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

Work Package C (WPC) - Collation and Analysis of Existing Acoustic Recordings

Andrew Bullmore, Matthew Cand
HOARE LEA Acoustics
140 Aztec West Business Park
Almondsbury
Bristol
BS32 4TX

Tel: 01454 201 020
Fax: 01454 201 704

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EXECUTIVE SUMMARY

The objective of Work Package C was to collate and assess existing evidence, and in particular available recorded samples of wind turbine noise containing amplitude modulation, in order to provide input to the research on further understanding the cause and effect of amplitude modulated wind turbine noise. A review of the available and published evidence was therefore undertaken at the outset of the project in order to provide some initial steer to the project overall. The review then continued throughout the project as further information became available. In order to maximise the usefulness to the research, relevant data was proactively sought from the wind turbine noise community. The data acquired was reviewed and analysed. Relevant existing data which had been acquired prior to the commencement of the project, and the analysis of this data made by members of the project team, was also used to allow prompt progress to be made towards achieving the project aims within the required timescales. The results of these analyses, and a selection of the audio samples used as the basis for these analyses, were used as an input to other work packages. A review of the available evidence and literature was also undertaken.

This Non-Technical Summary contains an overview of the report and its conclusions. No reliance should be placed on the content of this Non-Technical Summary until this report has been read in its entirety.

1 INTRODUCTION

1.1.1 The work presented in this report is part of project funded by RenewableUK and entitled 'Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect'. The project comprises a total of six separate work packages. The outcome results of each of the work packages have separately resulted in their own dedicated final reports. A seventh work package, WPF, has produced an overarching final report in which the key findings across the separate work packages have been collated and discussed.

1.1.2 This is the final report of Work Package WPC: 'collation and analysis of existing acoustic recordings'.

1.1.3 Wind turbine aerodynamic noise, by which is meant the noise produced by the rotating wind turbine blades, includes a steady component as well as, in some circumstances, a periodically fluctuating, or amplitude modulated (AM), component. However, AM may take different forms. One form of AM, commonly referred to as 'blade swish', is an inherent feature of the operation of all wind turbines. It can be explained by well understood mechanisms, it being the result of the directivity characteristics of the noise created by the air flowing over a turbine blade as it rotates. Because this type of AM is an inherent feature of the operation of wind turbines, whose origin can be explained and modelled, the present project adopts as its definition the term 'normal amplitude modulation' (NAM). The key driver for the project, however, is the recognition that some AM exhibits characteristics that fall outside those expected of NAM. Such characteristics include a greater depth of modulation, different directivity patterns or a changed noise character. For this reason the present project adopts as its definition the term 'other amplitude modulation', or 'OAM', for all observations of AM that lie outside that expected of NAM.

1.1.4 In recent years public concern has grown about the potential annoyance from wind turbine OAM noise. This concern has resulted in an increased interest to establish how AM, and in particular OAM, occurs, how it can be better defined and measured, and how it is generally perceived and responded to. It is the answers to these questions that the present project seeks to address.

1.1.5 To provide input to this research, it was identified early on that real-world acoustic data would be required as a key input. To allow prompt progress and to maximise the ability to achieve the project aims within the required timescales, it was considered essential to make use of relevant existing data. This existing data included both that acquired previously by some members of the project team and data available within the wind energy community as a whole. The latter data was proactively sought by the project team. In this manner, acoustic data became available to the project which had been collected for a wide variety of purposes. This constituted Work Package C of the current project, which was undertaken by Hoare Lea Acoustics.

1.1.6 As part of Work Package C of the project, the aforementioned acoustic data and associated recordings were analysed and any relevant observations collated. This provided the required input to other key elements of the project:

- Work Package A – Fundamental Research into the Causes of Amplitude Modulation
- Work Package B – Development of Objective Amplitude Modulation Measurement Methodology & Development of a Dose-Response Investigation

2 APPROACH AND METHODOLOGY

2.1 Review of available evidence

2.1.1 At the project outset, a review of the current knowledge and experience of AM was undertaken in order to provide a starting point for investigations. This review collated existing knowledge and reviewed any further studies or information since the work undertaken in 2007 by the

University of Salford [1] and commissioned by the UK Government. The review also sought to include relevant reports and potential data sources from projects outside the UK, where possible. The current status of this review is included as **Appendix A** to this report.

2.1.2 One of the complicating factors of the present study is that wind turbine noise generally only becomes an issue where it adversely affects residential neighbours to wind farms. The issue as to whether or not a particular wind farm may cause problematic noise therefore generally relies on the reliable and consistent reporting of its effects by those living in the vicinity of the wind farm. The review and interpretation of available information is complicated by the difficulty in establishing the relevance of reported experiences and disturbances of wind farm neighbours from wind turbine noise, and in particular the relevance of the widely varying descriptions used by those reporting it. The potential issue of relating subjective descriptions to actual effects applies particularly to the specific subject of Amplitude Modulation noise from wind farms, especially when it is appreciated that this potential feature of the noise may vary and/or take different forms, each of which may be self-reported using different descriptors across different subjects.

2.1.3 Previous research [2] undertaken in 2006 following reports of disturbance from a limited number of wind farms in the UK, reportedly from low-frequency noise, identified that in these cases the complaints were, in fact, more likely related to increased level of amplitude modulation of the blade passing noise. Although the blade passing frequencies at which the wind farm noise may modulate are relatively low (of the order of one Hertz), this does not mean that the noise itself directly contains such low or infrasound frequencies.

2.1.4 In comparison, a 2010 study [3] commissioned by the Danish Energy Authority to study low-frequency noise from large wind turbines identified the presence of low-frequency tones associated with the operation of mechanical components in a prototype turbine as the source of reported annoyance from a wind farm neighbour. As a result, the research focussed in detail on the study of the subjective response to tonal noise. So in that study as well, a specific feature of the noise was identified as the source of the reported annoyance.

2.1.5 These considerations are complicated to a degree by the historical presence of infrasound in downwind turbine designs due to blade flow/tower interaction effects, which have now been effectively designed out of modern turbines through the use of upwind designs. The above-referenced studies, as well as more recent research [4] presented in 2011, have confirmed that there is no significant level of infrasound emitted from modern wind turbines.

2.1.6 The foregoing findings highlight the difficulties in interpreting subjective descriptions of noise, in particular by non-specialised observers, which includes the majority of wind farm neighbours. Experience has shown that a process of undertaking objective measurements and recordings, and then comparing and relating the experiences of those exposed to noise with objective data (if possible directly) is often necessary to clarify the cause of these complaints with the required degree of certainty. Reported disturbances from wind turbine noise, even after discounting non-acoustic factors, may just as likely be due to excessive overall levels of noise and/or significant tonal components rather than being related to AM. Acoustic evidence available from situations where complaints have arisen from effects other than AM are therefore of no relevance to the present project, even though the subjective descriptions assigned to such data may initially have led the project team to investigate the reported noise further.

2.1.7 In circumstances when tones are present in the noise emissions from wind turbines, this may be described using terms such as ‘rumble’ or ‘pulsing’ which may be interpreted as describing modulation of the aerodynamic noise, when this is not the case. In specific situations, tonal noise emissions have been found to vary in time (*i.e.* modulate at the blade passing frequency) as the mechanical source producing this tone varies along with the blade loading, but this was in cases of significant tonal emissions which can be readily assessed using methods to evaluate (non-stationary) tones [5]. This was therefore excluded from the scope of the current project.

2.2 Terminology and conclusions

2.2.1 As a result of the review outlined in Appendix A, the use of the term 'AM' was also perceived as introducing a degree of confusion. This term strictly relates to amplitude modulated noise, which could be used as a characteristic for several other sources of ambient noise. It is in particular an intrinsic feature of the noise emitted at source from wind turbines due to their rotation, but it has also sometimes been used as a short-hand to refer to cases where this modulation was found to be increased, enhanced or more prominent than expected at receptor locations. For example, the 2007 study[1] by the University of Salford was based on a survey of reported disturbances from wind farm noise, but focused on reports in which the modulation was characterised by '*a sharper attack and a more clearly defined character than usual*', which it defined as 'AM'. Some observers have claimed, having reviewed the data from this research, that it underestimated the occurrence of amplitude modulation, but this interpretation is based on a wider definition of the term 'AM' than the one used by the authors of the report.

2.2.2 It is therefore important to distinguish between the 'normal' AM (NAM) which is understood to be an inherent feature of wind turbine noise, and 'other' instances of AM which have different characteristics.

2.2.3 The literature review undertaken identified research on this feature of the noise, from the early turbine designs in the late 90s, to recent noise models on larger, modern turbine designs, which can predict the modulation of the noise at source in normal conditions and were satisfactorily validated using near-field measurements. Therefore the mechanism explaining the 'normal' modulation of turbine noise and its characteristics is well understood, being a result of the directivity of the noise generated at the trailing edge noise of the blade as it rotates.

