INSTITUTE OF ACOUSTICS

IOA Noise Working Group (Wind Turbine Noise)

Amplitude Modulation Working Group

Discussion Document

Methods for Rating Amplitude Modulation in Wind Turbine Noise

FOREWORD

**** PLEASE READ BEFORE PROCEEDING TO THE MAIN DOCUMENT ****

This discussion document has been produced by a working group on behalf of the Institute of Acoustics consisting of the following members:

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This discussion document has been produced specifically to promote discussion of the relevant issues during the consultation on a metric for amplitude modulation (AM) from wind turbines, and as such does not necessarily represent the final AM metric that will be chosen, nor should it be treated as such until the final document is published in due course.

This document should be read in conjunction with the “IOA AMWG Consultation Questionnaire” which includes a questionnaire style response. Respondents to the consultation are encouraged to provide their comments on the form provided. A word version has been provided to allow respondents to increase box sizes as required.

All comments on the consultation draft should be sent electronically to:

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The closing date for the receipt of comments is **30th June 2015**. Late comments may not be reflected in the deliberations on the choice of the AM metric.

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0 EXECUTIVE SUMMARY

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 the degree to which wind turbine noise exhibits amplitude modulation (AM) – the regular fluctuation in the level of noise, the period of fluctuations being related to the rotational speed of the turbine. This characteristic might be described by a listener as a regular 'swish', 'whoomph' or 'thump'. Wind turbine AM has been observed in and around dwellings in the UK and elsewhere and in some cases has led to specific complaints from residents.

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 a planning condition that might be applied to control AM from new wind turbine developments. Planning conditions currently routinely applied to wind turbine installations have the effect of limiting overall noise levels and provide a means of controlling tonal noise characteristics, but do not directly address AM.

Wind turbine AM has been the subject of a significant 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 'level' or 'value' to the amount of AM in 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.

The Working Group has not addressed the question of what level of AM in wind turbine noise (when measured by any specific metric) is likely to result in adverse community response, or how that response should be evaluated. The psycho-acoustic aspects of AM will be the subject of further studies by others. However, sources of information on subjective response to amplitude modulated noise are referenced in this document to assist in further work.

This Consultation Draft presents the Working Group's preliminary observations and conclusions on methods of measurement and rating AM. Three methods for rating AM are proposed for consultation. Comments, observations and criticisms from interested parties are welcomed.

The background to the study, information on the composition of the Working Group, its Terms of Reference and key definitions are set out in Sections 1 to 3, supported by Appendices A and B.

0.1 Definition of AM

In the context of the objectives of the Working Group, 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[1] of the turbine rotor, as observed outdoors at residential distances in free-field conditions."

It should be noted that the study is mainly focussed on the measurement and assessment of the AM characteristics presented by current large wind turbines with 3-bladed rotors rotating at speeds up to about 20 rpm. Different metrics may be appropriate for smaller, higher-speed turbines. Also, the metric is intended to be applied to external measurements of noise experienced locations at 'residential distances', separation distances between large wind turbines and dwellings in the UK being typically 500 metres or greater. The measurements are made outdoors for consistency with other procedures for measuring wind turbine noise (such as ETSU-R-97).

0.2 Literature Review

Section 4 provides a review of the existing literature on AM. Some 30 key technical sources have been studied and relevant elements identified for discussion. A complete reference list is provided. A number of documents are summarised to illustrate the range of different metrics used to assign values to episodes of AM.

From the literature, three distinct types of AM metric have been adopted by different researchers:

0.2.1 Time-series methods

The simplest representation of an amplitude-modulated signal is a time-series plot of noise level against time, using a suitably short averaging time or sampling rate, typically 100 or 125 milliseconds (ms).

Where AM is steady and continuous, and in the absence of significant intermittent noise from other ambient sources, the level of AM in such a signal can be defined by a basic metric, based on the difference between the peaks and troughs (the modulation depth) in the time-series plot. Where the mean level and/or the modulation depths are time-varying (as in most cases), and when the signal is contaminated with other ambient noise, further analysis is required, which might involve averaging or statistical analysis.

There are alternative time-domain metrics which may be used for evaluating amplitude-modulated noise episodes. Fluctuation strength (measured in the unit vacils) is a measure of the audible sensation produced by regular changes in the level of tonal or broadband noise and is widely used in noise quality evaluation (for example, in the automotive industry). There are also Standards for measuring the impulsivity of noise events, which might be applied to fluctuating noise from a wind turbine. Various time-domain approaches have been evaluated in this study.

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

0.2.2 Frequency-domain methods

An alternative approach is to generate the frequency spectrum of the time-series waveform by Fourier transform. When AM is present, a Fourier transform of time-series data (e.g. 100 millisecond values) will result in a frequency spectrum exhibiting a clear peak at the frequency of modulation which is generally at the blade passing frequency (BPF) of the wind turbine and possibly at the harmonics of this frequency.

With appropriate scaling, the magnitude of the spectrum at the modulation frequency represents the average modulation (over the sampling period) of the modulation in the original time-series data. The transformation to the frequency domain discriminates (to a large extent) between AM, which has a periodic character related to the rotational speed of the wind turbine(s), and noise from other ambient sources.

0.2.3 Hybrid methods

The time-domain and frequency-domain approaches can be combined to construct a hybrid method. For example, the presence of AM within a sample of data can be detected using frequency-domain analysis as an initial 'filter'. These samples can then be assessed using a time-domain method. Other 'hybrid' approaches can be devised.

0.3 Evaluation of different forms of AM metric

From review of the literature, and in the light of the collected experience of the AMWG, the following conclusions were reached about the relative merits of the main three forms of metric for assessing AM:

0.3.1 Time-domain methods

Metrics based on peak-to-trough values of A-weighted time-series data provide valid values for AM when wind turbine noise is a dominant source and other sources of ambient noise are consistently low. This represents an intuitive approach, but a rating method can be difficult to define precisely. Furthermore, a time-domain method cannot discriminate between periodic variations in noise level occurring at BPF and variations (periodic or random) resulting from other ambient sources. The contribution of other noise sources, particularly individual short-term noise events, can lead to an overstatement of AM if a time-domain metric is applied. In most real cases, the data needs to be checked (by listening to audio recordings or visual inspection) to identify 'clean' data where AM is audible and there is no significant contamination by other sources. The need for careful data editing militates against the requirement to be able to reliably batch-process long-term measurements; in most cases occurrences of AM are intermittent and these occurrences may be unpredictable, so an investigation of AM may involve continuous measurements over weeks or months.

However, a metric based on time-series analysis has the benefit of relative simplicity in terms of measurement and data processing and can be measured by many standard sound level meters with minimal post-processing. It could be applied in situations where contamination from background noise is minimal, as a ‘first pass’ method, or to assess short-term episodes of AM where ‘clean’ data is identified.

0.3.2 Frequency domain metrics

In approximately 50% of the reviewed literature sources, researchers have adopted a metric based on a frequency–domain approach. Transforming to the frequency domain produces a modulation spectrum which clearly identifies fluctuations in noise with a periodicity corresponding to the blade passing frequency of wind turbines.

The use of a frequency-domain metric therefore has the advantage over a time-domain metric of discriminating between periodic fluctuations in noise levels which occur at BPF and fluctuations resulting from other ambient sources. The method lends itself to rapid processing of lengthy data samples without the need for time-consuming subjective filtering, reducing the risk of overstating the modulation depth because of contamination by other noise sources. The more complex computation required can readily be performed by bespoke software. But by their very nature, such methods require a certain degree of averaging over the study period, and can neglect the detailed characteristics of the signal.

0.3.3 Hybrid methods

A hybrid method applies a frequency-domain technique to identify noise samples exhibiting AM but the assessment of AM is performed on time-series data. This allows the identification of features such as variations in time and signal shape which may be lost as part of a frequency-domain analysis. Such an analysis might also be judged (superficially) to be more directly related to the actual time-varying signal as illustrated by the time-series plot.

0.3.4 Other Metrics

The WG considered the possible application of fluctuation strength and impulsivity metrics, which have established applications for the measurement and assessment of fluctuating or amplitude-modulated noise from other types of source. It was concluded that these metrics were not useful for the assessment of AM, which is not particularly impulsive in character and has relatively low noise levels (compared with other sources for which the fluctuation strength metric has been applied).

0.4 Outcome

On the basis of the literature review, and applying the collected experience of the AMWG, a number of time-domain, frequency-domain and hybrid metrics, based on or derived from those described in the literature have been 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.

As a result of this the AMWG proposes three types of metric for consultation: a time-series metric, a frequency domain metric, and a hybrid metric. These are briefly described below.

Method 1 – Time Domain

A time-series metric requiring statistical analysis of the A-weighted time series, based on the work of Tachibana's research group in Japan.

Method 2 – Frequency Domain

A frequency-domain method similar to those adopted by McLaughlin, Larsson and Öhlund, RenewableUK and others.

Method 3 – Hybrid Method: the reconstructed time series

A new hybrid method developed by the AMWG. After a preliminary Fourier analysis, the time-series data is filtered using parallel 1/3-octave filters set at the frequencies of BPF and the second and third harmonics of BPF. These components are then summed to reconstruct the time series of that component of the original signal attributable to amplitude-modulated wind turbine noise. Effectively, the method suppresses background noise and returns a 'clean' version of the time series of wind turbine noise only, retaining the energy at the first three harmonics. The resulting peaks and troughs in the reconstructed time series data are then averaged to provide a single value.

Specific common parameters for each metric were discussed and agreed, including the following key parameters:

- Data is sampled as short-term 100 millisecond L_{Aeq} values, and (for methods 2 and 3) in 1/3-octave bands
- The fundamental length of sample to be assessed (the minor time interval) is 10 seconds, to provide an adequate representation of fluctuations in noise levels for robust identification and analysis
- The values of AM measured by any metric in each 10 second interval are aggregated over a 10-minute period (the major time interval) to provide a single value, for consistency with other wind turbine noise monitoring procedures; representing the typical higher levels experienced over the 10 minute period.
- For methods 2 and 3, the data is frequency band-limited to cover the frequency range (by default 100 - 400Hz) over which wind turbine noise is likely to exhibit the highest levels of AM.

Extensive comparisons have been made between the three methods using real wind turbine noise data with variable AM. These comparisons are discussed in Section 9. The methods produce consistent values of their respective metrics, in that all demonstrate clear correlation with modulation depth and with each other. For any given noise sample, the metrics return different values for the modulation. It is clear that any criteria, limit or penalty system to be applied to AM will need to be specific to the metric adopted.

Measurement of wind turbine noise made for the purpose of evaluating AM involves specific requirements for instrumentation. These requirements are discussed in Section 10.

The AMWG intends to make available executable software to enable other workers to analyse their own data to allow them to judge the utility of the different metrics. This is referred to in Section 11.

1 INTRODUCTION

Amplitude modulation (AM) in wind turbine noise has been well documented in recent years in the UK and overseas and various researchers have devised methods of measuring it. However, the methods available yield different results and few are backed up with research on dose response relationships. In response to a request from the Institute of Acoustics Noise Working Group (IOA NWG), and approved by IOA Council, the IOA set up a working group to look at amplitude modulation in wind turbine noise. The aim of the group is to review the available evidence and to produce guidance on the technical aspects for the assessment of AM. The working group includes consultants, academics and representatives from wind farm developers and local authorities.

The working group has undertaken a comprehensive literature review to assess current research and different rating methods. There is currently no agreed methodology. There is little in the way of national standards. There is some guidance in Australia, New Zealand and Finland. In the UK, planning conditions tend to be at the discretion of a planning officer or inspector. There are not many windfarms with AM conditions although a well-known condition placed on the approved windfarm at Den Brook has been the subject of much debate and legal challenge. Other conditions have been imposed based on a proposed methodology by RenewableUK (RUK), although the RUK planning condition has been shown to underestimate the level of the amplitude modulation (Levet and Craven 2014).

The IOA AMWG has tried to set out the main issues in a way that explains the rationale behind each method. The intention of the AMWG post-consultation is to be definitive on what can be considered an appropriate methodology, but at this consultation stage, three methods are presented for consideration. The document also discusses psycho-acoustics response and instrumentation, along with proposed methods that have been put forward. It will hopefully promote discussion, and the group welcomes this to ensure that an informed response to the consultation can be provided. Feedback is encouraged on all aspects of each of the methods, whether positive or negative, with suggestions as appropriate. A consultation form is available on the IOA website. Software will be provided so that members can test the methods on real data.

The working group will not be proposing any limits or a definition for ‘excessive’ amplitude modulation. The purpose of the group is simply to use existing research to develop an agreed methodology for measurement of amplitude modulation. Any penalty scheme would be a matter of Government policy and is likely to be the subject of a separate Government-funded study.

2 TERMS OF REFERENCE

The agreed terms of reference are provided in Appendix A and are as follows:

- 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 consultation document
- Consider the consultation responses and, if appropriate, produce a final Guidance Note and / or consider the need for further research
- Provide software, if possible, to allow the analysis of AM data.

The outline Scope of Work, presenting the original plan of the working group is presented in Appendix B.

2.1 Success criteria

The Scope of Work also lists the success criteria which will be considered by the group when assessing AM metrics. These are as follows:

- **Achievability** – using the equipment & 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’, it is essential that the methodology is specific to nature of the signal and not sensitive general fluctuations.
- **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.

3 AM DEFINITION

In the first instance amplitude modulation must be defined. It is now generally accepted that there are two mechanisms causing amplitude modulation: ‘normal’ AM (blade swish) and ‘other’ AM. In both cases, the result is a regular fluctuation in amplitude at 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.

3.1 ‘Normal’ AM

An observer at ground level 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 the observer[2]. This effect is reduced for an observer on or close to the 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 recognized and was discussed in ETSU-R-97 in 1996.

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. Also, these comments refer to observations made on the sizes and types of wind turbines operating in the 1990s. 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).

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[3] adopts a 3 dB peak-to-trough value as the threshold above which AM is deemed to be ‘greater than expected’.

3.2 ‘Other’ AM

In some cases AM is observed at large distances from a wind turbine (or turbines). The sound is generally heard as a periodic ‘thumping’ or ‘whoomphing’ at relatively low frequencies. This type of noise was perhaps first 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 2006). The prevalence of this type of modulation is subject to debate. On sites where it

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

[3] see http://www.masenv.co.uk/Den_Brook_AM_Condition [Last Accessed April 2015]

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.

It was proposed in the RenewableUK 2013 study that the fundamental cause of this type of AM is transient stall conditions occurring as the blades rotate, giving rise to the periodic thumping at the blade passing frequency. Transient stall represents a fundamentally different mechanism from blade swish and can be heard at relatively large distances, primarily downwind[4] of the rotor blade. The RenewableUK AM report adopted the term ‘Other AM’ (OAM) for this characteristic. The terms ‘enhanced’ or ‘excess’ AM (EAM) have been used by others, although such definitions do not distinguish between the source mechanisms and presuppose a ‘normal’ level of AM, presumably relating back to blade swish as described in ETSU-R-97.

3.3 Recommendation

For the purposes of the Working Group, it is suggested that there is no need at this stage to adopt separate definitions for AM, dependent on the source mechanism, and 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 defined in the Scope of Work (Appendix B).

The following statement is therefore suggested to define the type of AM the Working Group is addressing:

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.

For most medium to large-sized turbines (typically with a generating capacity of 500 kW and above) the blade passing frequency (BPF) is typically just less than 1 Hz. Turbines below 500 kW or older models could have higher BPFs, and some micro-turbines have rattle/flap problems, which might show as AM. The applicability of the metric to smaller turbines will be reviewed when recommending a preferred metric.

4 LITERATURE REVIEW

4.1 Background

In approaching the task of identifying potential metrics for quantifying AM, the Working Group has relied extensively on reports and papers by other workers in the field. Many of these contributions have been published at international

[4] The stall source mechanism radiates equally upwind and downwind, but propagation effects reduce noise levels upwind.

conferences on wind turbine noise; and the number and quality of recent publications demonstrate that the issue of AM has attracted world-wide interest.

The AMWG has identified over 30 relevant published papers, reports and other information relating to the measurement and assessment of time-varying noise, focussing on information directly related to AM. These are listed in the references section. Many of the referenced papers have been presented at recent international conferences on wind turbine noise; some are subject to copyright and may not be freely available. Of particular relevance are sources that include:

(i) Proposals for metrics for AM and the application of these metrics to samples of wind turbine noise, and/or;

(ii) The results of listening tests designed to relate an 'annoyance' or 'loudness' score with the level of AM, as determined by the application of a specific metric or metrics – i.e. dose-response relationship.

