INSTITUTE OF ACOUSTICS

IOA Noise Working Group (Wind Turbine Noise)

Amplitude Modulation Working Group

Final Report

A Method for Rating Amplitude Modulation

in Wind Turbine Noise

9 Aug 2016   Version 1

FOREWORD

This report has been produced by the Amplitude Modulation Working Group (AMWG) on behalf of the UK Institute of Acoustics. The group consists of the following members:

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The group was established in July 2014 and held a series of meetings, usually on a monthly basis with additional conference calls. A discussion document was issued for consultation in April 2015. The group also presented material at conferences and one-day meetings to liaise with other interested parties, to promote discussion and consider options. This report is the culmination of the process and advocates a Reference Method to be used for rating amplitude modulation in wind turbine noise.

This document is based on current knowledge and research available to the authors as of June 2016 and was developed from analyses of data samples from various wind turbine developments and synthesised data from subjective testing. It represents the consensus view of the working group.

The document sets a method to be implemented by suitably competent practitioners familiar with acoustic analysis methods. The level of technical competence required is similar to that required for tonal analysis according to ETSU-R-97 / ISO 1996-2: 2007.

The group would like to thank Malcolm Hayes at Hayes McKenzie, Chair of the IOA's Wind Turbine Noise Working Group, Charles Ellis at the IOA and the peer reviewers: Peter Rogers of Sustainable Acoustics and Ed Clarke at Clarke Saunders Associates and all of those who commented on the discussion document.

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0   EXECUTIVE SUMMARY

0.1   Background

0.1.1 This document has been prepared by the Amplitude Modulation Working Group (AMWG) established by the UK Institute of Acoustics (IOA) to propose a method or methods for measuring and rating amplitude modulation (AM) in wind turbine noise. Amplitude modulation (in this context) is a regular fluctuation in the level of noise, the period of fluctuation being related to the rotational speed of the turbine. This characteristic of the sound might be described by a listener as a regular 'swish', 'whoomph' or 'thump', depending on the cause and the severity of the modulation. Wind turbine AM has been reported in and around dwellings in the UK and elsewhere and, in some cases, its more severe forms have led to specific complaints from residents.

0.1.2 Given public concern over the issue, there is a recognised need to define a robust procedure for measuring and assessing AM, to provide a consistent means of evaluating complaints and to form the basis of appropriate planning conditions that might be applied to regulate AM from new wind turbine developments. Most planning conditions, currently routinely applied to wind turbine installations, have had the effect of limiting overall noise levels and provide a means of controlling tonal noise characteristics, but have not directly addressed AM.

0.1.3 Amplitude modulation has only relatively recently been recognised as an issue for wind turbine developments, perhaps over the last 12 years or so, but has now been the subject of a significant number of research papers and reports in the UK and elsewhere. Some researchers have carried out listening tests to provide information on how people respond to amplitude modulated noise. However, researchers have adopted several different metrics to ascribe a value to the component of AM present in samples of wind turbine noise. The AMWG has reviewed the existing literature on the measurement of AM and carried out further research to enable progress to be made towards defining the most appropriate metric for AM to adopt in the UK.

0.1.4 The AMWG has not addressed the question of what level of AM in wind turbine noise (when measured by a specific metric) is likely to result in adverse community response or how that response should be evaluated. The psycho-acoustic aspects of AM are not within the scope of this study, but the proposed metric is intended to assist with such further research.

0.1.5 The background to the study, information on the composition of the AMWG, its Terms of Reference and key requirements for a metric are set out in the main body of the report.

0.1.6 This report presents the conclusions of the AMWG and recommends a metric to define the extent to which a sample of wind turbine noise exhibits AM. It sets out a procedure for obtaining input noise data and analysing this data to quantify the magnitude of AM.

0.2   Definition of AM

0.2.1   In the context of the objectives of the working group, AM is defined as:

"periodic fluctuations in the level of audible noise from a wind turbine (or wind turbines), the frequency of the fluctuations being related to the blade passing frequency[1] of the turbine rotor(s)."

0.3   Application of the metric

0.3.1   The method applies to the measurement and assessment of the AM characteristics presented by current large upwind turbines with three-bladed rotors rotating at speeds up to approximately 32 rpm. It could also be applied with care to other turbines. Also, the metric is intended to be applied to external measurements of noise experienced at 'residential distances'; separation distances between large wind turbines and dwellings in the UK being typically 500 metres or more. The measurements are made outdoors, primarily because of the practical difficulties associated with making repeatable noise measurements indoors. Reliance on external measurements is consistent with established standards and procedures for assessing environmental noise.

0.4   Consultation documents and responses

0.4.1   The AMWG published a Discussion Document in April 2015 (IOA AMWG, 2015). This document presented the group's preliminary observations and conclusions on methods of measurement and rating AM based on a review of the literature and the combined experience of the group. Three different approaches to developing an AM metric were presented. These were based on, or derived from, methods described in the literature and were evaluated by processing audio recordings and time series records of real and simulated wind turbine noise exhibiting varying levels of AM and with varying degrees of contamination by noise from other sources.

0.4.2   Following publication, comments, observations and criticisms were received from interested parties. A summary of the key points raised by consultees and the AMWG's comments on these points is provided in the main report. The individual consultation responses, for those who agreed to publication, are available on the IOA website.

0.5   Reference Method

0.5.1   As a result of this analysis, and taking input from the responses to the Discussion Document (IOA AMWG, 2015), the AMWG has now identified a method (the 'Reference Method') for adoption in reliably identifying the presence of amplitude modulated wind turbine noise within a sample of data, and of deriving a metric that, in the AMWG's view, best represents the degree of amplitude modulation present. The method is described in detail in Section 4. It is essentially a development of the Hybrid Reconstruction

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[1] Blade Passing Frequency (BPF, in Hz) = (Rotor RPM) x (No. of Blades) / 60

method (i.e. Method 3) previously described in the Discussion Document. It also draws on elements of the proposed Methods 1 and 2 and incorporates a newly developed 'prominence' criterion which has been found to be very effective in discriminating wind turbine AM from other sources, thereby reducing (but not eliminating) the need for detailed scrutiny of the data.

0.5.2   In outline, a Fourier transform is taken of band-limited time series data to determine the fundamental modulation frequency (which should be related to the turbine BPF) and the second and third harmonics. These components are then used to reconstruct a time series, which should relate only to wind turbine AM, with the influence of background sources minimised. The modulation depth is then calculated following the method of Tachibana *et. al.*, *i.e.* subtracting the L_{95} of the time-series from the L_5.

0.5.3   The Reference Method involves the following stages:

- Noise is measured in short-term, 100-millisecond L_{Aeq} values in 1/3-octave bands. Three frequency ranges or bands are evaluated: 50 - 200 Hz; 100 - 400 Hz and 200 - 800 Hz, and the results which exhibit the highest resulting levels of AM are used

- The fundamental length of input sample to be assessed (the minor time interval) is 10 seconds

- The hybrid reconstruction method is used to determine the AM value for each 10 second value

- The values of AM measured by the metric in each 10-second interval are aggregated over a 10-minute period (the major time interval) to provide a single value which is the AM rating for the 10 minute period.

0.5.4   The application of the Reference Method is illustrated in the main report through the analysis of data samples including those exhibiting wind turbine AM and also background noise with wind turbine noise absent. Measurement of wind turbine noise made for the purpose of evaluating AM using the Method involves specific requirements for instrumentation and these are described in the main report.

0.5.5   Implementation of the recommended Reference Method requires the use of specific bespoke computing routines programmed in Python, MATLAB or similar platforms. Details of the appropriate code for users to programme these routines will be made available through the IOA, with data samples for validation.

0.5.6   Although it is relatively complex, a degree of complexity is considered inevitable in a method that is sufficiently robust for determining compliance or non-compliance with specific thresholds or limits. A simple preliminary assessment method (the Indicative Method) is also described; this may be useful in some situations where wind turbine AM is subjectively apparent and when noise measurements with minimal contamination by other noise sources are available. However, the Indicative Method must be used with caution and is to be considered as secondary to the Reference Method and in no circumstances as a substitute for it.

1   INTRODUCTION

1.1.1   Amplitude modulation (AM) in wind turbine noise has been well documented in recent years in the UK and overseas and various researchers have proposed methods of ascribing a value to the level of AM in a noise sample (an AM metric) and of assessing the significance of that level. However, the application of different metrics yields different AM values, and few of the metrics are supported by research on dose-response relationships.   In response to a request from the Institute of Acoustics Noise Working Group (IOA NWG), and IOA Council, the IOA set up a working group to look at amplitude modulation in wind turbine noise – the Amplitude Modulation Working Group (AMWG). The aim of the group is to review the available evidence and to produce independent guidance on the technical aspects of the assessment of AM and to recommend an appropriate metric. The working group includes academics, representatives from wind farm developers and local authorities and acoustic consultants who have worked for developers, local authorities and objector groups (see Foreword).

1.1.2   It is now generally accepted that there are two manifestations of wind turbine AM.   An observer close to a wind turbine will experience 'blade swish' because of the directional characteristics of the noise radiated from the trailing edge of the blades as it rotates towards and then away from them[2]. This effect is reduced for an observer on or close to the (horizontal) turbine axis, and therefore would not generally be expected to be significant at typical separation distances, at least on relatively level sites. The RenewableUK AM project (RenewableUK 2013) has coined the term 'normal' AM (NAM) for this inherent characteristic of wind turbine noise, which has long been recognised and was discussed in ETSU-R-97 in 1996 (ETSU, 1996).

1.1.3   In some cases, a form of AM is observed at residential distances from a wind turbine (or turbines). The sound is generally heard as a periodic 'thumping' or 'whoomphing' noise containing relatively low frequencies. This type of noise was identified in 2002 to 2004 by Frits van den Berg (van den Berg 2005) and in a UK study on low frequency noise from wind farms in 2006 (Hayes, M. 2006). The prevalence of this type of modulation is subject to debate. On sites where it has been reported, occurrences appear to be occasional, although they can persist for several hours under some conditions, dependent on atmospheric factors, including wind speed and direction.

1.1.4   It was proposed in the RenewableUK 2013 study that the fundamental cause of this type of AM is transient stall of the airflow over the blades as these experience periodic (blade passing frequency related) changes in the inflow wind speed as they rotate.   Transient stall represents a fundamentally different mechanism from blade swish and can be heard at relatively large

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[2] In addition, complex Doppler effects due to the relative blade movement influence the characteristics of the noise.

distances, primarily downwind[3] of the rotor blade. The RenewableUK AM report adopted the term 'Other AM' (OAM) for this characteristic. Elsewhere it might be reported as Excessive Amplitude Modulation (EAM).

1.1.5 All AM source mechanisms result in a periodic fluctuation (modulation) in the amplitude (level) of the turbine noise, the frequency of the modulation being related to the Blade Passing Frequency (BPF) of the wind turbine blades (the rate at which the blades of the turbine pass a fixed point). For a three-bladed turbine rotating at 20 rpm, this equates to a modulation frequency of 1 Hz.

1.1.6 ETSU-R-97 refers to AM on pages 40 and 68. It is stated that AM of up to 3 dB 'peak to trough' is typical close to a wind turbine, and that fluctuations of up to 6 dB could be experienced in situations where there are two reflective surfaces close to the observer. The statements are not specific; there is no reference to distances or hub heights, and no statement of measurement averaging time. It might be reasonable to assume that the 'peak to trough' values are those evident in a root-mean-square (rms) 'fast' response time history (as suggested in Appendix A of the IEC 61400-11 standard). It should be appreciated that these comments refer to observations made on the sizes and types of wind turbines operating in the early 1990s and may or may not be applicable to the larger turbines currently in widespread use.

1.1.7 On the basis of the comments in ETSU-R-97, the value of 3 dB ('level of AM' or 'modulation depth') is sometimes referred to as the 'expected level' of AM. The Den Brook AM condition[4] adopts a 3 dB peak-to-trough value as the threshold above which AM is deemed to be 'greater than expected'.

1.1.8 There is currently no generally agreed rating methodology for wind turbine AM. New Zealand Standard NZS 6808: 2010 provided a penalty mechanism but noted that there was no objective test available. Authorities in Australia and Finland have published some guidance on rating methodologies and associated limits, although these are either unvalidated or in draft form. In the UK, planning conditions intended to address AM have been imposed on a small number of wind farms to develop a scheme of assessment. These conditions have been based either on the time-series method adopted at Den Brook, which has been the subject of much debate and legal challenge, or the frequency-domain method proposed by RenewableUK (RenewableUK, 2013). However, in virtually all cases, planning officers and inspectors, in granting wind farm planning permission, have declined to impose an AM condition; as either they have considered that the need for such a condition had not been demonstrated, or that there was no robust scientific basis for framing such a condition, or both. In a number of cases, a condition requiring a scheme for assessing AM to be agreed with the local planning authority has been imposed; this form of condition relies on the premise that an appropriate method of assessing AM will be available within the development timescale.

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[3] The stall source mechanism radiates equally upwind and downwind, but propagation effects reduce noise levels upwind.
[4] see http://www.masenv.co.uk/Den_Brook_AM_Condition [last accessed May 2016]

A scheme of this type has been discharged by Maldon District Council in respect of Turncole Wind Farm[5]. The scheme was based on an amended RenewableUK methodology.

1.1.9 Given public concern over the issue, there is a recognised need to define a repeatable and reproducible procedure for measuring and assessing AM, to provide a consistent means of evaluating complaints and to form the basis of a planning condition that might be applied to regulate AM from new wind turbine developments. Most planning conditions, currently routinely applied to wind turbine installations, have had the effect of limiting overall noise levels and provide a means of controlling tonal noise characteristics, but have not directly addressed AM.

1.1.10 The AMWG has undertaken a comprehensive literature review to assess current research and different rating methods for AM, particularly AM in wind turbine noise. Wind turbine AM has been the subject of a number of research papers and reports. Some researchers have carried out listening tests to provide information on how people respond to amplitude-modulated noise. However, researchers have adopted several different metrics to ascribe a 'value' to the 'level' of AM present in any particular sample of wind turbine noise. The AMWG has reviewed the existing literature on the measurement of AM and carried out further research to enable progress to be made towards defining the most appropriate metric for AM.

1.1.11 The AMWG has not addressed the question of what level of AM in wind turbine noise (when measured by a specific metric) is likely to result in adverse community response, or how that response should be evaluated. The psycho-acoustic aspects of AM are not within the scope of this study, but the proposed metric is intended to assist with such further research. However, the reference method developed has been applied to the synthesised stimuli which were used in the RenewableUK and Japanese research studies (see Section 8).

1.1.12 The background to the study, information on the composition of the working group, its Terms of Reference and key definitions are set out in the Appendices A and B.

1.1.13 The IOA AMWG set out the main issues in a Discussion Document (IOA AMWG, 2015) published in April 2015. This draft presented three methods for consideration, one in the time domain, one in the frequency domain and a 'hybrid' method combining time-and-frequency-domain methods.

1.1.14 Based on review of the consultation responses received (see Appendix C) and further discussion and research, this final report documents the Reference Method for rating AM as now proposed by the AMWG. The proposed Reference Method is described in detail in Section 4. In developing

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[5] Turncole Wind Farm Condition 25 Scheme for the Regulation of Amplitude Modulation Maldon District Council Planning Reference FUL/MAL/10/01070

the methodology, the AMWG defined procedures on the basis of professional judgement and experience, representing the best knowledge available at the time of writing. Section 4.7 discusses some of the key decisions made in defining the procedure and provides justification, based on the experience of the AMWG.

1.1.15 The AMWG does not propose any limits for amplitude modulation. The purpose of the group is simply to use existing research to develop a Reference Methodology for the measurement and rating of amplitude modulation. The definition of any limits of acceptability for AM, or consideration of how such limits might be incorporated into a wind farm planning condition, is outside the scope of the AMWG's work and is currently the subject of a separate Government-funded study.

2 AM DEFINITION

2.1.1 For the purposes of the working group, it is not considered to be appropriate to adopt separate definitions for AM dependent on the source mechanism (see Section 1). There is no agreed basis for defining any particular level or character of AM as 'enhanced', or 'excessive', or 'greater than expected'. The objective is to define a measurement protocol and associated metric which is technically robust and has a number of suitable attributes as defined in the Scope of Work (Appendix B).

2.1.2 The following statement therefore defines wind turbine AM in the context of the working group's objectives:

"Wind turbine amplitude modulation is defined as periodic fluctuations in the level of audible noise from a wind turbine (or wind turbines), the frequency of the fluctuations being related to the blade passing frequency[6] of the turbine rotor(s)."

Scope of application

2.1.3 For most medium to large-sized three-bladed upwind turbines (typically with a generating capacity of 500 kW and above) the blade passing frequency (BPF) is up to approximately 1.6 Hz. Turbines below 500 kW or older models could have higher BPFs, and some micro-turbines have rattle/flap problems, which might show the characteristics of AM on a time-history plot, but could subjectively be quite distinctive. Similarly, downwind turbines may have different acoustic characteristics that need consideration of lower frequencies. The AMWG study mainly focussed on the measurement and assessment of AM from current large upwind turbines with three-bladed rotors rotating at speeds up to approximately 20 rpm. However, the metric as designed captures all the first three harmonics of the signal for BPFs up to approximately 1.6 Hz. This corresponds to 32 rpm for a three-bladed turbine.

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[6] Blade Passing Frequency (Hz) = (Rotor RPM) x (No. of Blades) / 60

A higher sampling rate (with a period of less than 100 ms) would be required to capture faster fluctuations but this is untested by the AMWG.

2.1.4   The metric described in this document does not reflect any change in subjective response with modulation frequency. However, it does identify the modulation frequency and this could therefore be used in a subjective rating, if appropriate.

2.1.5   The assessment procedure and metric are intended to be applied to external measurements of noise experienced at locations at 'residential distances', separation distances between large wind turbines and dwellings in the UK being typically 500 metres or greater. The procedure is based on outdoor measurements in the vicinity of dwellings, primarily because of the practical difficulties associated with making repeatable noise measurements indoors. Reliance on external measurements is consistent with established standards and procedures for assessing environmental noise.

3   OUTCOME OF CONSULTATION RESPONSES & SELECTION OF METRIC

3.1.1   Responses to the Discussion Document – see Appendix C – demonstrated an overall preference for a frequency-domain method, mainly because of the ability of such a method to discriminate more objectively between fluctuations in noise levels resulting from wind turbine AM (which has a periodic characteristic related to the turbine rotational speed) and fluctuations resulting from other variable environmental noise sources (such as birdsong). This is particularly important for the purposes of analysing large datasets, perhaps involving many weeks or months of data, which would often require extensive subjective assessment to exclude spurious (non-wind turbine) noise if a time domain approach were adopted.

3.1.2   However, it was observed that the frequency-domain method presented in the Discussion Document (Method 2) could lead to an under-rating of AM, compared with a time-domain analysis, because the energy content in the higher harmonics of the modulation spectrum were not taken into account. It can be argued that this 'under-rating' effect would be offset by the ability of the frequency-domain method to reduce the influence of background noise, and also that allowance could be made for this in devising an acceptability-rating scale for AM. However, such an 'allowance' could not be uniquely defined because of the variations in the relative levels of the fundamental and harmonic components observed in the modulation spectra for different AM samples. Furthermore, achieving an increased 'dynamic range' in the output of the metric was considered useful.

3.1.3   Several respondents expressed support for a time-domain method, mainly on the basis of simplicity and the more 'transparent' nature of the signal analysis procedure compared with the frequency-domain method, but also because it was considered that the frequency-domain method resulted in an under-statement of AM.

3.1.4   Several respondents supported the hybrid method (Method 3), or at least considered it 'interesting', although reservations were expressed about its

apparent complexity. The method was considered to work well in quantifying amplitude modulation, however, implementing low bandwidth filters in the time domain presented a number of technical drawbacks such as filter ring-up time.

3.1.5   As a result of the consultation responses, and considerable further discussion and research, the AMWG has agreed to recommend a 'hybrid' method, essentially a development of Methods 2 and 3 described in the Discussion Document, although also drawing on aspects of Method 1. The method (the 'Reference Method') utilises a frequency-domain procedure to identify the presence of AM in wind turbine noise data and to extract the time-series of the AM component (although complete exclusion of background noise cannot be achieved). The level of AM is then assessed using a metric applied to the reconstructed time-series data. In the opinion of the AMWG, this hybrid method addresses the deficiencies of stand-alone time-series and frequency-domain methods. Also, because the final assessment is based on a 'reconstructed' time-domain signal, this enables any results to be related to published research into dose-response relationships, which is almost universally based on assessing AM values from time domain data. The Salford and 'Tachibana' test signals have been analysed using the Reference Method.

3.1.6   A degree of complexity is considered inevitable in a method that is sufficiently consistent for determining compliance or non-compliance with specific thresholds or limits. The level of technical competence required is similar to that required for tonal analysis according to ETSU-R-97 or ISO 1996-2: 2007. A simple preliminary assessment method (the Indicative Method - see Section 4.8) - is also described; this may be useful in situations where wind turbine AM is subjectively very apparent and where measurements are available exhibiting clear AM with minimal contamination by other noise sources. However, the Indicative Method must be used with caution and is to be considered as secondary to the Reference Method and in no circumstances as a substitute for it.