2.2.4 This could then be separated from the reports of 'other' types of AM (OAM)[1] which could not be easily defined or understood using the theory outline above. There was at the outset of this project little agreement on:

- how this could be defined exactly, given that observations and reports were inconclusive;
- its causes, frequency of occurrence and degrees of severity, which could be due, or at least exacerbated by, the limited data and limited reports of the phenomenon, which creates a level of uncertainty.

2.2.5 There was also a lack of results or consensus on:

- how modulation translates to the far-field (i.e. at significant distances from the turbines, say at distances of 10 rotor diameters from the turbines);
- modulation metrics and subjective response.

2.3 Data sources

2.3.1 In view of the above review, data and information was sought to provide input to the other elements of the present RenewableUK AM research project, thereby maximising its potential value and provide as complete as possible a view of the subject, providing additional certainty where possible.

2.3.2 The project team (lead by Hoare Lea Acoustics) sought to approach third parties with a view to compiling a database of wind farm acoustic recordings, including different types of AM. This included:

- researchers
- acousticians and consultants
- wind farm operators and developers

[1] The 'Introduction and Project Overview' (Section 1) to WPF contains a more detailed discussion concerning the definitions of NAM and OAM

- The UK Government
- advocacy groups and other interested parties

2.3.3 In particular, such an appeal was made as part of the presentation by the project team of a paper [6] at the 2011 Wind Turbine Noise Conference in Rome, which was attended by a great numbers of interested parties in the field.

2.3.4 **Appendix B** includes the data specification which was issued to third parties following initial contacts. It describes the requested acoustic data types, sometimes in order of preference as all may not be available, accessible or transferable. It also suggested relevant non-acoustic information which would assist in analysing the data.

2.3.5 A targeted search of relevant information and recordings available on the internet was also made, albeit bearing in mind that that significant caution should be exercised when considering the often limited information available for such data sources, along with the lack of quality control often associated with it.

2.3.6 The data measured on behalf of the UK Government as part of a previous research project[2] on this subject, the 2006 study by Hayes McKenzie Partnership for the UK Department of Trade and Industry (DTI), was also sought and obtained from the Department of Energy and Climate Change.

2.3.7 In addition to seeking data from third parties, use was made of data held by members of the project team, including several long term measurements at a number of UK sites (in England, Wales and Scotland, across a range of terrains and turbine types and for both internal and external measurement locations) which were identified as being relevant to the current Work Package.

2.4 Data content and type

2.4.1 Experience has shown that measurements of wind turbine AM (of all kinds) can be challenging, particularly when considering measurements in the far-field.

2.4.2 Wind turbine noise, due to its relatively low levels, is often masked to at least some degree by ambient noise, even in relatively quiet rural locations, due to the presence of a variety of other noise sources associated with natural effects and with animal and human activities, although the latter tend to diminish during evening and night-time periods.

2.4.3 In addition, the temporal characteristics of AM noise make the acquisition of meaningful acoustic data which can be directly related to wind turbine AM even more prone to corruption by extraneous noise. In particular, the more usual level metrics (L_{Aeq}, L_{A90}) or temporal resolution (minutes, hours) implemented by traditional averaging sound level meters to assess overall levels of wind turbine noise or other steady sources of noise, are inadequate. This is because, whilst metrics that average noise over longer periods (such as the 10 minute average $L_{A90,10min}$ traditionally used to measure wind turbine overall noise levels) are effective at removing the effects of intermittent extraneous noise from the measured noise levels, they also remove shorter term effects that may be related to the wind turbine noise itself. This includes any AM, which for modern, large scale wind turbines typically occurs at a modulation rate of 1 second or less. As a consequence, measurements with an increased temporal resolution of significantly below 1 second, and typically closer to 0.1 second, are required in order to resolve AM effects. The problem here is that these shorter term measured levels then become prone to corruption by other extraneous short term noise, such as may be caused by bird song, livestock, passing cars, agricultural activities, *etc*. The shorter term measured noise levels can then either be characterised by overall A-weighted levels, or analysed in more detailed in terms of individual frequencies bands (such as 1/1 or 1/3 octave bands), with concurrent audio recordings providing the fullest record of the characteristics of the noise (and also, where necessary, enabling the positive subjective separation of turbine noise from extraneous noise). Collecting this additional data represents a significant challenge, even with state-of-the art measurement and data storage equipment, particularly over long-term periods. Based on this experience, this type of higher-resolution data was sought where possible, but it was recognised that it would not be available in many cases.

2.4.4 Meteorological and turbine operational data allow the measured acoustic data to be related to the source conditions and atmospheric conditions. Any such data was sought, where available, as part of the work package. It must be recognised, however, that current practice is for wind data to be collected at a single height and location (typically the turbine hub height) with statistical information being based around 10 minute intervals. In recent years, remote meteorological scanning systems (SODAR or LIDAR) have become more widely used, allowing increased spatial sampling with measurement at different heights. Increased resolution in time is also possible with these systems. Notwithstanding the potential limitations of existing data even when available, obtaining site-specific meteorological and operational data often requires the collaboration of the wind farm operator and may not always be available to third parties. In the absence of other data, indicative area-wide meteorological information can be considered.

2.4.5 Where available, information on the wind farm sites in question was also collated including: site topography; turbine details, etc. Details of any associated complaints can also provide a useful guide to the analysis, provided one is mindful of the difficulties outlined above.

3 DATA OBTAINED AND ANALYSIS

3.1 Analysis of data and samples supplied

3.1.1 Following the request made according to the above procedure, a number of data packages were obtained from the sources identified.

3.1.2 The quality and quantity of the data acquired varied from clearly labelled and calibrated acoustic measurements to simple audio samples with very limited supporting information. Even in the latter case, it was nonetheless possible to analyse the character of the noise, but some questions remained as to the exact conditions of the measurements which could have affected the data collected to a more or less significant degree. Because of the recognised challenges involved in collecting long-term audio data outlined above, some of the quality of the audio files acquired was limited, particularly in historical recordings. Any such deficiencies were taken into account where possible when interpreting the data.

3.1.3 In other cases, the data requested was not obtained despite follow-up requests, but overall a good return rate is considered to have been achieved, particularly given the challenging nature of the subject and the implications in terms of confidentiality requirements.

3.1.4 The study focused on the data received which was considered relevant to the current project. Some of the data acquired, such as that from some wind farm sites in Australia, did not seem to contain elevated levels of modulation when reviewed both subjectively using amplified playback and objectively using detailed signal analysis. The analysis did, however, in some cases reveal the presence of low-frequency tones which may have been the cause of the reported disturbance. Earlier in this report, the difficulties in interpreting the subjective descriptions of noise features were highlighted. Methods for tonal noise analysis have been developed and standardised in the recent years [5], but remain technically complex and require specialised knowledge and experience to apply. Similarly the subjective response to tonal noise has received extensive study, but this feature can be difficult to discern directly for the untrained ear. Therefore, claims of reported significant modulation, when little was audible could, in some cases, be ascribed to misinterpretation of subjective descriptions of the noise, or to the erroneous use of tools such as Fourier analysis which may appear to show some modulation where this may, in fact, more likely be due to artefacts of the processing.

3.1.5 **Appendix C** presents illustrative results of the analysis of the frequency content and time evolution of representative samples of the data considered in the project. The samples shown typically correspond to the clearest periods of modulation observed within the dataset and/or reported as corresponding to complaint conditions, for illustrative purposes. This may not however be representative of the nature of the noise experience for other periods or indeed for the majority of the time in some cases.

3.1.6 The following sections outline the key datasets analysed, a sample of which are illustrated in Appendix C.

Van den Berg – Journal of Sound and Vibration article - 2004

3.1.7 F. van den Berg supplied an audio recording of approximately 10 minutes' duration. This corresponded to the period of modulation shown in a 2004 article in the Journal of Sound and Vibration [7] (Figure 8 in this article). This article described the measurement of modulated wind turbine sound 'with an impulsive character': see Appendix A. Measurements were made in the vicinity of a wind farm comprising 17 pitch-regulated, variable speed turbines, on relatively flat terrain. This recording was measured 750 m away from the nearest turbine of the wind farm in question, and approximately 2m from a reflective surface. The audio sample was supplied with a low-pass filtered applied above 1kHz to exclude the corrupting influence of background sources.

The Measurement of Low Frequency Noise at Three UK Wind Farms (for the DTI)

3.1.8 The full set of measurement data obtained at the three sites considered in the 2006 study by Hayes McKenzie Partnership (HMP) for the UK Department of Trade and Industry (DTI) was obtained. The project report details the measurements which were made in response to noise-related complaints at certain properties around three UK wind-farms, with measurements at various locations both inside and outside the properties concerned, which were related to complaint logs for the monitoring period.

3.1.9 Appendix C presents samples for the first two sites, from periods highlighted in the report[2]. For the third site, the data corresponding to the period highlighted was not available due to a hardware failure; the data for this site was reported to be affected by significant levels of water-course noise which limited the clarity of the recordings. The other series of measurements are, however, considered sufficiently representative based on the report for this project.