The task of setting thresholds of acceptability for AM, or defining any limits or penalty systems to be incorporated in measurement procedures for wind farms, is outside the scope of the AMWG and will be the subject of further research, funded by Government. However, it is self-evident that when applied to any measurement of an episode of AM, a robust metric should deliver a value that generally relates to the subjective response to that episode – and that a higher value of the metric would result in a greater adverse response. Hence papers that include (ii) above are particularly relevant to the work of the group. Psychoacoustic aspects of AM are discussed further in Section 4.7.

There are some published criteria (in some cases included in regulatory documents) for assessing the significance of AM, including specific limits. For example New Zealand Standard 6808: 2010 (NZS 2010). However, the criteria do not seem to be supported by any corresponding technical justification.

The information derived from the literature review was the subject of extensive discussion within the AMWG. This information, together with the collective experience of WG members and the results of further analysis of noise data from wind farm sites where AM has been identified, has led to the WG putting forward a number of candidate AM metrics which are presented in this consultation document.

Information sources were allocated to different members of the AMWG who provided summaries in a standard format. This included the AMWG's collected preliminary views on the merits and demerits of any particular AM metric, based on the success criteria set out in the Scope of Work.

4.2 Different Approaches to AM metrics

As an introduction, some explanation of the elements of the different forms of AM metrics proposed in the literature may be useful. Most researchers have adopted two basic approaches to the development of a metric for AM; these can be classified as 'time-series', or 'time-domain' methods, and 'frequency-domain' methods. These are not the only methods available but they are the most common; other methods are discussed in subsequent sections.

4.2.1 Time-series methods

The simplest representation of an amplitude-modulated, broad-band noise signal is a time-series plot, as shown in Figure 4.1. This represents broad-band noise subject to periodic amplitude modulation, the modulation frequency being approximately around 1 Hz in this case.

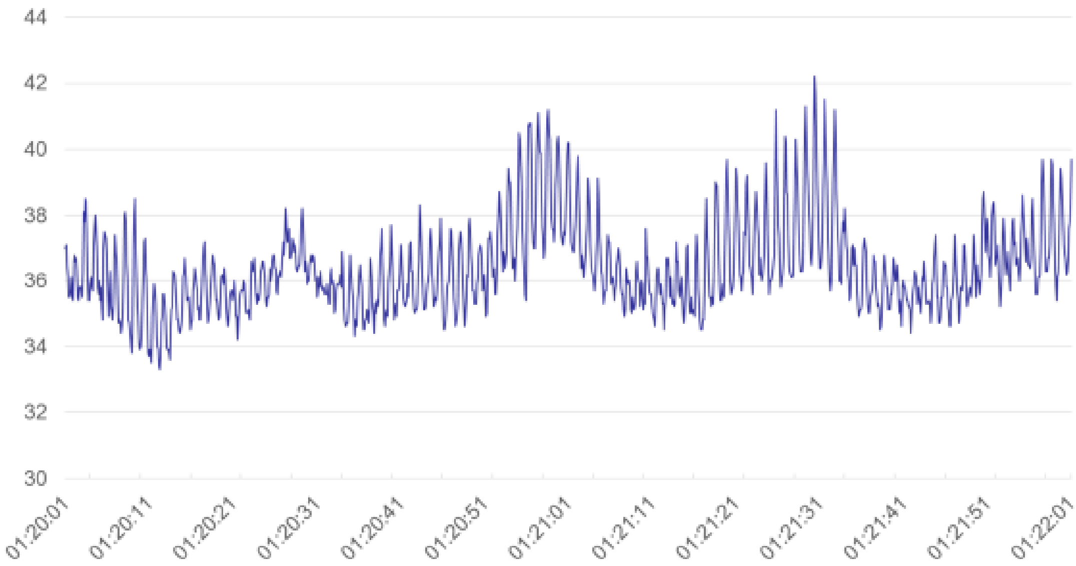

Figure 4.1 Variations in wind turbine noise measured over a 2 minute period, dB $L_{Aeq,\ 100ms}$

In this example, the noise level is presented in terms of the $L_{Aeq,100ms}$ level. The 'level' of amplitude modulation (or modulation depth) can perhaps most simply be defined in terms of the differences between successive peak and trough values. However it can be seen in the example above that the 'level' of AM is highly variable and there may be some other noise which briefly corrupts the results. Average values of peaks and troughs over a defined time interval might be adopted as a measure of AM. However, such averaging would lessen the significance of the worst periods. Furthermore, the variation in the mean level of the broadband noise (which is almost always present in external noise data at large source-receiver distances) may need to be taken into account by 'de-trending'.

Time series methods, used alone, have inherent limitations: the signal represented as a time-series includes both wind turbine noise and noise from other sources. Noise from other sources may include short term events which may result in enhanced noise peaks. Similarly background noise may mask the depth of the troughs. Corruption by background noise can be reduced by band-limiting the data to include only those frequency bands in which the wind turbine noise is dominant.

In any real situation, a time-series analysis alone cannot unambiguously identify periodic variations in wind turbine AM, as distinct from other time-varying noise. Ensuring that any assessment is carried out on 'clean' samples of noise signals therefore requires some filtering process, which might involve listening to audio files and forming a subjective judgment on the 'quality' of the data, or inspecting the time series to identify periods of regular AM. In addition, it is difficult to precisely define the modulation without ambiguity for realistic, complex signals.

Where many days or weeks of data are to be assessed, this filtering process could be laborious. Given the known variability of wind turbine noise and AM, this can be particularly problematic. For many purposes (in particular, for comparing levels of AM with specified regulatory limits) reliance on such filtering of data might be considered unsatisfactory as a subjective judgment would invariably be involved. However, time-series methods have the advantage of relative simplicity and some researchers have adopted these methods, whilst recognising their limitations unless they are presented with 'clean' data (i.e. signals dominated by AM noise).

4.2.2 Frequency domain methods

The main alternative approach used by several researchers in the field is to analyse the signal in the frequency domain, to precisely determine if modulation is occurring at a regular rate within the expected range of the Blade Passing Frequency. To generate a frequency spectrum, Fourier transform techniques can be used. For computational purposes, this is carried out as a Fast Fourier Transform (FFT). The FFT is widely used in signal analysis, for example to find tones.

Where AM is present and when the FFT is applied to a time-series representing the level[5] of the noise, the analysis results in a spectrum exhibiting a peak at the blade passing frequency (BPF) of the turbine(s) (Figure 4.2 for example, with a BPF of around 0.8 Hz).

[5] More precisely, this is the "envelope" of the acoustic signal representing the energy or level of the noise when averaged over a short time period such as 100 or 125 ms. This can be obtained most simply for example by using the $L_{Aeq,\ 100ms}$ or the $L_{AF,\ 100\ ms}$ indices provided by most modern sound level meters.

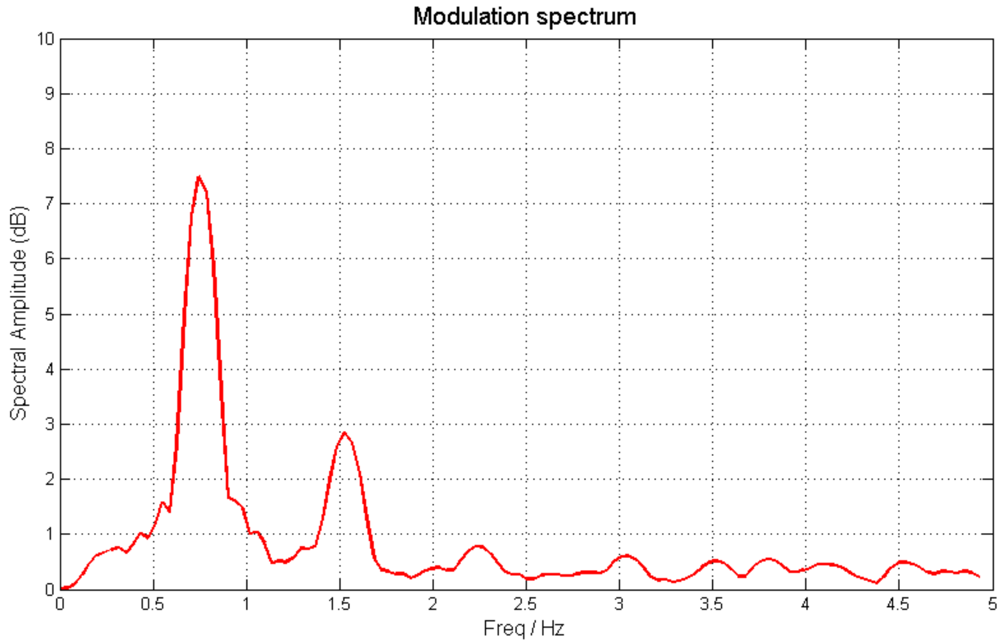

Figure 4.2 Example of a modulation spectrum

The level of the peak present at the BPF represents the magnitude of the modulation at this frequency over the period analysed. Through the Fourier process, this is averaged over the period of analysis. When suitably combined and normalised, the spectral level can directly represent the average peak-to-trough variation of the A-weighted level over the selected averaging time. This can be taken as a rating of the level/magnitude of AM in the sample.

In the example of Figure 4.2, there is also evidence of modulation at harmonics (2x, 3x etc.) of the fundamental frequency, for example the second harmonic at 1.5 Hz. This means that the shape of the level signal is not simply sinusoidal. Therefore, by only considering the amplitude of the fundamental peak (at BPF), the resulting measure may not directly match the (average) peak to trough level visible in the time series of the same sample. This can, however, be allowed when testing the subjective response.

It is important to note that the FFT analysis is not carried out on the acoustic pressure signal but on the time series as represented by the 100 millisecond values, i.e. the envelope of the pressure signal. Therefore the spectral peaks identified are not related to the spectrum of the noise and a peak at 1 Hz does not indicate infrasound in the wind turbine noise; it simply means the level of the broadband noise changes regularly at a rate of 1 Hz.

Applying an FFT to the time series is necessarily more complex than time domain methods and requires post-processing analysis. But this type of analysis does have the ability to discriminate between wind turbine AM and other modulated noise sources, as it presents clear evidence of the rate of modulation in the signal. Therefore modulation peaks not related to the BPF of the turbines can be discriminated and ignored. Therefore they can be applied to large quantities of data with only a minimal need for data to be filtered subjectively to eliminate corrupted data. Such 'automated' analysis does require the blade passing frequency of the turbines to be defined, at least within a specified range. These factors are discussed in detail in Section 7.2.

4.2.3 Hybrid methods

The methods proposed by other researchers for application to AM are, with few exceptions, based on either of the above basic approaches. However, the two basic approaches have in some cases been combined to construct a 'hybrid' method where the presence of AM can be detected using a frequency-domain technique as an initial filter to select samples exhibiting AM with contributions from extraneous noise that are not significant. The level of variation in these samples can then be assessed using a time-domain method.

4.3 Examples of time-domain metrics

4.3.1 Van Den Berg / di Napoli

Van den Berg reported AM as a time series and also described the modulation spectrum as the FFT of the time series (van den Berg 2005). He subtracted the L_{A95} from the L_{A05} samples to define AM for both the A-weighted signals and in 1/3-octave bands. Van den Berg reported that this AM rating was a stable value which was less sensitive to extreme events.

Di Napoli measured AM at a range of distances from both a single turbine and a small wind farm in a low background noise environment and made preliminary assessments during the evenings and night-time during the summer months. Samples of AM in the time domain were included for various conditions but he also investigated the Nordic impulsivity method and fluctuation strength – see section 4.6 (di Napoli 2009, di Napoli 2011).

4.3.2 MAS Environmental / Den Brook Condition

MAS Environmental in the UK proposed a criterion for 'greater than expected' AM based on examination of the $L_{Aeq,\ 125ms}$ time history. This was later changed to a 100 millisecond time history, although the choice of the sample period can result in slightly different levels. The 'greater than expected' threshold is exceeded if the following criteria are met:

- if the difference between successive peaks and troughs in any 2 second interval is greater than 3 dB;
- if this occurs at least five times in any minute;
- if this occurs at least six one-minute periods in any hour
- that the overall level is greater than 28 dB $L_{Aeq\ 1min}$

This is widely known as the 'Den Brook' condition (Stigwood, 2013), as these criteria were imposed as a planning condition for the proposed Den Brook Wind Farm by the planning inspector in 2009, based on advice provided by MAS Environmental. The test derived is understood to be based on the judgment and experience of its author rather than specific research results.

There is controversy over whether the defined criteria allow too many false positives since many environmental noises well away from wind farms apparently 'fail' this condition (Bass 2011).

The method is, arguably, not strictly a 'metric' in the sense that it does not quantify the relative depth of modulation of different periods, but rather provides an example of a pass / fail test for wind turbine amplitude modulation.

The MAS Environmental website[6] provides many examples of short periods of measured AM from wind farms presented as time series.

4.3.3 Tachibana et al

The work of Tachibana and his group (Yokoyama, Sakamoto et al. 2013) (Fukushima, Yamamoto et al. 2013) (Tachibana, Yanob et al. 2014) is perhaps one of the most comprehensive studies available as data was gathered from several wind farms and their proposed metric was studied in relation to subjective response studies carried out in a listening room.

In Part 1 (Fukushima, Yamamoto et al. 2013) the authors propose a simple metric for the rating of AM. This first de-trends a sample of time series data, calculating the difference between L_{AF} (fast) and L_{AS} (slow) rms sound pressure samples, to obtain a series of ΔL_A values (variations around the trend): see Section 6 for some examples. An estimate of the level of amplitude modulation in the signal is then determined through a statistical analysis of these variations, comparable to the approach used by Van den Berg (2005).

Specifically, the value used is the difference between the 95th and 5th percentile values[7] of the ΔL_A values, i.e.:

$$D_{AM} = \Delta L_{A5} - \Delta L_{A95}$$

The period of analysis used by the authors in Part 1 is specified as 3 minutes. This method is straightforward and could easily be automated or even implemented directly in a sound level meter, albeit one which can simultaneously measure the 'fast' and 'slow' weighted levels. This method does not account for periodicity in the signal, however, and is susceptible to corruption by any extraneous noise which is fluctuating, which is normally the case at time resolutions of less than 1 s. In particular, an impulse can corrupt the L_{AS} slow signal significantly. Therefore the metric would only be representative with 'clean' AM signals.

Part 2 of the Tachibana published research describes subjective studies in a listening room using synthesised signals simulating AM (Yokoyama, Sakamoto

[6] http://www.masenv.co.uk/listening_room [last accessed April 2015]

[7] In conventional statistics, the 95th percentile would be the larger value, and the 5th percentile the smaller value. In the original paper, the larger value is labelled as $\Delta L_{A,5}$, or 5% point, hence the resulting equation $D_{AM} = \Delta L_{A,5} – \Delta L_{A,95}$. However, clearly the author's intention is for the D_{AM} value to be based upon the 90% range, where one subtracts the smaller value from the larger value.

et al. 2013) . Subjects were asked to rate the 'noisiness' of sounds with varying modulation depth and to adjust the overall level of modulated sounds with a volume controller to match the equivalent 'noisiness' of an unmodulated stimulus. The research revealed that the apparent 'noisiness' increased as the modulation depth increased. However the relative noisiness of the modulated sound was no more than 2.5 dB on average for sounds with a modulation depth of up to 10 dB.

In the second part of the Japanese research project REF], (Yokoyama, Sakamoto et al. 2013) listening tests were performed to determine the subjective response (in terms of the relative 'noisiness' of the test signals), to various levels of modulation. As such, dose-response relationships were derived as a function of a parameter called the '*AM Index*'. The *AM Index* is a parameter based upon the design values of synthesised constant modulation depth stimuli signals. This parameter can be loosely related to the D_{AM} value using the stated values in Table 3, which is duplicated below in the form of Table 4.1.

Table 4.1: D_{AM} and *AM Index*

D_{AM} (35dB) (dB)	D_{AM} (45dB) (dB)	AM Index (dB)
0.8	0.8	0
1.2	1.1	1
1.7	1.7	2
2.3	2.3	3
3.0	3.0	4
4.3	4.3	6
5.5	5.6	8
6.7	6.9	10

As such, if it is desired to directly relate the modulation results to the psycho-acoustic response measured by the same authors, it is necessary to correct the calculated D_{AM} value to obtain the *AM Index* parameter described by the authors. This can be derived for example using an appropriate correction factor. Figure 4.3 below shows a second order polynomial relationship derived from the values detailed in Table 4.1.