3.1.7   The proposed Reference Method has several merits (set out in Section 7) and provides an objective benchmark for rating AM levels. However, it is possible for AM to be evaluated in different ways, including subjectively. It is noted that noise nuisance investigations, for example, need not be limited to any particular method of assessing wind turbine noise, and will often involve many other factors such as the time of day and the character of the neighbourhood. Furthermore, factors such as the duration and frequency of occurrence may be relevant in determining subjective response. Therefore, the availability of the Reference Method need not preclude other assessments being made. Nevertheless, the Reference Method can provide important information on frequency of occurrence and duration which is relevant and can be used to evaluate different operational conditions including mitigation, since a robust and reliable indicator of AM is achieved.

4 REFERENCE METHOD

4.1 Introduction

4.1.1 This section describes a reference assessment method which characterises a sample of amplitude modulated wind turbine noise by means of a single metric uniquely defining the level of AM within it. In the consensus view of the AMWG, and following consultation, this method was developed in order to best address the scope of works and success criteria provided.

4.1.2 Following an overview of the method, the parameters and principles for measurement and data processing are discussed below. Instrumentation for measuring AM is discussed in Section 5.

4.2 Overview of method

4.2.1 The proposed method is a 'hybrid' approach, based on a frequency domain method (using Discrete Fourier Transform or DFT), with its strength in discriminating wind turbine AM, but which retains time domain characteristics of the signal in the final output produced. It is similar to a method proposed elsewhere (Swinbanks, 2013).

4.2.2 The method is considered by the group to be a representative signal analysis technique which is not excessively complex, being comparable to tonal analysis techniques included in ETSU-R-97, whilst being effective on a wide range of signals and used in other applications such as SONAR for detecting propeller noise. The results obtained with this hybrid method are comparable to those obtained by Method 3 presented in the group's previous discussion document, in particular, in terms of the dynamic range obtained. In the same way, three harmonics of the signal are retained (if relevant) in order to represent the non-sinusoidal modulation more accurately.

4.2.3 Frequency analysis of the time signal allows the identification of the pattern of clear modulation which, when it occurs, is typical of wind turbine amplitude modulation and distinguishes it from a myriad of other time-varying sources found in all noise environments. Such a pattern becomes a distinct peak in the resulting power spectrum, which may be related to the Blade Passing Frequency (BPF) of the turbine(s) (particularly if it is consistent in time). As the BPF can vary for modern turbines, the method requires the range of expected blade passing frequencies to be defined. This can be determined from examination of 'waterfall' plots, or from turbine SCADA data, or with reference to published information on the turbines (see Section 4.3). It is not dependent on the availability of SCADA data, as it is acknowledged that this may not be provided.

4.2.4 In addition, following consultation, the AMWG developed a technique for evaluating the 'prominence' of the spectral peaks obtained (see Section 4.6). This represents how much a peak stands out above the noise floor of the power spectrum. In the experience of the group, this is a good indicator of clear modulation of the noise levels for the frequency of interest and an objective indicator of how clear the modulation is. Spectra generated from

irregular sources, such as impulses or bird noise, tend to create irregular spectra with low prominence. Although this criterion does not fully exclude all individual spurious periods, the prominence check and the requirement for at least 30 valid 10-second samples to calculate the 10-minute values provides a remarkably effective indicator of the presence of corruption and has been found to perform well in identifying AM associated with wind turbines for a range of sometimes very corrupted signals.

4.2.5   In outline, the method proceeds as follows:

- The input signal (a time series of band-limited, A-weighted, 1/3-octave L_{eq} data in 100 millisecond samples) is split into blocks of 10 seconds;

- It is transformed to the frequency domain using Fourier analysis to obtain a modulation spectrum;

- If a clear (prominent) peak is present at a rate expected from the turbines, a window[7] around that frequency (and the next two harmonics) is selected (subject to some tests);

- An inverse Fourier transform is applied to the filtered spectrum to reconstruct a filtered time-series;

- The modulation depth in the filtered time-series is then determined

- A value for a 10-minute period is calculated from a combination of the 10-second modulation depths within that period.

4.2.6   The modulation depth over 10 seconds is determined directly from the difference between the L_5 and L_{95} values within the filtered time-series (as in the approach of Fukushima, Yamamoto *et. al.*, 2013). It would also be possible to uniquely and objectively identify the peaks and troughs in the reconstructed signal by using modulation at the fundamental rate (also obtained by inverse Fourier transform) as a guide. This would in theory evaluate the variability of the modulation within each 10 second block. However, this adds complexity and the AMWG's investigations showed that this does not tend to provide significant benefit when considering the 10 second time intervals addressed in the analysis, and it is therefore proposed to retain the simpler $L_5 - L_{95}$ method as standard.

4.2.7   The method produces a single value for a 10-minute period. The variations in 10 second AM ratings over 10 minutes are available as one stage of the method, and this may also be of interest to some researchers in further studies; however there is little known at present about the subjective response to transient or variable AM. As noted above, considering valid 10-minute periods using the prominence requirements was found to be very effective at eliminating spurious noise (hence achieving a more repeatable measure). Therefore a metric based on determining a 10-minute value as recommended herein will be more robust.

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[7] The width of this window was chosen based on experience of typical modulation and allows the variation of modulation depth in the input signal to be represented.

4.2.8   The method is described in six steps as follows:

> **Step A**   Survey requirements and find appropriate acoustic frequency range – see Fig 4.2.1
>
> **Step B**   Calculate 10-minute average using methodologies C1, C2, C3 – see Fig 4.2.2
>
> **Step C1**   Determine modulation in a 10-second block – see Fig 4.2.3
>
> **Step C2**   Prominence Check – see Fig 4.2.4
>
> **Step C3**   Include Harmonics – see Fig 4.2.5.

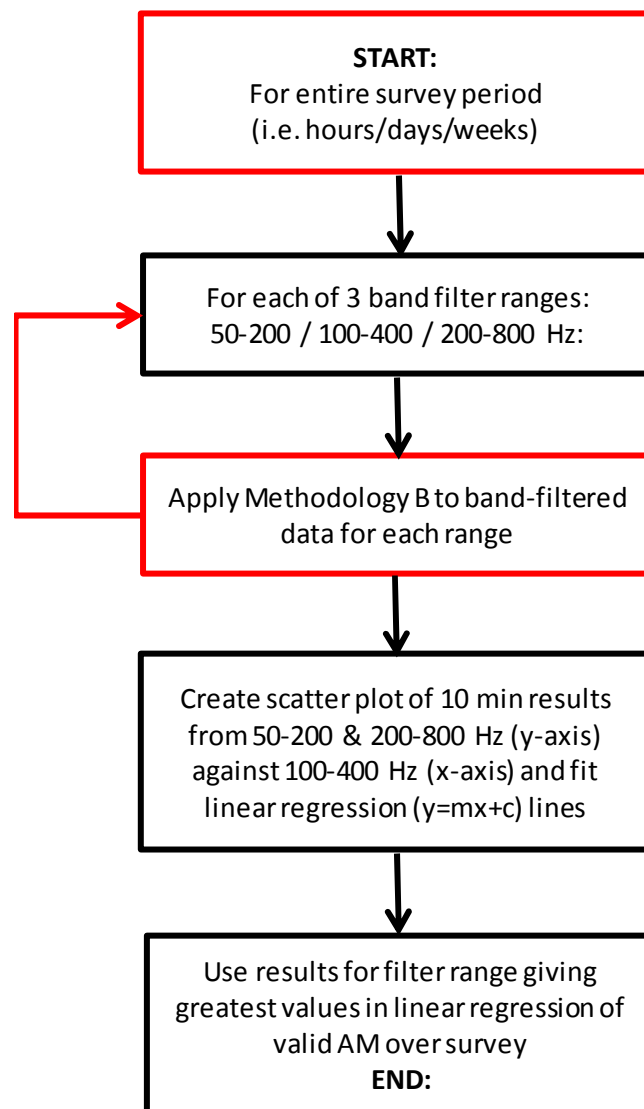4.2.9   These steps are shown in the following Figures 4.2.1 to 4.2.5 below.

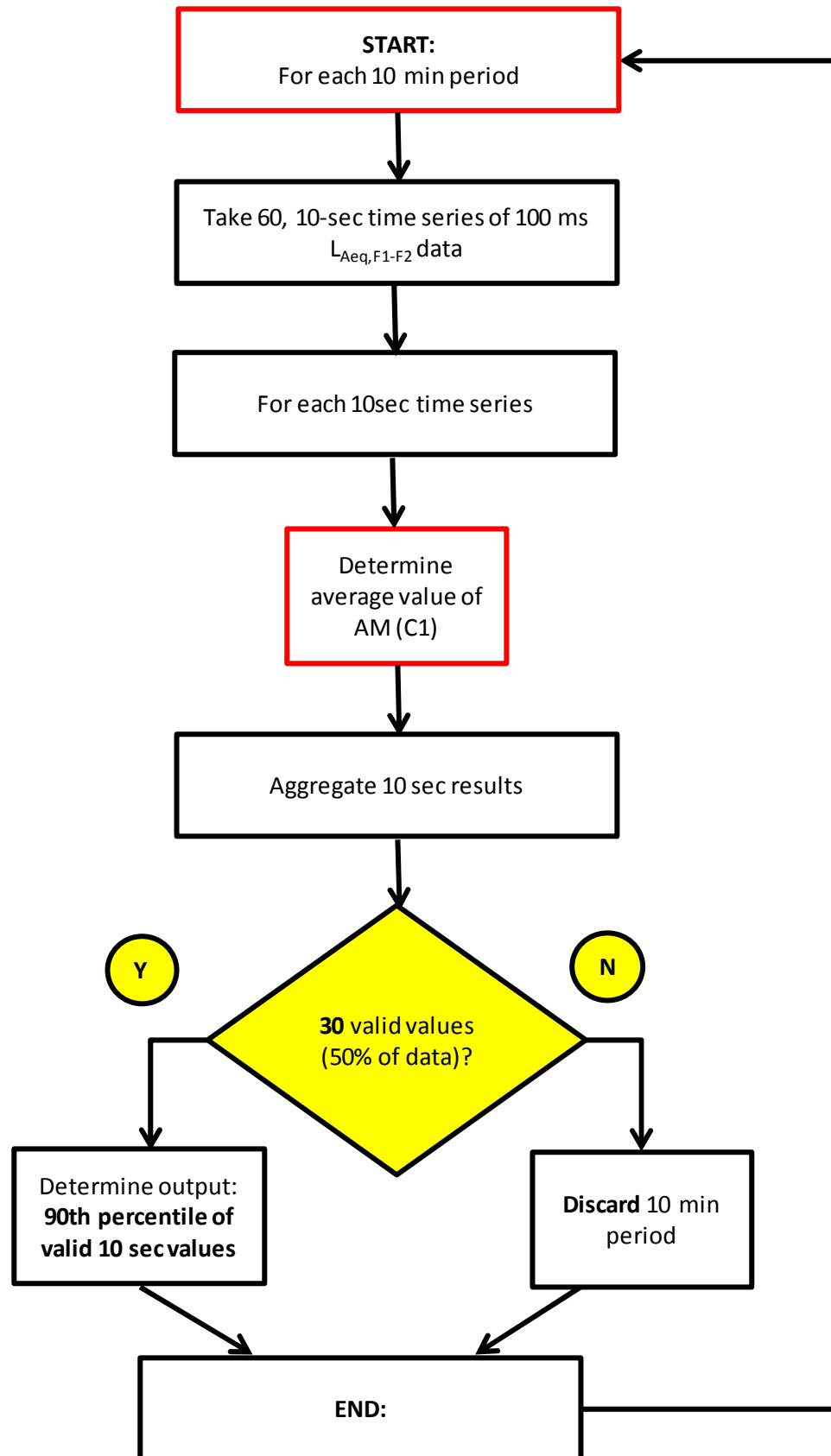**Figure 4.2.1 - 'Overall' Methodology**

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                          ┌─────────────────────────┐
                          │ START:                  │◄────────┐
                          │ For each 10 min period  │         │
                          └─────────────────────────┘         │
                                    │                          │
                          ┌─────────────────────────┐         │
                          │ Take 60, 10-sec time    │         │
                          │ series of 100 ms        │         │
                          │ L_Aeq,F1-F2 data        │         │
                          └─────────────────────────┘         │
                                    │                          │
                          ┌─────────────────────────┐         │
                          │ For each 10sec time     │         │
                          │ series                  │         │
                          └─────────────────────────┘         │
                                    │                          │
                          ┌─────────────────────────┐         │
                          │ Determine               │         │
                          │ average value of        │         │
                          │ AM (C1)                 │         │
                          └─────────────────────────┘         │
                                    │                          │
                          ┌─────────────────────────┐         │
                          │ Aggregate 10 sec results│         │
                          └─────────────────────────┘         │
```

START:
For each 10 min period

Take 60, 10-sec time series of 100 ms $L_{Aeq,F1\text{-}F2}$ data

For each 10sec time series

Determine average value of AM (C1)

Aggregate 10 sec results

Y   **30** valid values (50% of data)?   N

Determine output: **90th percentile of valid 10 sec values**

Discard 10 min period

END:

Figure 4.2.2 - B: 10 Minute Methodology

START:
For each **10 sec** period of 100 ms L_{Aeq} band-limited data

Detrend the time-series
Using **3rd** order polynomial

Calculate Fast Fourier Transform:
Phase & Amplitude with **0.1 Hz** resolution (Δf): 50 lines

Calculate Power Spectrum:
Square of the absolute magnitude of the complex FFT, normalised by $1/N^2$, where N=length of data, i.e. 100

Identify location of fundamental frequency (f_0):
Look for maximum peak in spectrum located within valid range defined

Has peak been found?

N

Y

Pass prominence (C2) check?

N

Y

Identify location of Nth harmonics (N = 2 and 3)
Search for peak at N times the fundamental frequency, f_0

Determine whether 2nd & 3rd harmonics need to be included (C3)

Filter complex FFT spectrum:
All zero except retain **(if included)**:
Fundamental $\pm \Delta f$
2nd Harmonic $\pm \Delta f$
3rd Harmonic $\pm \Delta f$

Calculate Inverse Fourier Transform:
Recreate filtered 10 sec time series (F)

Output:
95th percentile(F) -
5th percentile(F)

Reject 10 sec period

END:

Figure 4.2.3 - C1: 10 Second Methodology