3.1.10 Site 1 comprised seven fixed-speed pitch-regulated wind turbines, installed on hilly terrain. In easterly wind conditions, which were associated with the complaints, three of the turbines, the closest to the dwelling studied, tended to experience inappropriate wind conditions due to a local terrain feature. A noise reduction management system was therefore implemented to curtail the operation of some of the turbines in the wind conditions associated with the complaints, but this was not operating during the measurements. The analysis in Appendix C is shown for the external (free-field) measurement location, for the period highlighted in the HMP report (page 84 Annex 2).

3.1.11 Site 2 comprised sixteen stall-regulated wind turbines, located on a plateau amongst a rolling terrain. The measurements undertaken comprised internal and external (free-field) locations at a dwelling, which was located in a relatively sheltered hollow. The analysis shown in Appendix C was for one of the two periods highlighted in the HMP report (page 89 Annex 2) and in which the resident activated the recording system during the monthly measurement period.

Internet audio sample

3.1.12 Appendix C presents the analysis of an audio sample obtained from the internet [8], the sample being described as being representative of the experience of residential neighbours to a particular wind farm. There was very limited information available on the recording (location, equipment used etc.), which would assist in evaluating its quality, but it was reportedly made at a residential property and therefore in the far-field of the turbines. Some influence of unknown source (non-turbine related) was evident at higher frequencies (>1kHz), but the analysis shows clear levels of modulation of the noise at times.

Australia/New Zealand + USA data

3.1.13 As outlined in 3.1.4, the data received from various sources often did not contain significant levels of audible modulation. An example period is shown in Appendix C when a low level of modulation or rumbling is audible, although the exact conditions of the measurement were unclear. In some of the other recordings, the measurement appeared to have been made in the near-field of the turbines, where swish is expected to be experienced, but this would not necessarily be representative of conditions in the far-field.

D. Bowdler near-field recording

3.1.14 D. Bowdler supplied [9] a 25 second audio sample measured at the foot of a pitch-regulated wind turbine, approximately 45 degrees from a cross-wind direction. In the sample, a transition in the character of the modulating noise is clearly audible and apparent in the spectrogram between two different types of modulation, with the latter period having a clearly increased content at lower frequencies (in the 100 to 600Hz region). This sample is considered in WPA2 in further detail.

‘Other’ AM

3.1.15 This sample shows a spectrogram and time history for a period of ‘other’ AM, measured at a free-field location in the far-field of a wind farm site (>800m from the turbines), during a quiet period where little other sources of ambient noise were present. The terrain was relatively flat and the wind farm comprised several pitch-regulated machines. The modulation is dominated by frequencies in the region of 200-600Hz.

3.2 Summary of sample analysis

3.2.1 A representative selection of audio samples obtained was issued to the project team in the form of audio files. This information was used as input to inform those leading the other work packages.

3.2.2 Although the data was sometimes difficult to interpret due to interference from spurious sources of noise and natural variability, both of which are inherent to the analysis of wind turbine noise in the far-field, the analysis suggested that in periods of clear modulation, the observed far-field data fell broadly into two types of categories with differing spectral content:

A. A-weighted levels dominated by the 500-800Hz region;
B. A-weighted levels dominated by the 200-600Hz region, with a slight-low frequency bias (peaking around 300Hz)

3.2.3 For the first category, this frequency range is consistent with existing literature on modulated ‘swish’ noise from wind turbines, associated with trailing edge noise from the turbine blades: this was therefore labelled as ‘mid-frequency AM’ (MFAM). The second category is different and was therefore labelled as ‘reduced-frequency AM (RFAM)’.

3.2.4 It was also observed that the frequency at which the sound modulated typically varied between 0.8Hz (for modern machines) and 1.3Hz (for older models), which is consistent with the rotational rate of the turbines.

3.3 Overview of other field experience

3.3.1 The experience of members of the project team was also considered, based on measurements undertaken at sites where 'other' AM was observed in the far-field. This followed complaints from the neighbouring residents of the sites in question. The observations made were not considered typical of past experience around other wind farm sites, hence the use of the 'other AM' category. Due to client confidentiality, it was not possible to circulate details and results of these measurements, but some general analysis results were discussed to support the progress of the research project.

3.3.2 At these sites, periods of modulation were measured in the far-field of the turbines (*i.e.* distances of 500 to 1km) in which the character and frequency content of the modulation noise was of a similar character to that shown in Appendix C as 'other AM', although the influence of background sources of noise often represented a complicating factor.

3.3.3 During periods of modulation, short-term changes in measured A-weighted noise levels[2] of 5dB(A) or more could be observed at times, increasing to up to 10 dB(A) in exceptional cases. The modulation was dominated by frequencies in the 100-400 Hz region when measured internally, extending up to 600Hz externally but dominated by the 300 Hz region.

3.3.4 This feature was observed to be intermittent and often experienced for limited proportion of the total time, which is consistent with previously reported analysis [1]. But when present it can, at times, persist (to varying degrees) for extended periods of several minutes or hours.

3.3.5 Periods of modulation were in some cases associated with certain wind conditions (wind speeds and/or wind direction), although this dependence could be complex. It could generally not be established whether this was because the noise feature ceased to be generated or whether it was because the ambient conditions changed, leading to the noise being masked in the far-field. Further correlation with other operational parameters, apart from those indicating the turbine was generating, was generally inconclusive.

3.3.6 Based on the available data and the above analysis of the different instances reported, no common factors could be associated with different instances of site features or layout characteristic, topography, wind shear characteristics, turbine model and/or type, turbine proximity, turbine height or turbine proportions.

3.3.7 The foregoing experience, including the often contradictory evidence, led to the conclusion that the measurement parameters typically available for wind farm studies could not provide the required degree of evidence to directly identify potential causes for increased or atypical levels of modulation. It was the conclusion of the research group that a more extensive measurement survey and a detailed study of on-blade generation mechanisms was necessary to reach firmer conclusions.

[2] See WPF for a further discussion on the lack of absolute definition of modulation depth. These indicative values refer to the typical peak-to-trough changes in A-weighted $L_{eq,T}$ levels, where T is close to 100ms.

4 CONCLUSION

4.1.1 The objective of Work Package C was to collate and assess existing evidence, and in particular available recorded samples of wind turbine noise containing amplitude modulation, in order to provide input to the research on further understanding the cause and effect of amplitude modulated wind turbine noise. A review of the available and published evidence was therefore undertaken at the outset of the project in order to provide some initial steer to the project overall. The review then continued throughout the project as further information became available. In order to maximise the usefulness to the research, relevant data was proactively sought from the wind turbine noise community. The data acquired was reviewed and analysed. Relevant existing data which had been acquired prior to the commencement of the project, and the analysis of this data made by members of the project team, was also used to allow prompt progress to be made towards achieving the project aims within the required timescales. The results of these analyses, and a selection of the audio samples used as the basis for these analyses, were used as an input to other work packages.

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[7] Van den Berg, “Effects of the Wind Profile at Night on Wind Turbine Sound’, J. Sound Vib. 277 (4-5), 955-970 (2004)

[8] Recording available on: http://penbay2010.podomatic.com/entry/2010-07-17T01_27_09-07_00

[9] http://www.dickbowdler.co.uk/papers-publications/ “A sound file of swish and thump”

APPENDICES

Appendix A – Review of available literature and information

A.1 This appendix includes 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 in the UK but including as well available international experience.

A1) UK

ETSU-R-97

A.2 The ETSU-R-97 report [A1] 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.

A.3 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).’

A.4 Due to standing wave effects from reflection from building structures, the modulation in specific frequency bands can increase significantly.

A.5 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.6 A report for ETSU in the UK in 1999 [A2] 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.

A.7 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.

A.8 Jiggins [A3] 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.

A.9 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

A.10 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 sound arising from the operation of wind farms were published [A4]: 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.

A.11 This report was actually commissioned as a direct result of the claims made in the press concerning problems associated with low-frequency noise from wind turbines, including the potential effects of 'infrasound'. 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. 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. But 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.

A.12 Notwithstanding the conclusions above concerning both infrasound and low frequency sound, the DTI LFN Report went on to conclude 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'.

A.13 The specific sites studied were not named although this was subject to subsequent Freedom of Information requests. 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). Described as 'thumped', 'like a heart beat'.
- **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

A.14 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 [A5].

A.15 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.16 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*.'

A.17 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.*'

A.18 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*.'

A.19 Following receipt of the report, the UK Government [A6] 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.

A.20 Following a freedom of information request, the full data used to support the conclusions of the Salford University report was published on the internet [A7]. Four sites with noise complaints were identified by the local authorities as arising from turbine AM (as defined above). The report notes that AM may have been '*a possible factor in another eight sites*'.

First Site

A.21 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, which we understand comprised the addition of serrated edges to the turbine blades. 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.

Second Site

A.22 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.*'

A.23 A 'library' of conditions leading to complaints 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°.*'

A.24 Wind shear effects associated with conditions of high atmospheric stabily can be dismissed as a cause there, as they were found to be very limited at the site based on local anemometry measurements. However, the Salford report did note 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 may have resulted in elevated angles of attack of the flow on the blades.

