

CFA '18 LE HAVRE ■ 23-27 avril 2018
14^{ème} Congrès Français d'Acoustique



Modulation d'amplitude du bruit éolien

M. Cand

Hoare Lea, 155 Aztec West Business Park, Almondsbury, BS32 4UB Bristol, UK
matthewcand@hoarelea.com

En proximité d'une turbine, le bruit produit par la rotation des pales est toujours modulé (« bruissement ») : ceci représente une caractéristique fondamentale de ce type de source. De plus, cette propriété est bien comprise et a été le sujet de modèles validés avec succès. La situation est plus complexe quand on considère le bruit d'une turbine ou parc éolien à plus grande distance. Dans certains cas, des modulations de bruit marquées ont été observées, avec certaines propriétés qui n'étaient pas expliquées par les modèles standards, et représentant une source potentielle de gêne acoustique. Un large projet de recherche initié en Grande Bretagne conclut que le détachement de l'écoulement de l'air autour de la pale durant une partie de la rotation pourrait expliquer certains cas de modulation dite « atypique ». Ceci semble être confirmé par des expériences dans laquelle le niveau de modulation a été réduit en appliquant des modifications à certaines turbines. Cette recherche identifia aussi l'absence de méthode standard et objective pour quantifier le niveau de modulation observée dans les mesures acoustiques. Certaines techniques à cet effet furent proposées et développées par un groupe établi par l'Institut d'Acoustique du Royaume Uni. La méthode finale publiée en 2016 par ce groupe est efficace en pratique, même en présence de sources de bruit additionnelles.

1 Introduction

The issue of amplitude modulated noise (often referred to as 'blade swish' or 'AM') arising from the operation of wind turbines has been the subject of a high focus of attention. Whilst the acceptability of audible noise from wind turbines continues to be the subject of considerable debate, the specific issue of AM has been separately considered in a number of studies which have reported disturbance from this feature of the wind turbine noise. In some cases, however, the observed characteristics of the AM could not be explained by existing, validated theoretical models of 'blade swish'.

This has led to research into source and/or propagation mechanisms which could explain the observed differences between the well understood and quite 'normal' blade swish noise and this other manifestation of AM noise. There have also been investigations into a metric for describing and quantifying AM noise and on the subjective response to this feature, given the relatively limited knowledge compared to, for example, tonal noise.

The results of a large research project on these issues, which comprised both theoretical and experimental investigations, was published in late 2013. Since then, additional measurement results have supported the conclusions of this research. More recently, further progress has been made with regards to a potentially standard metric for the assessment of this feature of wind farm noise, and an investigation into the subjective rating of AM noise commissioned by the UK Government was published. This paper presents a summary of this research and the current state of knowledge on this subject.

2 Context

Aerodynamic noise from wind turbine is generated by the interaction of wind flow and the surfaces of a wind turbine's rotor blades. It is said to be amplitude modulated when its level exhibits periodic fluctuations; for a fixed observer this will be at a rate corresponding to the frequency at which each rotor blade passes a fixed point (the 'blade-passing frequency'). This amplitude modulation (AM) is always detected close to a rotating wind turbine, and is commonly described as 'swish'. The principal source of audible noise from the blades is "trailing-edge noise": caused by the interaction of turbulence in the boundary layer with the trailing (thinner) edges of the rotor

blades. Because this noise source has particular directional radiation characteristics [1], even in a smooth laminar flow, an observer close to the wind turbine would experience periodically varying levels of noise related to the passage of each blade. AM resulting from this trailing edge noise directivity effect was therefore termed 'Normal AM' (NAM), it being an inherent and therefore 'normal' feature of wind turbine noise.

This characteristic blade swish has been explained theoretically and demonstrated by measurements prior to the current research [1]. This research has confirmed the existence of periodic variations in overall noise level (i.e. 'blade swish', or NAM) of typically 5 dB(A) to 6 dB(A) in the crosswind direction from the rotor as each blade travels in a downwards trajectory towards an observation point located close to the ground. Theory suggests that this NAM would not be expected to be apparent (or with less than 3 dB(A) variation) either downwind or upwind of the rotor. Such theoretical expectations have been validated by measurements mainly in the near-field of wind turbines. In the far-field, at distances representative of residential neighbours of a wind farm, practical experience led to an expectation that modulation was limited.