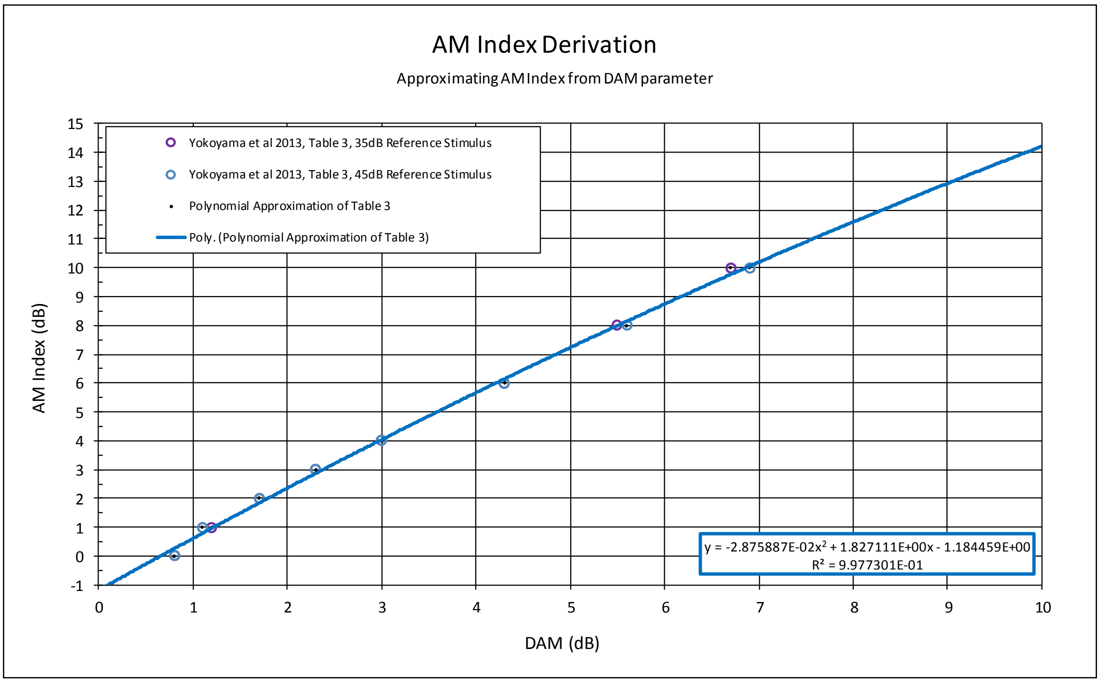

Figure 4.3 Approximation of AM Index parameter

4.4 Frequency-domain metrics

A number of researchers have investigated frequency domain metrics, which are broadly similar but differ in the details of their implementation.

4.4.1 Lee

Lee, Kim and others devised a method to obtain an AM rating based on recorded sound samples (Lee, Kim et al. 2009). The rating method involves a double FFT to derive the modulation spectrum in each frequency band. Modulation depth is extracted from the difference between the sound pressure level at BPF and the steady rms sound pressure level. A series of laboratory listening tests were then used to confirm that there was a correlation between the rating method and the subjective annoyance.

4.4.2 McLaughlin

(McLaughlin 2011) calculated a modulation spectrum (FFT) from octave band filtered noise data in time series form, and looked at samples having different AM character, e.g. ‘swish’, ‘thump’ etc.

He noted that different spectral characteristics (harmonic content) are associated with different subjective responses, although no conclusions are drawn on relative annoyance.

He concluded that modulation spectra are an effective method in separating AM out from other noise sources.

4.4.3 Lundmark

Lundmark presented a simple method for the investigation of modulation in wind turbine noise signals, based on the FFT analysis of the 125 ms sampled noise levels (Lundmark 2011). He notes that this represents a meaningful representation of the strength of the modulation in a signal (using an example from (van den Berg 2005) with a clear peak in the spectrum apparent from AM compared to a more general stochastic signal.

4.4.4 Larsson and Öhlund

Larsson and Öhlund (Larsson and Ohlund 2014) (Larson and Ohlund 2012) made noise measurements at 2 wind farms (2 x 2.5 MW, 12 x 2 MW turbines) in Sweden. They analysed time series recordings using an FFT technique (Lundmark 2011) to derive modulation spectra in octave bands from 10-630 Hz. They then used the highest value in the modulation spectrum in the range 0.5 to 1.0 Hz as indicative of AM.

They found that this approach had a low rate of false positives (3 %) for signals when there was no wind turbine noise, and was generally robust except in cases of strong masking by other sources. The authors were also able to analyse a large amount of collected data (a year or more) in a range of different conditions, and establish certain weather parameters that were more associated with increased modulation.

4.4.5 RenewableUK AM Research

The RenewableUK AM research project (RenewableUK 2013) comprised a wide ranging and comprehensive study of knowledge in the area of AM, and considered a number of related areas, including the following:

- literature and evidence review (Work package C)
- an investigation of AM source mechanisms for normal AM and other AM (Work Packages A1, A2 and D)
- measurement / rating approaches by Prof Paul White at ISVR (Work package B1)
- listening tests, by Salford University, using synthesised signals with a range of modulation depths and overall L_{Aeq} levels (Work package B2).

This latter study found that the annoyance scores showed a relatively weak correlation with modulation depth, with a stronger correlation with mean level.

The main research report describes the use of a main AM metric (Work Package F, section 4.4), based on the FFT analysis of short term L_{Aeq} levels. This was based on theoretical considerations which demonstrated that FFT methods are optimal in a specific statistical sense (Work Package B1), and on the successful application of these techniques to a range of long and short-term measurements in the field (Work Package D).

It is also explained that, given the nature of the signals encountered in the far-field of wind turbines, it can be useful to filter the data prior to processing it in order to exclude corruption from other sources in the environment. The report also stresses in particular that:

> *"[…] before considering subjective relationship and response to modulation at a certain level, it is crucial to consider how this level has been determined (method) and how the rating has been defined and scaled (normalisation), and also what inputs were considered (parameters)."*

4.4.6 RenewableUK proposed planning condition

Following the publication of the RenewableUK AM research, RenewableUK used the building blocks provided by the study, and the main metric method used in terms of metrics and dose-response relationships, to propose a planning condition for AM suitable for inclusion to typical planning conditions imposed on UK wind farms.

In outline, this proceeds as follows:

- the level of AM, at the BPF is determined from a Power Spectral Density (PSD) of a time series of $L_{Aeq,100msec}$ data for a 10 second period
- The PSD is integrated with a moving window of a width of 20% of the BPF.
- 60 such values are determined from consecutive, non-overlapping 10 second periods within a 10 minute interval
- these 60 values of AM are ranked and the average taken of the twelve highest values, in that 10 minute interval
- a scatter plot of the 10 min values of AM, against the standardised wind speed, at 10 min height, is created and the averaged value of AM at each integer wind speed determined
- a penalty is then determined for each integer wind speed, depending on the average level of AM, using a sliding scale of penalties in range 3-5 dB, if the AM is > 3 dB. This penalty added is to L_{A90} level, along with any tonal correction, in the usual compliance process
- the 3 dB 'threshold' value and penalty scheme is based on data obtained from the Salford University listening/subjective tests.

This methodology has been criticised in a REF review (Moroney and Constable 2011) although principally because the metric used sometimes under-estimates the peak to trough level of AM in the time series input. Note this would not however invalidate the rating method; it could be used with a different threshold or penalty mechanism.

A variation of this condition has been adopted as an agreed scheme for the regulation of amplitude modulation for the consented Turncole Wind Farm. In the agreed scheme, the penalty applies when level of AM is greater than 2.5 dB when determined as above and the wind farm is deemed to exceed the noise limits if the penalty is greater than 6 dB.

4.4.7 Gabriel/Vogl/McCabe

A paper by Gabriel considered recordings made by residents (at their properties) using instrumentation provided by the authors.(Gabriel, Vogl et al. 2013). They considered that modulation was a factor in the complaints and analysed some periods using different methods developed by (Vogl 2013). These methods comprised both a Fluctuation strength method (see below, 4.6.1) as well as a frequency domain method. The latter was based on a Fourier transform of the Hilbert transform of the acoustic signal. The Hilbert transform represents another way of calculating the envelope of the acoustic signal. As noted in RenewableUK (RenewableUK 2013) (see Work Package B1), for the modulation frequencies considered (less than 2 Hz for most wind turbines), there is little difference between using the Hilbert Transform and a short-term average such as the $L_{Aeq,\ 100ms}$.

This approach used by Vogl is similar to the one used by McCabe (McCabe 2011) which derived a Hilbert transformation of 1/3-octave filtered signals, and applied FFT analysis to the results to obtain a spectrum, which was then normalised to yield a 'modulation factor'. The author was then able to analyse a large dataset and determined a relation between the modulation factor and the magnitude of wind shear measured at the site.

4.5 Hybrid metrics

4.5.1 Cooper and Evans

The objective of this work (Cooper and Evans 2013) was to measure noise from a wind farm to determine compliance with the interim AM limits in New Zealand Standard NZS 6808: 2010, which are defined 5 dB peak to trough as an A-weighted level, or 6 dB peak to trough in a 1/3-octave band. Their work was carried out on an Australian wind farm but a draft guideline had suggested how the New Zealand standard could be applied in Victoria, Australia.

The authors applied an FFT method to detect genuine AM (i.e. periodic peaks related to BPF) and to reject non-related peaks, using time windows of varying length, and a number of tests based on their experience with analysis of the data. In particular, the relatively slow variation with time of the BPF was used. They then applied peak to trough tests to the original time series data which had been identified as containing genuine AM. They claim that their technique largely eliminates 'false positive' exceedances of the limit although it was less successful in filtering out non-wind turbine related peaks in 1/3-octave bands.

4.5.2 Den Brook – The Condition 21 Scheme

Condition 20 of the planning conditions for Den Brook specifies a methodology for detecting 'unacceptable' levels of AM at surrounding properties, described in outline in section 4.3.2. The primary problem with this methodology is that it is subject to a high rate of 'false positives', so that it is unable to distinguish between genuine AM and normal variability in noise levels resulting from changes in the wind or from other noise sources. This occurs because the methodology contains nothing which ties the fluctuations in level to the BPF.

Condition 21 requires the operator to propose a scheme to the local authority to implement the above and a scheme has been agreed which remedies the primary problem of Condition 20 – the high rate of false positives. In outline the Condition 21 scheme provides a screening process which:

- filters out all samples of noise data which do not contain genuine AM and which might otherwise result in a false positives
- only allows those samples which potentially contain 'greater than expected' AM through to Condition 20.

The core of the scheme is as follows:

- separate hours of data are assessed
- for each hour of data, a time series of 60 values of the $L_{Aeq,1min}$ are determined and, if any are less than 28 dB(A), those periods are ignored
- each 1 min period remaining is split into six, consecutive 10 second periods
- for each 10 second period the average level of peak to trough AM. at the BPF (integrated from 0.9 – 1.1 f_c) is determined from an FFT of a time series of $L_{Aeq,100ms}$
- if six or more 10 second periods with an hour verifiably contain AM greater than 2.5 dB[8] then the entire hour of data is assessed using Condition 20.

The method shares many commonalities with the RenewableUK AM methodology described in Section 4.4.5.

4.6 Other Methods

4.6.1 Fluctuation strength

Fluctuation strength (FS) is a complex, time-domain metric intended to provide a measure of the audible sensation produced by regular changes in the amplitude of tonal or broadband noise (Zwicker and Fastl 1999). It has been established that the value of FS can be related to 'noisiness' and / or 'annoyance' and the metric has applications in, for example, noise quality evaluation for domestic products and in the automotive industry.

FS is applicable for modulation frequencies up to around 20 Hz. The value of FS (expressed in units of 'vacils') depends on the rate of fluctuation (i.e. the frequency of modulation), the overall level and the modulation factor (which is not the same as the modulation depth that would be measured on a time-series plot, because of temporal masking).

For broadband noise, the FS metric 'peaks' at a modulation frequency of 4 Hz and increases with both depth of modulation and overall level. This represents the known psycho-acoustic characteristics of the response to modulated signals (Zwicker and Fastl 1999). This was confirmed for example in subjective

[8] Note that this threshold has not been selected to represent an 'acceptable' level of AM. Rather it was chosen as a level at which it is reasonable to conclude that genuine AM is present.

testing undertaken by the University of Salford (RenewableUK, 2013, Work Package B2)[9]. This means that the FS metric takes into account the rate of the modulation, whereas most of the other metrics considered by the AMWG do not incorporate this.

Commercial software is available to compute values of FS for a given sample of data, although it is evident that the metric is not robustly defined and it is reported that software from different suppliers can produce different values for the same data input.

When applied to wind turbine noise, Seong and Lee reported that FS did not correlate better with the subjective response to AM than other metrics. (Seong, Lee et al. 2013). FS has also been applied to AM by others including: (Persson Waye and Ohrstrom 2002) (Legarth 2007); (Lenchine 2009) and (Van den Berg 2006), but generally showed inconsistent results in subjective response tests.

The AMWG have concluded that although FS is an apparently established metric for periodically fluctuating noise there is no evidence that it is a strong candidate for a wind turbine AM metric. As concluded by Finnish research (Siponen 2011) the FS metric is relatively insensitive at the modulation depths and overall noise levels experienced at residential locations around wind farms and instead very sensitive to the influence of corrupting sources such as bird noise. There are also uncertainties involved in computing repeatable FS values. Therefore the AMWG have excluded FS as a potential AM metric.

However, the clear indication that subjective response to amplitude-modulated noise is dependent on the modulation frequency and overall noise level, in addition to modulation depth, should be borne in mind when developing other metrics, defining threshold criteria and considering psycho-acoustic aspects of AM.

4.6.2 Impulsivity

There are various methods available for rating ‘impulsivity’ or the prominence of impulsive sounds. It is also part of wind turbine testing according to the German FGW standard, albeit based on measurements on a ground board. Various researchers (Large and Stigwood 2014) (di Napoli 2011) have used Nordtest method NT ACOU 112 to rate AM and the test of impulsivity provided in Annex E or BS 4142: 2014 is based on this method.

The Impulse Adjustment proposed by the DIN 45645-1:1996 standard was used by the AMWG to rate several samples of wind turbine AM. However the experience gained was that only fairly extreme examples of AM were given a high rating and as such the impulsivity score was not a good metric for

[9] Tests undertaken showed that signals with a modulation at a frequency of 1.5 Hz (period 0.6 s) was on average around 25 % more annoying than a slower modulation at 0.8 Hz (period 1.3 s): see work package B2 Table 8.5 and Figure 8.7 page 53. The tests also showed a strong relation with the overall level of the noise in addition to the modulation depth.

quantifying varying levels of AM. Therefore impulsivity metrics have been rejected as potential metrics by the AMWG.

4.7 Psycho-acoustical Aspects of Amplitude Modulation

Determination of a robust method of quantifying the amplitude modulation in terms of a numerical scale is the first part of the exercise. The numerical scale must then be interpreted in terms of the level of subjective response. Typical response scales might be as follows, although other descriptions and scale lengths are used (ISO:15666 2003).

0 No disturbance

1 Slight awareness, but not annoying

2 Moderately annoying

3 Very annoying

4 Unbearably annoying

The annoyance response to wind turbine amplitude modulation is a function:

$$\text{Annoyance response} = F(m, \tau, f, L, \psi)$$

where:

m is the modulation depth

τ is a modulation rise time

f is the modulation frequency, which may have harmonics

L is the average level

ψ is a factor which accounts for psychological responses.

The psychological factor, ψ, becomes very variable at low sound levels.

Assuming that a measurement method and associated assessment criteria have been developed, it cannot be expected that these will satisfy all people. It must be accepted that noise criteria do not meet the needs of everyone – there are always ‘sensitivity outliers’ whose requirements cannot be met.

The following subsections illustrate the range of approaches to quantifying subjective responses to amplitude modulation, in which annoyance is determined for different parameters of the amplitude modulated sound.

4.7.1 Correlations of Amplitude Modulation and Subjective Response

Seong

Seong showed that the L_{AFMax} gave good correlation with subjective response (Seong, Lee et al. 2013). This method uses the peaks of the amplitude modulation for assessment and could be a simple field measurement for initial assessment during steady periods of AM. Figure 4.4, which is based on synthesised sounds, shows that a mid-annoyance rating, level 4 occurs at about 44 dB L_{AFmax}.