Third Site

A.25 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.

Fourth Site

A.26 The noise character was described as AM, with 'swoosh swish' and 'beating (rhythmic)'. During the site visit, council representatives reportedly experienced audible blade noise 'whoosh'.

Bowdler review

A.27 Bowdler [A8] 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 [A1] and [A2] are consistent with the subsequent work of Oerlemans and Scheper [A9], 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 [A10] 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*.'

A.28 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 model of Oerlemans and Scheper, at 45 degrees from crosswind there is a combination of both high absolute noise level and deeper modulation.

A.29 He argues that effects of radiation directivity may not always decrease with increased separation distance in some situations, in particular at 45 degrees from downwind, because of the shadowing effect form the tower in one case. He also considers that the Oerlemans model can be interpreted as describing normal turbine swish as opposed to the other types of AM.

A.30 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.

A2) Europe

A.31 As noted in Reference [A5], European regulations on wind turbine noise are generally stated in terms of maximum dB(A) noise levels and make no explicit allowances for AM, although some national standards provide methods for rating characteristics such as impulsivity.

Van den Berg publications

A.32 Van den Berg [A11] 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.

A.33 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(A) (peak to trough) measured at 750 m from the nearest turbine, 2 m away from a reflective surface and 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 ~3 s; 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.

A.34 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 the paper. Van den Berg has stated that he did not consider the form of the turbine layout (i.e. turbines in line or 'randomly' laid out) was not more likely to lead to 'impulsiveness' (verbal evidence at the Bald Hills Wind Farm Project hearing, as reported in Ref. [A12]).

A.35 The varying depth of modulation reported in the JSV article 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.

A.36 Bowdler in [A8] 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 [A9] 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

A.37 In 2009, Di Napoli presented [A13] measurements made at single, isolated 1 MW turbine (66 m hub height, 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-trough for at least a few seconds.

A.38 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.

A.39 In 2011 the same author reported [A14] measurements at different distances from a wind farm in Finland 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 up to 2km. 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.

Other

A.40 Legarth [A15] notes that for modern turbines, the modulation was dominated by the frequencies in the range of 350 to 700Hz, based on recordings made at distances of 1.5 to 3 hub heights. This is compared to studies in 1996, with smaller turbines, where it was found that the dominating frequencies were closer to 1kHz. Legarth notes that the rotating speed for larger machines also tends to be smaller.

A.41 Lundmark [A16] states that some complaints have been registered in Sweden concerning 'swish/whoosh' noises from wind turbines '*of a certain type under some meteorological conditions*', but no further details are provided. Data is shown for short periods of audible modulation at a particular site, but it is stated that this did not correspond to '*serious complaints*'.

A3) Australia

A.42 A 2006 review of the subject [A17] 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.43 A report by Fowler [A12] 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 [A18] 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.

A.44 Another recent review [A19] 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 [A20] 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*'.

A.45 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.46 A report by Thorne for one of the residents [A21] 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. The available measurement data did not demonstrate clear evidence of strong modulation at far-field locations.

A4) New Zealand

A.47 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.

A.48 Ref [A21] 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.

A.49 The planning conditions for the West Wind project [A22] 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.50 A noise compliance report published by the operator [A23] 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.

A.51 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 one of the tests 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.52 A subsequent report [A24] 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.

References for Appendix A

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[A7] Renewable Energy Foundation website, http://www.ref.org.uk, 06 February 2009.

[A8] D. Bowdler, Institute of Acoustics Bulletin, Vol 33 no 4, 08/07/2008.

[A9] Stefan Oerlemans and Gerard Schepers. Prediction of Wind Turbine Noise and Comparison To Experiment. Second International Meeting on Wind Turbine Noise, Lyon, France, September 20–21, 2007.

[A10] Stefan Oerlemans and Gerard Schepers, Prediction of Wind Turbine Noise Directivity and Swish, Third International Meeting on Wind Turbine Noise Aalborg Denmark 17 – 19 June 2009.

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[A16] G. Lundmark, Measurement of Swish Noise, a New Method. Fourth International Meeting on Wind Turbine Noise, Rome, Italy, April 2011.

[A17] Complaints from noise of wind turbines – Australian and New Zealand experience Colin Tickell, Proceedings of Acoustics 2006, 20-22 Nov 2006, Christchurch New Zealand.

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[A19] Wind Farms Technical Paper, Environmental Noise, Sonus Pty Ltd, Adelaide, Australia, November 2010.

[A20] Environment Protection Heritage Council (EPHC), 2009 and 2010, 'National Wind Farm Development Guidelines – Public Consultation Draft', Adelaide

[A21] Dr Bob Thorne, Noise Measurement Services Pty Ltd (Brisbane) Noise Impact Assessment Report, Waubra Wind Farm Report No 1537 - Rev 1 - July 2010

[A22] Wellington Environment Court Decision W59/2007, 20th July 2007

[A23] M. Hayes, P. Botha, Project West Wind Wind Farm, Noise Compliance Assessment, 17th March 2010

[A24] P. Botha, Project West Wind Wind Farm Noise Compliance Assessment, 14th September 2010

Appendix B – Data request – specification issued

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. A research project is underway, 100 % funded by RenewableUK, which aims to improve understanding of the phenomenon.

It would be most interesting to test any model or metric 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. The project team is seeking to approach others researchers and acousticians with a view to compiling a database of wind farm acoustic recordings, including AM in some cases. The following describes requested data types, sometimes in order of preference as all may not be available, accessible or transferable.

Confidentiality

The data would of course be used in a confidential manner, and assurances can be given in this respect if required. If there are problems relating to commercial confidentiality, this would be addressed by removing any meta-data enabling identification of the data source if required.

Contributions would be acknowledged in publications (unless otherwise requested).

General data and site description

Identification of the site is not essential. A general description of the wind farm would be more interesting, including:

- Type of turbines and power regulation used (pitch or stall regulation, variable speed etc)
- Number and size of turbines (exact or approximate)
- Age or status of wind farm (construction year / status)
- If any noise complaints: description of situation (resolved, ongoing, scale?)

Data

The data may cover an extended period or simply sample representative periods.

Acoustic data

In order of preference:

- Audio data:
  - Uncompressed and/or calibrated long-term recordings
  - Compressed samples
  - Source: sound level meter or hand-held recorder, microphone etc.
  - Calibrated level if available
- Noise levels:
  - Short-term sampling rate LAeq or LAfast data (for example 100ms sample rate)
  - Third-octave band data: short term as above or averaged over short-term intervals (less than 5 minutes)
  - Source: class 1 or 2 sound level meter, analyser, etc
- Description:
  - **measurement position**: distance from turbines, environment
  - **measurement type**: close to the ground, on tripod/ground board, wind shield present etc.
  - **Environment**: Internal/external, proximity of reflective surfaces, walls etc, trees or other sources

Non-acoustic data

- **Anemometry information**: wind speed/direction at hub height and/or different heights, mast or LIDAR/SODAR. If not available, approximate or subjective description of conditions during measurement period
- **Turbine operational data**: full operational records of turbine status (power, yaw, nacelle wind speed etc). If not available, approximate or subjective description of status during measurement period
- **Subjective descriptions** of noise from measurement operator or from complaintants (if any)

Format

- For audio data an uncompressed format (WAV or similar) is preferred, but if not available or difficult, compressed samples (MP3 or similar) would be useful.
- For acoustic data, a spreadsheet or similar text output format would be useful, but proprietary instrument or software data may be processed directly.
- Data may be transmitted by email if not extensive in size, otherwise CD/DVD or web transfer may be arranged