```
┌─────────────────────────────────┐
│           START:                │
│ Identify frequency of fundamental f0: │
│   Example: 0.7 Hz (freq bin 7)  │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│ Determine power spectral level A at │
│   fundamental frequency - A     │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│ Determine average level around the │
│ peak: B= average of two lines either side │
│   of (fundamental ±1) triplet   │
│ Above example: Mean of lines (4;5;9;10) │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│  Determine Prominence Ratio C:  │
│          C = A/B                │
└─────────────────────────────────┘
                │
                ▼
        ◇ C ≥ 4? ◇
      Y           N
      │           │
      ▼           ▼
┌───────────┐ ┌───────────┐
│   Yes:    │ │    No:    │
│ Valid 10 sec │ │ Reject 10 sec │
│  period   │ │  period   │
└───────────┘ └───────────┘
```
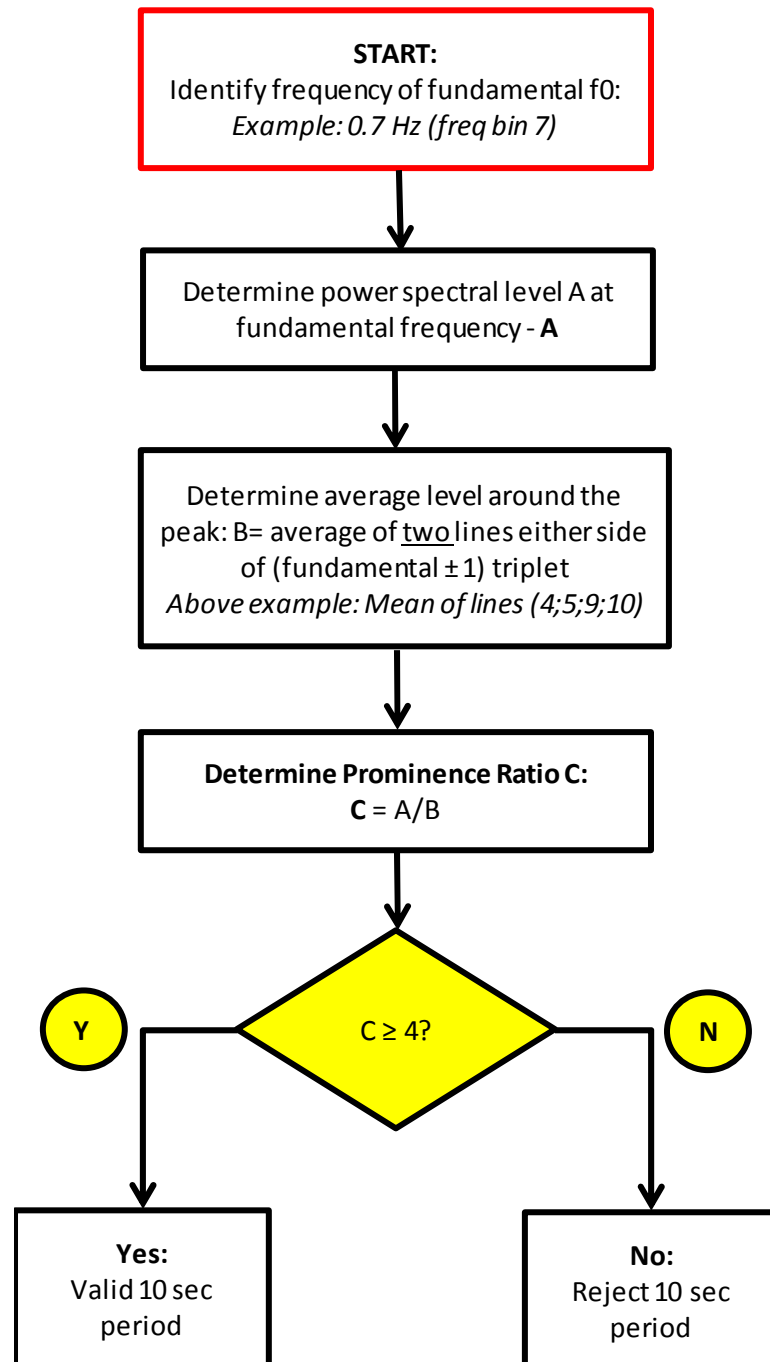
Figure 4.2.4 - C2: Prominence Check Methodology

Given location of fundamental:
Only retain in derived (complex) FFT spectrum the following lines
fundamental ± Δf

Calculate Inverse Fourier Transform:
Recreate filtered 10 sec time series for fundamental only (F^0)

Output:
A = max-min of recreated series

A > 1.5 dB?
— N
— Y

For 2nd & 3rd Harmonics:

Is harmonic a local maximum in power spectrum?
— N → Exclude
— Y

Given location of harmonic:
Filter Phase & Amplitude:
All zero except:
Harmonic ± Δf

Calculate Inverse Fourier Transform:
Recreate filtered 10 sec time series for harmonic only

Output:
B and C = max-min of recreated series
B = 2nd & **C** = 3rd

B or C > 1.5 dB?
— Y
— N

Include

Exclude

Fundamental & included harmonics

Fundamental only:
Reject harmonics

END:

Figure 4.2.5 - C3: Decision Methodology for Including Harmonics

4.3   Input data

4.3.1   The input data to the analysis should be A-weighted, band-filtered 100-millisecond L_{eq} values. The analysis should be done for the following three frequency ranges:

- 50 to 200 Hz
- 100 to 400 Hz (reference)
- 200 to 800 Hz.

4.3.2   The range encompasses seven 1/3-octave bands. The specific range chosen is the one which tends to give the highest modulation values over a representative range of *valid* data measured. This can be evaluated by plotting the analysed, valid data as a scatter plot (x-y graph) with the reference 100 to 400 Hz range values as the x-axis – see Fig 4.3.1.
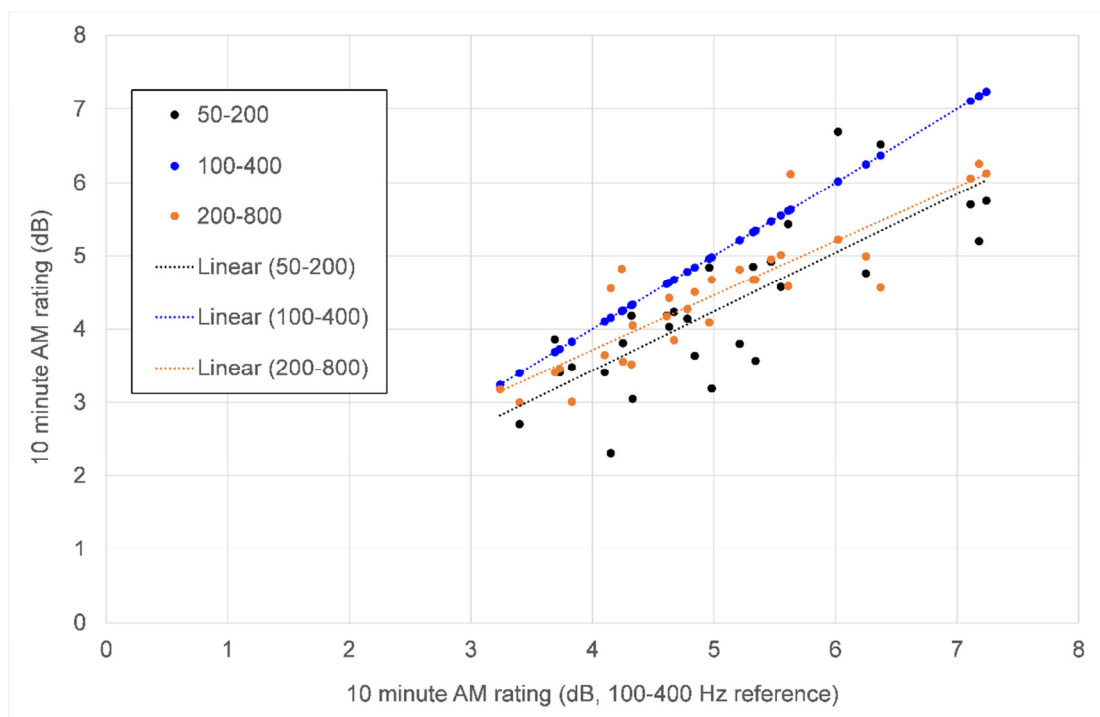
Fig 4.3.1   Comparison of ratings obtained with different frequency bands. This example shows that the 100-400Hz range should be used

4.3.3   It should be borne in mind that for the higher frequency range, data may be more prone to corruption from other sources, such as bird calls, and the resulting spectra should be scrutinised more carefully. Similarly, the lower frequency range might be more affected by wind noise.

Discussion

4.3.4   Focussing on a limited frequency range dominated by modulation assists in both the identification of AM and in excluding spurious data. It also results in higher levels of AM compared to those obtained from broadband (A-weighted) analysis. In fact, the band-limited data can detect AM which might have been masked using a broadband analysis based on overall L_{Aeq} values.

4.3.5 A range comprising seven 1/3-octave bands has been found to offer a good compromise between reduction of variability and discrimination. Compared with the choice of the single 1/3-octave band, there is a reduced sensitivity to the choice made, and it results in a cleaner and clearer analysis result.

4.3.6 In the experience of the AMWG, based on a number of cases of modulation measured at typical residential separation distances, the range of 100 – 400 Hz has been found to be representative of frequencies dominating the modulation for the majority of cases. In other specific cases, in which separation distances were reduced, or the turbines were of relatively smaller scale, a range of higher frequencies was found to be more suitable. It is therefore not possible to determine a single range that would best represent different situations and the method, based on analysis of three ranges, represents a prescriptive way to account for the different spectral characteristics encountered.

4.3.7 Frequencies higher than 800 Hz were found to generally not include much AM signal, but did feature corrupting sources such as bird or insect noise. For frequencies less than 50 Hz, there was, in the experience of the group and in available literature, little evidence of substantial audible modulation present, and in addition, the clear possibility of corruption from other sources. Downwind turbines may require analysis of lower frequencies (if audible); this would need to be considered on a case-by-case basis.

Deriving band-limited input data in practice

4.3.8 Many modern sound level meters offer the possibility to log 1/3-octave band spectra in 100 millisecond periods to obtain the required information directly. The 1/3-octaves should be either measured A-weighted, or have the A-weighting corrections applied to each band as a post-processing step. The resulting A-weighted bands should then be summed (logarithmically) within each of the above frequency ranges of interest in order to obtain a band-pass filtered $L_{Aeq,100ms\ (BP)}$ signal.

4.3.9 While it is possible to post-process audio recordings to A-weight them and filter them over the frequency band of interest, this entails significant practical difficulties: high resolution audio recordings would be required, which have large storage requirements; post-processing requires specialist software and is generally not straightforward. Therefore, the preferred approach is to use directly logged 1/3-octave band L_{eq} values, between 50 and 800 Hz, in 100 millisecond resolution, either A-weighted or with the A-weighting corrections applied in post-processing. L_{eq} 1/3-octave bands were chosen in preference to fast time-weighted 1/3-octave bands as the former are more precisely defined and allow summing up in the manner prescribed. They also lead to a higher result as they result in more pronounced peaks and troughs[8].

---

[8] A comparative study for turbines modulating at around 0.7 Hz indicated that AM ratings obtained with the L_{eq} bands could be around 0.5 to 1dB higher than those obtained with fast time-weighted analysis on the same signal, depending on the characteristics of the signal.

Input parameters – modulation frequency range

4.3.10 The method requires, as input, a range of modulation frequencies in which the main (or fundamental) modulation frequency is expected to be found. This assists in excluding apparent 'modulation' which is not related to the turbines.

4.3.11 Knowledge of the turbine type and its possible rotational rates, or turbine operational (SCADA) data, can assist in defining this range. For example, for a three-bladed turbine rotating at 20 rpm, the BPF modulation frequency would be 1 Hz. In practice, the rotational rate can vary between turbines on a particular site and it may not possible or practical (except maybe in the simplest cases) to define a single expected BPF for each 10 minute analysis period based on operational data. This is why it was found effective to specify a range and determine the highest modulation peak found within this range.

4.3.12 It may be necessary, for example if the BPF is unknown, to proceed iteratively and first define a wider range (in a preliminary analysis) which is then refined based on the results of the modulation spectrum analysis, in order to minimise the influence of other sources.

4.3.13 If a consistent fundamental modulation frequency is apparent over a period of time, which also coincides with a potential blade passing frequency, this is a strong indication that the modulation results are related to the wind turbine operation. This is in these cases clearly apparent as a trend on a plot of the modulation spectrum with time[9]; this is known as a waterfall plot. The use of such waterfall visualisation (see Fig 4.3.2) is in practice very effective in assisting with defining the valid range to use.
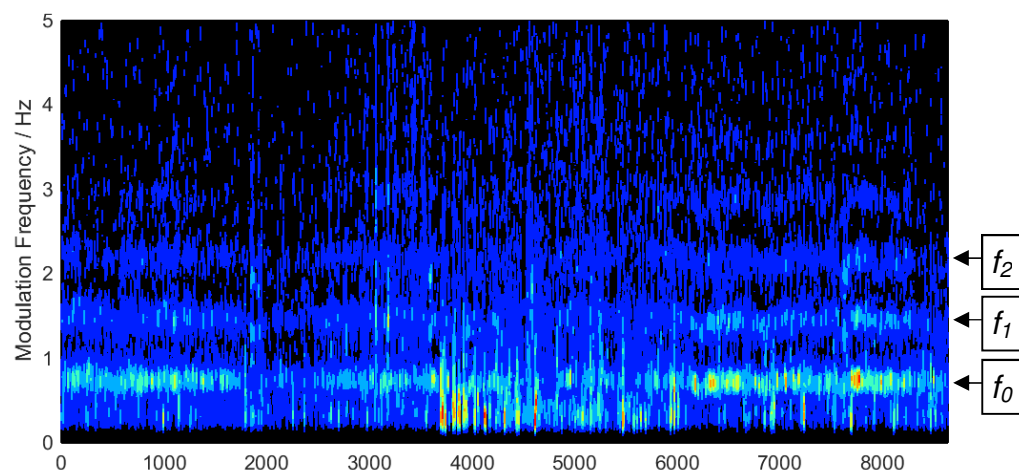
Figure 4.3.2 Typical waterfall plot (showing evolution of the modulation frequency (vertical axis) with time (horizontal axis, 10 s blocks) with a clear trend of modulation apparent at times just below 1 Hz – see the horizontal lines. The harmonics are also visible. Spurious non-modulating events tend to be represented by vertical lines.

---

[9] Waterfall plots are a representation of the magnitude of the power spectrum S, as defined in section 4.5, changing as a function of time. Trends appear more clearly if the square root of S is plotted as in the example of Figure 4.3.2.

4.4   Assessment time periods

4.4.1 The main aim in analysing data is to characterise the short-term fluctuations in the modulation, whilst relating these to standard longer time intervals used in the analysis of wind turbine noise. Sometimes this will be related to complaint investigations. It is also necessary to analyse data as a function of wind speed in 10-minute periods. It is necessary that the noise input data has an agreed format and length. The AMWG therefore considers that the analysis period should be separated into 'major' and 'minor' time intervals.

Minor time interval

4.4.2 The 100 millisecond samples should be separated into consecutive, non-overlapping 10-second blocks (the 'minor' time interval). There are 60 such minor time intervals in each major interval.

4.4.3 A 10-second block will only be considered valid if not excluded for the following reasons:

- The 'prominence' ratio is less than four (automatic processing) (see Section 4.6)

- There are no local maxima within the expected modulation frequency range in the power spectrum

- Manually excluded for other reasons (according to the practitioner).

Major time interval

4.4.4 The 'major' time interval for analysis is 10 minutes. It is proposed that a representative rating for AM is derived using the 90^{th} percentile[10] of the distribution calculated within each 10 minute period. This value is only calculated over the distribution of valid 10 second samples, and only if the 10 minute period contains at least 50 % (*i.e.* 30) valid samples. The main test for a 10 second block being valid is whether there is a local peak within the expected modulation frequency range and whether this spectral peak is sufficiently prominent (see Section 4.6).

4.4.5 The criterion of requiring 50 % valid 10-second blocks (or 30 minor periods in a 10 minute period with sufficiently high prominence) has been found, on a range of sample data available to the AMWG, to be a very effective indicator to exclude spurious data where little continuous AM attributable to wind turbines could be detected – see, for example, Fig 4.4.1 below. In other words, this was, in the majority of cases, an objective indicator of the presence of sustained wind turbine AM with varying magnitude. This criterion was chosen to be conservative, to minimise the risk of false exclusion of valid data, and so it is possible that some samples, i.e. 10-minute major periods with more than 50 % valid 10-second blocks still represent erroneous data (or false positives). Conversely the 50 % criterion will exclude isolated periods of sporadic AM.

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[10] The highest 10% of the 10-second values analysed, which is the equivalent of the L_{10} for noise levels.
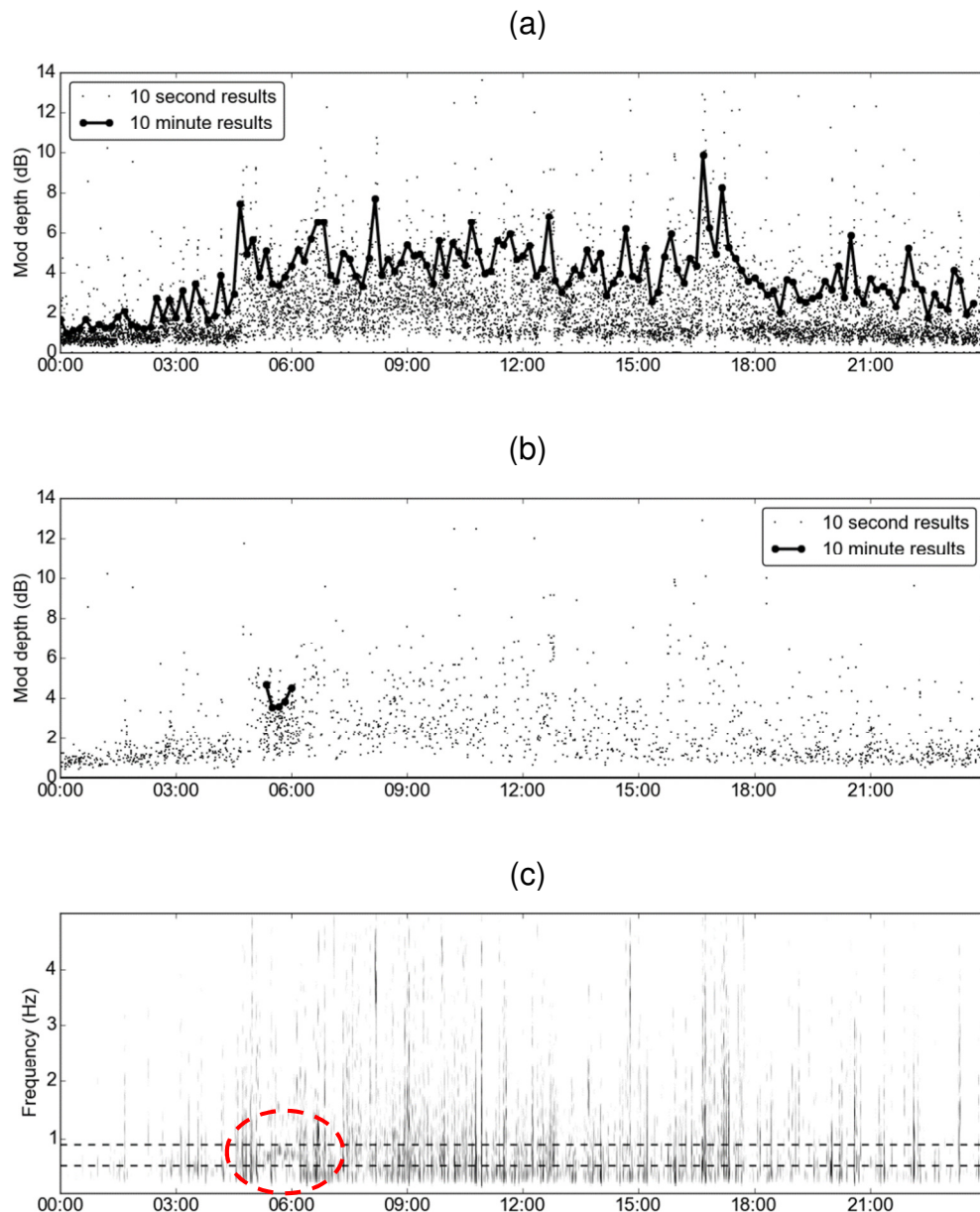
(a)

(b)

(c)

Fig. 4.4.1   Results of the analysis using the reference method over one day at a site with a relatively large amount of corruption from non-turbine sources (birds, trees etc.) The 10-minute results are shown both without (a) and with (b) the above criteria of sufficient valid data with high prominence, and no manual input. It was verified in this case that the only valid period in which 10-minute results are retained in (b) corresponds to the only period in which the turbines operated on that day. Panel (c) shows a waterfall plot, which shows that there is only a consistent trend of modulation apparent in the expected modulation frequency range (shown by dashed lines) for the valid period for which 10-minute results are obtained in panel (b).

4.4.6 As for any acoustic data analysis, the practitioner will retain the ultimate responsibility for selecting valid periods of data if there is any doubt as to their suitability. This can be done in practice by a combination of the following:

- **Review of 'waterfall' plots**: a graph of the calculated modulation spectrum over longer periods of time (at least one hour or 30 minutes) clearly shows trends of consistent AM over these periods, which are characteristic of wind turbine AM. This provides an objective indicator of AM occurring at a certain frequency. Conversely, periods with apparent 'modulation' occurring at all or wrong frequencies indicate spurious sources. For example in Fig 4.3.2 or 4.4.1 above, horizontal lines represent periods of clear turbine modulation at the rate indicated, whereas spurious periods are characterised by vertical lines.

- **Review of spectrogram plots:** a figure showing the acoustic frequency content of the raw noise data (e.g. third octave content on a 100ms basis) is helpful in identifying the main sources of noise and clarifying whether it is wind turbine related, although it may not be practical to undertake this for the entire measured period.

- **Reviewing operational data for the turbines**: this may show that turbines were, or were not operational, and whether they were operational at a rate consistent with the modulation frequency detected.

- **Listening to audio recordings if available:** this can assist in identifying/confirming the sources of noise analysed by listening to sample periods. It is considered useful in any case to form a subjective view of the character of the noise which is being evaluated; it should however be borne in mind that amplification of the audio signal, to make it audible, inherently changes its character and perception.

4.4.7 In the experience of the AMWG, the use of the prominence test and other processing to determine the AM rating in a 10-minute period in the reference method acts as a very effective pre-selection filter, meaning that the exclusion of spurious data is practicable even on large datasets, negating the need for a subjective review of the entire data set. There should be sufficient valid data remaining to undertake a meaningful analysis of the valid periods, particularly at night when spurious sources tend to decrease.

Discussion

4.4.8 AM, and indeed wind turbine noise in general, is variable. It is recognised that the choice of a 10 second block as the minor time interval may appear arbitrary, but on the basis of comparative analysis, the AMWG considers 10 seconds to be a representative minimum period for analysis. This describes approximately 10 cycles of AM at 1 Hz. It was observed on typical data that the 90th percentile value (of the 10 second values)[11], determined over a 10 minute period, provided a broad to good representation of the upper range of the individual peak-to-trough variability over the same 10-minute period (Levet, 2015).

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[11] As defined in statistics, i.e. 90% of the samples are at or below this value.

4.4.9   Comments from the discussion document suggested the use of a wider minor time interval (such as 30 seconds or one minute). This would increase the frequency resolution of the analysis and therefore the potential discrimination of wind-turbine related AM, but at the cost of further averaging of the variability observed. Investigations made by the AMWG using a minor interval of 30 seconds, but considering in further detail the variability observed in each interval showed that similar results could be obtained as with the method proposed. Therefore, it was considered that increasing the minor interval to 30 seconds offered no significant benefits.

4.4.10 The major time interval of 10 minutes is clearly desirable for any method to obtain an indicative AM rating for each such interval, using a data reduction method. This is because of the standard use of 10 minute periods to analyse wind turbine noise, for example in ETSU-R-97. Wind data and SCADA data from the wind turbine are also generally available in 10-minute periods, as is meteorological data. Furthermore, an AM rating applied to each 10 minute period can be used to collect statistics on the frequency of occurrence and, if appropriate, could be related to a penalty which could then be added to the measured noise levels to determine a rating level for comparison with planning conditions. Other penalty mechanisms and planning conditions could be formulated, but clearly, in the context of UK practice, it is useful to determine an AM metric in 10 minute intervals.

4.5   Signal analysis

Reference Method

4.5.1   Having discussed input data and assessment time periods, this section provides specific details of the signal processing required to calculate modulation depth (and frequency) for each 10-second block of 100 ms data. Before describing the details (which should be read with care), it is useful to describe an overview of the analysis of a 10-second block of data. This highlights the simple principle upon which the method is based. The analysis, which in essence is based on a time-series, comprises the following:

1. De-trending the time-series to reduce the influence of variations in noise levels below the modulation frequency

2. Using Fourier analysis to assess the power spectrum and remove energy not associated with fundamental (and harmonic) modulation frequency (which itself should be related to the wind turbine(s))

3. Performing an inverse Fourier transform to provide a 'clean' time-series containing energy only at the fundamental modulation frequency (and associated harmonics)

4. Calculating the modulation depth by subtracting the L_{95} from the L_5 of the reconstructed time-series.

4.5.2   The full procedure, detailing all specifics of the signal processing, is described below (and outlined in Figure 4.2.3):

1. The time-series is de-trended using a 3rd order polynomial 'best fit'.

2. The Discrete Fourier Transform (DFT) is calculated and both the real and imaginary parts of the output are retained. No window function should be used in the transform (*i.e.* rectangular window). Furthermore, no padding should be applied to the input; therefore the output will have a frequency resolution of 0.1 Hz. This also restricts the maximum modulation frequency that can be assessed to 5/3 or just below 1.7 Hz.

3. The power spectrum is calculated from the DFT output using the following equation:

