complaints identified by the local authorities as arising from turbine AM were: Bears Down (designated 'First Site' in Sections 4.1 to 4.4 of the University of Salford report), Askam ('Second site'), Deeping St Nicholas ('Third site') and Llyn Alaw ('Fourth site'). The report notes that AM may have been "*a possible factor in another eight sites*".

1) Bears Down

Several complaints were received from 4 locations: "*Loud/noisy*", "*rhythmic*" "*thumping*", "*sometimes overlapping*", "*like a washing machine*". No complaints were recorded following remedial works in 2004. The Salford analysis suggests that the weather conditions in which the AM was found to occur would be present on average around 15% of the time.

2) Askam (Far Old Park Farm, Ireleth, Askam-In-Furness)

In the report by the local authority, AM was described as being "like train in next field" and "percussive" with what was termed the "Van Den Berg effect (i.e. AM) apparent occasionally". This is thought to refer to the results published by Van Den Berg which are described below. "*The characteristics of the noise -chopping, whoomphing etc- are very noticeable even at levels below 35dB(A). An example: LA90 34dB, noise judged to be a nuisance at 600m UPWIND of turbines.*" "*A consultant considered the nature of the topography i.e. landform sloping downwards from the turbines contributed to the characteristics of the noise*". Measurements "*have indicated that third octave band levels when complaints were received before the implementation of wind turbine control features, indicated level changes of 12–15dB.*" The available information suggests that this corresponds to "site 1" in the DTI LFN report.

A "library" of conditions leading to nuisance was arduously built up and noise management system put in place. Complaints have reduced dramatically since this system was put in place. It was found that "*AM occurred specifically for Easterly winds and for speeds from the cut-in speed, of around 5m/s, up to 10 m/s measured at a height of 10m above ground level*". Specifically, "*AM on this site was associated with three specific wind turbines. To alleviate the problem, a turbine control system was programmed to shut down these three machines for wind directions between 55° and 130°.*"

Wind shear effects associated with atmospheric stability effects can be dismissed as a cause there, as they were found to be very limited at the site, based on anemometry measurements. But the Salford report noted that "*topographical effects result in some wind turbines being 'unsure' as to the wind direction. This is caused by the wind turbine wind vane being influenced by the wind direction at the hub height of the rotor but the wind direction at the lower arc of the rotor may be from a different direction*." This would result in the turbine blades, at some points in their rotation, not being fully pointed into the wind.

3) Deeping St Nicholas

One complainant describes periods of operation when amplitude modulation of the aerodynamic noise (AM) is clearly audible inside and outside the building. The Salford report notes that this occurred when the wind direction was in a narrow sector, and the wind speed in a given range (neither very high or very low). Analysis of long-term anemometry data led the authors to conclude that the range of conditions associated with AM would be expected to occur for 7% of the year on average.

4) Llyn Allaw

The noise character was described as AM, with “swoosh swish” and “beating (rhythmic)”. During the site visit, council representatives experienced audible blade noise woosh.

Bowdler review

Bowdler [8] reviews the state of knowledge at the time of the article to assist with further work on the subject. He notes that the general descriptions of AM in refs [1] and [2] are consistent with the subsequent work of Oerlemans and Scheper [9], 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. More recent research by these authors [10] has validated this model using measurements, and shown 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*.”

Bowdler describes his observation that, in a crosswind direction the swish reduces, and that the “maximum modulation” is experienced at 45 degrees from the crosswind direction. In the work of Oerlemans and Scheper, this intermediate location does not correspond to the worst-case modulation depth; however at 45 degrees from crosswind there is a combination of both high absolute noise level and deeper modulation.

These effects of radiation directivity could be expected to decrease with increased separation distance, as the directivity effects relative to the observer reduce in magnitude. However, Bowlder argues that this might not be the case in some situations, in particular 45 degrees from downwind, because of a shadowing effect form the tower in one case. He also considers that the Oerlemans model can be interpreted as describing “standard” turbine swish as opposed to the enhanced impulsive “thumping” described by others.

Bowdler also reviews the complaints related to AM at Deeping St Nicholas and proposes a likely correlation of specific “thump” occurrences to the 45-degrees-from-crosswind conditions discussed above; however this interpretation need to be taken with caution because of uncertainties as to the exact wind direction reference used. Bowdler also discusses the Wharrels Hill site but notes that “thump” was not observed there.

Europe

As noted in Reference [5], European regulations on wind turbine noise are generally stated in terms of maximum dB(A) noise levels and make no particular allowances for AM.

Van den Berg publications

Van den Berg [11] 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. Because of the presence of a reflective surface, this is consistent with comments in ETSU-R-97. 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 a clear impulsive shape. The frequency and conditions of occurrence are not described.

Van den Berg distinguishes the standard "swish", which can be heard during most conditions and the more pronounced "thump" described in the paper. Van den Berg has stated (in verbal evidence at the Bald Hills Wind Farm Project hearing, as reported in Ref. [14]) that the layout (i.e. turbines in line or "randomly" laid out) was not more likely to lead to "impulsiveness".

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 surprising 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 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 [9] to be marginal acoustically. Bowdler notes that in other publications, Van den Berg has attributed AM clapping or beating to wind velocity differentials across the turbine rotor associated with wind shear, and Bowdler suggests similar differentials could occur with turbulence of meteorological or topographical origin.