In the UK, a measurement study [2] was initiated following complaints of what was initially believed to be problematic levels of low frequency noise arising from a limited number of operational wind farms. It was, however, determined that it was the modulation of the broadband noise from the turbines, at the rate of the turbines passing a fixed point (or "blade-passing frequency"), i.e. AM, which was causing the complaints. A subsequent survey of local authorities suggested instances of this noise were limited [3].

Around the same time, instances of relatively high levels of AM noise were reported to have been detected in the far-field of wind farm sites in Europe, down-wind from the turbines (see for example [4,5]). In these cases, the magnitude of the variations in noise levels was reported to be higher than that predicted due to NAM (5 to 10 dB), and the noise was generally described as being more impulsive in character, better described as a 'whoosh' or 'thump' rather than a 'swish', with increased dominance of frequencies in the 200-400 Hz region. These occurrences cannot be accounted for by the established trailing edge noise mechanism of normal blade swish (NAM). It was therefore concluded that other source generation mechanisms and/or propagation effects must be responsible. AM phenomena with characteristics falling outside those expected of NAM became termed 'Other AM' (OAM).

Whilst the existence of OAM was starting to become acknowledged at that time [6], the causal mechanisms of OAM were not understood and, as a consequence, no specific information was available to guide operators or manufacturers towards the likelihood of occurrence of OAM or appropriate remedial actions to mitigate its effects in circumstances where it did occur.

3 OAM Mechanism

An extensive research programme on this subject was commissioned by RenewableUK in 2011 and published [7] in 2013. As part of this research, the existing model of NAM referenced above [1] was further developed to account for non-uniform flow into the rotor disc [8]. This study, as well as independently reported work [9] concluded that variation of wind speed across the rotor disc because of increased vertical wind shear cannot, in itself, lead to increased modulation or account for the observed characteristics of OAM.

The noise model in [8] was further developed to include the effect of the separation of the flow from the blades for part of their rotation, or transient blade stall. In the model, transient stall was triggered for part of the rotation by a vertical wind gradient, or wind shear. The increases in the inflow wind speed increased the effective angle of attack of the flow onto the blade, therefore potentially triggering stall. Such flow separation may then only occur over a small area of each turbine blade, and over a limited part of the blade's rotation: for example, only as it passes over the top of its path, as in Figure 1. It was recognised, however, that other flow non-uniformities (such as turbulence, the wake of another turbine etc.) could trigger similar effects.

Whatever the cause of such localised blade stall, the turbulent air in the stalled region creates an increase in noise generation with a lower frequency content and different directivity characteristics when compared to trailing edge noise. Thus, a momentary and periodic increase in noise level is created by the partial blade stall. This results in modulation with significantly different characteristics to NAM. Specifically, the change in directivity of stall noise (illustrated in Figure 1) is predicted to result in significant modulation levels in upwind and downwind directions (Figure 2).

As downwind directions are those in which the highest overall noise levels are generally experienced in the far-field of the turbines due to favourable propagation conditions, it follows that OAM noise will most likely be present under such downwind propagation conditions, and this is consistent with observations in the field. Radiation of OAM in the upwind direction is also predicted and has been observed in the far field under some circumstances (but less frequently).

The foregoing combination of a transient stall source generation mechanism and its associated directivity effects, taken together with propagation effects, was identified as potentially explaining the different acoustical characteristics and predominantly downwind impact of OAM when compared to the more limited and predominantly crosswind impacts of NAM. This suggested a source effect as the main explanation: although propagation effects were considered, they were unlikely to explain all the observed characteristics of OAM.