$$S \ = \frac{|F\{x\}|^2}{n^2} \ ,$$

   - where $F\{x\}$ is the output of the DFT and n is the number of samples in the time-series (100 in this case).

   - Care should be taken to ensure correct handling of the indices referring to the positive and negative frequencies in the DFT output. Given that the input to the DFT is real, the indices corresponding to the negative frequencies may be excluded in the calculation of the power spectrum. This will result in a power spectrum with half the magnitude, however this is of no great consequence as only relative levels are considered in the analysis of the power spectrum. However, indices corresponding to the negative frequencies will be required later when performing the inverse Fourier transform.

4. The highest peak (local maximum) is identified within the user-defined allowable range of fundamental modulation frequencies (e.g. between 0.4 and 0.8 Hz, for example, see Figure 4.5.1). The frequency at which the peak is found is considered the fundamental frequency of modulation for the 10-second block. If there are no local maxima within the defined range, the 10-second block should be excluded from the wider analysis as it is considered that there is either no AM, or the block is corrupted.

5. The prominence of the peak at the fundamental frequency is calculated (following the procedure described in Section 4.6). If the prominence ratio is less than **4**, the 10-second block is excluded from the wider analysis as this indicates that AM at the BPF could not be readily identified.

6. For each harmonic (2nd and 3rd), determine whether or not to include the harmonic energy in the inverse Fourier transform using the following method:

   a) Estimate the harmonic frequencies by multiplying the fundamental frequency by 2 or 3 (for 2nd and 3rd harmonics respectively).

b) If the line at this frequency is not a local maximum in the power spectrum, check N lines either side for a local maximum (where N is one for 2nd harmonic and two for the 3rd harmonic). If no local maximum is found, do not include this harmonic in the inverse transform (Step 7). If more than one local maximum is found, the largest is chosen.

c) Assuming a local maximum is found for the harmonic frequency, two additional conditions must be met for the harmonic to be included in the inverse transform, namely:

   i. The peak to peak amplitude[12] of the time-series generated by performing an inverse transform[13] with only the energy at the fundamental frequency must be greater than 1.5 dB.

   ii. The peak to peak amplitude of the time-series generated by performing an inverse transform with only the energy at that specific harmonic must be greater than 1.5 dB.

d) If any of the aforementioned conditions are not met, the energy at that harmonic should not be included in the inverse transform.

7. The inverse Fourier transform is performed in the following manner:

a) An array of zeros is created, the same size as the output from the DFT.

b) Take the index of the fundamental frequency identified in the power spectrum, along with one index either side (totalling three lines), and insert the corresponding indices from the original DFT output (including real and imaginary components) into the corresponding indices of the newly created array of zeros. Repeat this for the indices of the corresponding negative frequencies.

c) Do the same for each harmonic identified for inclusion in the inverse transform (each time taking three lines centred on the harmonic frequency and also including the corresponding negative frequencies).

d) Perform an inverse Fourier transform on the newly created array, which should include components (from the original DFT output, complex numbers) only at the fundamental frequency and identified harmonics (three lines at each). The output of this transform should be real, without any imaginary part.

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[12] Defined here as the maximum of the entire 10-second time-series minus the minimum of the same.
[13] The inverse transform should be performed in a manner similar to that described in Point 7, i.e. with three lines – the line of the peak and one either side.

8. The output of the inverse Fourier transform will be a time-series resembling[14] the original time-series, but containing only energy relating to the identified frequencies.

9. The modulation depth for the 10-second block is calculated by subtracting the 5[th] percentile (L_{95}) of the reconstructed time-series from the 95[th] percentile (L_5) in the manner of Fukushima and Yamamoto (2013). This will tend to represent the highest typical modulation in the 10-second block.

4.5.3 Figures highlighting key parts of the method are shown below.
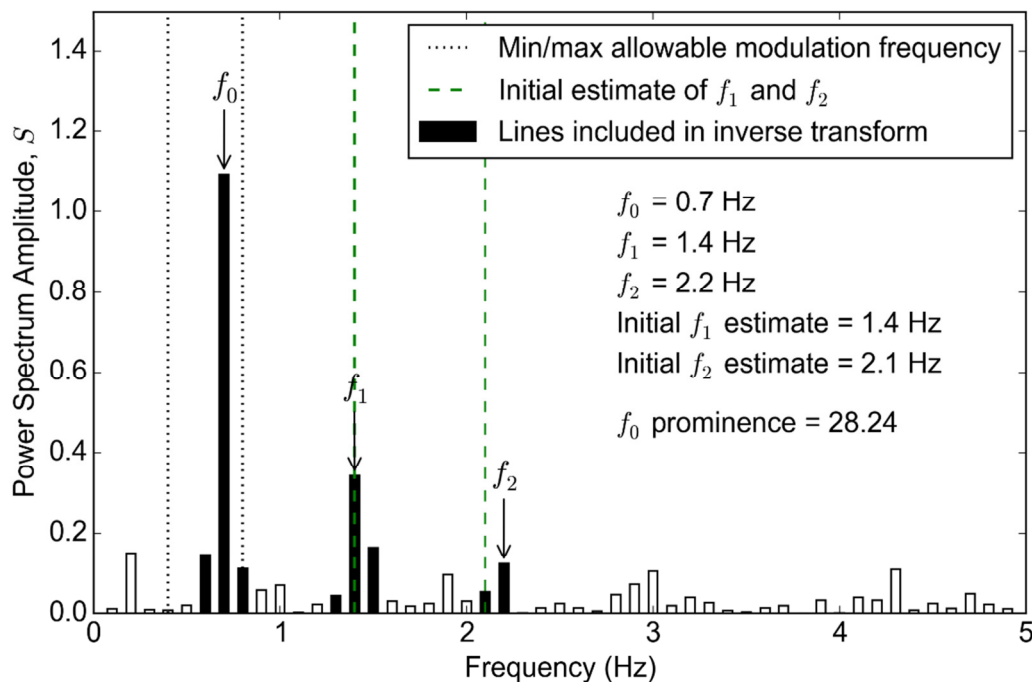
Figure 4.5.1: The power spectrum for a 10-second block. The fundamental frequency, f_0, has been identified within the range of allowable modulation frequencies (marked as dotted lines). Initial estimates of the frequencies of the second and third harmonics are shown as dashed green lines. The estimated frequency of the second harmonic, f_1, is a local maximum. The estimated frequency of the third harmonic is not a local maximum and the highest peak within two lines of the estimated frequency is identified as the true frequency of the third harmonic, f_2. Lines to be included in the inverse Fourier transform are marked (showing, in each case, the central line plus one line either side, i.e. three lines).

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[14] A useful verification check for any user implementing the procedure is to first include all lines in the spectrum and check that the result of the inverse Fourier transform is the same as the original (de-trended) time series.
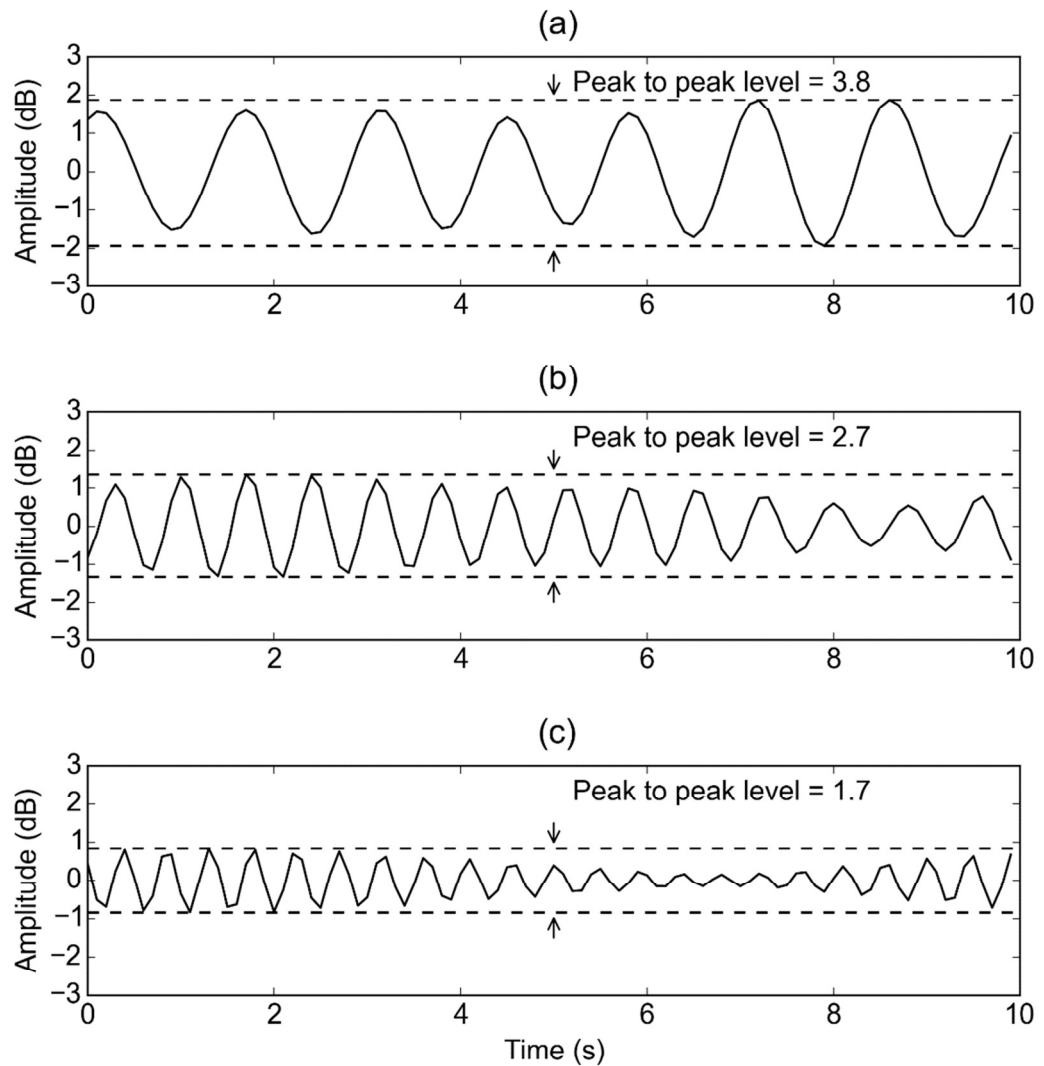
Figure 4.5.2: The inverse Fourier transform of energy at the fundamental frequency and the second and third harmonics, shown in panels (a), (b) and (c) respectively. The figure shows that the peak to peak levels for all harmonics exceeds the criterion specified in Step 6c(ii) of the method description and therefore energy at all harmonics should be included in the final inverse Fourier transform.
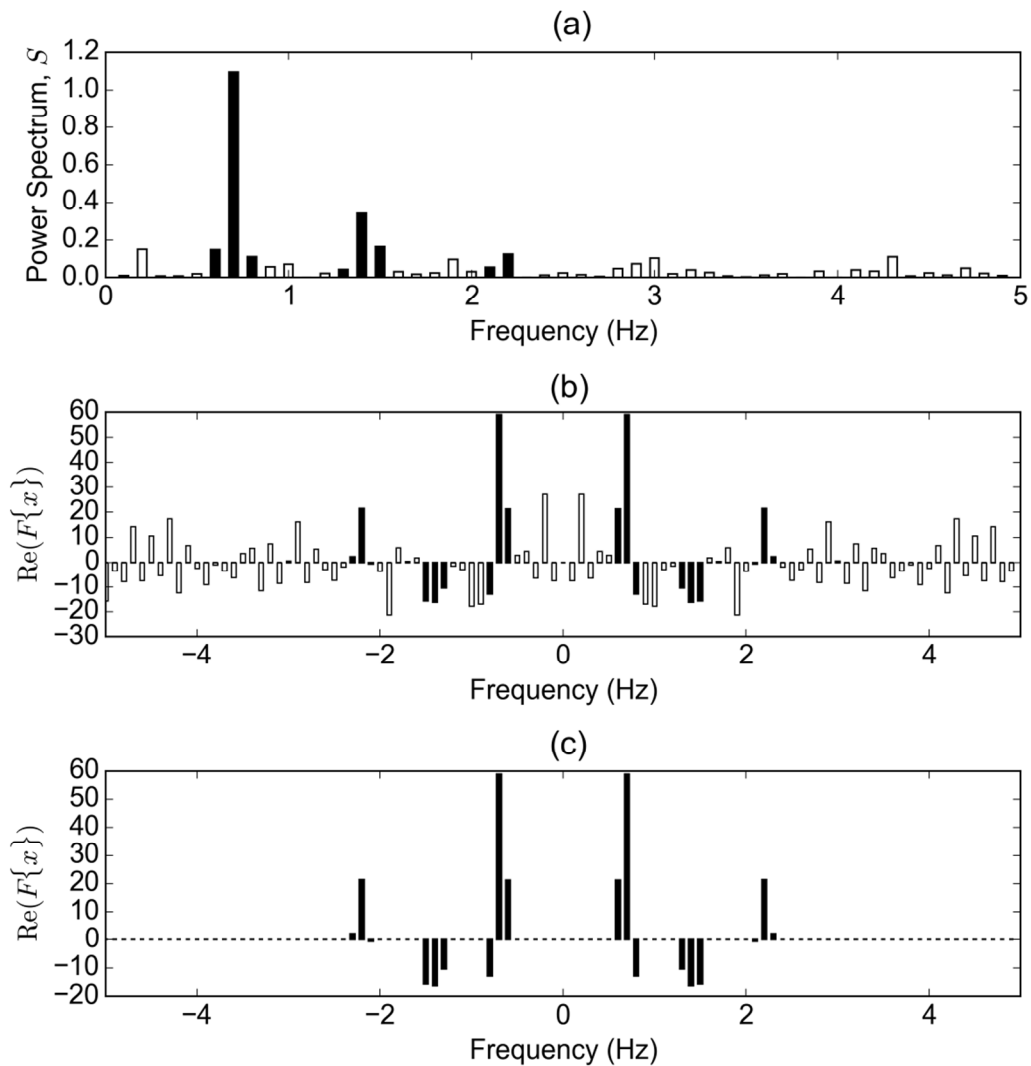
Figure 4.5.3: A clarification on indices to include in the inverse Fourier transform. Panel (a) shows the power spectrum and the identification of indices to include. Panel (b) shows the original output from the DFT (only the real part is shown here) with the identified indices shown as black lines. Note that the complex conjugates are also shown as black lines (the negative frequency components). Panel (c) shows the array with the identified indices included, and zeros at all other values. The inverse Fourier transform is performed on this array.
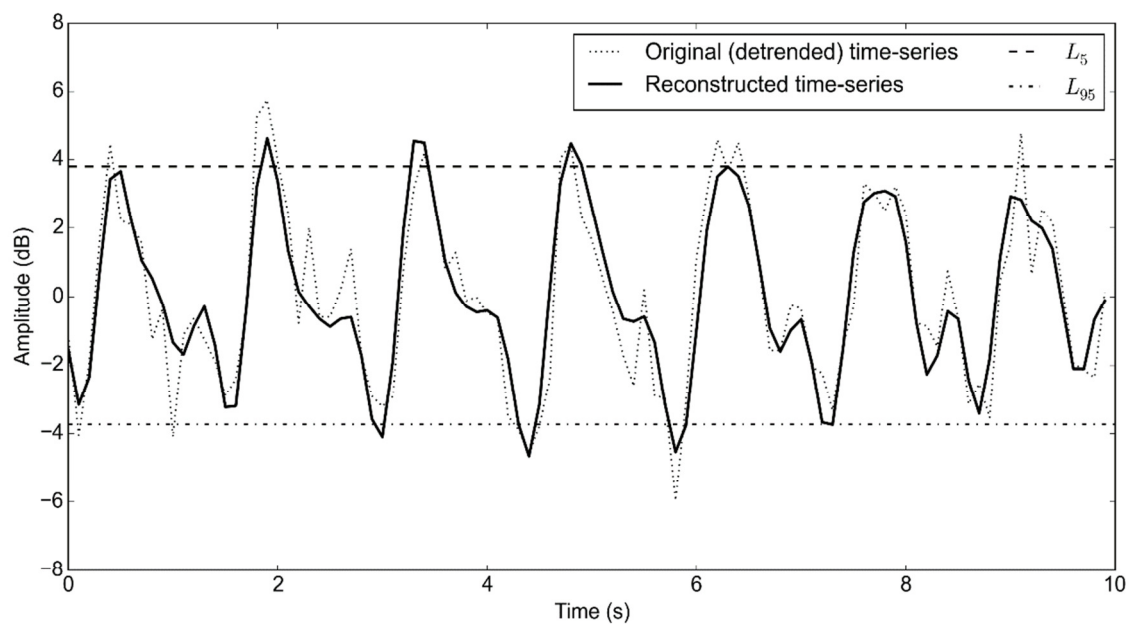
Figure 4.5.4:   The original time-series (detrended with a 3rd order polynomial) and the reconstructed time-series. The modulation depth is calculated by subtracting the L_{95} from the L_5.

Possible output – individual peaks and troughs

4.5.4 A reconstituted time series is generated as part of the reference method. This could be used as the basis for identifying individual peaks and troughs. The reconstructed fundamental signal can provide a guide for locating the peaks and troughs using a search window equal to half of the fundamental period.

4.5.5 Note that this is not part of the proposed Reference Method, but this level of detail is achievable if deemed beneficial to the analysis. It is however more difficult to ensure, for an individual 10 second period, that all peaks relate to wind turbine AM, as the longer-term 10 minute analysis described above is more robust in this respect. It was also determined, following investigations by the AMWG, that despite the additional complexity introduced, the additional information acquired did not have significant benefits compared with the L_5 – L_{95} approach of the Reference Method.

4.6   Prominence noise exclusions

4.6.1 The method described in Section 4.5 provides a reasonable level of noise suppression, i.e. the reported level of modulation is low when there is no wind turbine AM present in the signal. However, extraneous noise can often incorrectly manifest as high levels of AM. It is possible to greatly reduce the number of false positives by assessing the prominence of the peaks in the power spectrum. This exploits the fact that genuine wind turbine AM produces very pronounced peaks in the power spectrum of the modulation envelope. Excluding samples with indistinct peaks greatly reduces the

number of false positives whilst introducing a negligible number of false negatives.

4.6.2 The proposed method for assessing the prominence of the fundamental is described below:

1. The magnitude of the fundamental peak, L_{pk}, is taken as the amplitude of a single line in the power spectrum at the frequency of the peak.

2. The two lines either side of the peak are ignored.

3. The masking level, L_m, is taken as the linear average of two lines each side of the peak (beyond those lines immediately adjacent to the peak).

4. The prominence, p, of the peak is calculated using:

$$p = \frac{L_{pk}}{L_m}$$

4.6.3 An example clarifying the classification of masking lines in the power spectrum is shown below. The lines adjacent to the peak are ignored. The masking lines are the two lines beyond the adjacent lines either side of the peak.
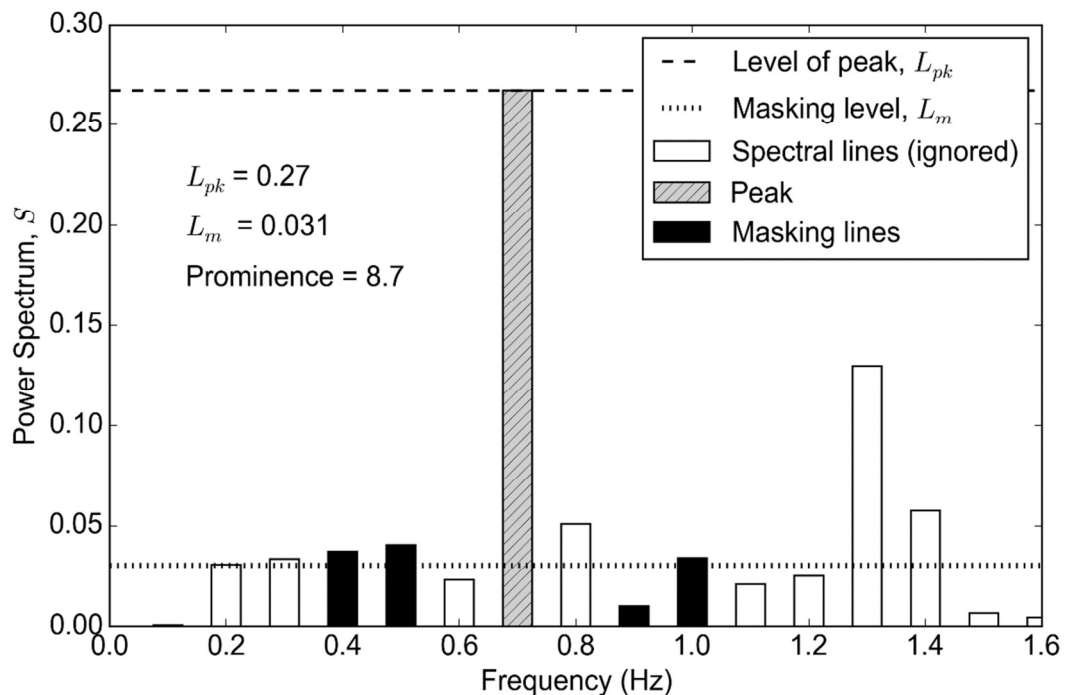
Figure 4.6.1: An example calculation of the peak prominence

4.7   Discussion

4.7.1   The examples of Figure 4.7.1 below show that a complex modulating time-series can be accurately reconstructed using the first three harmonics. A balance has to be made when deciding how many harmonics to include – using too many will increase the noise floor while including too few will result in missing the true amplitudes of the peaks and troughs when harmonic energy is present. The use of the first three harmonics has been found to provide a good representation of the original time-series in the large majority of cases, whilst maintaining a reasonably low noise floor.

4.7.2   Notwithstanding the above, it can be seen in some of these examples that short small peaks (and less often troughs) are occasionally not fully represented in the reconstructed series. This could be a consequence of the spectral windowing undertaken, which means these very short variations cannot be represented. The peak could also be extraneous noise in a frequency band outside that of the bands considered, in which case it would be right to reject it. Despite these occasional discrepancies, the average peak-to-trough level is well represented by the reconstruction method in most cases. There is also limited evidence that turbine-related short impulses occur outside of periods of sustained modulation, which would be in any case adequately detected and rated by the proposed method.

a)   b)

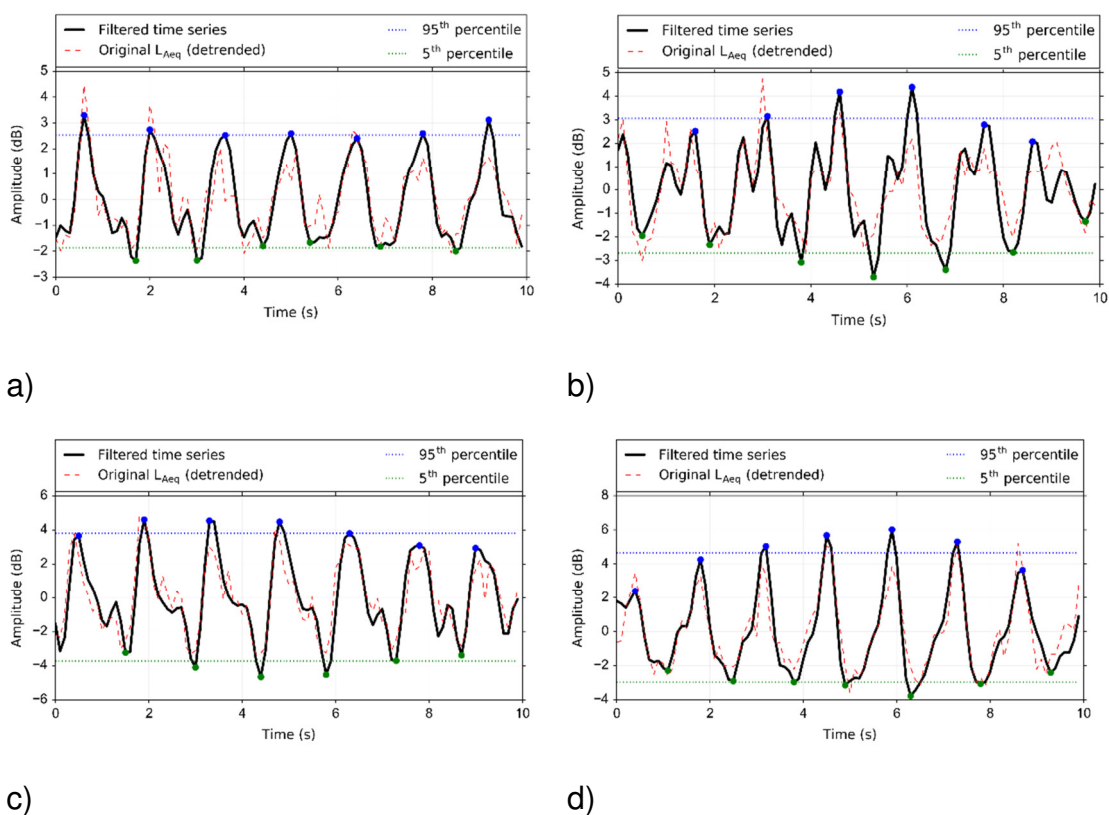c)   d)

Figure 4.7.1   Examples (a to d) of 10-second blocks of AM time-series reconstructed using the reference method compared with the (unfiltered) $L_{Aeq, 100ms}$ signal

4.7.3 Figure 4.7.2 below provides an example of a six hour period of persistent and mainly clear AM analysed using the Reference Method. The chart shows both the individual 10-second results (grey dots) and the 10-minute derived values (black line) when valid, using the prominence test. The second half of the chart shows a waterfall plot of the modulation frequency changing with time. Dotted lines represent the valid range of modulation frequency used; as the modulation remains within these bounds, the method continues to work well despite the relatively variable modulation frequency associated with changes in the turbine rotational speed. It can be seen that the AM ratings obtained vary in accordance with the magnitude apparent in the waterfall plot and the valid 10-minute values obtained are consistently typical of the highest 10-second results. Furthermore, a period corrupted by bird song from just after 5am (visible as vertical bars on the waterfall plot) was excluded using the prominence criterion, with the exception of one 10-minute sample (with a similar rating obtained as for the previous valid period).
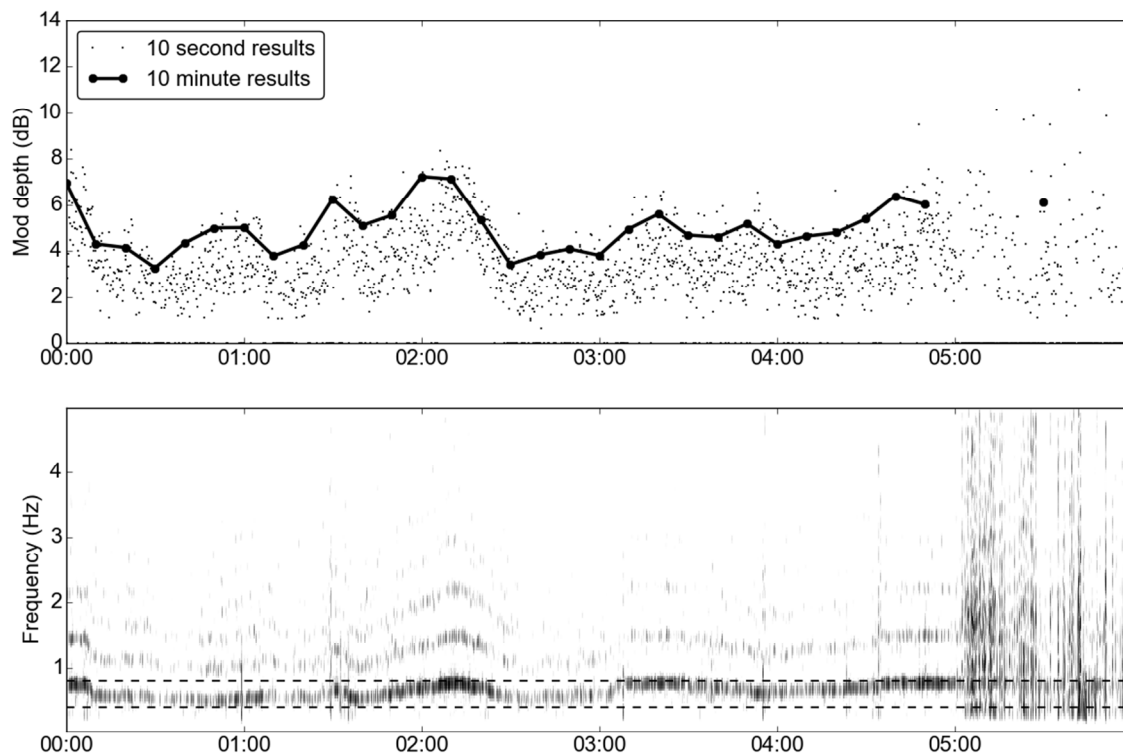

Figure 4.7.2 – Example of AM analysis results for a six-hour period

4.7.4 In the development of the methodology, it was necessary to reach a number of decisions on the most appropriate form of the input data and analysis parameters. Those finally agreed are set out below with the associated rationale for their adoption**:**

Input data:

- A sample rate of 0.1 Hz (100 ms data) – this is a pragmatic choice which is short enough to resolve the variation in sound pressure level resulting from AM but long enough to avoid the capture of unnecessarily high resolution data. Also it is the shortest period commonly available on many modern sound level meters. This means that for high modulation rates of 1.6 Hz or more, it may not be possible to resolve the signal or its harmonics.

- Recording in 1/3-octave bands from at least 50 to 800 Hz – this range is a pragmatic choice based on the collective experience of the authors and captures the range of frequencies within which audible AM is expected to occur. It is also a range which is possible to capture with many modern SLMs without considerable measurement challenges.

- Use of L_{eq} 100 ms data (rather than L_{max} or L_f[15]) – this allows the 1/3-octave band levels to be easily combined and reduces noise corruption. The use of $L_{Aeq, 100ms}$ rather than $L_{pAF, 100ms}$ in 1/3-octave frequency bands also results in a peakier signal and is therefore more conservative.

- The use of A-weighting – this gives consideration to the response of the human ear and hence the human response to AM, is consistent with ETSU-R-97 and reduces wind noise influence. Comparative testing indicated more robust results with the A-weighting applied.

- Measurements made according to the IOA GPG recommendations – this underpins the measurement methodology i.e. where to measure, when not to measure, wind speeds etc.

Analysis parameters:

- A major time interval of 10 minutes – this choice is consistent with the typical averaging times used for meteorological and SCADA data and so allows a straightforward correlation between the two;

- A minor time interval of 10 seconds – this is a pragmatic choice which is short enough that the evolution in level of AM over a 10 minute period can be captured but long enough to capture periodicity and for a meaningful AM level to be uniquely determined;

- Use of $L_5 – L_{95}$ over 10 seconds: this will weigh the result towards the higher peaks in the 10-second block without being too sensitive to extremes (which increase noise), whilst also providing a simple approach;

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[15] *i.e.* time-weighted sound pressure level data.

- Use of the 90th percentile of 10-second ratings distribution – this was a pragmatic choice, considered to represent the typical worst-case instances of AM within a 10-minute interval, based on the observed variability of AM in the field, without being excessively sensitive to possibly spurious extreme values (which increase noise);

- The requirement for a minimum of 30, 10-second values of AM per 10 min before a valid AM result can be determined – this is a pragmatic choice which accepts that there may be some data loss due to external noise sources, whilst still allowing a meaningful rating to be determined from partial data. It was found to be very effective in practice on a range of data;

- Use of a prominence ratio of ≥ 4 for accepting/rejecting a 10-second block; this corresponds to a peak which is 6 dB (10log(4)) above the spectral noise floor. This value is a pragmatic (and conservative) choice, based on data analysis for the available sites, which is considered to represent a balance between rejecting extraneous samples and retaining samples featuring AM;

- Use of DFT analysis as a key element of the methodology – this allows the identification of patterns of noise occurring at the BPF (modulation frequency) and harmonics;

- Use of a frequency resolution of 0.1 Hz in the FFT – this is the maximum resolution possible from 10 seconds of 100 ms data without padding the data;

- Use of an amplitude level of 1.5 dB as a threshold for the fundamental and harmonics. Excluding energy which is not associated with wind turbine noise is beneficial in reducing the noise floor of the metric, but obviously must not exclude wind turbine AM. A value of 1.5 dB was determined as a threshold based on the typical peak-to-peak variations in the background / extraneous noise on the sample data available. Variations in background noise are often greater than 1.5 dB but this was chosen as a conservative threshold to minimise false negatives;

- Use of the first three harmonics of AM to capture and reconstruct the time series – this is a pragmatic choice, based on the experimental observation that, for the majority of data samples most of the modulation energy is associated with the first three harmonics. Higher harmonics were poorly resolved and their use increased noise;

- Use of a rectangular windowing function within the DFT process (i.e. no window) – this allows the average level of AM over the entire period to be determined.

4.8   Indicative Method (After 'Tachibana' et. al.)

4.8.1   It is accepted that some people may want to measure wind farm noise on an ad-hoc basis, perhaps with attended measurements with a sound level meter. The method devised by a group of Japanese researchers led by Pr. Tachibana (Fukushima, Yamamoto et al, 2013) would be suitable in this context although, it is subject to corruption by extraneous noise and therefore is only suitable where there is clean data and the values obtained are not directly comparable with the reference method. It is therefore not suitable for use in planning conditions, but can be used to describe short uncorrupted samples of amplitude modulation. Note that the method requires the sound level meter to measure the fast and slow time-weighted sound pressure level simultaneously. Not all sound level meters can do this; an estimation method is therefore provided as an alternative. A brief description of the method is provided here.

4.8.2   The A-weighted short-term sound pressure level values with fast and slow time weightings are measured. Data should be measured as the sound pressure level, $L_{p(A)}$ fast and slow in 100 millisecond samples. The time varying difference in the two parameters is calculated.

$$\Delta L_A(t) = L_{A,F}(t) - L_{A,S}(t)$$

Where:

$\Delta L_A(t)$ is the difference in A-weighted sound pressure levels, between the two time weightings