Finland – Di Napoli

In 2009, Di Napoli presented [12] measurements made at single, isolated 1 MW turbine (66 m hub, pitch regulated), located approximately 750 m from holiday houses in Finland. Measurement made at a point 530 m from the turbine showed some AM, with levels generally varying with wind speed but some periods of clear, apparently impulsive peaks at blade passing frequency, with a worst-case amplitude of 5 dB peak-to-peak 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.

Australia

A 2006 review of the subject [13] concluded that there were little publicly available records of complaints from large modern wind farms at the time, with the exception of the Toora Wind Farm, located in South Gippsland Shire Council, Victoria, Australia.

A report by Fowler [14] notes that residents near Toora have reportedly complained about the audible rhythmic noise, and the turbine blade rotation being “clearly audible”. The author of the latter report therefore argues that a 5 dB penalty should be added for “special audible characteristics” which was specified in the New Zealand standard NZ6808:1998 [15] applicable at the time. But it is not clear however if this modulation was typical of turbines or if some enhanced modulation was experienced at this site. The author might apply this penalty to all wind turbines according to his interpretation of the NZ standard, due to the inherent character of the wind turbine noise.

Another recent review [16] suggests that, based on the available information, the general inclusion of this penalty for all wind farm schemes would not be justified. It cites the first draft of the Australian National Wind Farm Development Guidelines [17] for which excessive swish is referred to as one of the potential Special Audible Characteristics (or SACs), but recommends for example that *“[w]ith the exception of tonality, the assessment of SACs will not be carried out during the noise impact assessment phase, that is, pre-construction*”.

The wind farm at Waubra (Victoria) is another site which has received some attention in the press as some residents have complaining about the health effects impacts of wind turbine noise. The descriptions from some residents include: “*when in sync, every minute or two you can hear 3-4 big wooshes that you can actually feel*”. *“[You] feel that you have motion sickness*”, “*I wake up 5-6 times at night*”.

A report by Thorne for one of the residents [18] has described “*pulsing at low frequency*” which some residents believe is at the origin of their problems. However, the frequency of occurrence of this feature was not determined. It is not therefore known whether this modulation was a continuous feature of the site which would then potentially warrant a penalty for “special audible characteristics”. The author suggests that this “*rumble/thump*” may be caused by the downstream wake from adjacent turbines or by interaction of the blade with the tower.

New Zealand

West Wind, Meridian's wind farm near Wellington, comprises 62 Turbines on elevated hills with valleys either side. It was officially opened in April 2009. Since

then, the company's been dealing with complaints from people living in the adjacent Makara Valley, as reported in the media.

Ref [18] quotes one resident as saying: *"[we] get the low frequency thump/whump inside the house, is very similar to a truck driving past or boy racers sub-woofer 100m away[…] we have no line of sight [sic] turbines and the closest one is 1.35km away. […]. The sound is extremely 'penetrating' and while we have a new house with insulation and double glazing, the low frequency modulation is still very evident in the dead of night. It is actually less obvious outside as the ambient noise screens out the sound."* The rumble/thump is reportedly heard just before or after wind gusts.

The planning conditions for the West Wind project [19] require a penalty of 5 dB be added for "special audible characteristics", such as tonality or "audible modulation". The text then goes on to clarify that *"a test for modulation is if the measured peak to trough levels exceed 5 dBA on a regularly varying basis or if the spectral characteristics, third octave band levels, exhibit a peak to trough variation that exceeds 6dB on a regular basis in respect of the blade pass frequency*". The recently revised New Zealand standard NZS6808:2010 has a test for modulation that is similar to those conditions.

A noise compliance report published by the operator [20] describes measurements undertaken at various locations around the wind farm. It showed clear levels of tonality in the measured turbine noise. Mitigation measures are described which aimed to reduce the tonal noise emissions by changing the operation of the turbines. The presence of these tones was said to explain the audibility of the wind farm even at relatively large separation distances.

The report then goes on to consider amplitude modulation. It argues that (in theory) during "high power conditions", the use of turbine blade pitch adjustment may lead to aerodynamic noise becoming more audible at receiver locations, and that this may be more easily perceived in sheltered rather than exposed locations. Following an analysis of complaint records (mentioning "*whoosh*") and a review of the measurements, the report concludes that audible modulation has only found been found to occur for very short periods, i.e. no more than 5 seconds in a 1 minute recording, and on no regular basis. Although some modulation which met the level test of the condition of the condition (>6 dB change in the 160 Hz octave band), this was for such brief intervals that it was considered inappropriate to apply a penalty for this characteristic.

A subsequent report [21] notes that following the progressive implementation of mitigation measures across the wind farm (between February and April 2010), tonality levels and the number of complaints from residents both reduced significantly.

Conclusions

On the basis of this review, it is apparent that there remains some debate on the definition of AM, let alone its causes. Some instances of 'enhanced' AM are reported as distinctly audible at distances in excess of 500 metres, sometimes impulsive in nature when they usually come to be described as 'thump'. However, the low frequency of occurrence of this feature is notable and to date has made definitive research on the subject difficult.

The mechanisms causing enhanced AM need to be understood so that the risk of its occurring on a particular site can be mimimised by design, and effective remedial action can be taken on sites where it is found to occur after installation. One possible source mechanism is cyclic variation in aerodynamic blade loading 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 'at source' 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. 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. Fundamental to developing a 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. It is planned to undertake carefully controlled listening tests to assess and develop this metric, which 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.

It is planned to publish and disseminate the outcome of this research. The authors would like to invite contributions from the wind turbine noise research community on the subject. Assistance in the collation of relevant audio or acoustic data would be particularly appreciated.

Acknowledgements

The financial support of RenewableUK for this research project is gratefully acknowledged.

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