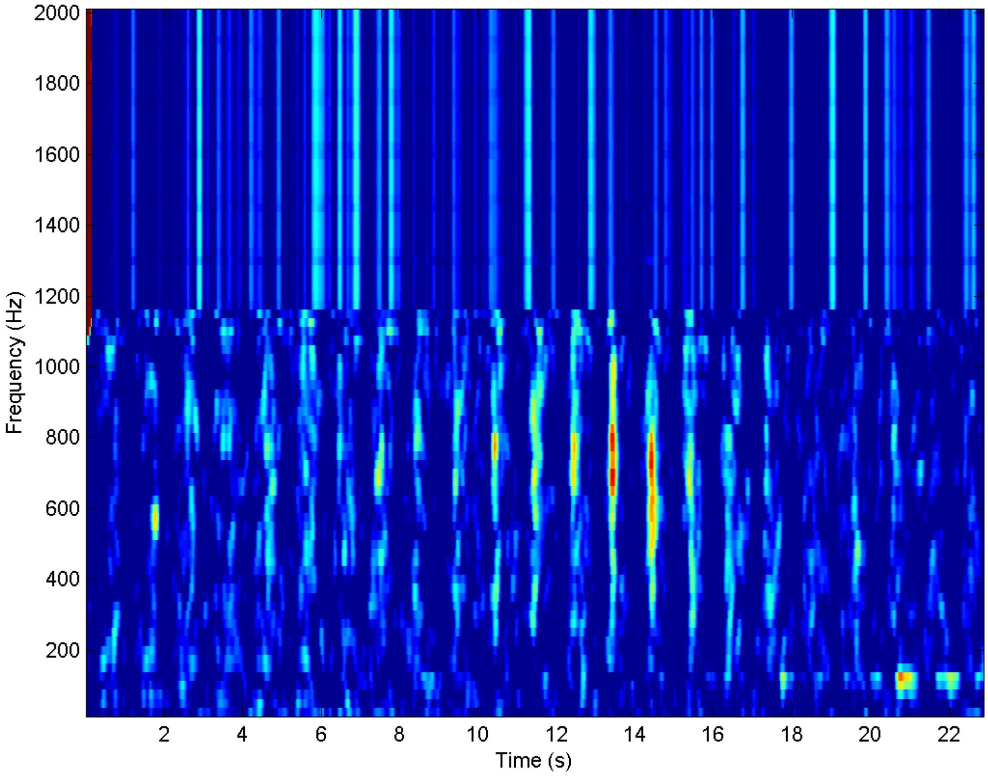
Appendix C – Sample data analysis

This appendix presents illustrative results of the analysis of the frequency content and time evolution of representative samples of the data considered in the present work package C. The samples shown typically correspond to the clearest periods of modulation observed within the dataset and/or reported as corresponding to complaint conditions, for illustrative purposes. This may not however be representative of the nature of the noise experience for other periods or indeed for the majority of the time in some cases.

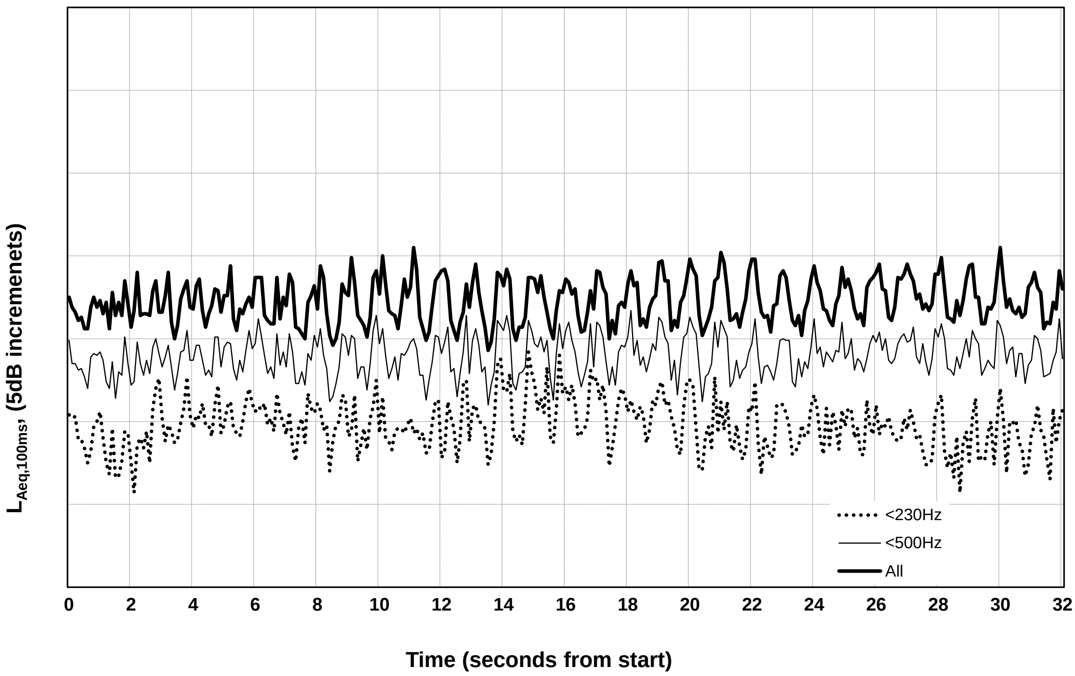
For each of the illustrative periods, two analysis graphs are shown:

- A spectrogram analysis is shown for frequencies up to 2kHz. In some cases (as indicated), the spectrogram is shown A-weighted. These spectrograms are a graphical representation of the evolution of the frequency content of the signal over time.
- A time history of the evolution of A-weighted L_{eq} levels with time, both for the signal as acquired and when low-pass filtered to retain only lower frequencies (up to 500Hz or up to 230Hz). This was derived from the audio signal, but as calibration data was not always available, this is not shown on an absolute scale of measured noise levels. The vertical scale mark corresponds to 5dB increments.

Fig. C1) **Van Den Berg sample – Journal of Sound and Vibration article – *extract*:** a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering



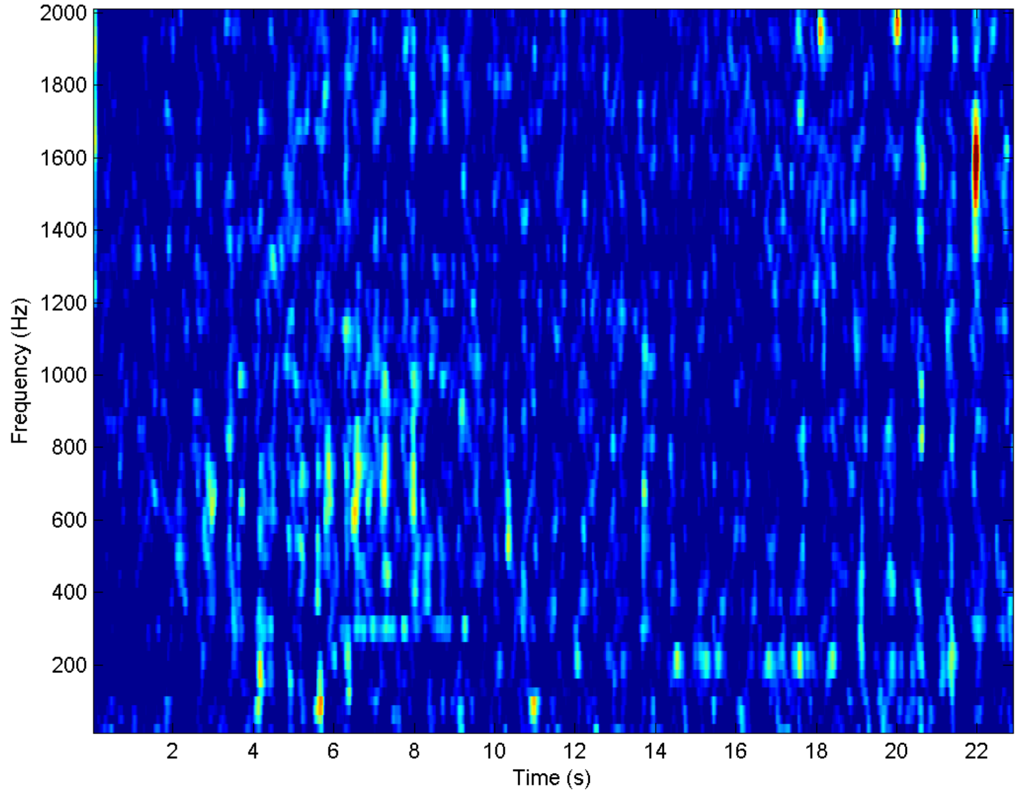
a)



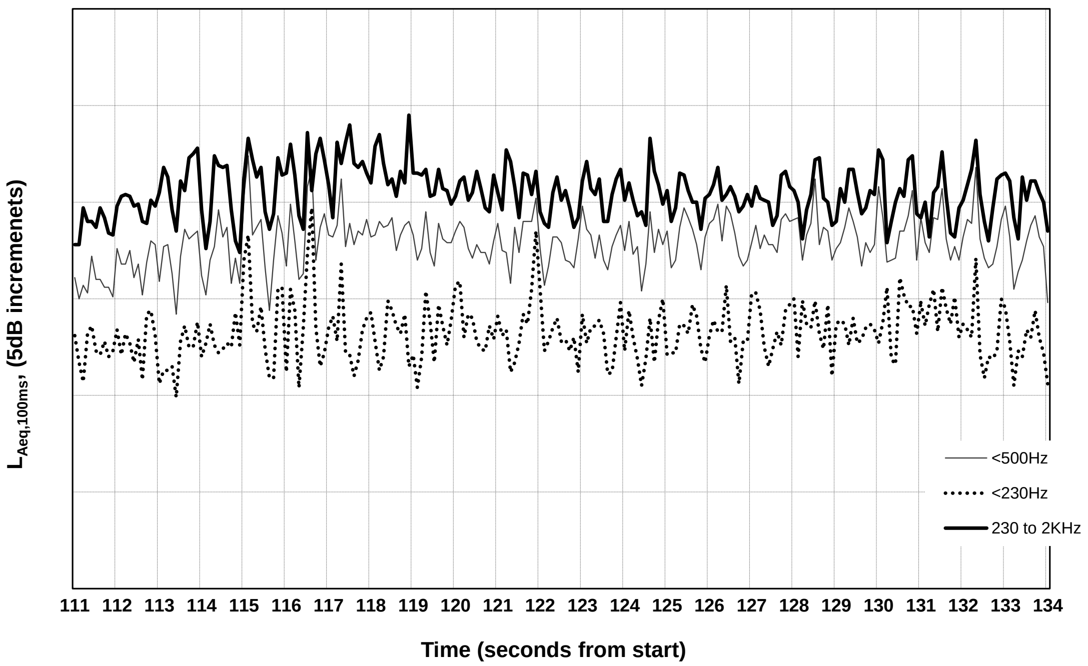
b)

Note: the modulation frequency when present is close to a rate of 1Hz.