$L_{A,F}(t)$ is the A-weighted sound pressure level, with Fast time weighting (i.e. time constant = 125 ms)

$L_{A,S}(t)$ is the A-weighted sound pressure level, with Slow time weighting (i.e. time constant = 1 s)

4.8.3   The above subtraction step is analogous to the de-trending step in the reference method. See Figure 4.8.1 below.

4.8.4   The Japanese researchers chose a 3-minute period for their analyses. However, the longer the sample, the greater the risk of corruption from extraneous noise. In fact, it can be used on shorter samples including 10-second periods as shown in Figure 4.8.1. Note however that some form of averaging or other processing of the individual samples must be used to obtain a representative value. For example, the 90[th] percentile could be used to calculate a 10-minute value providing that all samples are uncorrupted.

4.8.5   The slow weighted time response can either be measured directly by the sound level meter (if possible) or derived by post-processing audio files (if available), or calculated using the following equation from Section 6.1 of the Nordtest 112 standard (2002):

$$L_{AS}(t) = 10 \cdot \log\left[\frac{\left(\left(\frac{\tau}{\Delta t} - 1\right) \cdot 10^{\frac{L_{AS,t-1}}{10}} + 10^{\frac{L_{Af,t}}{10}}\right)}{\left(\frac{\tau}{\Delta t}\right)}\right]$$

4.8.6   In this case, the first ~3 seconds of data may need to be excluded from the final analysis, as the approximated measure will need a certain amount of data before it is correctly representative of the general level of the previous 1 second.
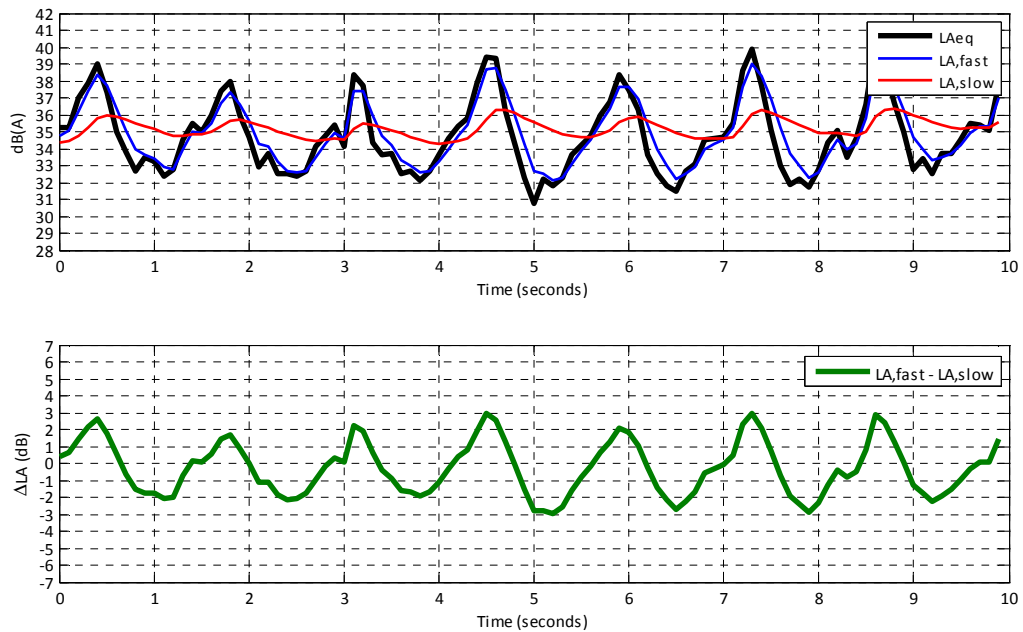

Figure 4.8.1 Derivation of ΔL$_A$(t)

4.8.7   The magnitude of modulation is then examined on a statistical basis, where a cumulative distribution is calculated on the $\Delta L_A(t)$ values within the sample. On the cumulative distribution of $\Delta L_A(t)$ values, the modulation depth parameter D_{AM}, is defined from the 90% range.

$$D_{AM} = \Delta L_{A,5} - \Delta L_{A,95}$$

Where:

D_{AM} is the depth of modulation (dB)

$\Delta L_{A,5}$ is the 5% point on the cumulative distribution of $\Delta L_A(t)$, within the period

$\Delta L_{A,95}$ is the 95% point on the cumulative distribution of $\Delta L_A(t)$, within the period

4.8.8   Figure 4.8.2 shows an example cumulative distribution of the period shown in Figure 4.8.1, and the derivation of the D_{AM} value.
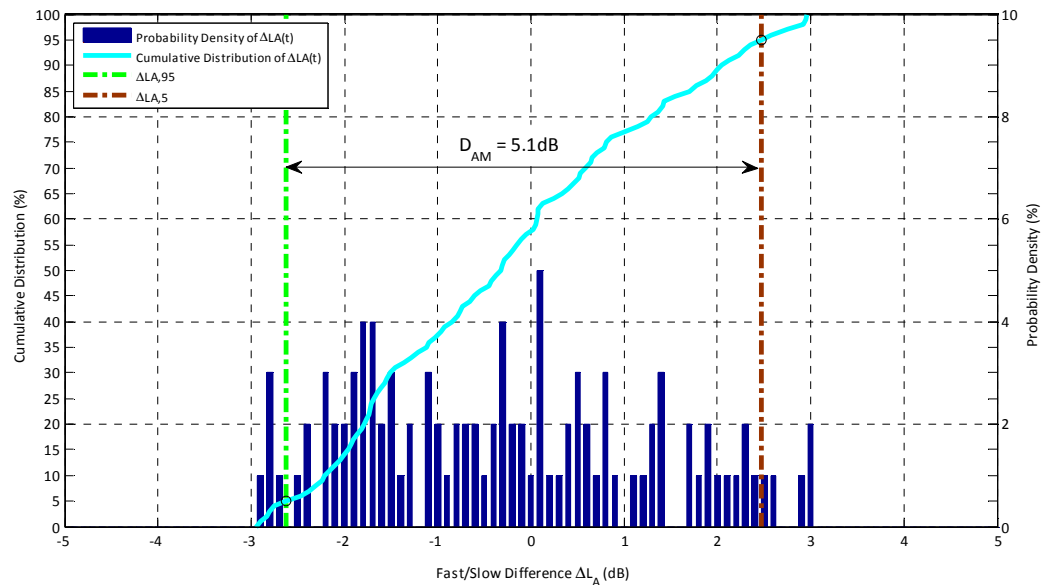
Figure 4.8.2 Cumulative distribution of ΔL$_A$(t) and derivation of DAM

Limitations of the Indicative Method

4.8.9 The indicative method for measuring AM is based only on analysis of the differences between two statistical measures of an A-weighted time-varying noise. It does not specifically provide a measure of modulation occurring at the blade passing frequency (or frequencies) of the wind turbines concerned. Rather, it provides a measure of variation, at whatever modulation frequency is occurring. With 'clean' signals that are dominated by wind farm noise, the method will be a reasonable measure of modulation at blade passage frequencies. However, as the method is based upon short-term A-weighted sound pressure levels, there is a high probability that some periods will be contaminated by extraneous noise sources. Steps can be taken to reduce that probability, e.g. by focussing on night-time or evening periods, when the level of other ambient noise is generally at its lowest. However, the influence of spurious noise sources is unavoidable if long-term monitoring is carried out. Consequently, there is a need for rigorous visual and/or aural examination of the data to ensure that the resulting modulation depth values are related to the actual wind turbine noise under assessment.

4.8.10 The auto-correlation function of the $\Delta L_A(t)$ values proposed by the Japanese researchers is also a useful tool in identifying periods that are not related to wind farm modulation. If the resulting modulation frequency is significantly different to the expected wind farm blade passage frequencies, then that period can be excluded from the overall analysis. However the converse is not always true, in that a modulation frequency indicated by the auto-correlation function that is similar to the expected blade passage frequency may not always be due to wind farm noise. There may be other noise sources in the environment such as bird song that give rise to similar modulation frequencies.

4.8.11 For instances of significant variation in underlying overall level, a sound pressure level with slow time weighting may not always fairly represent the mid-point between the 'peaks' and 'troughs' i.e. at times, the slow time-weighted sound pressure level may not react quickly enough to reflect the drift in underlying level. This results in a relatively large D_{AM} value, as the cumulative distribution of the $\Delta L_A(t)$ values picks up several instances of large differences between the two channels, partly due to the slow channel not reflecting the large drift. This effect is mostly seen when extraneous noise sources corrupt the measurements. When this effect occurs with wind farm noise, the D_{AM} parameter may revert from a measure of modulation to a measure of a variation. This is why this method is only suitable for the rapid evaluation of short samples.

4.8.12 Extracting the 90% range from the cumulative distribution function means the resulting D_{AM} value tends towards the two extremes of the time series. Taking the 95th percentile point, essentially finds one of the largest positive differences in the two channels, i.e. one of the largest 'peaks'. Taking the 5th percentile point essentially finds one of the largest negative differences in the two channels, i.e. one of the largest 'troughs'. Therefore if there is significant intermittency in modulation within the analysis subsection, the method tends to be representative of the larger modulation depths.

4.8.13 The Indicative Method must be used with caution and is to be considered as secondary to the reference method and in no circumstances as a substitute for it when the level of AM is being assessed against a specific criterion or limit (such as might be specified in a planning condition).

5   INSTRUMENTATION

5.1   General requirements

5.1.1 In principle, the instrumentation requirements are little different to those specified in the existing IOA Good Practice Guide and Supplementary Guidance Note 1: Data Collection (IOA 2013) (IOA 2014). However, the main requirements will be re-iterated here, along with specific considerations relating to amplitude modulation only.

5.1.2 In order that the AM measurements are resistant to the effects of wind turbulence, the existing guidance regarding windshields is recommended.

5.1.3 Similarly, any correction required for microphone orientation should be used. For example, if a free field microphone is used at grazing incidence (i.e. mounted vertically) with an outdoor enclosure (e.g. rain cover, birdspikes, windshield, etc.), the response should be corrected back to free field.

5.1.4 However, these corrections may not be significant in the frequency range proposed for AM metrics.

5.1.5 The main difference with normal wind turbine noise measurements is the requirement to log data at sufficient resolution in order to capture the variations in levels associated with AM. A resolution of 100 milliseconds is

required rather than the 10-minute averaging used in ETSU-R-97. Furthermore 1/3-octave band measurements are required.

5.2   Noise measuring equipment

5.2.1   As the focus of this document is metrics for AM, it is outside the scope to specify a mandatory length of time for AM surveys; it is likely, in any case, that this will be defined elsewhere in separate guidance.

5.2.2   Having said that, as a general principle, it is likely that the best description of AM will be obtained if data is collected over as broad a range of conditions as are typical for the site in question, or related to specific conditions highlighted for example as part of complaints. This may involve specification of the range of wind speeds, directions, times of day, atmospheric stabilities etc.

5.2.3   Noise measuring equipment for AM can be divided into three types:

1)   Equipment which can measure amplitude modulation directly

2)   Equipment which can measure and log sound levels, from which amplitude modulation may be subsequently derived by post-processing

3)   Equipment which simply records the audio signal, for subsequent post-processing.

5.3   On-line AM measurement

5.3.1   Although no such equipment is currently available, there may be sufficient demand to may make it worthwhile for a manufacturer to develop an instrument which calculates and logs an AM-related parameter.

5.3.2   In such a case, the instrument shall meet the relevant performance requirements of the second type, although it may not be necessary to display or store all the same measurement parameters.

5.4   Sound level logging equipment

5.4.1   To ensure a common, or at least a minimum level of fidelity, the minimum requirements for the sound level meters are those specified in the IOA's Good Practice Guide. This includes the specification of the wind shield and, in general, the same equipment used for noise compliance measurements can be used to capture suitable data for AM analysis (IOA 2013) (IOA 2014).

5.4.2   Instruments for storing sound level with time shall meet the requirements of BS EN 61672-1: 2013 to Class 1 accuracy.

5.4.3   Older equipment may also be used which is designed to BS EN 60651: 1994 and BS EN 60804 : 2001 to Type 1 accuracy.

5.4.4   The 1/3-octave filters shall meet the requirements of BS EN 61260-1: 2014 to Class 1 accuracy.

5.4.5   The instrument shall be capable of measuring and storing the $L_{Aeq,\ 100ms}$, and optionally the L_{pAF} and L_{pAS} simultaneously with the same time resolution.

5.4.6   The instrument shall be able to measure and store the $L_{eq,100ms}$ 1/3-octave spectra at least over the range 50 Hz to 800 Hz.

5.4.7   In order to minimise the influence of instrument noise on AM depth, the lower limit of the instrument linearity range shall be no higher than 25 dB(A).

5.5   Audio recording equipment

5.5.1   Audio recordings, if necessary, shall preferably be done by using one of the instruments above, thus ensuring a minimum level of accuracy.

5.5.2   Recordings should be made with a bit depth of 24 bit, although 16 bit recordings may be made, as long as care is taken to optimise the dynamic range due to instrument noise, and high level fluctuations due to wind turbulence.

5.5.3   Recordings shall be uncompressed, with a minimum sample rate of 12 kHz.

5.5.4   'Lossy' audio compression such as MP3 is not acceptable for post-processing purposes. Lossless compression such as to ALAC or FLAC formats may be used. However, if the only purpose of the audio is to play back audio to subjectively identify samples with wind turbine AM, as opposed to other noises, then compression to minimise data storage would be acceptable.

5.5.5   The recording front end (including the microphone/preamplifier/windshield), if not one of the instruments above, shall meet the requirements of the relevant parts of BS EN 61672-1 Class 1 (or BS EN 60651 Type 1), including frequency response, linearity and dynamic range. The onus is on the user to verify these requirements are met.

5.5.6   If available, calibration information shall be readable from the file header, otherwise, a calibration signal shall be recorded using the same settings as those for the measurement. This subsequently allows the recording to be scaled correctly for sound levels.

5.5.7   Alternatively, where it is possible to record audio for the entire period of interest, it is also possible to calculate the band-limited 100-millisecond L_{Aeq} values from the audio data using suitable software, the performance of which can be suitably verified (see 5.4.1 to 5.4.4). In this event, high quality recordings are required and careful consideration should be given to obtaining calibration recordings so that all data can be converted into absolute units.

6   MEASUREMENT PROCEDURE

6.1.1   Measurements of the noise data required to fulfil the requirements of this methodology, as defined in Section 4, should be made in accordance with the requirements of the IOA's Good Practice Guide to the Assessment and Rating of Wind Turbine Noise (IOA NWG, 2013).

6.1.2   The length of survey required in order to obtain sufficient data for a comprehensive description of the variation in AM with external factors, for example wind speed, direction, time of day etc. will depend on both the climatology of the site and the underlying reason for which measurements have been made. This may be related to complaint investigations or may simply be used to demonstrate compliance with pre-agreed limits on acceptable levels of AM.

6.1.3   Attention is drawn to the fact that, as for any measurement, critically reviewing the data and analysis, through for example listening to audio recordings, remains a fundamental part of the analysis methodology. The automated process described here will enable the elimination of a portion of the measured data which does not contain sustained wind turbine derived AM, identifying those periods which do, to enable the analyst to focus their listening efforts on the key samples of audio data.

7   EVALUATION OF METHOD AGAINST ADOPTED SUCCESS CRITERIA

7.1.1   The following presents an assessment of the reference method against the success criteria adopted by the AMWG, as set out in Appendix B.

7.1.2   **Achievability**:   The proposed reference method has already been implemented and trialled by different members of the AMWG, using input data measured by different modern sound level meters, and consistent results have been obtained.   The provision of software code will assist other practitioners in readily applying the method.

7.1.3   **Reality**: The method was extensively trialled on real wind turbine noise data measured at a variety of sites exhibiting varying levels of AM, including data with significant contributions from other noise sources ('corruption') and data with no AM evident.   The results from this method produce a value of AM when wind turbine AM is present and a low or no value when AM is absent.

7.1.4   **Robustness**: This method is relatively robust; in particular, the proposed prominence criterion works very effectively in minimising the influence of non-turbine sources and the requirement for 30 valid results in a 10-minute period further identifies persistent AM. The thresholds used were set conservatively to also minimise the risk of 'false negatives' (i.e. failure to detect AM when it is present). Whilst false positives (i.e. generating a value for AM when no AM is present) cannot be fully eliminated, this is the case for any numerical method. The selected approach was the most robust of all the methods evaluated by the AMWG.

7.1.5   **Location**: As described in Appendix C, it is proposed that this method applies to free-field external measurements as is standard practice for wind farm noise measurements.

7.1.6   **Objectivity**: The proposed method applies a metric to provide a numerical value which characterises the peak-to-trough variations in that component of measured overall noise that can be attributed to a wind turbine or turbines.

7.1.7 **Repeatability and reproducibility**: The AMWG undertook an internal 'round robin' test which demonstrated that different members independently were able to implement and test the method and obtain effectively identical values of the AM metric across a range of test data. The production of software code will enable other practitioners to achieve consistent and repeatable results.

7.1.8 **Specificity**: The method includes the application of frequency-band-limiting to the input data, selection of relevant modulation frequencies and use of a 'prominence test' to help to discriminate between wind turbine noise and other noise sources. The Reference Method and resulting metric are specific to the detection and rating of AM in wind turbine noise.

7.1.9 **Automation**: The method has been proven to rapidly process large amounts of data, which is essential for this application because AM, if it occurs, is generally only evident in some conditions and may occur very infrequently. There is a recognised need for a practitioner to review the analysis to reduce the risk of 'false positive' results, but the need for subjective examination of data is much reduced, compared with other methods, by the incorporation of objective indicators and tests to allow spurious data to be identified and rejected.

7.1.10 **Relativity**: The method assigns a specific value, in dB, to the level of AM within a sample of wind turbine noise. The range of values generated provides discrimination of different levels of AM and an effective dynamic range, and can be related to the results of studies of the subjective response to noise exhibiting amplitude modulation.

7.1.11 It can be seen from the example of Figure 4.7.2 above that the Reference Method determines an AM rating which varies in accordance with the visual waterfall plot and consistently picks out values which are typical of the highest 10-second periods. This therefore meets the above requirements for objectivity and relativity. Furthermore, a period corresponding to bird song is excluded, apart from one 10-minute sample, thus demonstrating specificity, and the suitability of the Reference Method for automation.

8   APPLICATION OF THE REFERENCE METHOD TO TEST STUDY STIMULI

8.1   Background

8.1.1 The AMWG obtained the synthesised test samples (as .wav files) used in the subjective studies undertaken both by Salford University for the RenewableUK project and the large Japanese research team (Tachibana *et. al.*). The results have been processed using the Reference Method to determine the AM rating. These could be used to translate the results of subject studies with the AM rated with the Reference Method. Such studies are outside the scope of the AMWG but are provided for information. As the files were of synthesised constant AM with no temporal variation, the analysis has been based on the 10-second methodology only. The results are shown below.

8.2   RenewableUK Salford Stimuli

8.2.1   The stimuli used by Salford University in Work Package B2 (WPB2) of the RenewableUK research were classified in terms of modulation depth and overall L_{Aeq} levels. To obtain the results with the Reference Method, the audio samples were A-weighted and band-pass filtered in the time domain. The results are shown in Figure 8.2.1 below for the 30, 35 and 40 dB(A) samples in the three frequency ranges.