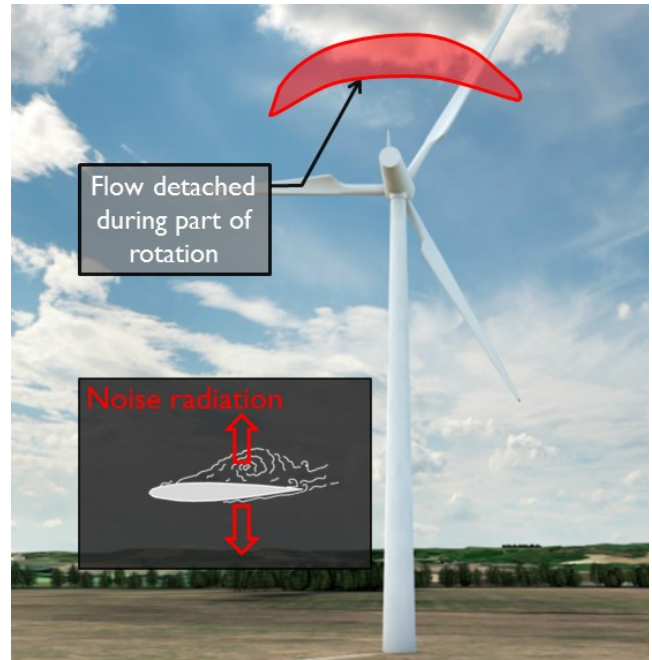


Figure 1: Illustration of detached flow over part of the rotation (partial stall)

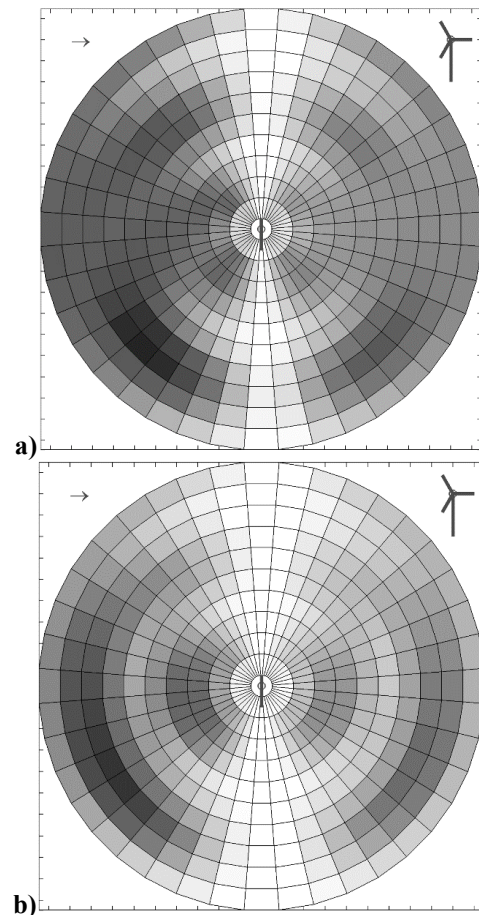


Figure 2 - Sample predicted noise footprints calculated for moderate wind shear for a) attached flow and b) partially detached flow. This shows an aerial view of the turbine, with wind blowing from left to right, variations in noise levels from black to white illustrate the presence of modulation. The pattern illustrates that modulation is mainly present in the cross-wind in a) (no stall) and up and down-wind for b) (stall case). Figures from [8].

4 Validation work

4.1 Initial site measurements

As part of the RenewableUK work, detailed measurements [10] were made at a site where ‘Other AM’ had been experienced in order to further study the characteristics and directivity of this noise feature. Levels of AM were measured at different distances from the turbines, at a combination of near- and far-field locations (at distances of 1, 3 and 10 rotor diameters from the nearest turbines) in different directions. Detailed anemometry and turbine operational data were also captured at resolution of 1 to 3 seconds.

A detailed analysis of the modulation identified in specific periods, including phased shutdown of adjacent turbines, showed that OAM could occur with each turbine operating in isolation, thus appearing to exclude interaction of the flow between the turbines as a dominant causal factor. During periods of marked modulation, no elevated atmospheric turbulence was found to be present which further excluded turbulence ingestion as a direct source mechanism.

Higher levels of modulation were identified as being experienced with increasing distance from the turbine. The observed directivity of the OAM in the far-field was found to be highest downwind and more limited cross-wind, which was the opposite of the situation in the near-field and as expected for NAM. See, for example, Figure 3 which represents an example of a period of marked and relatively impulsive modulation observed in the far-field downwind location, but simultaneous measurements in the cross-wind direction do not show the same modulation. This observed specific directivity of the OAM is consistent with the theoretical modelling of the partial stall generation mechanism, which results from the particular directivity of the stall source on the blade.