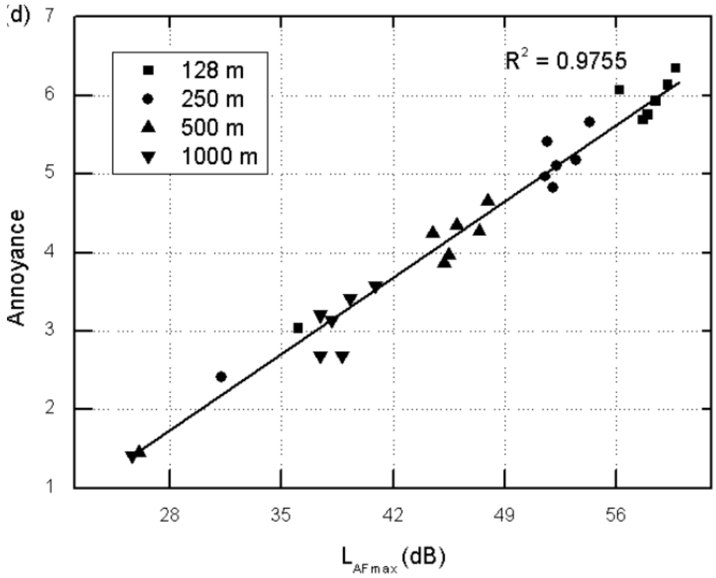

Figure 4.4 Annoyance and Maximum Level

Lee

Lee et al used laboratory tests, based on field measurements, with five levels of amplitude modulation depth, in the range from 2 dB to 5 dB, and showed that the annoyance increased with both modulation depth and average level (Lee, Kim et al. 2011). As the maximum level derives from the average level <u>and</u> the modulation depth, this is consistent with Seong, above.

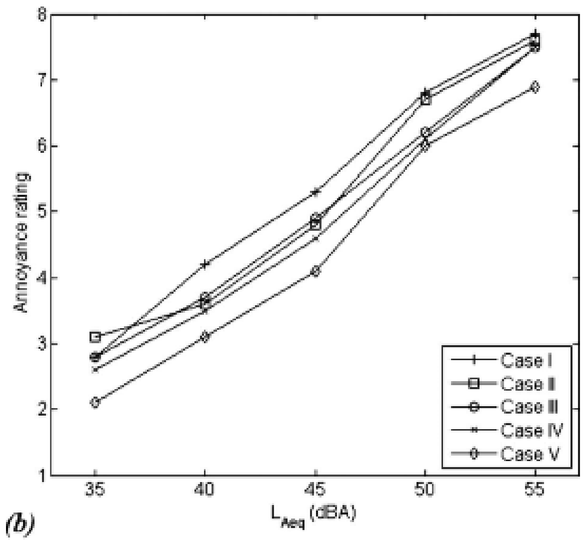

Fig 4.5 Annoyance and L_{eq} with modulation depths

In the figure above Case I represents a modulation depth of 5 dB whereas Case V represents a modulation depth of 2 dB.

RenewableUK

The work supported by RenewableUK (RenewableUK 2013) produced a number of results, of which Figure 4.6 is of interest, as it is similar to that by Lee, above.

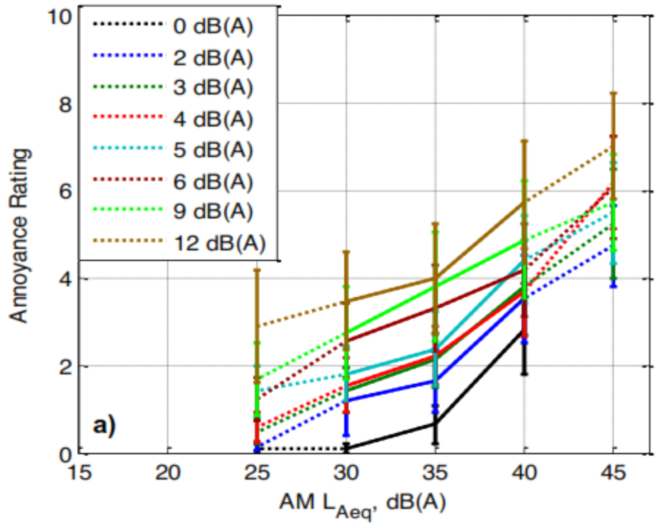

Fig 4.6 Annoyance and L_{eq} for different modulation depths

5 Yokoyama, Sakamoto & Tachibana

The work of Tachibana's Japanese group included noisiness matching of the AM signal against a fixed reference signal, as shown in Figure 4.7 for a 45 dB reference signal. Yokoyama's method gives equal annoyance curves for variation in modulation depth (Yokoyama, Sakamoto et al. 2013).

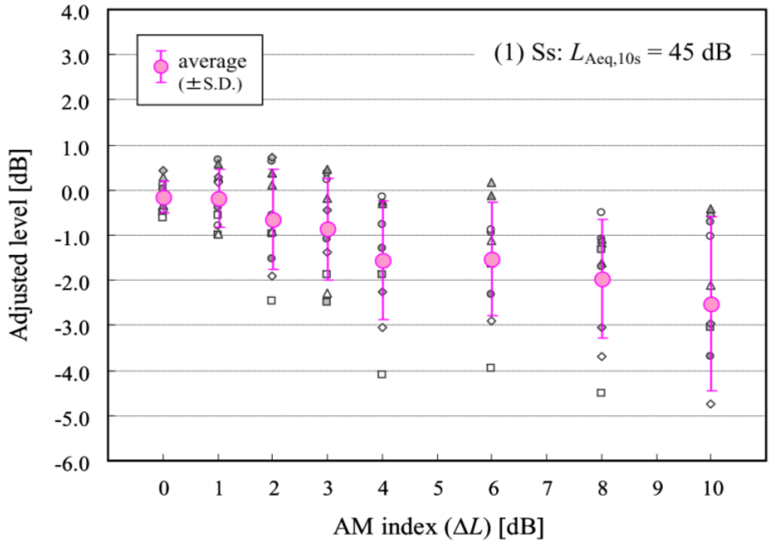

Fig 4.7 Reduction of AM signal required to maintain comparability with reference signal

In the figure above, a signal with an AM index of 10 dB (D_{AM} = 6.9) (Section 4.3.3) was found to be subjectively 2.5 dB noisier in comparison with the unmodulated reference signal.

6 Ioannidou

Ioannidou extends the work to include time variation of amplitude modulation (Ioannidou 2014). Figure 4.8 shows annoyance rating against Mean Modulation Depth over Time (MDT). Higher values of MDT are classified as OAM; this is a variance from the definition in the RenewableUK work. There is a surprisingly small variation in annoyance with MDT and little apparent difference between what the author describes as NAM and OAM.

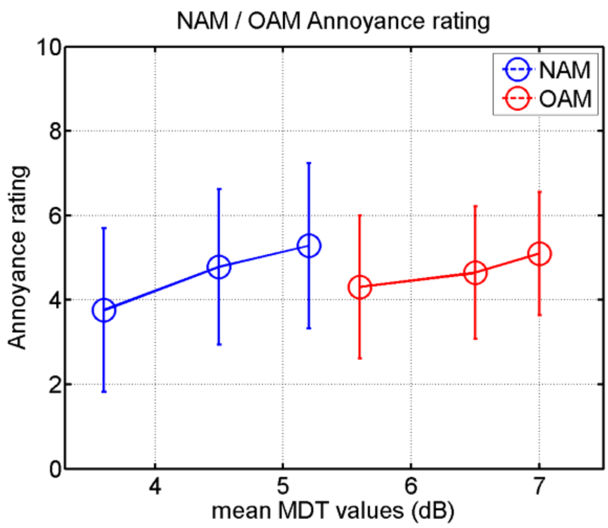

Fig 4.8 Annoyance and MDT

4.8 Summary of Literature Review

AM metrics based on analysis of time series data have the virtues of simplicity and may be seen as 'intuitive' since the output values can be directly related to the depth of modulation as presented on a time series plot. Many of the subjective test results are based on correlation with time domain metrics, albeit based on well-defined and often artificial samples.

However, time-domain metrics have the basic deficiency that they can only be applied reliably to AM when 'clean' data is available. These methods do not inherently discriminate between noise 'peaks' associated with AM (which is periodic in character) and noise peaks caused by other sources in the local environment, such as barking dogs, birdsong and domestic activity.

Including extraneous noise peaks when determining a time series metric for AM would generally result on an over-statement of AM. This could indicate that a specified limit for AM was being exceeded, when in reality the exceedance was due to the contribution of the extraneous noise - so called 'false positive' results.

It is clearly possible to 'filter' noise data, by examination of time series data and/or by listening to audio recordings, to exclude data obviously contaminated by extraneous noise, but for large amounts of data, this can be laborious and the need for such filtering militates against automatic data processing to detect and evaluate AM. Given the known variability of wind turbine noise and AM, and the need in the experience of the AMWG of undertaking long-term measurements, this can be particularly problematic. If large datasets need to be manually inspected, this introduces more subjective decisions within the assessment process, which is not a desirable feature for a robust and repeatable metric.

Despite the limitations, the AMWG considers that a simple time domain metric should be retained as a potential candidate for evaluating AM for the consultation document. Such a metric could serve as a 'first pass' tool for estimating the severity of AM for specific periods identified, although in its simplest form, it is unable to discriminate between AM and extraneous noise events. The method from Tachibana's group is proposed.

Frequency domain methods in contrast provide objective evidence of the modulation occurring at a certain rate in the form of a modulation spectrum (see Figure 4.2 for example). This can be related to the known or expected rotational rate of the turbine in order to specifically relate the analysis to wind turbine noise. This minimises the degree of filtering of the data which is necessary, and is a standard technique used for example in tonal analysis, which explains its use by a wide range of authors. With the addition of pre-filtering of the acoustic data, the number of false-negatives is minimised. Such techniques have also proved to be effective in a wide range of different field applications with realistic conditions. There is however no standard techniques currently widely adopted, with different authors using different parameters and normalisations.

By their very nature, frequency domain methods require a certain degree of averaging in order to identify a pattern in the measured noise levels. Most applications of these methods focus on the level detected at the blade passing frequency, as consideration of the harmonics of the signal can be complex, and the modulation at BPF is considered representative of the general magnitude of the modulation for signals in practice. This can however miss certain detailed features of the signals, although there is currently limited knowledge regarding the subjective significance of these detailed features. The AMWG has therefore also considered hybrid methods which allow combining the two different approaches.

5 TOWARDS AN AGREED METRIC

The overarching aim of the IOA AMWG is to develop an assessment method which contains a means of characterising a sample of amplitude modulated wind turbine noise by means of a single metric uniquely defining the level of AM within it.

Irrespective of the metric agreed, there is a need to define certain parameters and principles for measurement and data processing etc. These are discussed below. Instrumentation for measuring AM is discussed in Section 10.

5.1 Measurement Units

For this document, the use of 100 millisecond L_{eq} values is proposed. It would equally be possible to use Fast 'rms' sound pressure values sampled in 100 millisecond periods, or indeed 125 millisecond samples, but for standardisation a basic unit must be agreed. An AM time history is shown below in terms of $L_{Aeq, 100ms}$ and the L_{AF} sampled at 100 millisecond intervals.

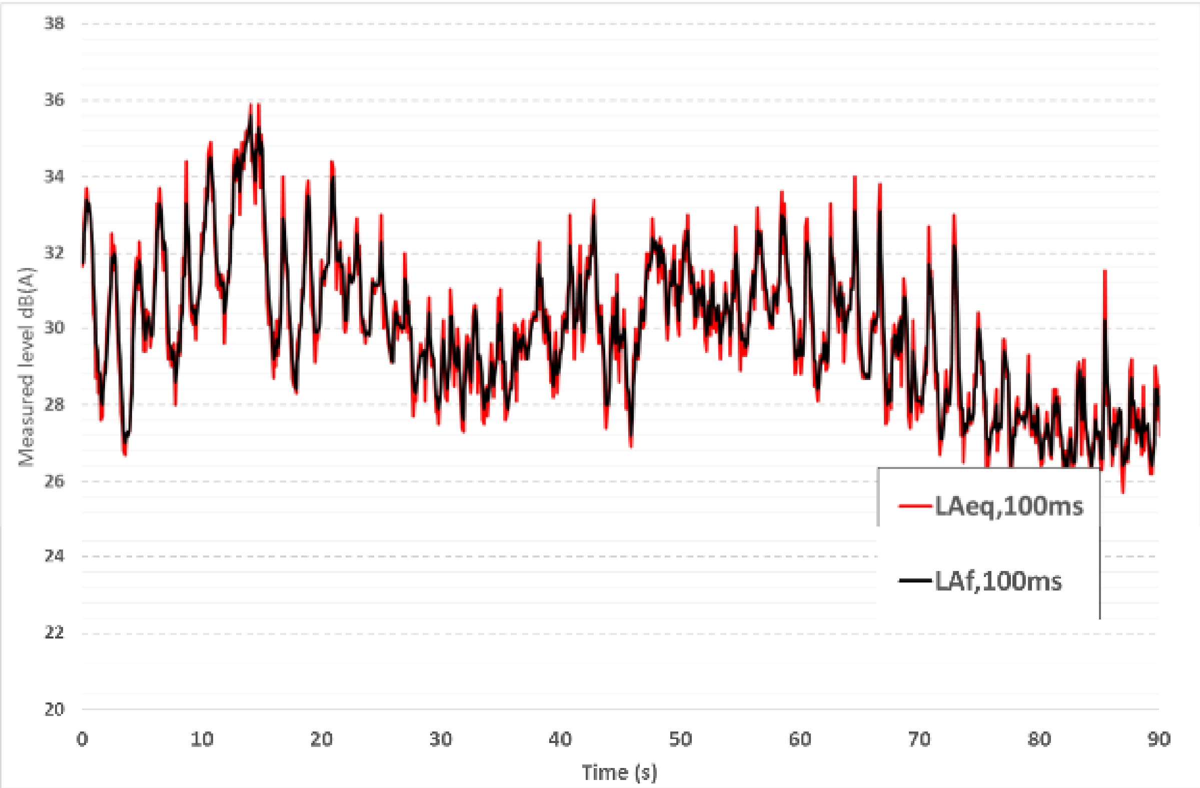

Figure 5.1 AM over a 90 s period with both $L_{Aeq, 100ms}$ and $L_{AF, 100ms}$

It can be seen that the L_{Aeq} samples result in a 'peakier' signal than the L_{AF} data.

5.2 Data Analysis

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 used has an agreed format and length. The AMWG considers that the analysis period is best separated into 'major' and 'minor' time intervals.

5.2.1 Major Time Interval

It is agreed that the major time interval for analysis should be 10 minutes and it is clearly desirable for any method to obtain an indicative AM rating for each such interval. 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 is also generally available in 10-minute periods, as is meteorological data from the UK Met. Office. 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, AM should be defined in 10 minute intervals.

5.2.2 Minor Time Interval

AM, and indeed wind turbine noise in general, is variable. To characterise the variability of AM observed in practice, it is necessary to process the 100 millisecond samples in some way to obtain a single rating value in a 10 minute interval. It is proposed that these 10 minute statistics are derived from the analysis of variations in the average levels of AM calculated within consecutive, non-overlapping 10 second periods – the minor time interval. Clearly there are 60 such minor time intervals in each major interval.

It is recognised that the choice of a 10 second period as the minor time interval may appear arbitrary, but on the basis of comparative analysis, the AMWG considers 10 seconds to be a representative period for analysis. This describes approximately 10 cycles of AM at 1 Hz.

5.2.3 Defining a 10-minute Value

The indicative 10 minute value of AM chosen clearly needs to be obtained from the sixty, 10 second results using a defined data reduction method. In this context, simply averaging all the results might not be suitable given the range of variations which can be experienced in practice. Instead, to represent the higher end of the range of values experienced in any 10 minute period, it is proposed to use the 90^{th} percentile of the distribution calculated within each 10 minute period. This is the highest 10% of the 10 second values, which is the equivalent of the L_{A10} for noise levels. An example is shown in Figure 5.2 below.