8.2.2   The AM ratings obtained with the Reference Method generally produced higher results than the Salford design modulation depth. For these samples, the 50 – 200 Hz frequency range produces the greatest AM ratings.
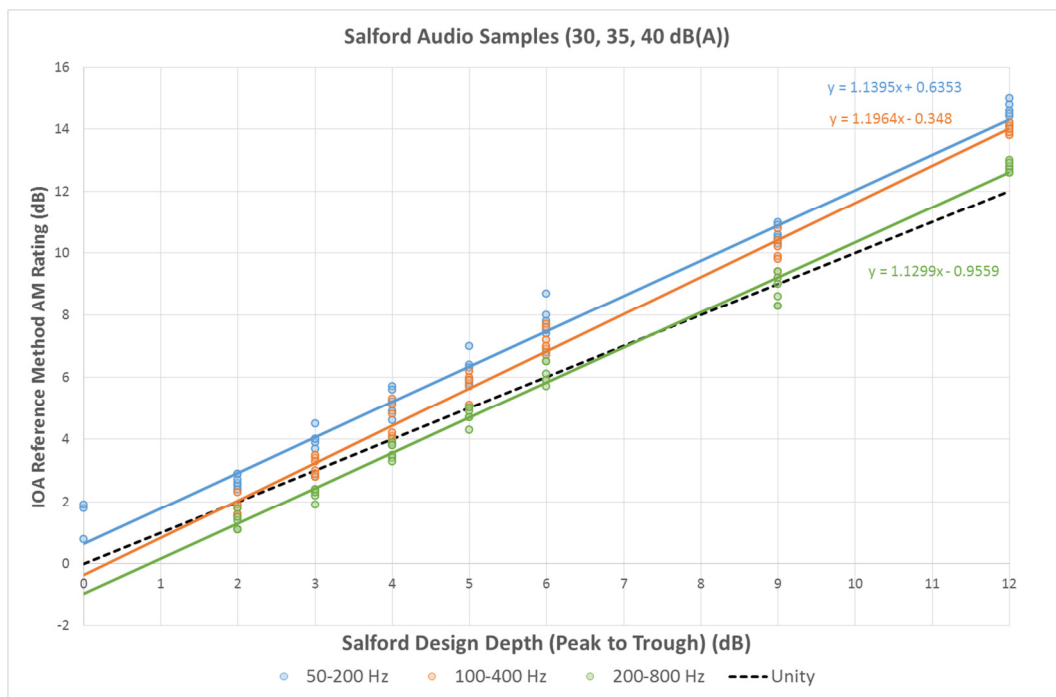

Salford Audio Samples (30, 35, 40 dB(A))

y = 1.1395x + 0.6353
y = 1.1964x - 0.348
y = 1.1299x - 0.9559

IOA Reference Method AM Rating (dB)

Salford Design Depth (Peak to Trough) (dB)

50-200 Hz   100-400 Hz   200-800 Hz   ----Unity

Figure 8.2.1 Analysis of Salford Stimuli with the IOA Reference Method

8.2.3   In the Salford study, results of additional tests are presented (in Figure 9.5 of the Work Package B2 report) in which the participants were asked to adjust the level of an unmodulated broadband signal (an Adaptive BroadBand Signal (ABBS)) to the level at which it was found to be equally annoying as the modulated test stimulus. The results with the Salford modulation depth can be replaced with the results of the IOA Reference Method: see Figure 8.2.2.
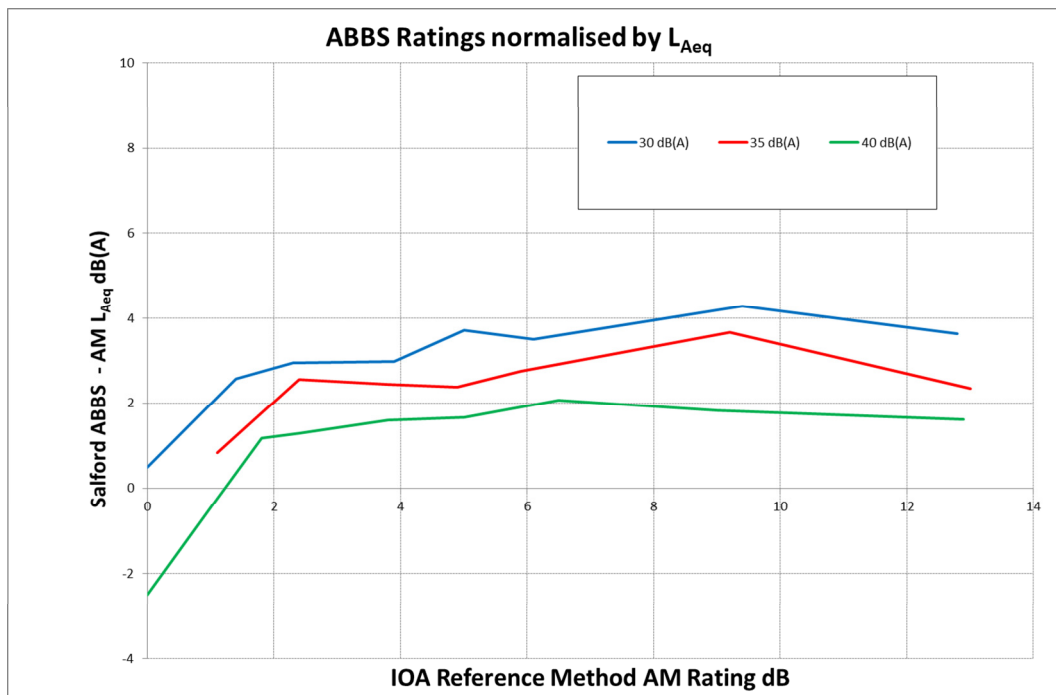
Figure 8.2.2 Comparison of Salford ABBS – AM L_{Aeq} results for IOA AM Rating (average values only 30, 35 & 40 dB(A), error bars omitted)

8.2.4   The WPB2 report also presented an alternative analysis, in Section 9.6 and 22, showing the adjustment relative to the L_{A90} levels of the samples. It noted the potential relevance of such an approach and recommend further investigation using this parameter in future studies. Figure 8.2.3 below reproduces Figure 22.2b of the report using the Reference Method ratings.
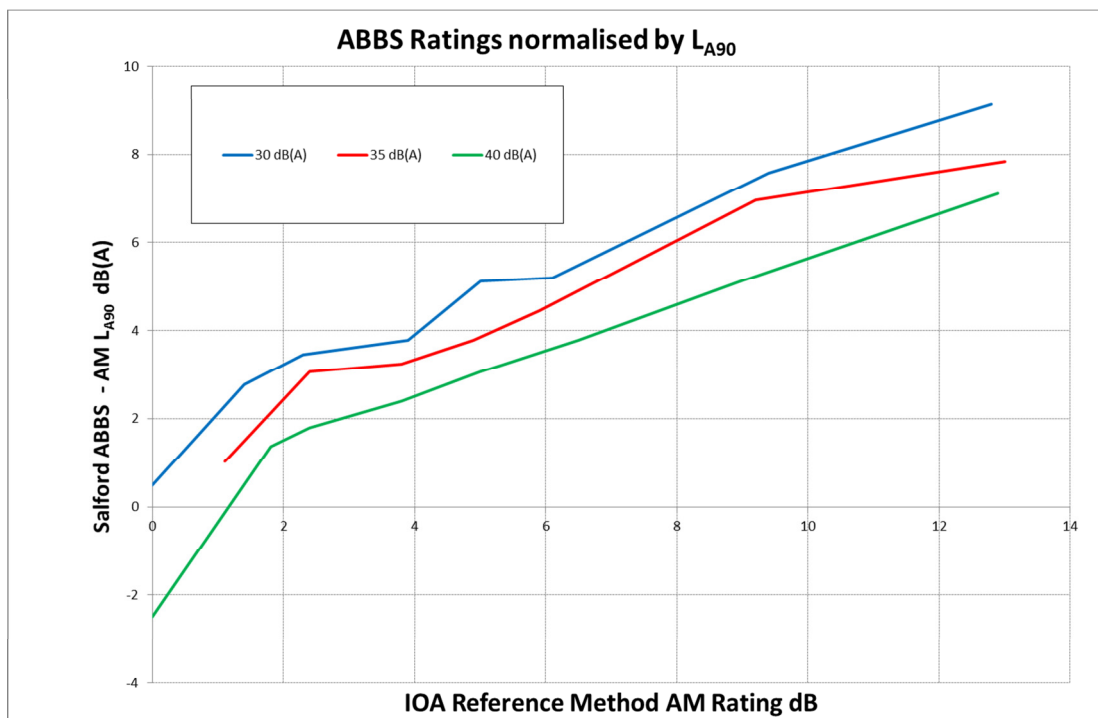

Figure 8.2.3 Comparison of Salford ABBS – AM L_{A90} results for IOA AM Rating (average values only 30, 35 & 40 dB(A), error bars omitted)

8.2.5   The Salford study noted that the difference between the L_{Aeq} and L_{A90} results could be partially explained by the difference between the L_{Aeq} and L_{A90} values for the test samples.   Caution should however be used when interpreting these last results as this may not relate to the $L_{A90,10min}$ values used in ETSU-R-97 measurements.   The differences between L_{A90} and L_{Aeq} of more than 3 dB (WPB2 Table 22.1) obtained for some of the 20 s artificial stimuli (9 and 12 dB design modulation) have not been observed in practice over 10 minutes even for clean samples of strong modulation.

8.3   Tachibana Stimuli

8.3.1   A similar analysis has been carried out for the stimuli used by Japanese researchers (Yokoyama, S., et al. (2013)) led by Professor Tachibana.   The results are shown below in Figure 8.3.1. Please note that this is shown with reference to the AM Index values used to design the stimuli rather than the D_{AM} metric defined in the research or in Section 4.8, which is different.

8.3.2   Again, the results show a good correspondence with the design depth used in the study and this could then allow a translation to the Tachibana AM results based on the IOA Reference Method.
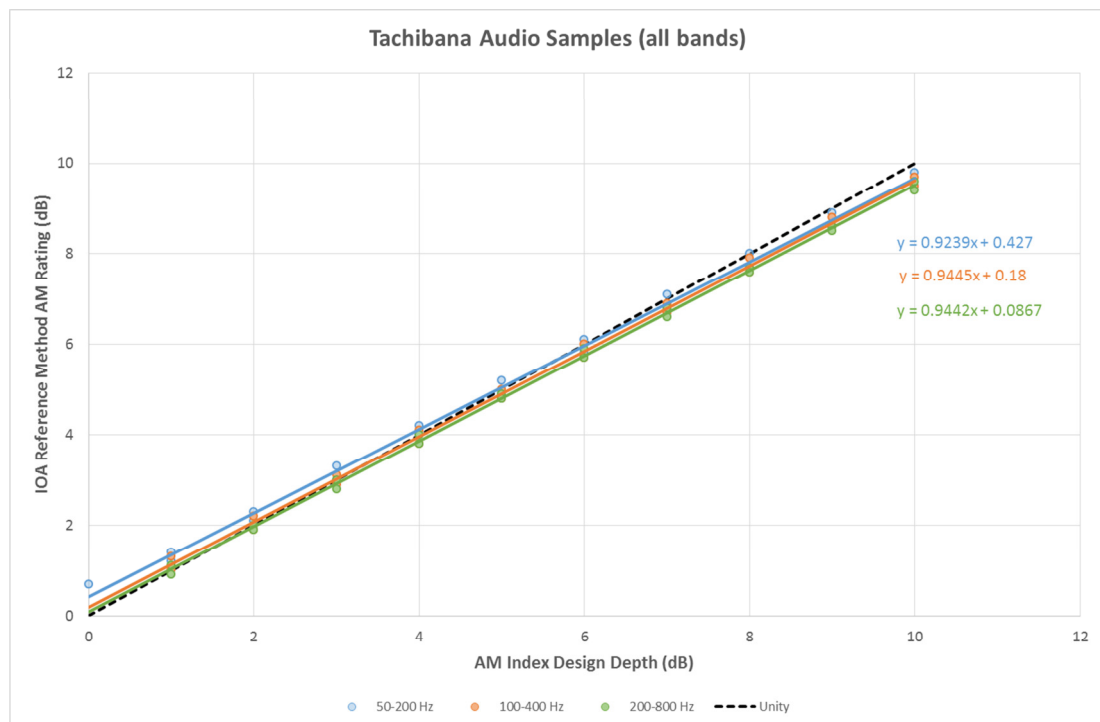

Figure 8.3.1 Analysis of Tachibana audio samples with the IOA Reference Method

9   SOFTWARE

9.1.1   Software will be provided when available, with data samples for validation purposes.

10   REFERENCES[16]

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ETSU-R-97 (1996), "the Assessment and Rating of Noise from Wind Farms", Final Report for the Department of Trade & Industry, The Working Group on Noise from Wind Turbines, September 1996

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IOA (2014). "Good Practice Guide - Supplementary Guidance Note 5 - Post Completion Measurements"

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Levet, T (2015), "Application of the AM metrics – case studies", IOA Acoustics 2015 conference, Harrogate, UK, 15 October 2015

NordTest 112 (2002) "Prominence Of Impulsive Sounds And For Adjustment Of L_{Aeq}"

RenewableUK (2013). "Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect"

Swinbanks, M.A. (MAS Research Ltd), (2013), "Assessment of RES Revised Condition 20 for Evaluating Excessive Amplitude Modulation", May 2013

Yokoyama, S., et al. (2013). "Study on the amplitude modulation of wind turbine noise: part 2- Auditory experiments " Proc Internoise 2013, Innsbruck.

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[16] Note that this section lists solely the documents explicitly referenced in this final report. For a complete list of documents considered in the entire process this list need to be combined with the references presented in Section 12 of the AMWG 'Discussion Document' published in April 2015.

APPENDICES

Appendix A Terms of Reference

INSTITUTE OF ACOUSTICS

IOA Noise Working Group (Wind Turbine Noise)

Amplitude Modulation Working Group

Terms of Reference

INTRODUCTION

In response to a request from the Institute of Acoustics Noise Working Group (IOA NWG), and approved by IOA Council, the IOA has agreed to set up a working group to look at the issue known as 'amplitude modulation'. The aim of the group will be to review the available evidence, and to produce guidance on the technical aspects for the assessment of AM in wind turbine noise.

The membership of the AM Working Group (AMWG) is drawn from the membership of the IOA and the CIEH, and seeks to include different representatives of the consultancy, academic, development and local authority sectors.

The AMWG will report to the IOA NWG, who in turn report to IOA Council.

ROLES AND RESPONSIBILITIES

The role of the AMWG is to provide advice to the IOA NWG on current good practice in the assessment of AM within wind turbine noise assessment.

The working group should:

- Undertake a literature review of available research and evidence on amplitude modulation and current methods in use, as appropriate; and on psycho-acoustic effects of AM

- Consider the design parameters for an AM metric and assessment method to be used in the UK

- Consider the various metrics and methodologies available to describe AM, and develop a preferred option if possible, or identify alternatives for the IOA membership to consider

- Produce a first draft of a consultation document with explanatory notes / justifications for consultation

- Consult the IOA membership and where appropriate other relevant technical experts on the draft guidance document

- Consider the consultation responses and if appropriate, produce a final Supplementary Guidance Note and / or consider the need for further research

- Provide software, if possible, to allow the analysis of AM data.

It is expected that the Supplementary Guidance Note will report on the metrics and methods considered, propose a preferred metric and assessment methodology and illustrate how it might work in practice. The primary goal is to develop a methodology which could be used within the planning regime; consideration must be given to use within the statutory nuisance regime as well.

If a consensus view on a particular issue cannot be reached between members of the working group, the various options should be listed out, with the pros and cons of each option discussed. Specific consultation questions to be put to the IOA NWG / peer review group should be aimed firstly at resolving these issues.

It is expected that the working group's activities will be of relevance to:

i.   Acoustic consultants

ii.   Local authorities;

iii.   Developers

iv.   Academics carrying out research on wind turbine noise

v.   Turbine manufacturers

vi.   The general public living close to wind turbines.

The activities of the working group initially relate to technical acoustic issues only, and therefore the initial membership will be drawn from groups i) to iv).

There may be occasions when the subject matter under discussion could benefit from input from other specialist representatives. When such occasions arise the working group may agree additional representation. If this results in additional costs these should be referred to the IOA Executive for approval.

WORKING ARRANGEMENTS

Meeting frequency

The working group will meet as often as necessary; at least four times provided a quorum is present.

Meeting quorum and leadership

A quorum is defined as five members of the working group. The working group meetings should be chaired by the chairperson, who will also act as the group's liaison to the IOA NWG. In the absence of the appointed chairperson, those present shall elect a temporary chairperson.

Administration

The other arrangements for the AMWG are:-

- Secretariat duties will be performed by a member of the AMWG appointed by the chairperson

- An agenda for each meeting will be drawn up and circulated to the working group (copied to the steering group for information) no less than two working days in advance of each meeting

- AOB can be tabled at the discretion of the chairperson

- Notes and summary action points of each meeting will be produced and sent to AMWG members (copied to the IOA NWG for information) within 10 working days of each meeting

- The AMWG will conduct most of its business via teleconference calls and email, but will meet at least once prior to the publication of the draft guidance for consultation with the IOA NWG and then as often as necessary. Meeting notes listing key actions will be made available to the IOA Council via the IOA Executive and published on the IOA website

- The AMWG will report formally to the IOA NWG chairperson, and shall provide ongoing reports as required

- The Terms of Reference for the AMWG, and any subsequent amendments, will be approved by the IOA NWG.

AMWG members will be entitled to claim travel expenses to meetings, at a rate to be set by the IOA Executive. No other payments will be made.

Proposed Timescales

The AMWG will agree a work programme, which is expected to cover a period of five months from the Inception meeting to the publication of a consultation draft and software. A six week consultation is envisaged, followed by a further four-week period during which the working group will consider the responses and produce a final version of the document and software for approval by IOA Council.

Ownership

Editorial ownership of the output document(s) will be retained by IOA Council.

Version 5 – 30 09 2014

Appendix B Scope of Work

INSTITUTE OF ACOUSTICS

IOA Noise Working Group (Wind Turbine Noise)

Amplitude Modulation Working Group

Outline Scope of Work

INTRODUCTION

In response to a request from the Institute of Acoustics Noise Working Group (IOA NWG), and approved by IOA Council, the IOA has agreed to set up a working group to look at the issue known as 'amplitude modulation' (AM). The aim of this 'AM Working Group' will be to review the available evidence, and to produce guidance on the technical elements for the assessment of AM in wind turbine noise.

This document defines:

- The membership of the AMWG

- The schedule of meetings that the AM WG will hold

- The aim of the AM WG

- The criteria by which the different options available for analysis of AM will be assessed

- The work packages necessary to achieve these aims.

The Terms of Reference of the AMWG are defined separately, and should be read in conjunction with this document.

MEMBERSHIP

The IOA NWG reports to IOA Council and comprises the following members:

- Richard Perkins, Parsons Brinckerhoff (Chair)

- Matthew Cand, Hoare Lea Acoustics

- Bob Davis, R Davis Associates

- Chris Jordan, Northern Group Systems (Environmental Health)

- Malcolm Hayes, Hayes McKenzie Partnership

The AM WG reports to the IOA NWG and comprises the following individuals:

- Gavin Irvine, Ion Acoustics (Chair)

- Matthew Cand, Hoare Lea Acoustics

- Bob Davis, Robert Davis Associates

- Dave Coles, 24 Acoustics

- Samuel Miller

- Tom Levet, Hayes McKenzie Partnership

- John Shelton, AcSoft

- Jeremy Bass, RES

- David Sexton, West Devon Borough Council

- Geoff Leventhall, Acoustical Consultant

The membership of the AM Working Group (AM WG) is drawn from the membership of the IOA and CIEH and seeks to include different representatives of the consultancy, academic, development and local authority sectors.

It is anticipated that the IOA NWG will provide oversight to the AM WG and participate in meetings and discussions at their discretion.

SCHEDULE OF MEETINGS

It is planned that the AM WG will hold face-to-face meetings of all members on the following dates:

- Wed 10 Sep   Kick-off meeting

- Wed 8 Oct 2014   Update #1

- Wed 12 Nov 2014   Update #2

- Wed 3 Dec 2014.   Update #3

Between meetings, conference calls between AM WG members will be held at fortnightly intervals.

The timescale for the work of the group is set out in the Terms of Reference.

GOALS

The overarching aim of the group is to develop the technical elements of an assessment method for amplitude modulated noise from wind turbines and wind farms. This will be:

- Based on best available science

- based on the most up-to-date psycho-acoustic and technical information on modulation available

- Provided in the format to allow straightforward inclusion in 'standard' forms of planning conditions for wind turbines [subject to thresholds or penalties set by others]

- Accompanied by software where necessary to allow the condition to be implemented by all parties.

To achieve this, the assessment method will need to contain a means of characterising a sample of amplitude modulated wind turbine noise data, with an agreed format and length, by means of a single metric uniquely defining the level of AM within it.

The results of the work of the AM WG will be communicated to the acoustics community via a Supplementary Guidance Note (SGN) or other document, thus providing additional information to that provided in the original IOA Good Practice Guide to 'The Assessment and Rating of Noise from Wind Farms' – ETSU-R-97.

WORK PLANS

To achieve the goals of the WG, it is anticipated that there will be a number of work packages.

WP1   AM definition and target audience

To provide clarity surrounding the issue of wind turbine AM, current definitions of AM will be reviewed and/or combined.

The WP will also consider the respective needs for the target audience, and ensure the final guidance document is appropriate where possible.

WP2   Data collation

The aim of this WP is to compile as much measured AM data as possible from as wide a range of wind turbine sites, in terms of terrain and meteorological complexity, and turbine types, hub height, as possible. Such data will be essential for identifying and testing the preferred AM metric.

WP3   Literature review

A literature review will be performed of all known literature relevant to the assessment and rating of wind turbine AM. The aim of the task is to compile a list of the different 'rating' methods currently available for AM, this to include the following:

- the 'Den Brook' method – see Condition 20 in the planning conditions and the scheme proposed by RES to satisfy a planning requirement to implement the above condition

- Work by MAS Environmental

- The RenewableUK method, published in December 2013 and recent modifications to the RenewableUK method which would correct some of the shortcomings – see Tom Levet (metric) and Jeremy Bass (penalty scheme)

- The method published by Tachibana et al of Japan

- The German Impulsiveness Rating

- Australian research by Evans and Cooper, Acoustics 2013

- Lee et al, 2009 + 2012

- McCabe, WTN11, 2011

- McLaughlin, WTN11, 2011

- Gunnar Lundmark, WTN11, 2011

- Larsson & Öhlund, Internoise 2011 and WTN2013

- Gabriel, WTN2013

- Carlo di Napoli, WTN2009 & WTN2011.

- Any national standards such as those of South Australia and New Zealand

- Other AM information (non-wind turbine) e.g. psycho-acoustic effects, Zwicker Fastl

WP4   Critical comparison of available methods

The intention is that the outcome of WP3 is an evidence basis on which to determine the preferred AM metric. This will comprise three elements:

- A review of the evidence of WP3 identifying common, desirable elements of the different methods available. This could include:

    o Methods based in the time domain

    o Methods based in the frequency domain or

    o A combination of the two.

- The review would also consider other hybrid methods to be developed from the above if appropriate

- The most promising method(s) will be implemented in software to allow a direct comparison of them based on the assessment of real-world data samples from WP2.

The content of subsequent work packages will be dependent on the outcome of WP3 and WP4

These could include the following potential work packages:

WP5 data requirements

To ensure a common, or at least a minimum level of fidelity, the minimum requirements for data loggers will be defined.

Parameters to be considered for data loggers could include:

- Instrument and windshield specifications

- The measurement index, L_{eq}, L_p, L_F etc.

- Short-term logging in 100 millisecond or 125 millisecond periods

- The maximum noise floor permitted

- frequency weighting network, e.g. A, C or none

- 1/3ˉoctave band or octave band logging

- Audio recording ability.

For audio-recordings the following parameters could be considered

- Minimum length, in seconds/minutes

- Sample rate, in Hertz

- Bit rate

- Stereo or mono

- File format, e.g. WAV or MPG.

WP6 Data reduction definition

Given a suitable metric, the aim of this WP is to characterise an AM sample in terms of the following:

- The major time interval for analysis, e.g. 10 min

- The minor time interval for analysis

- Averaging or statistical analysis of AM samples.

WP7 Develop software

So that all parties involved in the assessment of wind turbine AM noise can do so with equal facility, a software package will be developed for implementing the preferred AM methodology.

This could be provided as a stand-alone executable program running on PCs with the Windows operating system, but other options will be considered.

WP8 Batch processing

It would be desirable that any AM methodology can be implemented in software which allows the 'bulk' processing of suitable data. This is because AM is typically only present in certain specific meteorological conditions, so that it may be necessary to screen large amounts of data to identify those periods which contain AM.

Ideally the software should discriminate wind turbine AM from other modulated noise sources, although it may be necessary for samples to be checked by listening where there is some doubt about their validity. The extent to which the software should do this must be defined. Where the software can only provide limited reliability, such that additional checks are required, then the process for checking and verifying data must be determined.

WP9 Psycho-acoustic significance