At the same time, in the immediate near-field, the opposite and standard pattern of modulation (mainly cross-wind modulation of no more than 6 dB(A)) was apparent. The lack of strong OAM in the near-field represents a key challenge in the assessment of this feature. This is likely due to source directivity effects.

Periods of OAM in the far-field were examined alongside the turbine operational and meteorological parameters available. The observed modulation levels were strongly variable which suggests the influence of propagation effects. A more detailed analysis revealed a low or sometimes negative relation with the vertical gradient of wind speed and wind direction experienced across the turbine rotor. In one specific example, a period of relatively strong modulation was observed as the wind speed increased and the wind shear decreased. However, further analysis showed that this high AM period was associated with a relatively rapid variation in the relative angle of flow incidence, which was estimated using operational information from the turbine control system. See [10] for further details.

These results supported the hypothetical source mechanism described. It was however acknowledged that this represented a complex subject which required more research and investigations.

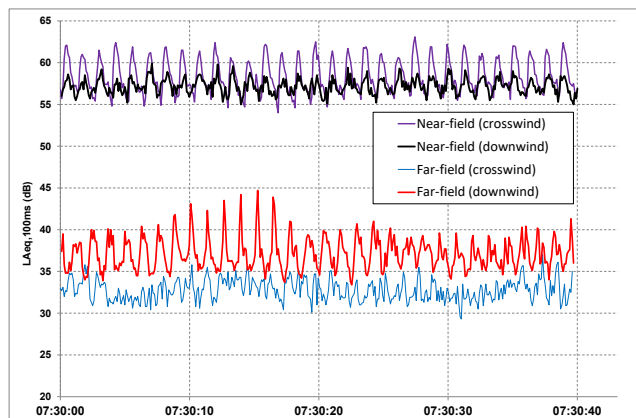


Figure 3: Simultaneous time history of measured $L_{Aeq,100ms}$ levels for a sample OAM period showing: two far-field (downwind and cross-wind) and two near-field locations (cross- and down-wind).

4.2 Additional modelling and blade study

In the absence of techniques such as actual blade surface measurements, it was not possible to positively identify the occurrence of stall as part of the measurements of [10] described above. However, work by Madsen [11], undertaken independently of the above described project, provided further support to this hypothesis through the analysis of detailed on-blade surface pressure measurements which showed cyclical stall occurrence linked to variations in the measured angle of attack of the wind on the blade. Madsen also outlined theoretical modelling suggesting risk factors for stall occurrence, along with potential mitigation measures which would in theory reduce this risk and therefore, potentially, the incidence of OAM.

4.3 Mitigation studies

Following publication of the RenewableUK research, additional investigations were undertaken at sites at which OAM was found to be present. Ref. [12] describes the results of two studies in which the prevalence of AM in the noise was compared before and after mitigation measures were put in place, with significant reductions in AM prevalence observed in both cases.

Figure 4 shows the results of the analysis at the one of the sites studied. The site was a large-scale modern wind farm consisting of more than 5 turbines with a generating capacity of more than 2 MW each, situated in relatively flat terrain. Measurements were undertaken at two locations, both situated approximately 1 km away from the nearest turbines, following complaints from the residents. Instances of OAM were observed at times, particularly in conditions of increased wind shear.

At this site, mitigation took the form of a modification to the operation of the turbine via changes to the turbine control software. The standard operating pitch angle, describing the rotation of the blade around its axis, was modified with the specific aim of reducing the angle of attack of the flow on the blades (by several degrees) for the wind speed region over which OAM had been detected. Detailed 1/3 octave band noise data measured at 100 ms

resolution was analysed in accordance with a metric representing the magnitude of the modulation.

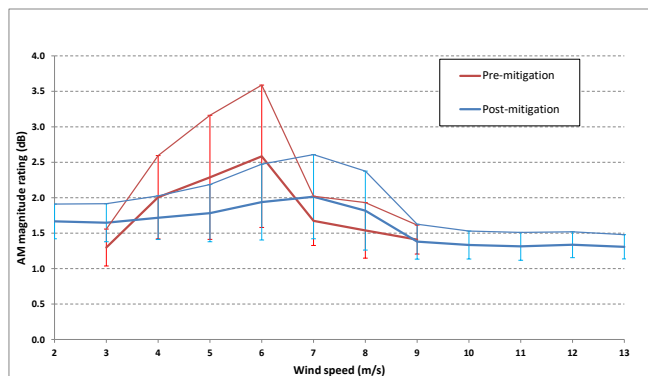


Figure 4: statistical analysis of rated AM magnitude for the periods analysed both pre- and post-mitigation, as a function of wind speed. Mitigation was applied in the range of 4 to 7 m/s. Error bars represent one standard deviation (average + 1 deviation noted by thinner line). Results at one site and one location from [12].