Fig. C2) **DTI LFN study – Site 1 -** extract: a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering



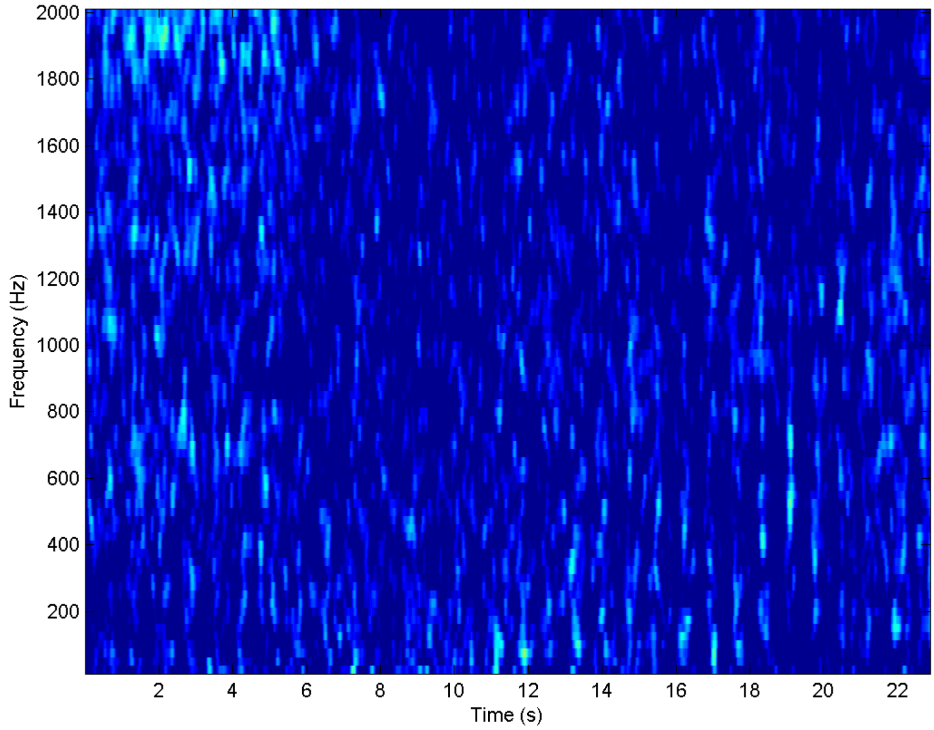
a)



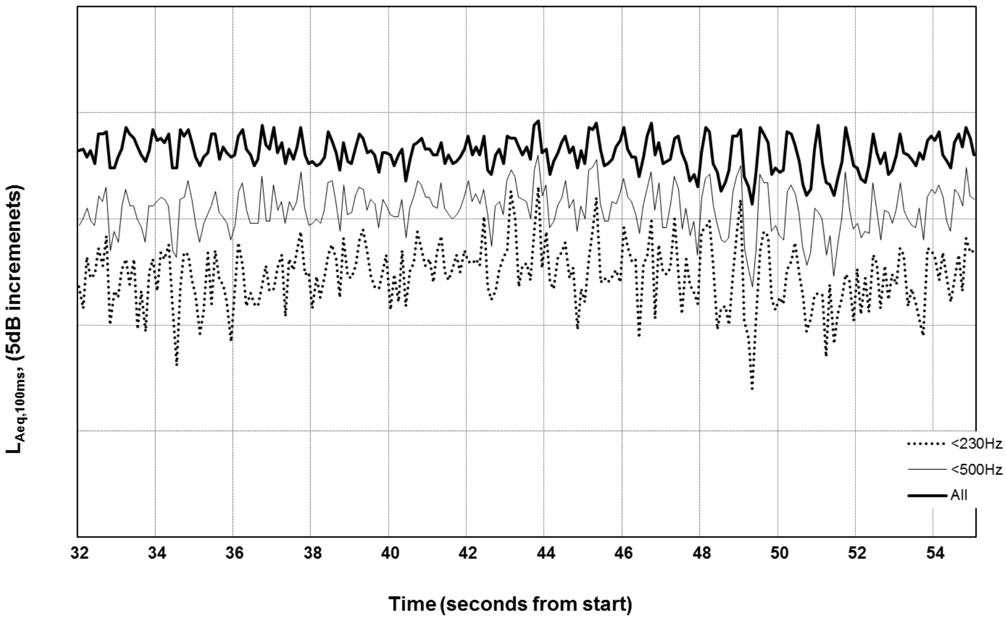
b)

Note: the modulation frequency when present is close to a rate of 1.4Hz.

Fig. C3) **DTI LFN study – Site 2**: a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering, both measured externally, free-field location; c) comparison between external/internal recording for a concurrent time period

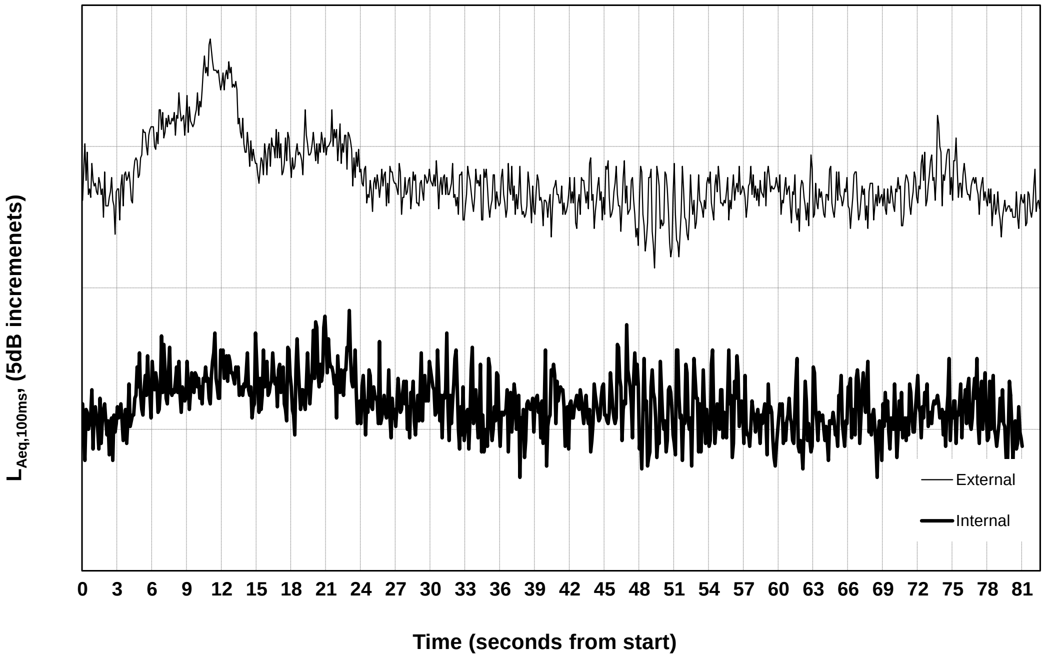


a)



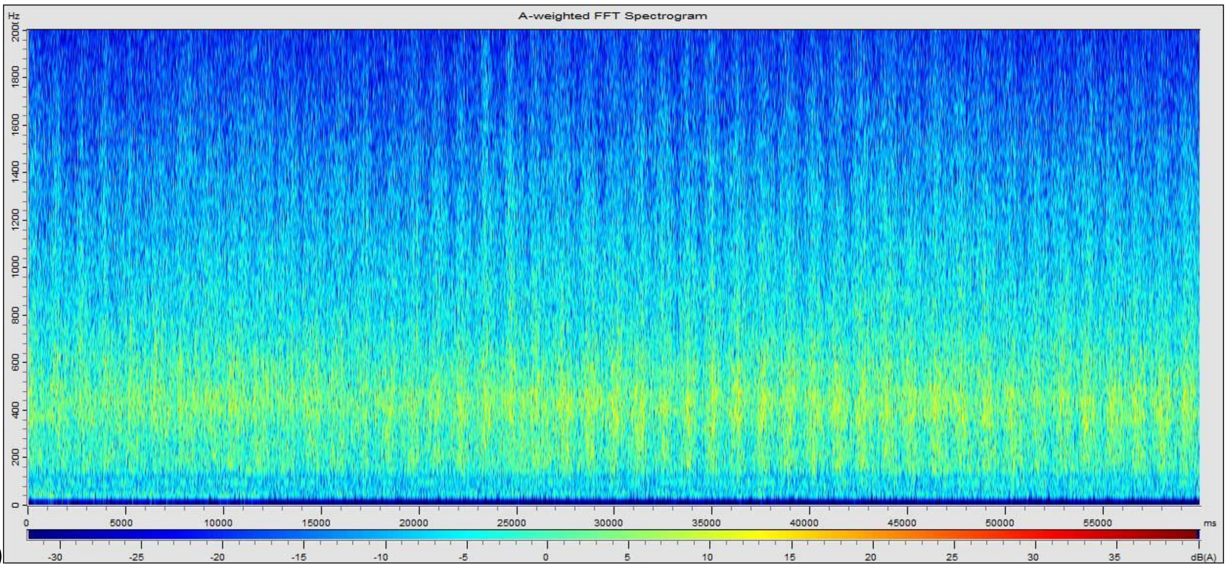
b)

Note: the modulation frequency, when present, is close to a rate of 1.3-1.4Hz.