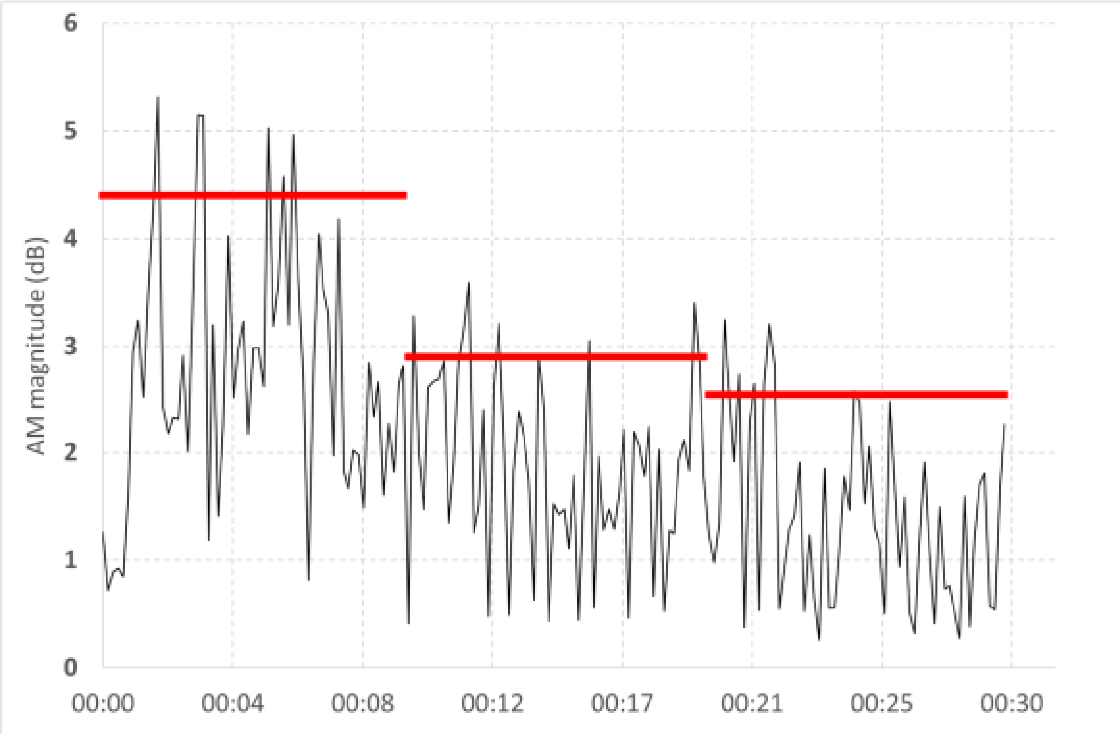

Figure 5.2 Example plot of calculated modulation depth based on the calculated spectrum for each 10s period (black line) and calculated 90th percentile value for each 10minute period (red lines).

In any 10 minute period, some 10 second samples may be contaminated by extraneous noise. These must be removed from the analysis. It is proposed that if more than 12 such 10 second samples are contaminated, then the 10 minute sample should be excluded.

5.3 Frequency Analysis

To assist in the identification of AM, it is helpful to focus on a limited frequency range. The benefits of this are in terms of excluding spurious data from, for example, birdsong. A band-limited analysis will achieve this. At the same time it will result in higher levels of AM compared to those obtained from broadband analysis, as the (AM) signal-to-noise ratio is effectively increased by only assessing the frequency range where AM occurs. Therefore it is recommended to use band-limited data for some methods.

While it is possible to post-process audio recordings to determine the frequency content, this entails significant practical difficulties; audio recordings have large storage requirements and their post-processing requires specialist software and is generally not straightforward. It is therefore convenient to log 1/3-octave band spectra in 100 millisecond periods to obtain this information directly; many modern sound levels meters offer this capability. The 1/3-octaves should be A-weighted.

5.3.1 Frequency Range of Interest

The measured acoustic signal needs to be filtered in the relevant frequency range. The appropriate range is chosen to be representative of the frequencies at which modulation associated with the turbines occurs. In several known cases of modulation at typical residential separation distances, the range of 100 - 400 Hz has been found to be representative for this purpose, and therefore this range (comprising seven 1/3-octave bands) should be used as default for the analysis.

This should identify periods of clear modulation (for example using a review of the "waterfall" analysis discussed in Section 7). In some 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; in these cases, it is recommended that the range of 200 - 800 Hz be used instead. The use of the higher frequency range (200 to 800 Hz) must be justified (for example using analysis of these selected periods of clear modulation). It should be borne in mind that at higher frequencies, data may be more prone to corruption from other sources such as bird calls, and the resulting spectra should be scrutinised.

The signal used is obtained in the following manner:

- The acoustic signal is band-pass filtered in the chosen region (i.e. 100 - 400 Hz by default)
- An A-weighted band-limited short-term equivalent noise level ($L_{Aeq,100ms}$) is generated.

5.3.2 Benefits of Band-limited Analysis

The use of the range of 100-400 Hz will filter out noise in the ambient environment occurring at frequencies below 100 Hz (which tends to be influenced by wind noise mainly) and above 500 Hz (which will eliminate most bird noise) and many transient sources. The resulting band-limited signal will also be more representative of the noise level experienced indoors, as the building envelope will tend to reduce high frequency sounds better than low frequency sounds. The effect of band-limiting the data is illustrated in Figure 5.3 below showing the time-series when calculated from un-filtered and filtered data.

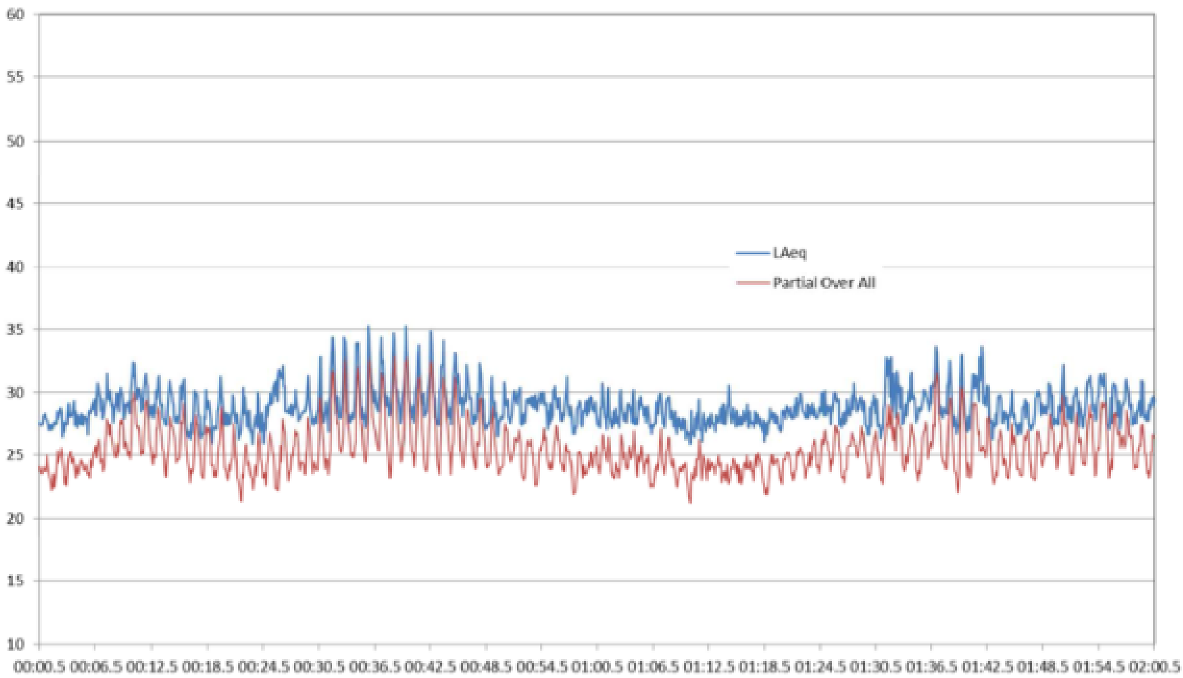

Figure 5.3 Example of a modulation spectrum for an individual 2 minute period – this shows two different A-weighted $L_{Aeq,100ms}$ signals: one un-filtered (blue) and a "partial over all" level (red) filtered for the range of 100-400 Hz.

In the example above, with variable AM at a low absolute level, it can be seen that the troughs in the modulation are not fully revealed in the broadband signal. Therefore although the broadband peaks are higher, the ability of the band-limited data to reveal the troughs results in a greater modulation depth and therefore a greater AM rating. In fact, the band-limited data can show AM which would have been masked using a broad-band analysis.

The use of a wider band means there is a reduced sensitivity to the choice of the single 1/3-octave band. It also results in a cleaner and clearer analysis result.

5.4 Recommended Methods

Based on the critical review of AM rating and detection metrics and the foregoing considerations, the AMWG have proposed three candidate methods for consultation. These are:

- A Time Domain Method – Method 1
- A Frequency Domain Method – Method 2
- A Hybrid Method – Method 3

These three methods are described in detail in Sections 6, 7 and 8. The Tachibana method uses A-weighted data for simplicity. The other two methods are derived using band-limited data.

6 METHOD 1 - TIME SERIES METHOD (AFTER 'TACHIBANA')

6.1 Method Overview

As part of a wider research study, a method for quantifying the amount of modulation in real world signals was proposed in 2013 by a group of Japanese researchers led by Tachibana (Fukushima, Yamamoto et al. 2013). A brief description of the method is provided here. The A-weighted short-term sound pressure level values with Fast and Slow time weightings are measured. The time varying difference in the two parameters is derived, with the intention of eliminating the residual drift in the overall mean sound pressure level. This step is analogous to the de-trending step in the FFT-based method.

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

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)

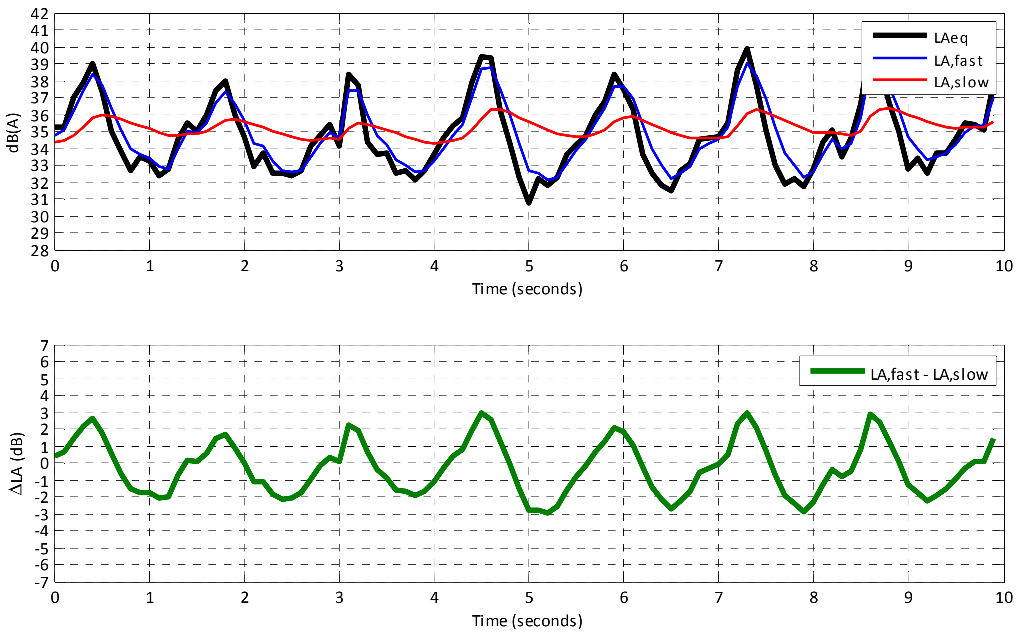

Figure 6.1 Derivation of $\Delta L_A(t)$

The magnitude of modulation is examined on a statistical basis, where a cumulative distribution is calculated on the $\Delta L_A(t)$ values within the 10 second minor time interval. 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 10s period

$\Delta L_{A,95}$ is the 95% point on the cumulative distribution of $\Delta L_A(t)$, within the 10s period

Figure 6.2 shows an example cumulative distribution of the 10 s period shown in Figure 6.1, and the derivation of the D_{AM} value.

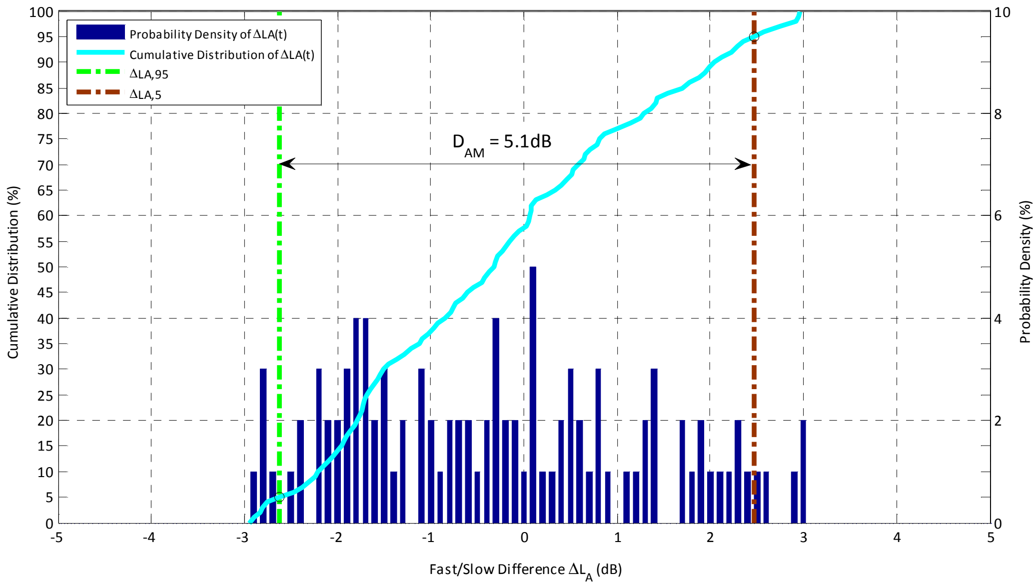

Figure 6.2 Cumulative Distribution of $\Delta L_A(t)$ and Derivation of D_{AM}

The authors (Fukushima, Yamamoto et al. 2013) recommend that the auto-correlation function of the $\Delta L_A(t)$ values is also calculated. This gives an indication of any dominant periodicity of the signals, and hence the modulation frequency.

6.2 Proposed Implementation

6.2.1 Calculation of $\Delta L_A(t)$

In its nature, it is a straightforward method that can be implemented easily in standard spreadsheet software. For the AMWG implementation, for consistency with the approach in other methods, it is proposed that $L_{Aeq,\ 100ms}$ are used instead of the L_{pA} Fast values. The slow weighted time response can then be measured directly by the sound level meter or calculated using the equation from Section 6.1 of Nordtest 112.

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

Where: τ is the time constant (1 s for Slow time weightings) and Δt is 100 milliseconds.

Such an approach will result in slightly higher D_{AM} values than the use of the measured Fast time-weighted sound pressure level. The magnitude of this effect may be an overestimate of around 1 dB at a 5 dB D_{AM} value.

Additionally, if the Slow time-weighted sound pressure level is approximated using the above equation, then the first ~3 s 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 s. The Slow time weighted sound pressure levels could also be derived by post-processing audio files if available.

6.2.2 Limitations

The method is a statistical one, based upon the difference between two signals. As such, it does not specifically provide a measure of modulation at blade passage frequencies of the wind farm under assessment. Rather it provides a measure of variation, at whatever 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 good 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. However, the influence of spurious noise sources is unavoidable. Consequently, there is a need for rigorous manual interrogation of the results to ensure that the resulting modulation depth values are related to the actual wind turbine noise under assessment. One-third octave or narrow-band spectrograms may be useful in this process, as is listening to the simultaneously recorded audio.

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 other noise sources in the environment such as bird song that give rise to similar modulation frequencies. Adapting this method to automatically exclude corrupted data could form the basis of another hybrid method.

6.2.3 Significant variation in underlying overall level

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 quick 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. As wind farm noise generally has a relatively constant underlying level within a 10s period, this effect is mostly seen when extraneous noise sources corrupt the measurements. When this effect does happen with wind farm noise, the D_{AM} parameter may revert from a measure of modulation to a measure of a variation.

6.2.4 Variation in modulation depth within minor interval

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 within the interval.

7.0 METHOD 2 - FOURIER ANALYSIS METHOD (FFT)

This method is based on a frequency domain analysis (FFT) of the variation in the signal amplitude (or envelope) and provides an objective measure of how much the level of the noise varies at a regular rate when AM occurs. This provides an objective measure of the modulation present in acoustic signals with short-term resolution (100 milliseconds or similar) which are generally too complex or unwieldy to analyse manually. A similar approach has been used by several other researchers in the field – see Section 4.4.

This method is similar to the approach presented in the RenewableUK work (RenewableUK 2013) but some adjustments were made following a review undertaken by the AMWG. The main one being the recommendation to analyse the band-limited A-weighted signal, over a limited frequency range which is specific to the modulation – see Section 5.3.