A significant reduction in the average modulation rating is apparent in Figure 4 following mitigation over the range of 4 to 7 m/s. It was over this range that disturbance was previously noted and the mitigation was targeted. Complaints of noise from the wind farm are understood to have subsided at the site following the turbine operational control changes. Further details are included in [12], which also presents results at a site in which effective mitigation involved physical modifications to the turbine blades. In both cases, the mitigation was designed to reduce the likelihood of stall on the blade: these results therefore support the OAM mechanism identified above.

5 AM metric and potential rating

5.1 Defining AM depth

‘Modulation depth’ can be defined as the difference between the ‘peaks’ and ‘troughs’ of short-term measured noise levels. Although apparent in many cases in plots of $L_{Aeq,100ms}$ or similar, such as those of Figure 3, rating the magnitude of the modulation in a robust and objective way, that is repeatable and applicable to real measured data, represents a perhaps surprisingly complex problem.

The feature of AM that assists in its detection and analysis is the fact that the noise has a periodic character. Fourier-transform analysis techniques of the signal envelope (this signal envelope typically being provided by the $L_{Aeq,100ms}$ or similar) can be used to objectively identify the modulation frequency and then rate the magnitude of the modulation at this frequency.

White [13] showed that such methods represent an optimal way of determining modulation parameters in a specific statistical sense, particularly when applied to narrow-band signals. Several authors (for example [14,15]) used this type of method but the exact analysis parameters used and the normalisation process varied. Application to real data, including corruption from a number of non-turbine sources, represents a key challenge in practice.

5.2 IOA metric

The UK Institute of Acoustics (IOA) formed a dedicated working group to develop a suitable AM rating method, following a period of public consultation. The outcome of this work was published in 2016 [16]. The final document includes both a detailed reference method as well as an “indicative method”, based on a simpler technique [17] that can be used with standard sound level meter outputs, but which is less robust. The reference method provides a decibel level each 10 minutes which represents the magnitude of the modulation in the noise, and minimises the influence of sources not related to wind turbines. The IOA document does not however provide any thresholds or criteria for using the resulting AM values.

The reference method is based on taking a Fourier transform of the signal to determine the fundamental modulation frequency of the signal (related to the wind turbine rotation rate), then identifying the second & third harmonics of this signal (if present). These components of the signal are then isolated and used to reconstruct the signal in the time domain using inverse Fourier transform. A simple statistical analysis (similar to [17]) is then applied to determine the depth of the modulation. This was shown to lead to similar outcomes as if a more detailed analysis of individual modulation peak/troughs is applied. The noise data input to the analysis is initially band-limited in three different frequency band regions: 50-200 Hz, 100-400 Hz and 200-800 Hz, to account for the different frequencies which can dominate modulation depending on site and/or turbine specific characteristics.

Given the practical experience that wind turbine AM can vary strongly, be relatively intermittent and last for only short “bursts”, the input data is separated into 10 second intervals which are analysed independently. For each 10-minute period, the metric provides an assessment value based on the highest 10% of the individual AM ratings derived for each of the 10 second blocks: this provides an indication of typical worst-case AM levels experienced during a certain period.

Given the relatively steady nature of wind turbine noise compared to other naturally occurring varying sources of noise, the method incorporates a test requiring that each 10-second assessment period should contain a clear peak in the detected AM. This peak should lay at a frequency within an expected range (based on the turbine operational parameters). The majority of that period’s total 10-minute duration should also include such “clear” peaks. This criterion has been found to be remarkably efficient [16] at excluding spurious periods of apparent AM due to sources other than the wind turbines. This was even the case during day-time periods where many sources such as bird noise either corrupt the analysis or appear to create erroneous “modulation”.

A sample of basic code in the Python language for the reference method was published [18]. Other researchers have started to investigate the application of this proposed method on large datasets with success [19].