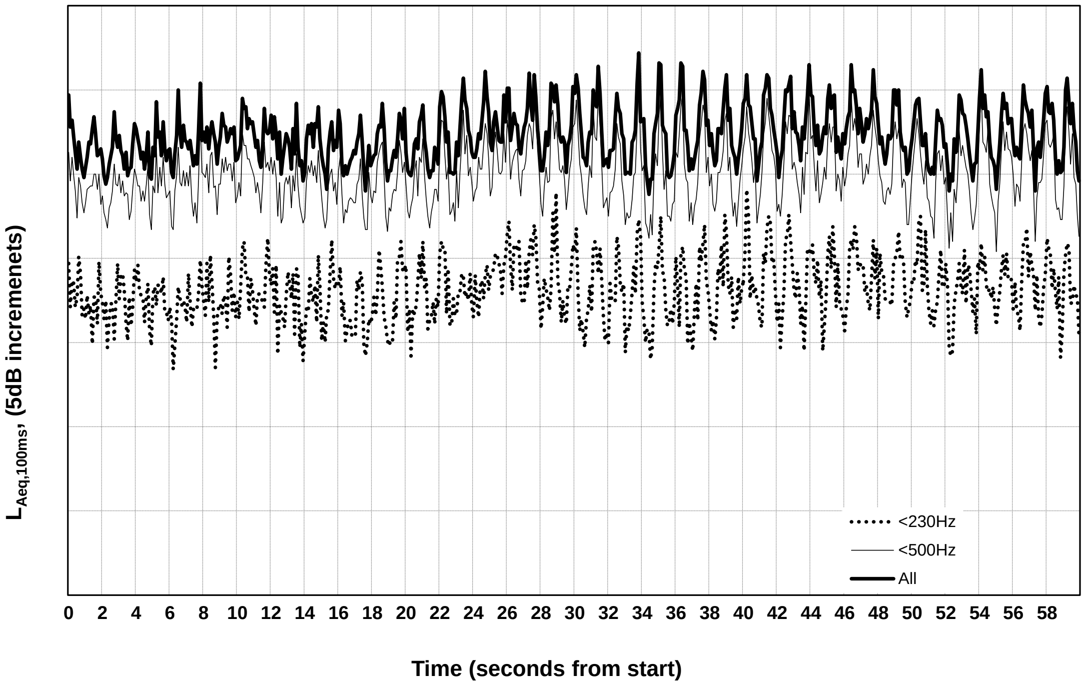

$L_{Aeq,100ms}$, (5dB incremenets)
External
Internal
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57 60 63 66 69 72 75 78 81
Time (seconds from start)

c)

Fig. C4) **'Other' AM (measured externally, free-field location)**: a) spectrogram (A-weighted) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering



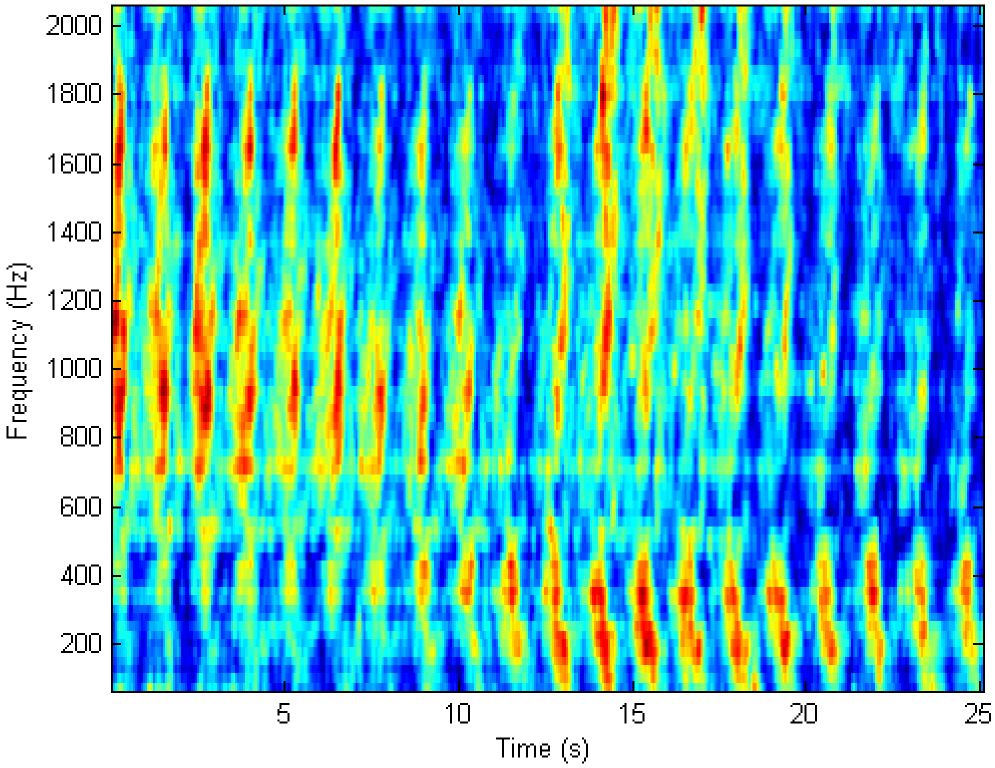
a)



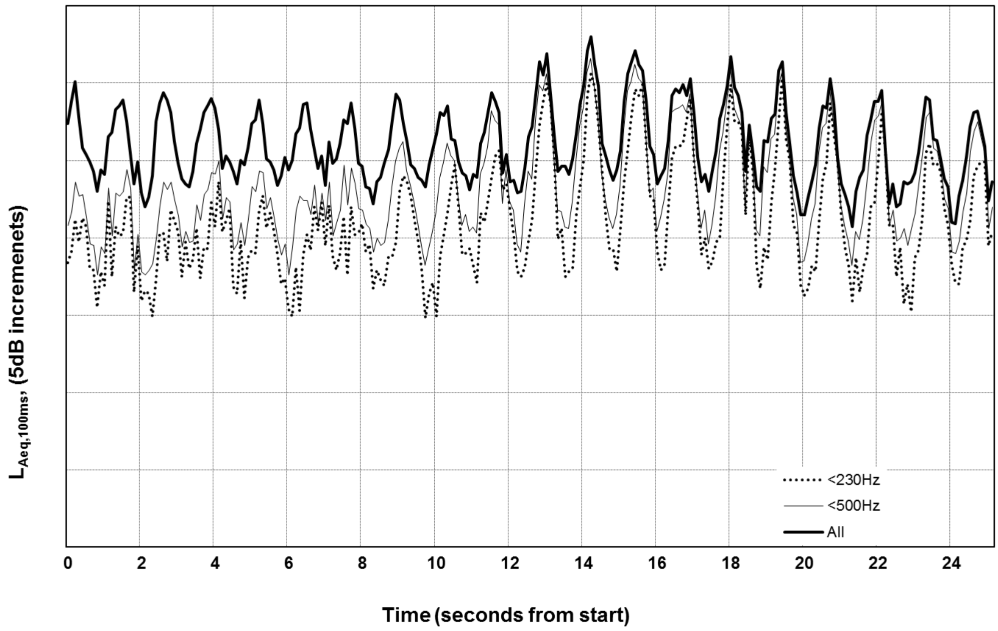
b)

Note: the modulation frequency, when present, is close at a rate of 0.8Hz.