To be able to create a meaningful planning control for wind turbine AM noise, two elements are necessary: a metric, i.e. a number, which represents the level of AM present within a sample of wind turbine noise, and a scheme for providing a context for interpreting that number which encapsulates the typical psycho-acoustic response to AM.

This context might take a number of different forms, for example a stand-alone scheme, a penalty scheme or a hybrid of the two. For example, it might be:

• A stand-alone condition, which applies irrespective of overall wind turbine noise levels

• Integrated into the overall compliance process for wind turbine noise via a penalty added to wind turbine noise levels

• A hybrid of the two. For example, a penalty scheme for low to moderate levels of AM and an automatic fail, irrespective of overall noise levels, for higher levels of AM.

The aim of this WP will be to collate papers relating to the psycho-acoustic response to AM, with a view to identifying possible ways forward. This may involve re-analysis, using the new metric, of the audio data used in the RenewableUK funded listening tests, at the University of Salford. The AM

WG can make recommendations about the form, and nature, of the psycho-acoustic consequences of a given level of AM, if the available evidence supports a view, which might include:

• The nature of the test, i.e. stand-alone, a penalty or hybrid scheme

• If a penalty scheme is recommended, how this might be defined.

It should be stressed that the intention of this work package is to collate the information needed to help decision makers make an informed decision on how an appropriate threshold or penalty might be applied, if the available evidence supports this, or to recommend further work which would assist.

SUCCESS CRITERIA

A number of criteria will be considered by the group when assessing the output of each work package as follows:

Achievability – using the equipment and software typically available to acoustic professionals

Reality – work with samples of 'noisy', real-world data, not just, artificial simulated data created for testing purposes

Robustness – minimising the influence of 'noise' in test data, which can make signal detection difficult, to ensure low rates of false positives and negatives

Location – the chosen methodology will be applicable to measurements in free-field conditions, external to affected premises, so that it can be used in conjunction with current good practice in wind turbine compliance measurements

Objectivity – providing a unique number which characterises the level of AM in each case

Repeatability and reproducibility – returning the same unique number for a given sample of test data irrespective of who runs the test, where or when or how

Specificity – as AM is currently defined as 'the modulation of the broadband noise emission of a wind turbine at the blade passing frequency (BPF)', it is essential that the methodology is specific to the BPF and not sensitive to variation at any other frequencies

Automation – the ability to process large data sets. This is necessary because AM is typically only present in certain specific conditions, so that it is necessary to screen large amounts of data to identify those periods which contain AM

Relativity – relatable to the psycho-acoustic, or subjective, response of individuals to AM noise.

Appendix C IOA AMWG responses to Consultation Document

Summary of responses and working group comments

The IOA Discussion Document on Methods for Rating Amplitude Modulation was issued on 23 April 2015. This section summarises the responses and provides the AMWG's considered comments on the points raised.

Responses - general

Twenty individuals (some presumably representing the views of their companies or organisations) responded to the Discussion Document by providing replies to specific questions and, in some cases, providing additional comments. Two responses were received from non-UK sources. Most responses will be published in un-edited form except that some details will be redacted to preserve anonymity where this has been requested. It is recognised that the significance of comments made by individuals is likely to be influenced by their professional and commercial affiliations (if any) as well as the experience of the person concerned. In reviewing responses, the AMWG has attempted to take these factors into account, in an objective way, when considering the weight to be given to any particular response, suggestion or criticism.

In addition to the formal consultation, since the date of the Discussion Document further input on signal processing has been provided by Professor Paul White of the Institute of Sound and Vibration Research, University of Southampton. The AMWG gratefully acknowledges the contributions made by the respondents to the Discussion Document, and to Professor White.

Respondents were asked to address 20 specific questions and to make further comments as they thought necessary. The following commentary summarises the main points raised in answer to the questions.   Some responses were comprehensive and complex. Every effort has been made to take account of all issues raised, including issues not referred to in the summary below.

Q1   Definition – wind turbine amplitude modulation (AM)

The definition of AM in the consultation document was as follows:

In the context of the objectives of the working group, wind turbine AM is defined as periodic fluctuations in the level of broadband noise from a wind turbine (or wind turbines), the frequency of the fluctuations being the blade passing frequency of the turbine rotor, as observed outdoors at residential distances in free-field conditions.

The majority of respondents agreed with the definition but some proposed additions or amendments as follows:

- The definition should specify 'audible' noise rather than 'broadband' noise.

- The reference to the measurement location and free-field conditions should be omitted since this is not relevant to the definition of AM but only to the application of a metric.

- The definition should distinguish between 'normal' and 'other' AM.

AMWG comments

The AMWG accepted the first two points and the definition has been amended as follows:

"Wind turbine amplitude modulation is defined as periodic fluctuations in the level of audible noise from a wind turbine (or wind turbines), the frequency of the fluctuations being related to the blade passing frequency[1] of the turbine rotor(s)."

The third point was discussed, but the AMWG considers that the source mechanism is not relevant to the experience of AM.

Q2   Is the AM definition applicable to small turbines?

This question produced a mixed response. Some respondents did not make any comment or said that they had no experience of small turbines. The question of 'what is a small turbine?' was raised. There was wide agreement that smaller turbines would exhibit different characteristics – different dominant blade noise frequencies, higher modulation frequencies, with the possibility that some fluctuations in levels resulting from mechanical sources ('rattling' or 'flapping' noises have been observed from some micro turbines, for example) rather than aerodynamic sources. The majority view was that although the definition of AM applied, in principle, to any wind turbine, the assessment of AM from smaller turbines would require different measurement and analysis parameters, and even if a common metric could be devised, its application to small turbines was likely to require different acceptability criteria to be developed.

AMWG comments

This question would perhaps have been better framed if directed towards the *application of an AM metric* rather than the definition of AM. Most of the measured data of wind turbine noise exhibiting AM relates to turbines with outputs in excess of 500kW; experience of AM from smaller turbines is limited. Therefore the AMWG has focused its study of AM metrics on data from wind turbines of 500kW capacity upwards.

Q3   Is it appropriate to measure AM outdoors in free-field?

This question generated considerable discussion. Most respondents observed that complaints regarding AM often concerned indoor noise, particularly at night. It could therefore be thought logical to measure noise inside dwellings. Furthermore experience suggests that there is a variable 'transfer function' between indoor and outdoor perception of AM and in some cases, higher levels of AM may be detected indoors than outdoors. However, most respondents accepted the difficulties in

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[1] The blade passing frequency (Hz) = rotor rpm times No. of Blades / 60

measuring noise inside, including the influence of room modes and the resulting spatial variations in noise level, as well as to the influence of domestic noise sources. An analysis of a domestic source was provided by one respondent who noted the similarity with wind turbine AM, albeit at a non-typical modulation frequency. This is shown below in Figure C1. The source in this case is snoring. This also represents an example of the limitations of the sole review of time-series data.
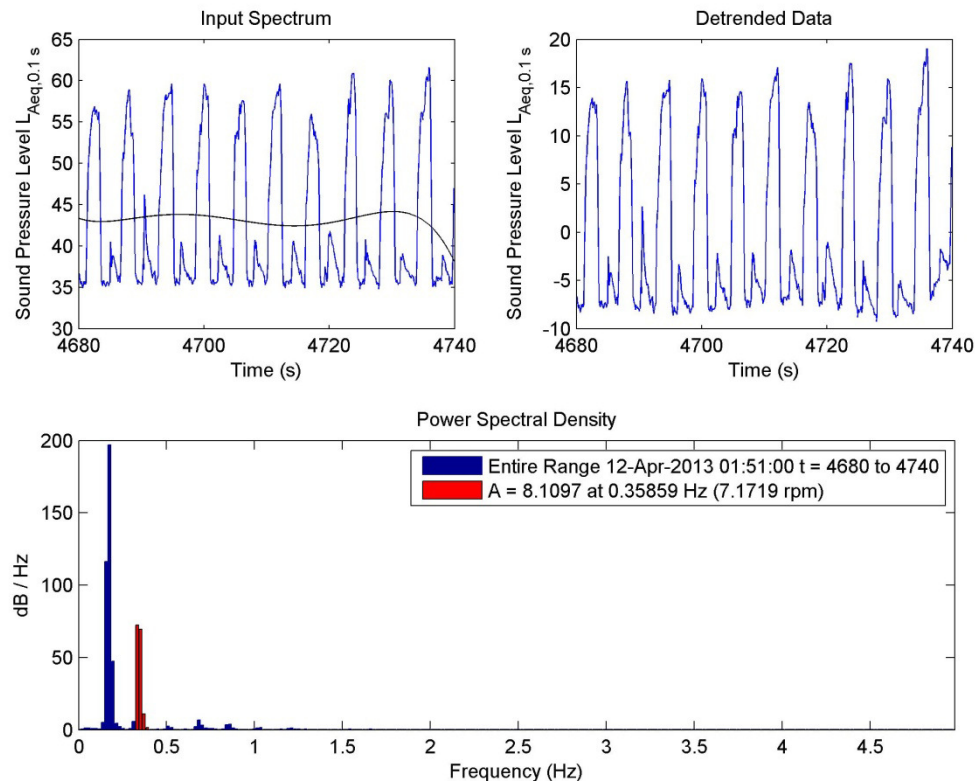

Figure C1 – 'AM' in noise from snoring

For the purposes of defining and applying a method for rating AM, most thought that measuring indoors presented too many practical difficulties and outdoor measurements were strongly preferred. Measuring outside is also consistent with most other environmental noise assessment procedures. It was suggested by some that additional indoor measurements would be appropriate if complaints related specifically to noise indoors.

AMWG comments

The working group's objective is to define a metric that can be used reliably within the planning system, and external measurements are the only practicable option. For specific complaint or nuisance measurements, Investigators are of course free to make internal measurements and assessments in connection with the specific issues.   Indoor measurements are problematic for a variety of reasons including, access difficulties, corruption by other sources, and room modes which could result in different responses in different positions in the room. These factors can cause a large variation in noise levels which can affect reproducibility.   It is considered

unnecessary to account for all of these factors when wind turbine AM can be measured reliably outdoors. Furthermore the noise data input to the recommended metric is band-limited to reduce the influence of high- and low-frequency background noise. To some (although indeterminate) extent, this reflects the sound attenuation characteristics of building facades and windows in preferentially reducing higher frequencies rather than low, which may mean that the outdoor metric better reflects the perception of AM indoors, compared with a metric based on broadband A-weighted noise data where other sources may mask the AM. This is a possible incidental benefit of band-limiting which is incorporated into the recommended method for other reasons.

Q4   Are there any other rating methods or important references that the AMWG should consider?

There was only limited feedback on this question. One respondent suggested that standards such as BS 4142:2014 could be used, or guidance for assessing music noise, since both are suited to the assessment of sound with 'character'. The same respondent referred to the 'hybrid' method adopted by Evans and Cooper (already referenced in the Discussion Document). No other relevant references were identified. One respondent gave the opinion that there were no robust dose-response relationship studies (because of small test subject numbers in all published studies) and in any event that none of the proposed forms of metric could be related to the results of those studies.

AMWG comments

The AMWG considered, but rejected, adoption of the BS 4142 method for rating impulsive characteristics as not sufficiently discriminating wind turbine AM. Other criteria in the standard (apart from tonality) were partly subjective, or would depend on user-judgment and were subject 'to context'. It was concluded that it was not suitable for evaluating AM. The question of the robustness of the available research into dose-response relationships for AM is a matter for others and outside the scope of the WG.

More generally, the AMWG recognises that the response of any individual to AM noise is complex and subject to a wide range of factors in addition to its level, including: the characteristics of the noise (in spectrum and time), the context in which it is heard, the health, attitude and experiences of the person hearing the noise etc. But this is also the case for any other noise, and yet, in the interest of providing objective quantifications of noise levels, all standards used in the UK are based on metrics such as L_{90} and L_{eq} which provide some form of averaging or processing but represent a reasonable and practicable representation of the noise levels and their variation. This is therefore the approach retained by the AMWG.

Overall there was a clear preference for the frequency-domain method (Method 2 in the Discussion Document), although of those preferring this method, a second or equal preference was generally given to the hybrid method (Method 3). It is noted however that this was overwhelmingly the case for a group of respondents which included wind farm developers. Another group of responses generally preferred the time-domain method (Method 1) on the basis of its intuitive nature and technical simplicity. The Northern Ireland Environmental Protection Group also adopted this view, although their preferred metric of the three presented was the hybrid method (See Question 14). A few respondents recommended that the domain/method chosen should be that which is shown to be the most robust and best correlates with subjective response.

AMWG comments

The AMWG strongly believes that frequency analysis is an essential tool in identifying the presence of AM. Using Fourier analysis to detect amplitude modulation is widely used by wind farm researchers in the literature, and in other fields, for example in detecting propeller noise using Sonar. This provides an objective indicator of the fluctuation rate which can allow excluding the majority of the contamination by other sources. The AMWG also considers that a time-domain method, used alone, is too susceptible to corruption by ambient noise sources and cannot be reliably applied, particularly to large datasets, and relies substantially on subjective judgment.

However, using time series data does provide a more easily-grasped and intuitive presentation of level and variation of AM within a noise sample. As a result of further research, the AMWG has decided to adopt a hybrid method, which utilises a frequency-domain analysis to identify the presence of AM in background noise and to 'reconstruct' a time-series plot of the modulated wind turbine noise, with background noise (to a large extent) removed.

The method retains the energy in the first three harmonics of the modulation spectrum. The AMWG believes that the adoption of this method, and the use of the prominence criteria developed, addresses many of the issues put forward in response the Discussion Document (see also Q8, Q9 and Q10 below).

Q6   Do you agree with time intervals proposed, that is: 100 millisecond
        samples, 10-second blocks, 10-minute periods?

Differing views were expressed about the suggested time intervals proposed and also about the way in which levels within each time 'block' were analysed to produce 'average' or 'typical' values, and what criterion should be applied to label data as 'spurious' and to be discarded.

There was general agreement on the acquisition of data in terms of $L_{eq,100ms}$. Similarly, a metric that defines a level of AM within a 10-minute period, by aggregating the levels in successive shorter sampling intervals, was considered by most to be a pragmatic choice. The adoption of a 10-minute reference interval is consistent with ETSU-R-97 and reflects averaging periods for anemometry and SCADA data. However, some respondents gave the opinion that any form of 'averaging' over 10 minutes could understate the impact of varying levels of AM with short periods of high level.

The case for adopting 10-second sampling intervals was less clear. It was noted that longer intervals (say 30 seconds) would provide longer averaging times and therefore improved frequency resolution.

AMWG comments

There was considerable debate within the AMWG over whether to adopt longer sampling intervals (perhaps 30 seconds) to obtain better frequency resolution. This would also allow the harmonics of the modulation frequency to be better defined. However, if a longer sampling interval were used, there would need to be a method for accounting for the variability within the longer interval, whereas the variation within a 10-second interval is relatively small such that the level of AM can be reasonably represented, for example by averaging the peak and trough values in the time-series. It is therefore recommended that the method characterises the varying AM by outputting the individual 10-second values. If appropriate, in terms of the subjective response, it would be possible to devise an AM rating based on individual 10-second values, rather than a 10-minute period, although the method as formulated provides a 10-minute value.

Q7   Do you agree with the band-limiting filtering approach for rating AM?

Most respondents were in favour of band-limiting the measured data as an initial stage of the analysis (typically using pass bands corresponding to some combinations of the 100-800Hz one-third octave filters), on the basis that it has the effect of reducing the influence of high-frequency background noise. One response was forthright: "*Yes, excellent method. Focusses on the frequencies imported for OAM, and also ditches the extraneous noise*". There were some concerns: filtering may exclude noise at some frequencies which exhibit amplitude modulation, thereby understating the level of AM present and there were some comments that low frequency noise was not being addressed. Conversely, reduction of background noise could result in an overstatement of AM, compared with an assessment based on broadband A-weighted levels, because in some cases background noise has the effect of 'filling in the troughs' and therefore reducing the measured modulation.

AMWG comments

The band-limited frequency range have been tested on data from several sites and has shown a clear ability to provide useful discrimination between noise level fluctuations caused by wind turbine AM and those resulting from other ambient

sources. Band-limiting may also address (at least to some extent) the issue of whether external measurements can adequately be used to assess AM in situations where complaints relate to internal noise (see Q3).