5.3 Towards an AM penalty

A number of studies have assessed the subjective response to wind farm noise: for example [14, 20, 21]. These results suggest in particular that, although the

magnitude of AM was a factor in the annoyance response, it appeared to be less significant than the overall level of the noise (as rated by the L_{Aeq} parameter for example).

The UK Government commissioned a review of the available evidence on this subject, with a view to recommend how this feature may be controlled. The outcome of this research has been published [22] in October 2016.

The resulting report recommends the use of a “character penalty” approach, in which a correction is applied to the overall A-weighted noise level to account for AM in the noise in a manner similar to that used to assess tonality in some national regulations. This penalty is based on the above-described IOA metric for AM [16]. The researchers make several recommendations but explain that the current state of knowledge on the subject and the implications of their proposed control is limited and that a period of testing and review over the next few years would be beneficial.

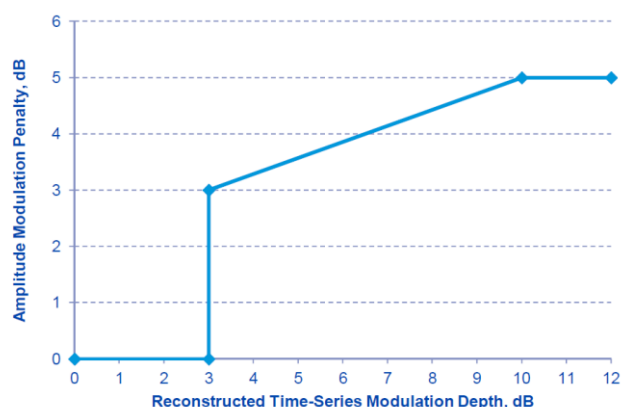


Figure 5: proposed level penalty regime proposed in [22], based on the output of the reference metric of [16].

6 Conclusions

Since the earliest reports more than 13 years ago of the occurrence of unexplained amplitude modulation (AM) features in the noise from some wind farms, the knowledge of this subject has progressed significantly. Instances of elevated modulation can lead to disturbance for residents neighbouring operational wind farms. There are strong grounds to conclude that some instances of atypical AM experienced in the far-field of the turbines are associated with specific source effects, namely detached flow on the blades. This has pointed towards the development of mitigation measures which have been shown to be successful in real-world applications. This knowledge can inform turbine and blade designers and manufacturers to help them minimise the potential occurrence of this noise feature.

Significant progress has also been made in the development of effective AM detection and rating methods. This points towards a more standardised international approach to this problem being agreed in the near future. The UK Government has produced draft recommendations which may form the basis of routine control of this feature, much like tonality in the noise is currently controlled in several countries. But the details of how this may be applied are still the subject of some debate in the UK.

It is also important to acknowledge that this remains a very complex subject, not least because of the relation to

blade aeroacoustics and interaction with turbine characteristics and operational parameters, weather and wind conditions over the entire blade rotor, and potentially also turbine-turbine interaction [23]. This aspect of wind farm noise should in the author’s view be the subject of more international acoustics research.

Acknowledgements

This paper summarises in part the results of a research project which was undertaken with the financial support of RenewableUK, which is gratefully acknowledged, along with the contribution of the other authors including Malcolm Smith and Paul White (Institute of Sound & Vibration Research), Robert Davis (Robert Davis Associates) and Stefan Oerlemans.

The work of the IOA AM working group, with little financial support, is also acknowledged.