7.1 Core of the method

This algorithm undertakes a frequency analysis of the acoustic signal envelope, using a Fast Fourier Transform (FFT), to produce a modulation spectrum, as follows:

- An A-weighted noise amplitude signal is provided in 100 millisecond resolution. This is obtained from filtering the acoustic spectrum within a prescribed range

- the envelope signal is separated into 'blocks' of 10 sec length
- the stationary component of the signal is removed using a de-trending technique: a 5th order polynomial is fitted to the data over the 10 sec block and is then subtracted
- a power spectral density (PSD) of the envelope is calculated using a rectangular window, a spectrum resolution of Δf=5/128 Hz and a maximum frequency of 5 Hz[10]
- the resulting spectrum is then integrated in the frequency domain using a moving summation of fixed width equal to 0.16 Hz[11]
- the PSD is then normalised as **2**√**(2** Δf **PSD)**
- A peak corresponding to the blade passing frequency is determined for each 10 second block.

These steps are illustrated in Figure 7.1 and 7.2 below. More details and examples of methods for some of the steps above are also set out in the following sections.

The output provided for each 10 second data block comprises:

- a modulation spectrum
- the amplitude and frequency of the peak in the spectrum at the blade passing frequency.

The amplitude of the integrated spectrum at the BPF (in dB) represents the magnitude of modulation for each 10 second period.

[10] As the sampling frequency is 10 Hz, the analysis is undertaken up to modulation frequencies of 5 Hz, therefore this provides a resolution of 0.04 Hz.
[11] This represents 4 spectral lines.

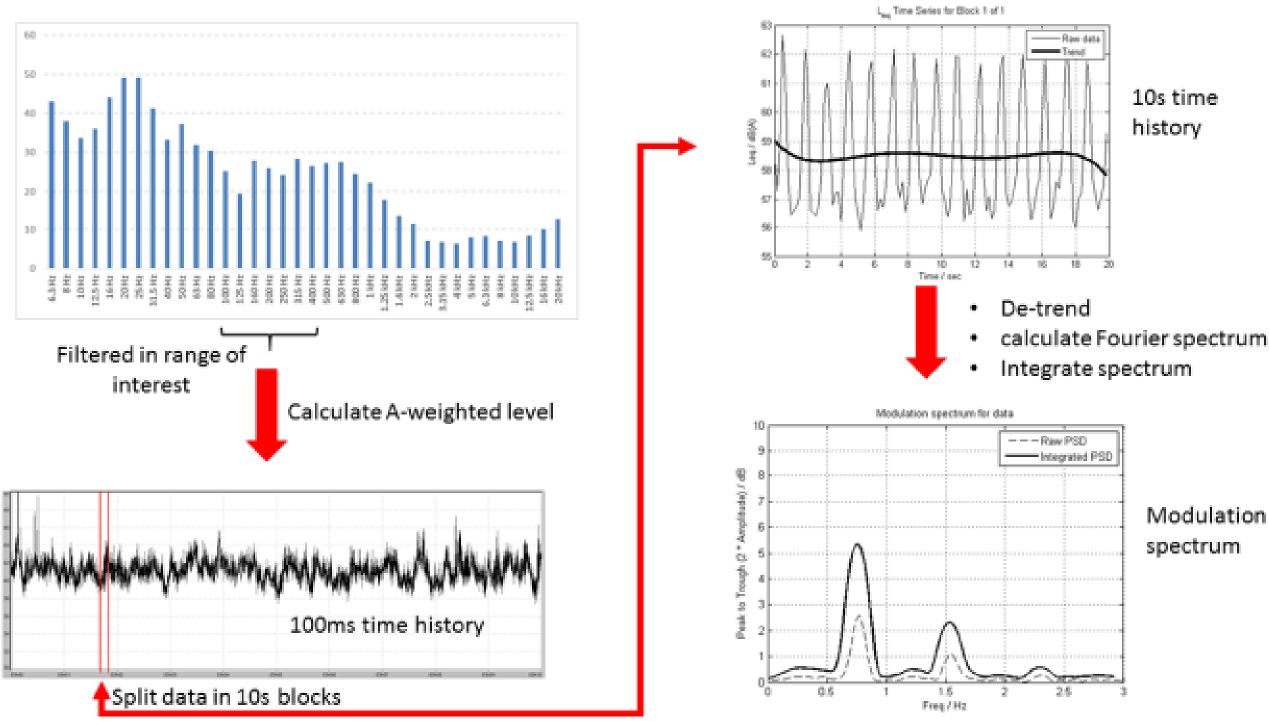

Figure 7.1 Data processing outline for Fourier analysis method

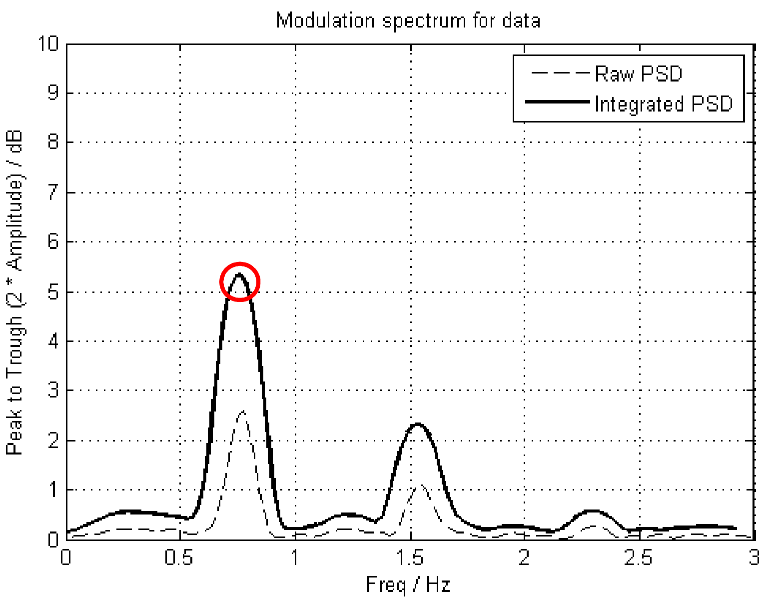

Figure 7.2 Example of a modulation spectrum for an individual 10 sec period block – peak identified (red) at approximately 5.2 dB (AM amplitude) and 0.8 Hz (BPF)

It is noted that this method does not include the energy in the 2nd harmonic, or any subsequent harmonics.

7.2 Determining the modulation peak

For each 10 sec block, following calculation of the modulation spectrum, it is necessary to determine the peak which is related to modulation from the wind turbine, i.e. at BPF. Example methods for determining this are set out here.

7.2.1 Using SCADA (System Control And Data Acquisition)

The rotational speed of the turbine during the measurement period may be known from operational data provided by the control system (SCADA). This may allow determining the BPF and eliminating peaks in the modulation spectrum which are not consistent with this rotational speed. For a large wind farm, there may be some uncertainty as to the turbine to consider, although the rotational speed is unlikely to vary significantly. Only a 10 minute average RPM may be available, which will lead to some degree of uncertainty[12] for any specific 10 sec interval:. Therefore a certain tolerance is required (0.2 Hz is suggested, although in some cases more detailed statistics, such as min or max, may be available).

7.2.2 Maximum in range

The maximum level of the integrated modulation spectrum may not correspond to modulation associated with the turbine. But knowledge of the turbine type, and/or observations on site may determine the likely blade passing frequency (BPF) range for the analysis. This will depend on the possible or likely rotational rate of the turbines. For example, for a 3-bladed turbine known to be potentially rotating between 8 to 18 RPM, the associated frequency range can be calculated using f = *3*RPM/60*, in this case between 0.4 to 0.9 Hz. It is also possible to undertake a first pass analysis with a wider range, and refine the range based on the modulation observed, using, for example the waterfall analysis.

Once the range is defined, the magnitude of the modulation is taken as the maximum value of the modulation spectrum in this range. This is the recommended default method in the case that the instantaneous rotational rate is not known.

7.3 Comparison with RenewableUK methodology

The main difference between the published RenewableUK template planning condition and this method is that the analysis has been conducted on a *band-filtered* signal for frequencies between 100 and 400 Hz (by default). The rating for a 10-minute period is also calculated as the 90th percentile rather than averaging the 20 highest values.

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[12] See for example Renewable-UK (2013), *WPD - Measurement and Analysis of New Acoustic Recordings*, Figure 3.11 page 32.

Compared to undertaking the analysis on the A-weighted signal, as in the RUK template condition, the analysis on band-pass filtered data has several advantages:

- It provides increased discrimination of modulation;
- It is less sensitive to extraneous noise;
- It results in higher values;

This can also be observed in Figure 7.3

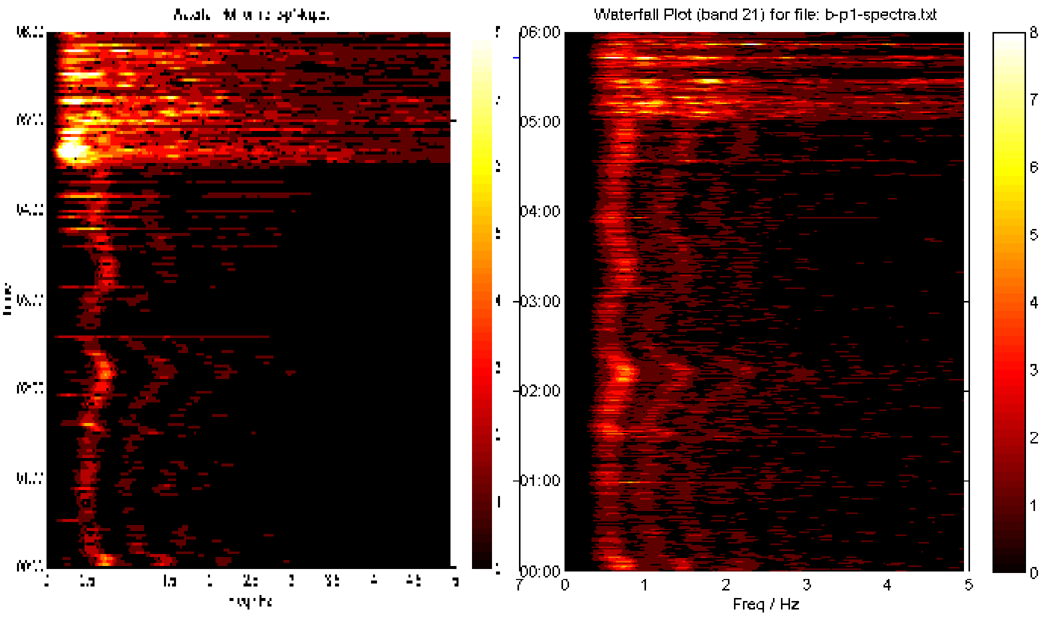


Figure 7.3 comparing the long-term FFT analysis of modulation spectra for A-weighted signal (left) with band-filtered signal (right, 100-400 Hz) – the horizontal axis shows the modulation frequency and the vertical axis is time (hh:mm)

This shows that, in this example, a period around 04:30-05:00 in which AM was present was masked by bird-noise in the analysis based on A-weighted signal but becomes apparent when undertaking the analysis on band-passed data.

On the other hand, undertaking the analysis on a filtered signal with a wider frequency range (that is seven 1/3-octaves) has advantages over analysis for a single 1/3-octave band (as considered for example in the RenewableUK work (see Work Package D). In particular, this reduces the “static” or noise in the analysis.

7.3.1 Analysis where only historic A-weighted data is available

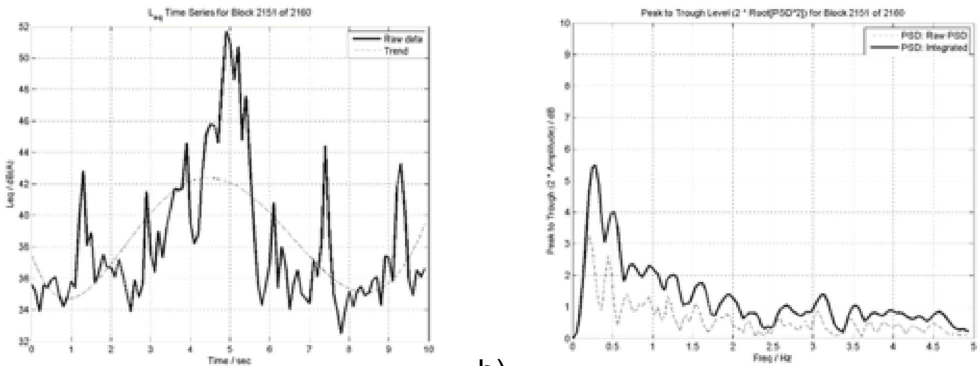
The analysis of a specific band-filtered signal is preferred and applying the method to broadband A-weighted $L_{Aeq,100ms}$ data only should be avoided. However in some cases only A-weighted data may be available, for example when analysing historic data.

If only A-weighted levels were measured and no frequency information is available, the above method could be applied to unfiltered signals as an approximation. As this tends to give lower results than for a comparable analysis based on band-passed signals, the values obtained should be increased using a correction factor. In this case, the AM rating obtained using this method shall be corrected by multiplying the dB rating, obtained from the analysis of unfiltered A-weighted signals, by a factor of 1.3. This is an empirical correction factor derived from the analysis of several results.

7.4 Output and interpretation

Despite the extensive filtering and analysis in this method, the influence of non-turbine sources of noise, such as human activity during the daytime, animal and wind noise, can have a residual influence on the analysis. This can sometimes give spurious high readings of apparent modulation which were not associated with the operation of the turbines. At other times (particularly at night), the influence of such sources is reduced but can still be present at times (see IOA GPG supplementary Guidance note 5).

But the Fourier analysis of the signal which is undertaken allows an objective analysis of such corruption in the cases studied. In the example below (Figure 7.4), a pattern of varying noise levels is visible in the time history of the A-weighted levels (a) which is difficult to interpret; however, in the Fourier analysis (b), it is clear that there is no modulation peak concentrated at a single frequency which could be the blade passing frequency of a turbine.



a) b)

Figure 7.4 Example of Fourier analysis obtained for a period contaminated by spurious noise sources (a): analysed signal, b) "modulation" spectrum)

Given the nature of wind farm noise, spurious periods are detected most clearly on a plot of the modulation spectrum over longer period of time (at least one hour or 30 minutes) as trends can then be clearly identified. A plot combining a number of spectra is called a "waterfall" plot: an example is shown in Figure 7.5 below, for a period of approximately 6 hours. AM from a wind farm was present in this example and this is clear from the trend visible in the plot at frequencies typical of the rotation of the turbine (around 0.7 Hz which corresponds to a repetition every 1.4 s or 14 rotations per minute for a three-bladed turbine). Spurious sources such as bird noise are clearly distinguished from the constant trend characteristic of wind turbine noise. This therefore represents an objective representation of the wind turbine modulation.

Where spurious sources remain despite the filtering undertaken, this is clearly identifiable as vertical lines in the waterfall spectrum of Figure 7.5, with values over a wide range of frequencies not associated with the BPF. These periods can therefore be discarded from the analysis. Valid data showing consistent wind turbine AM is indicated in contrast by broadly horizontal lines in the plot. A similar approach is used in practice for the analysis of tonality in line with ETSU-R-97 for which the Fourier spectra clearly indicate the relevant frequencies involved and requires removal of periods affected by sources which do not have the same frequencies as those characteristic of the turbine sources.