Q8   Is the default frequency range (*for band-limiting*) appropriate? What other frequency ranges could be considered, taking into account the desirability to characterize the frequency range in which AM occurs?

Several respondents noted the difficulty in selecting the appropriate frequency range for band-limiting the input data. Some suggested that this must be done on a case-by-case basis. One observed that the same model of turbine could exhibit significant AM in the 80 Hz band and the 500 Hz band at different times. It was agreed that frequencies above 800 Hz were often corrupted by extraneous noise. Some respondents expressed concerns regarding what was perceived as the exclusion of modulation occurring at frequencies lower than 100 Hz.

AMWG comments

The band-limited approach is of great benefit for detecting AM in noise, and minimising influence of other sources. Band filtering is also a pragmatic way of addressing concerns of indoor impact from evidence of previous reports of apparent increased modulation internally. The adoption of different frequency ranges can yield different results and no single 'default' range can be specified. Although the frequency content of modulation can vary due to a range of effects, the aim is to provide a consistent, reasonable and pragmatic representation of the modulation which is not excessively sensitive to spurious variations.

Concerning lower frequencies, the remit of the group, based on the definition agreed, is to consider modulation which is audible. The experience of the group and all evidence available shows that noise produced by modern upwind turbines at low frequencies below 20Hz is at low and inaudible levels in the far-field. The AMWG was not convinced by the thoroughness or relevance of studies in other countries cited to show effects of very low frequencies (<20Hz), as these often do not consider the effects of audible noise. It should also be noted that low-frequency tonal emissions from turbines are already covered by the method set out in ETSU-R-97.

Varying the band-filtering region around the reference 100-400Hz, to higher or lower frequencies, has been actively considered by the group based on the available data. On the basis of these investigations, the AMWG has agreed to provide three ranges: 50 Hz to 200 Hz, 100 Hz to 400 Hz and 200 Hz to 800 Hz. The data is processed for each of these ranges and then the range yielding the highest results chosen.

Q9   Do you think the time series method proposed is suitable for rating AM? If not, can you explain why?

Most respondents agreed that a time-domain method, based on examination of a time-series plot to determine the typical, average, or maximum peak-to-trough values, is very suitable for the assessment of short-term 'clean' wind turbine noise data with minimal corruption by other ambient noise. The method has the benefit of relative simplicity. However, the strong majority view was that it was not suitable for rigorous assessment of AM, especially when there was significant noise from other sources, because it was unable to discriminate between fluctuations in noise levels resulting from wind turbine AM and those resulting from variations in other ambient noise. Significant subjective (visual or aural) screening is required to overcome this fundamental deficiency, which is considered to be impracticable for the analysis of long-term data (perhaps covering periods of weeks or months) One respondent strongly supported a simple time-series method, stating that long-term measurements were not required and that data corrupted by other noise could be readily detected by inspection.

AMWG comments

There is some benefit in having a simple method of assessing AM, for example for the purpose of forming an initial conclusion about the validity of a noise complaint. A method of the form proposed by Japanese researchers (Fukushima, Yamamoto et al. 2013) provides such a method, which was more precisely defined than some of the other methods proposed, but is still subject to corruption from extraneous noise (as its authors recognised). Any output from such a method would be open to question unless accompanied by time histories which demonstrated (on subjective judgement) the presence of clear AM with no significant contribution from other ambient noise, or using tools such as autocorrelation spectra. However the AMWG does not consider that the method is a robust basis for an assessment metric which may be adopted in a planning condition.

Wind turbine AM, where it occurs, is an intermittent occurrence. The assessment of AM on a particular site would generally involve long-term measurements to establish the frequency and duration of occurrence and the particular wind conditions. Reliance on a time-domain method only, which may appear more direct to non-specialists, is not considered to be practicable or robust, because unlike a frequency-domain method, it is unable to detect WTAM on the basis of its distinctive periodicity and therefore requires significant subjective 'filtering'.

Q10   Do you think the frequency domain method proposed is suitable for rating AM? If not, can you explain why?

As in Q5, most respondents considered the frequency-domain method (Method 2) appropriate and more robust and reliable than time-domain methods. Difficulties in choosing the appropriate range for the blade passing frequency were highlighted, as this can be variable. Some stated that the methodology was difficult to explain to lay persons. An error in the methodology relating to the number of FFT lines was pointed out by several respondents.   The exclusion of energy in the higher

harmonics of the modulation spectrum was criticised by several respondents on the grounds that this can lead to levels of AM being understated (compared with a time-series analysis).

AMWG comments

With regards to the 'under-estimation' concerns, there were indications that some respondents may have applied the methodology erroneously. It should in any case be noted that the aim of the method was not necessarily to match the peak-to-trough variations but to provide a meaningful and robust *representation* of the magnitude of modulation in a signal, which would *scale* with the level of the modulation present. The question of the threshold of acceptance or of different effects is separate, and must be adapted to each method ('accounted for in the establishment of any assessment method that should be used' as one response notes). It is however true that obtaining higher values for higher levels of AM provides a higher "dynamic range" in the output of the metric which is valuable and provides better discrimination and difference with the noise 'floor 'inherent in any numerical method.

Overall, the comments and criticisms were accepted and/or taken into account. The recommended hybrid method is designed to overcome the criticisms of the original Method 2; in particular, the contribution of higher harmonics is included.

Q11   Should other parameters be used in the application of this (FFT) method and why?

There were few responses to this question, and perhaps its intention was not clear. Some responses repeated points which arose in answer to other questions – inclusion of harmonics, sample intervals etc. One raised the issue that the method is only assessing modulation depth (peak to trough values) whereas this is only one of the factors influencing response to AM, although the other potential factors were not identified. Some responses considered the technical parameters used in detail.

AMWG comments

The FFT method is no longer being pursued and therefore this question is not now directly relevant. The point made about the possible relevance of other factors, in addition to modulation depth, is applicable to all the methods considered. The AMWG accepts that there may be other factors influencing response to AM (variability, intermittency, event duration, suddenness of onset etc.) but in the absence of any dose-response data relating to these factors it is not possible to ascribe any significance to them or to incorporate descriptive parameters for them in the AM metric. As noted above (see Q4), the proposed method provides a reasonable and objective representation of the level of modulation.

Some of the detailed responses represented useful feedback which prompted further studies and investigations, for example of different frequency resolution and sampling approaches as described elsewhere. A-weighting of the input signal was questioned but seen by the AMWG as beneficial in reducing corruption from wind

noise (a concern for other respondents). One respondent outlined an approach in which a model was fitted to the derived spectra in order to assist rejecting periods where the spectrum did not exhibit a clear peak at a certain frequency and its harmonics; this has been actively considered by the AMWG and is a basis for the 'prominence' approach used in the reference method.

Q12   Do you think the hybrid method proposed is suitable for rating AM? If not, can you explain why?

This method (Method 3) attracted favourable comments. Some used the term 'best of both worlds'. Reservations were expressed on the grounds of complexity and it being difficult to understand. Respondents who did not favour the frequency-domain method (Method 2) and preferred the time-domain method (Method 1) also objected to this method, although judged it to be slightly preferable to Method 2.

AMWG comments

The AMWG has now proposed a hybrid method which represents a development from the methods described in the consultation document. It is accepted that the method is relatively complex, although less than the Method 3 previously described, but the degree of complexity is considered inevitable in a method that is sufficiently robust for determining compliance or non-compliance with specific thresholds or limits. One benefit is that the interim output is a reconstructed time series that can be compared with the original unprocessed time series, which is a significant aid to validating the method and rendering it more 'transparent'. Furthermore, the AMWG aims to provide a software code which will assist several stakeholders in implementing the method.

Q13   Should other parameters be used in the application of this (hybrid) method and why?

Most respondents did not answer this question; again, the point of the question was perhaps not clear (as one respondent noted). There were some comments about correcting for the 'continuum' (or masking level) in the spectrum and providing criteria for uncertainty, and for the need to compare the reconstructed time series with the 'original'. It was also noted that multiple descriptors could be used to characterise the resulting time series including the L_{50} and L_{max} values.

AMWG comments

The AMWG has decided that it is reasonable to characterise the level of AM in each 10-minute interval by a single value. However, since the time series is reconstructed, with knowledge that allows the peaks and troughs to be identified, they could be characterised by any combination of statistical parameters. There is no robust basis for adopting any specific parameters, but in the judgement of the AMWG the adopted parameters are reasonable. They can readily be modified if

further dose-response data becomes available which indicates that other parameters provide better correlation with subjective response.

Q14   Of the three methods proposed, which is your preferred method?

When asked this specific question, rather than the 'in principle' question (Q5), most respondents preferred the frequency-domain method (Method 2) although some favoured the hybrid method (Method 3). For both methods, some reservations were expressed about complexity. Again the response was split between groups which preferred a Fourier-based approach and those who preferred a time method. Some also stated again that the preferred method is the one which best represents subjective response. Others stated that more refinements were required to all methods and therefore qualified their response.

AMWG comments

For similar reasons to those set out in response to Q5 above, the AMWG considers that the hybrid method should help to address the clear difference in views between those favouring a time-domain method and the majority who favour a frequency-domain method. The assessment stage in the hybrid method is performed on the (reconstructed) time series but a frequency-domain technique is used to identify AM components and minimise the effect of other ambient noise. The hybrid method has been significantly enhanced since the issue of the Discussion Document and comments to that document have been taken into account.

Q15   Is there another alternative method not recommended by the AMWG which would be preferable? Explain why

Most respondents did not comment. No substantially different method was proposed. Time series methods using subjective filtering, rather than 'automated' methods, were (again) identified by a small number as being preferred. One respondent raised the possibility of using BS 4142:2014. Two respondents suggested improvements to the proposed methods: improving the frequency-domain method (Method 2) to include the harmonics in the modulation spectrum and improving the frequency resolution, and modifying the 'Tachibana' (time series) method (Method 1) by using band-limited data to reduce the influence of background noise.

AMWG comments

The AMWG members are guided by the adopted success criteria (Appendix B) which (amongst other requirements) specify that any adopted assessment method/metric is specific to wind turbine noise, objective, and is applicable to long-term noise monitoring. Furthermore, the scope of the AMWG was to specifically rate modulation in wind turbine noise rather than characterise wind turbine noise more generally. For this reason it has rejected a time-series approach and methods such as BS 4142:2014 primarily on the grounds that their application requires

significant subjective intervention. The impulsive rating in BS 4142 was rejected at an early stage because it does not characterise AM very well as it is better suited to noises with a more rapid rise time. A hybrid method is now recommended by the AMWG.

Q16   Are the proposed requirements for instrumentation appropriate?

Most respondents were satisfied that application of any of the methods would not incur additional instrumentation requirements, although it was suggested that 100ms averaging intervals might be too long for assessment of AM from small turbines. One respondent suggested that reliance only on 100ms L_{eq} data is inadequate – audio recording was also required and some processing technique to reduce spurious noise generated by wind at the microphone was desirable. The question of whether the noise floor of Class 1 instrumentation was low enough to adequately measure the full range of AM in all cases was raised, as was the question of the specification of microphone windscreens. Some of the references to instrumentation standards were incorrect in the consultation document.

AMWG comments

The noise floor of Class 1 instrumentation is not a concern for outdoor noise measurements. It is agreed that the specification of microphone windscreens for use in high wind speeds requires further research, but such research is outside the scope of the AMWG's brief. Nonetheless, the use of correct band-filtering can assist in minimising wind noise corruption. The AMWG recommends that audio recordings are obtained.

Q17   Would you like instrument manufacturers to make available an 'AM rating' option for sound level meters

Generally it was considered unlikely that instrumentation manufacturers would provide such an analysis option, since the demand and therefore the market would be limited. Also provision of such a facility would risk AM being over-stated: the need for visual and/or aural scrutiny of data was still necessary for all methods, to identify and discard noise samples influenced by extraneous noise. An instrument which produced an 'instant' rating might discourage users from carrying out this essential filtering exercise.

AMWG comments

The AMWG agree that the market for instrument manufacturers would be small and there is no specific requirement for such a development. For the recommended method the AMWG, through the IOA, will make available software to perform the necessary analysis (see Q18). However, it would be very desirable for the 'front end' instrumentation to provide 100ms L_{eq} data in one-third octave bands for direct input into the analysis software; not all current Class 1 sound level meters can provide this output. The desirability of obtaining audio data is accepted.

Q18   Should the IOA make available software for rating AM?

Most respondents stated that software (required for Methods 2 and 3) was necessary or desirable and it should be 'open-source' and therefore 'transparent' and allow individuals to modify it. There was no particular consensus view on whether the software should be made available through the IOA.

AMWG comments

It is intended that software will be made available through to IOA to implement the recommended hybrid method. The means of supply has not been determined. The software code will be made available, open source with appropriate disclaimers.

Q19 Do you have any comments on the software released?

Trial software for applying the methods proposed in the Discussion Document had been released although few respondents had tested this. Various comments were received including requests for the source code. Some refinements were requested including file naming, additional outputs in terms of graphs etc. and a request for the software to work with audio files as an input.

AMWG comments

The output software provided to date was necessarily basic in nature, but the software for applying the recommended hybrid method has been greatly refined; the source code for implementing the recommended method will be released so it can be implemented by a wide range of users and can be further developed and refined by experienced users.

Q20   Recommendations for further study and any other comments

There were a few responses. The Northern Ireland Group suggested further work should be done on single turbines, while others required more research on subjective aspects and on the mechanisms causing AM. The issue of the design and performance of microphone windscreens was also raised.

AMWG comments

Further research is very desirable in a number of areas relating to the measurement and assessment of wind turbine noise, including those identified by respondents. However, it considers that the existing information base is adequate to support the recommended AM metric.