References

- [1] Oerlemans, S. and Schepers, G. (2009), Prediction of Wind Turbine Noise Directivity and Swish, Third International Meeting on Wind Turbine Noise Aalborg Denmark 17 – 19 June 2009.
- [2] Hayes McKenzie Partnership (2006), The Measurement of Low Frequency Noise at Three UK Wind Farms, Report for the Department of Trade and Industry (UK), contract W/45/00656/00/00.
- [3] Moorhouse, A., Hayes, M., von Hünenbein, S., Piper, B. and Adams M. (2007), Research into Aerodynamic Modulation of Wind Turbine Noise, Report by the University of Salford for the Department for Business, Enterprise and Regulatory Reform, URN 07/1235, Contract NANR233.
- [4] Van den Berg, F. (2004) Effects of the Wind Profile at Night on Wind Turbine Sound, *J. Sound Vib.*, 277 (4-5), pp. 955-970.
- [5] Di Napoli, C. (2011), Long Distance Amplitude Modulation of Wind Turbine Noise, 4th International Conference on Wind Turbine Noise, Rome, 12-14 April 2011.
- [6] Bullmore, A., Jiggins, M., Cand, M., Smith, M., von Hünenbein, S. and Davis, R. (2011), Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect, Fourth International Meeting on Wind Turbine Noise, Rome, Italy 12-14 April 2011.
- [7] Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect, Renewable UK, December 2013. <http://www.renewableuk.com/default.asp?page=IndustryStatementOAM>
- [8] Oerlemans, S. (2011). An explanation for enhanced amplitude modulation of wind turbine noise, Netherlands National Aerospace Laboratory (NLR), report NLR-CR-2011-071. Included in [7].
- [9] Boorsma, K., Schepers J. G. (2011), Enhanced Wind Turbine Noise Prediction Tool SILANT, Fourth

- International Meeting on Wind Turbine Noise, Rome, Italy.
- [10] Cand, M., Bullmore, A., Wilson, B. (2012). RenewableUK research Work Package D (WPD) - Measurement and Analysis of New Acoustic Recordings. Included in [7].
- [11] Madsen, H. A., Fischer A. and Kragh K. A. (2013). Mechanisms and Causes of Amplitude Modulation (AM) and Other Amplitude Modulation (OAM) of Aeroacoustic Wind Turbine Noise, Technical University of Denmark report I-0095. Included in [7].
- [12] Cand M., Bullmore, A. (2015), Measurements demonstrating mitigation of far-field AM from wind turbines, 6th International Meeting on Wind Turbine Noise, Glasgow 20-13 April 2015.
- [13] White, P. (2012). The Measurement and Definition of Amplitude Modulations, RenewableUK AM Research, Work Package WPB1
- [14] Lee, S., Kim, K., Lee, S., Kim, H., and Lee, S. (2009). An estimation method of the amplitude modulation in wind turbine noise for community response assessment, Third International Meeting on Wind Turbine Noise, Aalborg, DK, June 2009.
- [15] Lundmark, G. (2011). Measurement of Swish Noise; a New Method. Fourth International Meeting on Wind Turbine Noise, Rome, Italy 12-14 April 2011.
- [16] Institute of Acoustics (IOA) Amplitude Modulation Working Group, Final Report, A Method for Rating Amplitude Modulation in Wind Turbine Noise, June 2016. <http://ioa.org.uk/publications/wind-turbine-noise>
- [17] Fukushima, A., Yamamoto et. al. (2013). "Study on the amplitude modulation of wind turbine noise: Part 1 – Physical investigation" Proc Internoise 2013.
- [18] <https://sourceforge.net/projects/iaa-am-code/>
- [19] A. Fukushima, H. Tachibana, Comparison of the IOA method and Japanese F-S method for quantitative assessment of amplitude modulation of wind turbine noise – A study based on the field measurement results in Japan. 7th International Conference on Wind Turbine Noise, Rotterdam – 2nd to 5th May 2017.
- [20] Yokoyama, S., Koboyashi, T., Sakamoto, S., & Tachibana, H. (2015). Subjective experiments on the auditory impression of the amplitude modulation sound contained in wind turbine noise. 6th International Meeting on Wind Turbine Noise, Glasgow, 2015.
- [21] Work Package B(2): Development of an AM Dose-Response Relationship, University of Salford Manchester, Sabine von Hünerbein, Andrew King, Benjamin Piper, Matthew Cand. Included in [7].
- [22] Review of the evidence on the response to amplitude modulation from wind turbines, “Wind Turbine AM Review: Phase 2 Report”, WSP for UK Department for Business, Energy & Industrial Strategy. <https://www.gov.uk/government/publications/review-of-the-evidence-on-the-response-to-amplitude-modulation-from-wind-turbines>
- [23] E. Barlas, W. J. Zhu, W. Z. Shen, K. O. Dag, P. Moriarty, Investigation of Amplitude Modulation Noise with a Fully Coupled Noise Source and Propagation Model, 7th International Conference on Wind Turbine Noise, Rotterdam – 2nd to 5th May 2017.