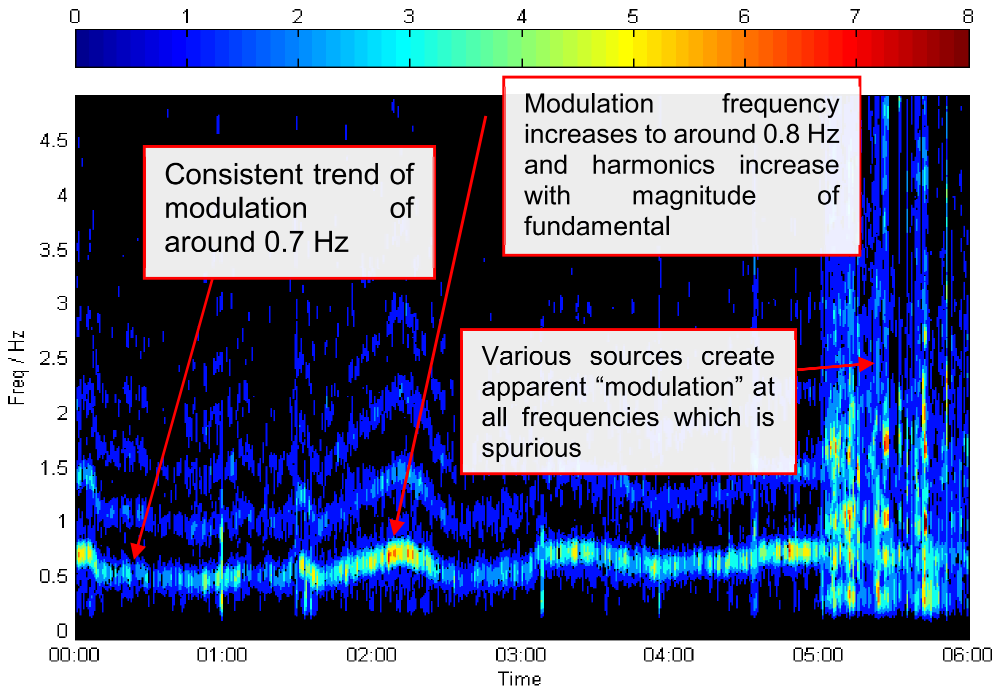


Figure 7.5 Waterfall plot example

7.5 Choice of parameters

Following a sensitivity analysis undertaken on actual measured data, it was determined that:

- The 10s rectangular window analysis provided a meaningful measure of the average modulation within that window. Looking at shorter windows or using a moving Hann-type window (with overlap) provided more values and additional time resolution, but when analysed statistically over a 10 minute period this resulted in similar values
- The rectangular window provided a good balance between frequency resolution and good representation of the amplitude
- The amplitude of the fundamental of the signal is retained as a meaningful measure of the modulation as it was determined that this

parameter scaled with the amplitude of the rest of the signal for typically observed AM signals. This is similar to the approach used by other researchers: see Section 4.4. The amplitude of the second and subsequent harmonics in the PSD of the input signal cannot be added directly as this ignores the phase information of the signal. Except in the clearest of signals, the amplitude of many of the higher harmonics will be contaminated by inherent noise and practical limitations of the signal analysis rather than representing actual features of the signal

8 METHOD 3 - HYBRID RECONSTRUCTION METHOD

8.1 Overview

The reconstruction method is a hybrid between an FFT-based method and a time-series method to determine the peak-to-trough modulation depth. The blade passing frequency is determined (typically using an FFT of the 100 ms data) which then forms the basis of digital filters implemented in the time-domain. The result is a cleaned version of the time-series with reduced extraneous noise whilst retaining energy at the first three harmonics. The amplitudes of the peaks and troughs are then identified, which provide a means of calculating the peak to trough level of modulation, typically by taking the average level of the troughs from the average level of the peaks.

The method takes the strengths of the FFT based method in discriminating wind turbine AM but retains the time domain characteristics of the signal. However the method requires complex filtering and data processing.

8.2 Description of Methodology

As described in Section 5, it is considered appropriate to perform analysis on band-filtered data (100 to 400 Hz by default) rather than overall A-weighted data in 10 second intervals. For each 10 second block:

1. The modulation frequency f_0 is determined (following the methodologies described in Section 7.2)
2. Coefficients for three 1/3-octave band pass filters are calculated, centred on f_0, f_1 and f_2, where f_0 is the BPF, $f_1 = 2*f_0$, and $f_2 = 3*f_0$. The filters should be 3rd-order Butterworth filters, with standard 1/3-octave band limits as edge frequencies[13]
3. The time-series is then filtered (in parallel) by each of the three band pass filters. It is essential to apply each filter twice, once forward and once backwards, to ensure linear phase. Given the narrow bandwidth of the filters, it is also necessary to include 10 seconds of data either side of the 10 second block in question to account for filter ring-up time. To clarify, if the 10 second block being analysed starts at 13:10:20, filtering should be performed on data between 13:10:10 and 13:10:40. For each of the three

[13] Note the centre frequencies for the 1/3-octave bands are centred on the relevant modulation frequencies and are not the preferred centre frequencies defined in BS EN 61260. The edge frequency should be calculated using the equations stated in this standard.

filters applied, the 10 second analysis block is cut from the middle of the 30 second block after filtering. This is further clarified in Figure 8.1

4. The three filtered signals are summed linearly (subject to conditions) to produce a reconstructed time-series, as shown in Figure 8.2. Three conditions are applied to determine whether f_1 and f_2 should be included in the reconstructed time-series. These conditions are proposed as an effective means of reducing false positives. The proposed conditions are:
   a. The maximum value minus the minimum value of the time-series filtered around f_0 (here denoted as $L_{pk\text{-}pk,0}$) should be greater than 1.5 dB;
   b. The maximum value minus the minimum value of the time-series filtered around the harmonic in question (here denoted as $L_{pk\text{-}pk,i}$) should be greater than 1.0 dB;
   c. $L_{pk\text{-}pk,i}$ should be less than $L_{pk\text{-}pk,0}$.
5. The peaks and troughs are identified using the following method:
   a. The location of local maxima are identified in the time-series filtered around f_0;
   b. Windows (of width half a cycle at f_0) are placed on the reconstructed signal, centred at the location of local maxima identified in Step (a).
   c. Peaks are identified as the maximum values within each window.
   d. The windows are then moved half a cycle and the troughs are identified by taking the minimum value within each window.
6. With the peaks and troughs identified, the mean level of amplitude modulation for the 10 second block in question can be calculated by taking the average of the troughs from the average of the peaks, as shown in Figure 8.3.

A block diagram showing the processing workflow is shown in Figure 8.4.

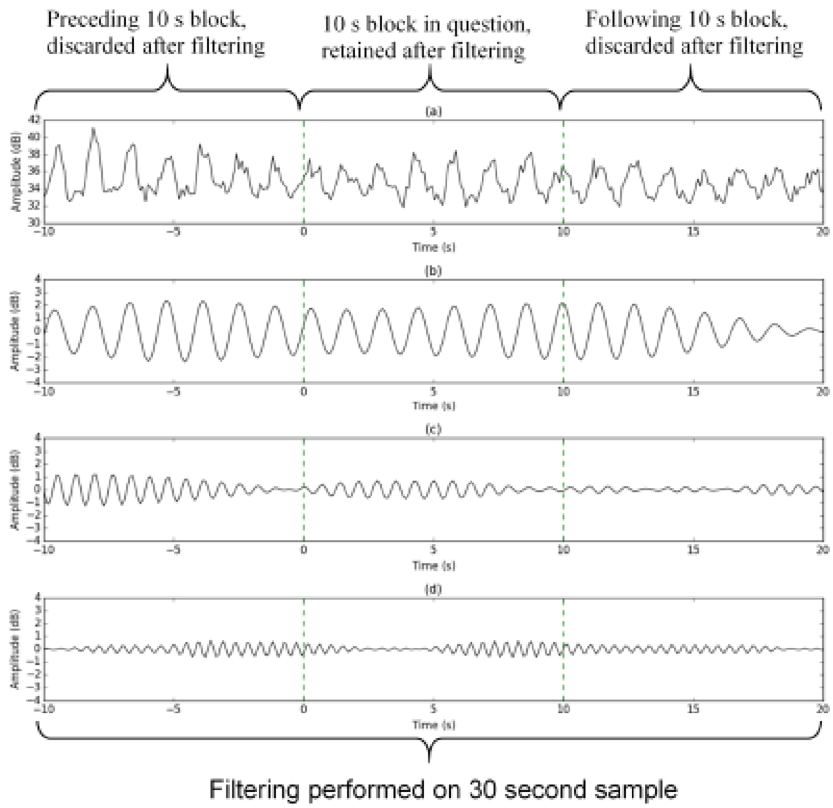


Figure 8.1 The 30 second block of data to be filtered. The raw signal is shown in (a). The raw signal filtered around f_0, f_1 and f_2 is shown in (b), (c) and (d) respectively.

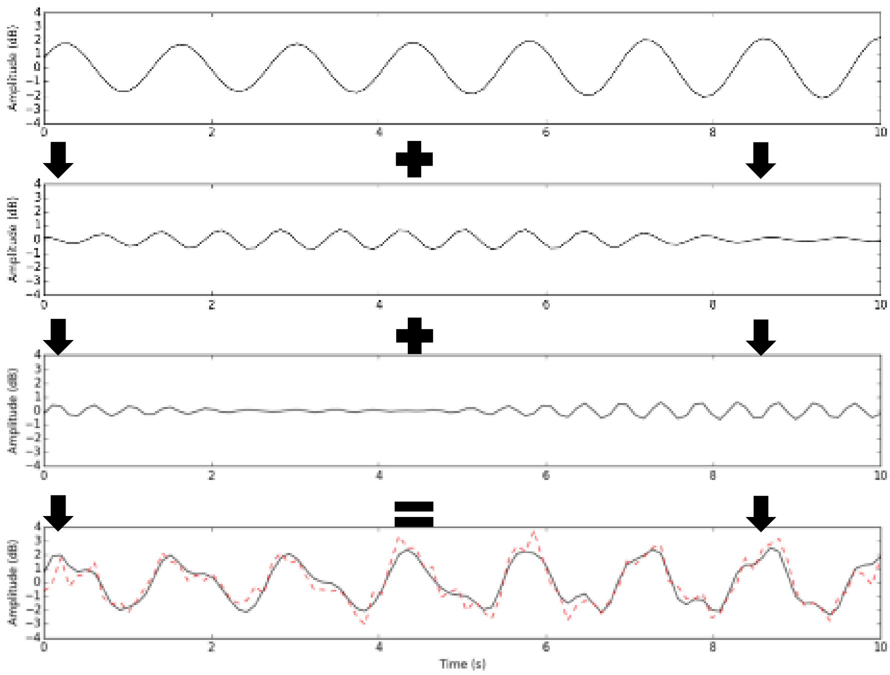


Figure 8.2 The three filtered signals, which sum together to give the reconstructed time-series shown in the bottom chart. The dashed red line shows the original data (detrended) for comparison.

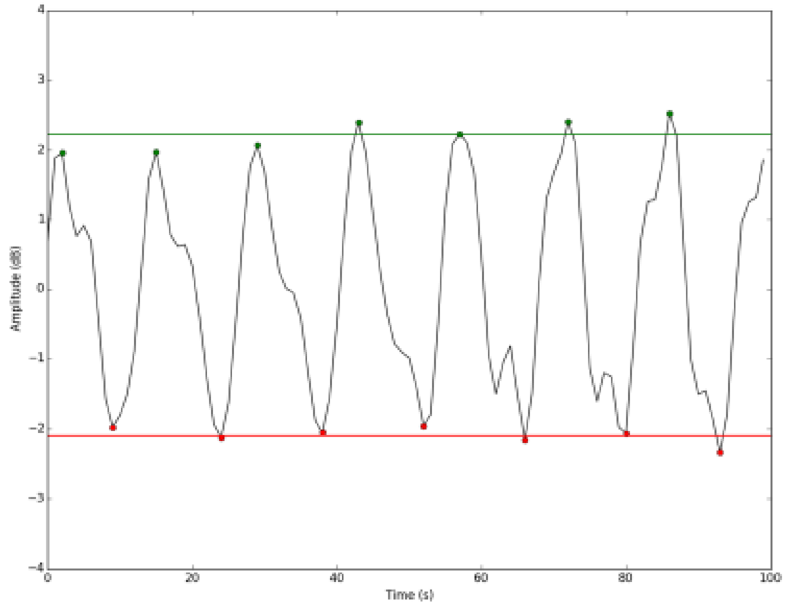


Figure 8.3 The reconstructed time-series with peaks and troughs marked by green and red dots respectively. The average peak and trough levels are shown by the horizontal green and red lines respectively.

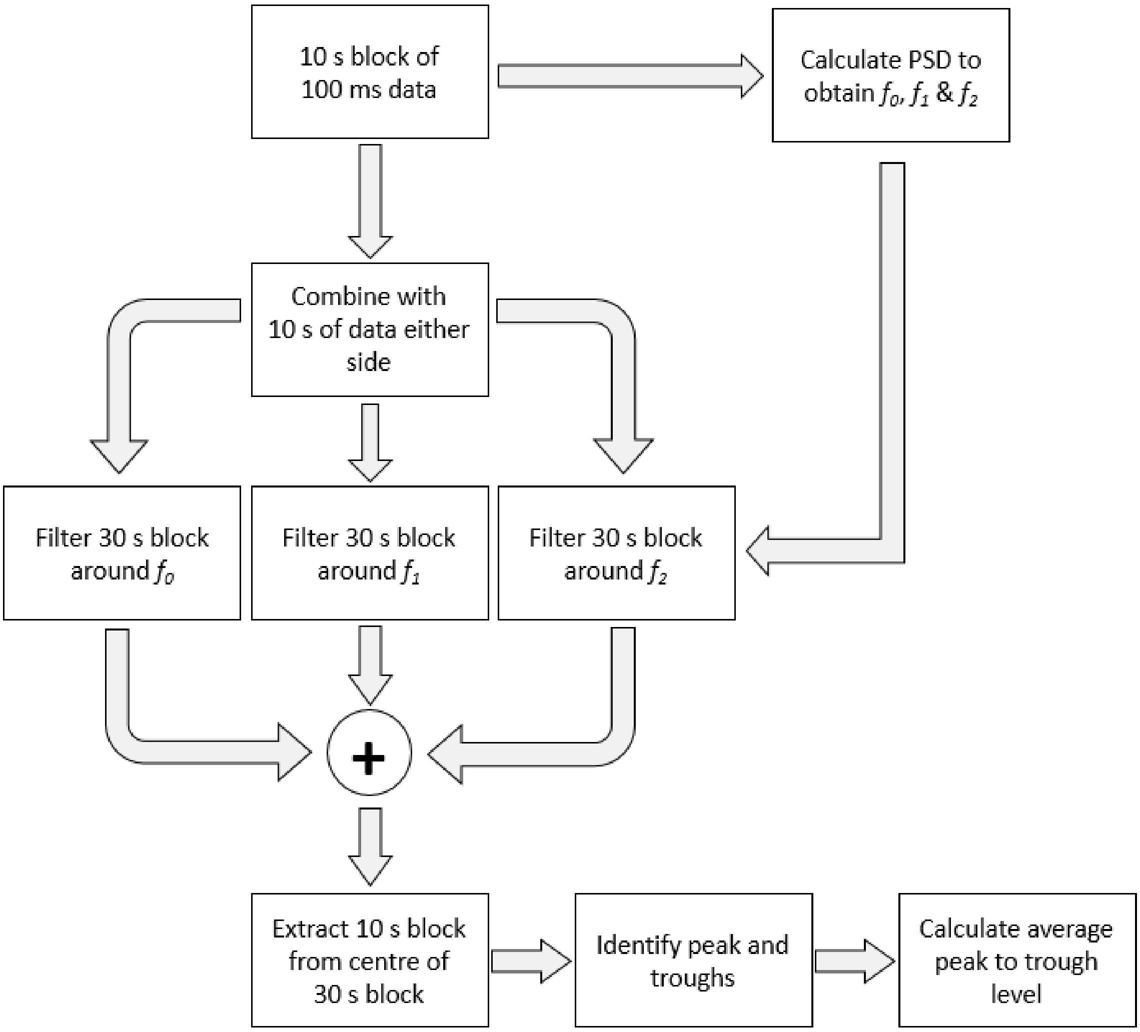


Figure 8.4 A block diagram showing the processing workflow.

8.3 Some Examples

The reconstruction method provides a means of estimating the peak to trough level in an amplitude modulation time-series. The figures below show a number of examples of different time-series, each with the reconstructed signal shown in black and the original (detrended) time-series shown in dashed red.