Fig. C5) **Bowdler Near-field measurements:** a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering



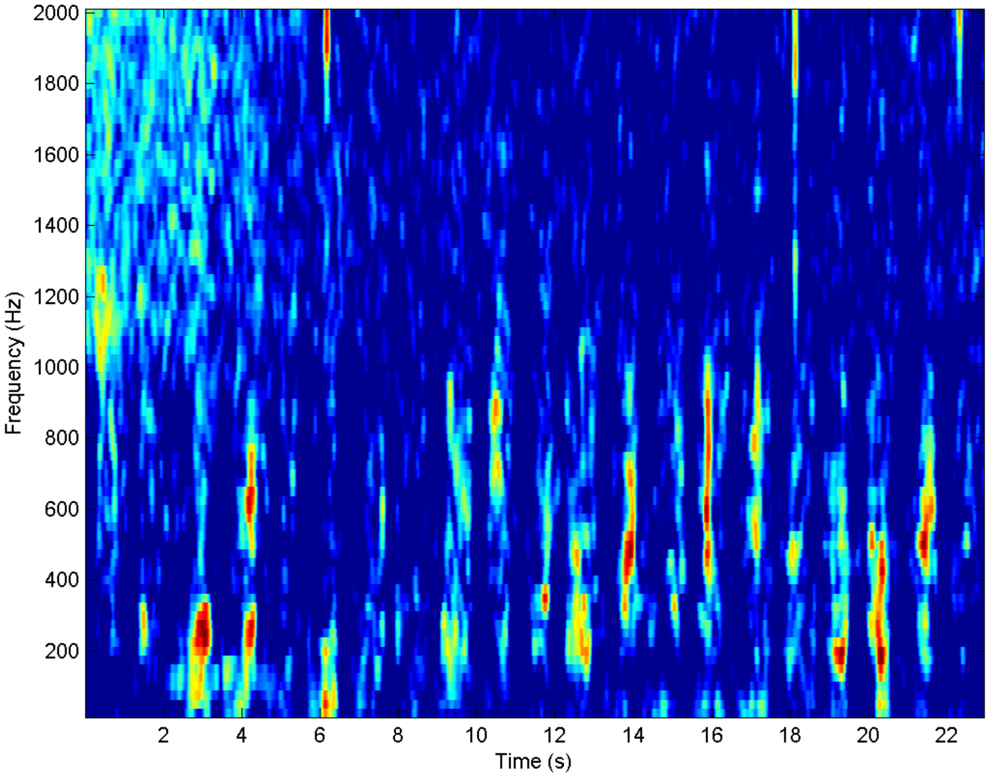
a)



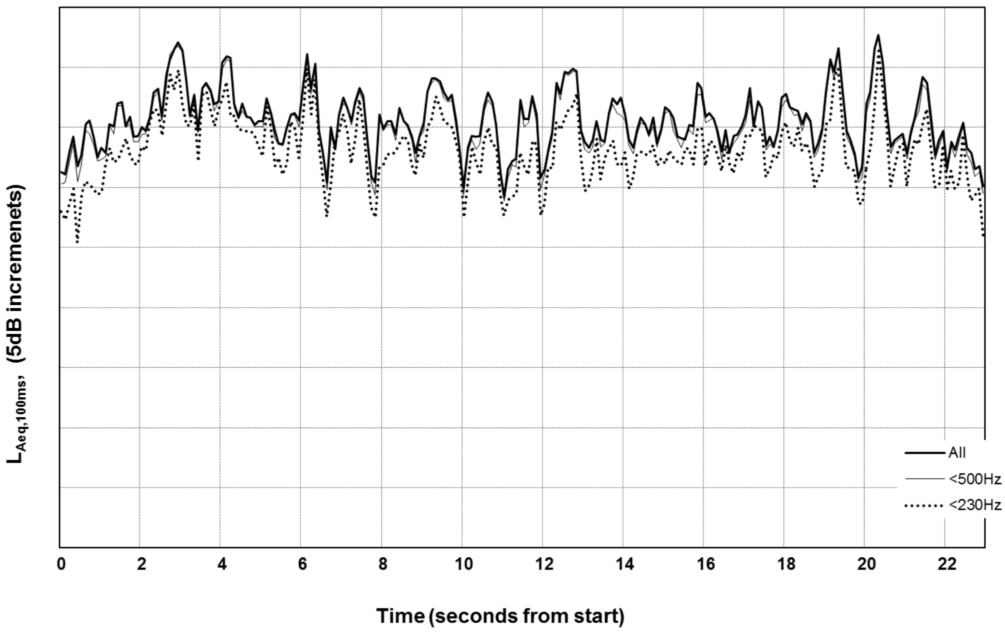
b)

Note: the modulation frequency is unclear but appears close to a rate of 0.8Hz.

Fig. C6) **Web-sourced audio:** a) spectrogram (linear) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering



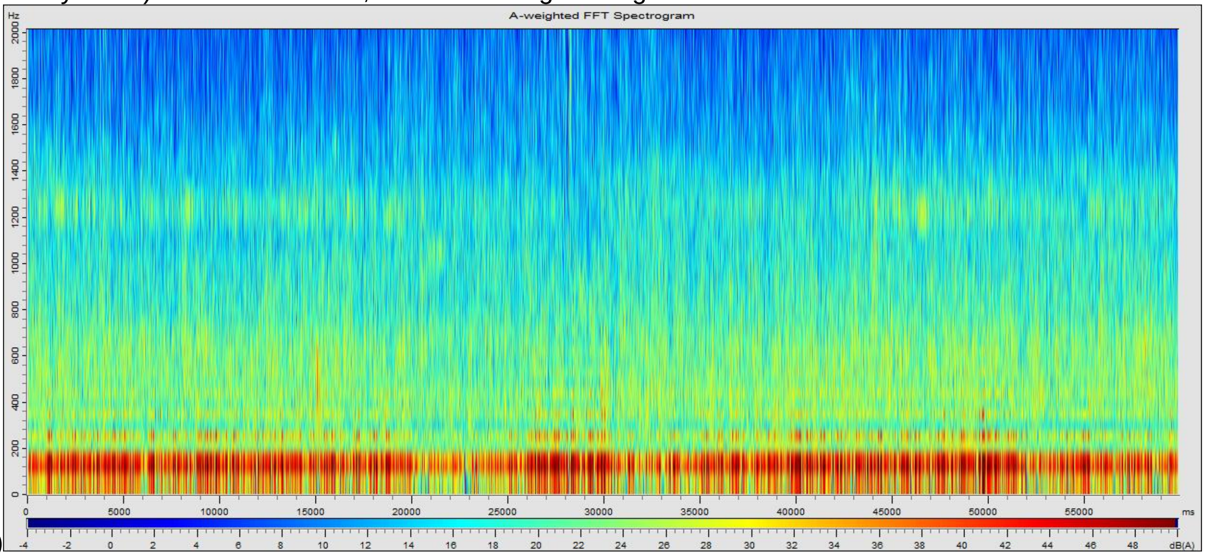
a)



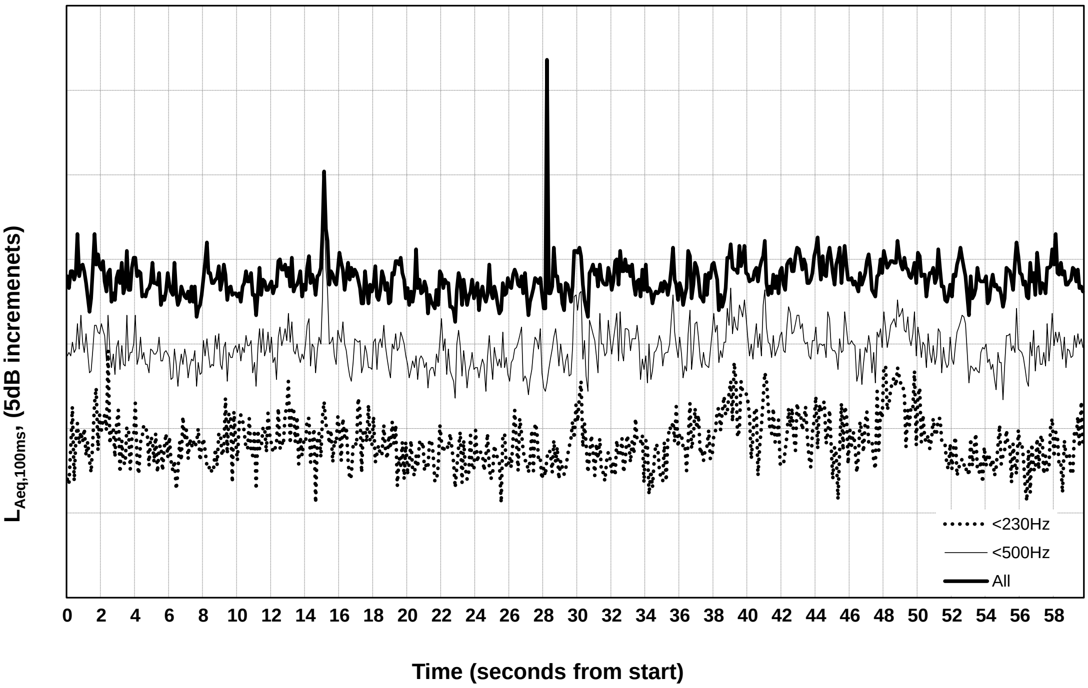
b)

Note: the modulation frequency is unclear but appears close to a rate of 0.8Hz.

Fig. C7) **Sample data from Australian site**: a) spectrogram (A-weighted) and b) noise levels history (arbitrary scale) 100ms resolution, with increasing filtering



a)



b)

Note: some light modulation is just audible, at a rate of around 0.8Hz.