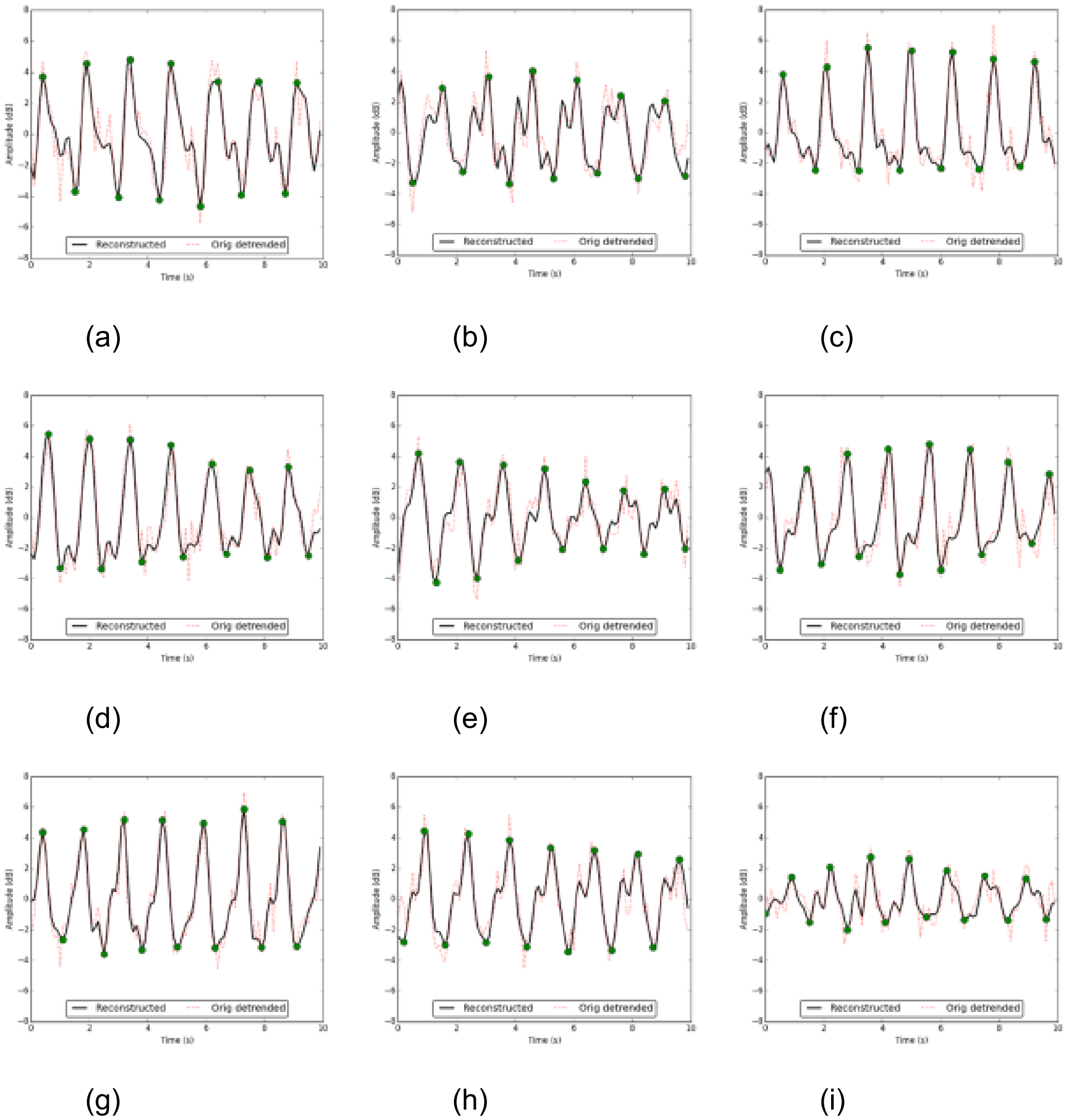


Figure 8.5 Examples of the reconstructed time-series

The figures above show that a complex time-series can be accurately reconstructed using the first three harmonics. A balance has to be made when deciding how many harmonics to include - including 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 whilst maintaining a low noise floor.

It should be noted that the figures compare the reconstructed signal, which has been filtered to remove the DC component, with the original signal, which is detrended using a 5th order polynomial. This is not comparing like for like and small differences between the two time-series should be expected. However, notwithstanding the above, it can be seen in Figure 8.5 that short small peaks (and less often toughs) are occasionally not fully represented, e.g. the second and penultimate peaks in Figure 8.5(c). There are a number of possible reasons for this. It may be that the time response of the filters is too slow to pick up these short variations. The peak may also be extraneous noise in a frequency band outside that of the filters; in which case it is right to reject it. Despite these occasional discrepancies, the average peak-to-trough level is well represented by the reconstruction method in most cases.

8.4 Noise Floor

The term ‘noise floor’ here refers to the values obtained when the method is applied to background noise (i.e. samples with no wind turbine amplitude modulation present). Given the relatively narrow bandwidth of the 1/3-octave filters, extraneous noise can be reduced, as all noise outside of the 1/3-octave band centred on the modulation frequency is filtered out of the signal. Figure 8.6 shows examples of such instances of modulated noise in the original signal which is reduced by the reconstruction method.

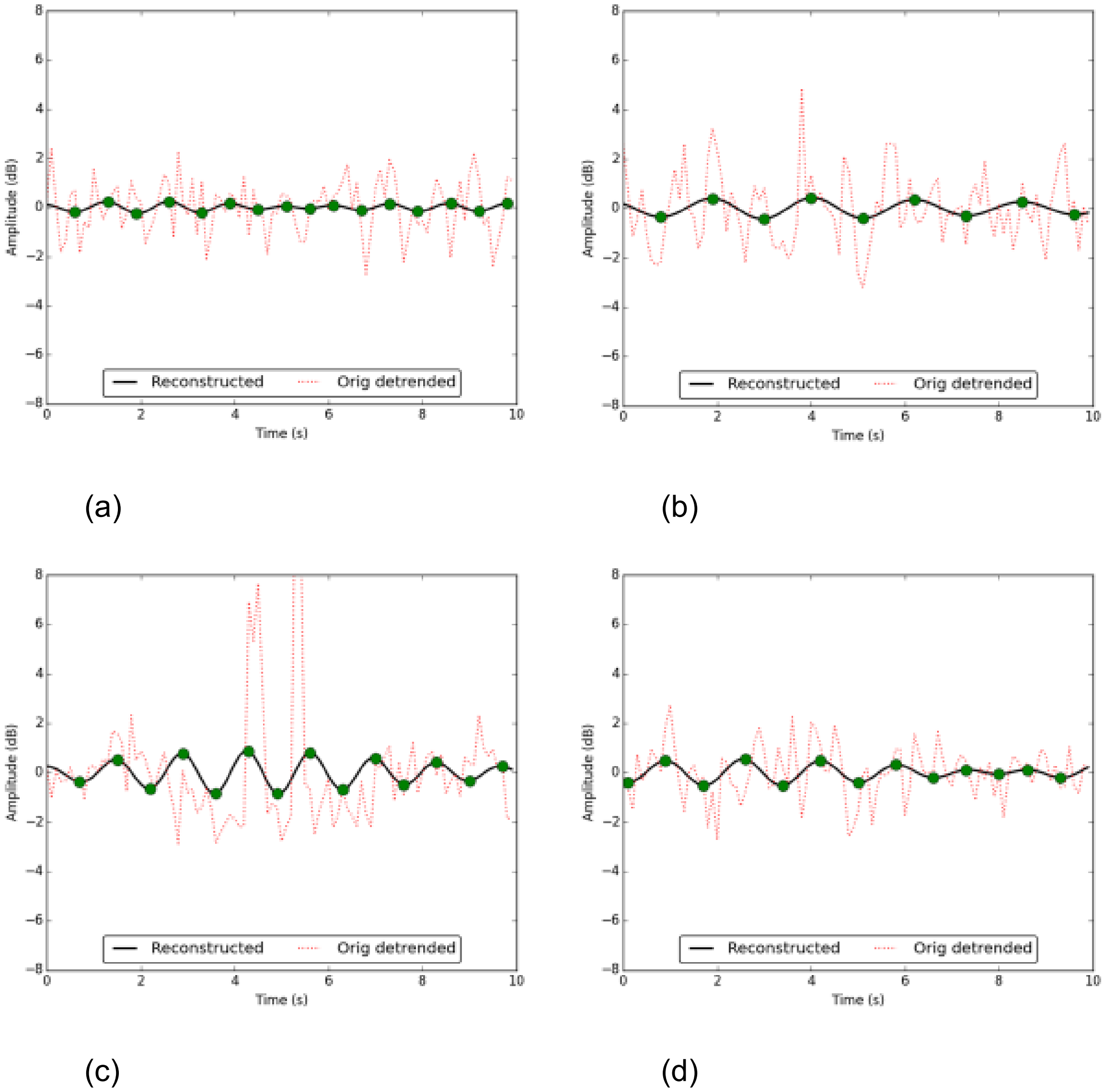


Figure 8.6 Examples of noise suppression

8.5 Similarity to FFT Based Method

It should be noted that the reconstruction method is not wholly dissimilar to the FFT-based method. The width of a third-octave band filter at typical modulation frequencies is comparable to the width of the integrating window used in the FFT-based method. A similar goal is therefore achieved by filtering in the time domain compared to integrating the output of a power spectral density in the frequency domain. The difference in resulting amplitudes can be mostly accredited to the inclusion of harmonic content in the reconstruction method.

9 COMPARISON OF METHODS

The different methods considered were investigated on a range of available datasets, both on artificial stimuli, used in the study of subjective response from AM, and on real measurements taken at locations neighbouring actual operating wind farms. The current section presents some results of this analysis, focusing on the three recommended methods described in the previous sections.

Please note that some of this output is based on earlier implementations of the methods, which may have had slightly different parameters than those stated in the above descriptions, but the outputs are nevertheless considered representative for the purpose of this consultation document.

9.1 Artificial stimuli

9.1.1 RenewableUK Work

This section shows results of applying the proposed methods to the artificial stimuli used in research undertaken by the University of Salford (RenewableUK 2013), and kindly provided by the researchers. Different results are obtained for each of the methods, which highlights that it is necessary to take care in relating the output of different metrics to the results of subjective testing. Each of the charts provides a comparison with the simplified stimuli design parameter used by the original researchers.

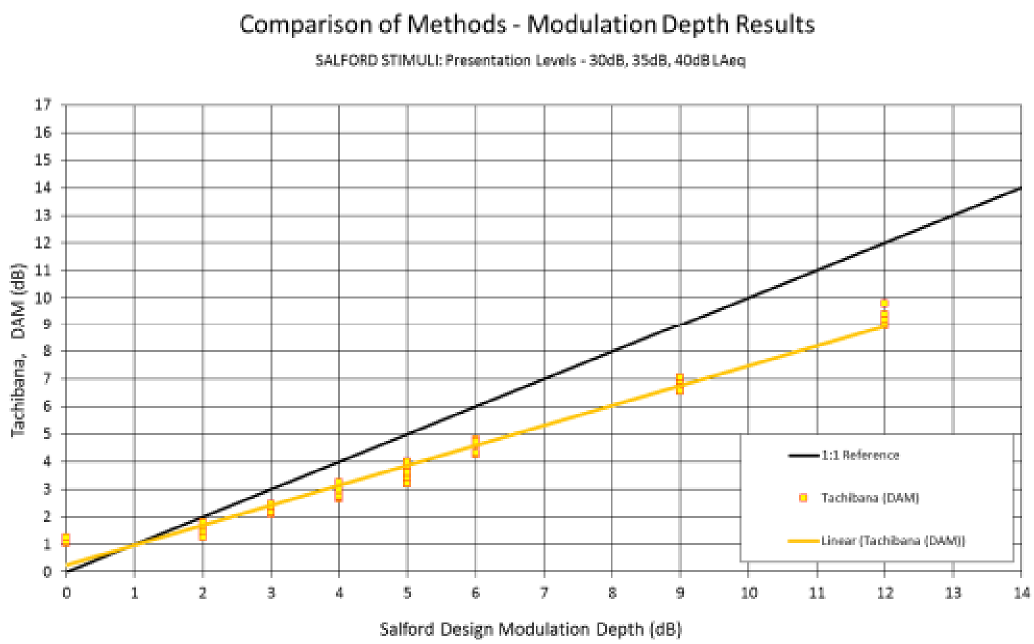


Figure 9.1 Analysis of the artificial stimuli used by the Salford researchers using Method 1 (D_{AM}, vertical axis) as a function of the stimuli design level (horizontal axis)

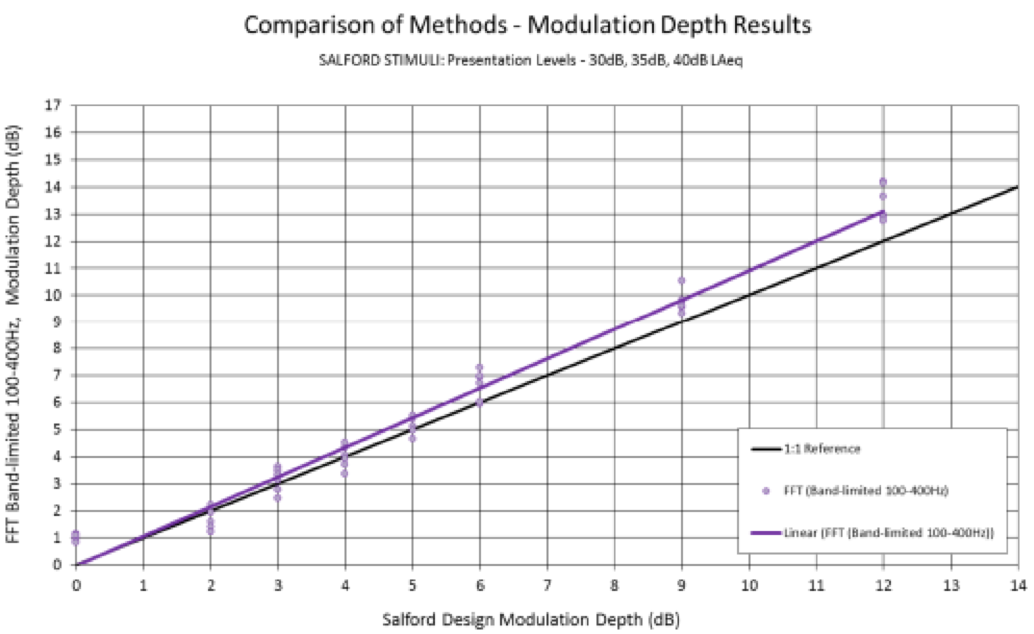


Figure 9.2 Analysis of the artificial stimuli used by the Salford researchers using Method 2 (Band-passed FFT, vertical axis) as a function of the stimuli design level (horizontal axis)

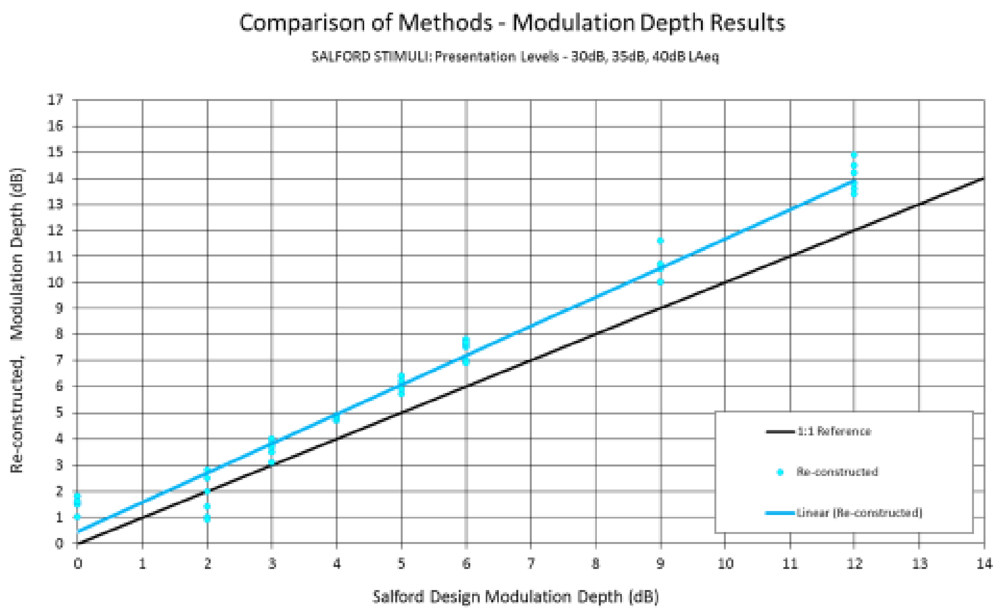


Figure 9.3 Analysis of the artificial stimuli used by the Salford researchers using Method 3 (reconstruction method, vertical axis) as a function of the stimuli design level (horizontal axis)

9.1.2 Japanese work

This section shows results of applying the proposed methods to the artificial stimuli used in research undertaken by researchers in Japan (Yokoyama, Sakamoto et al. 2013), and kindly provided to the AMWG by the authors. Compared to the stimuli used in the RenewableUK work, these were more broadband and regular, which explains the differences in the ratings obtained.

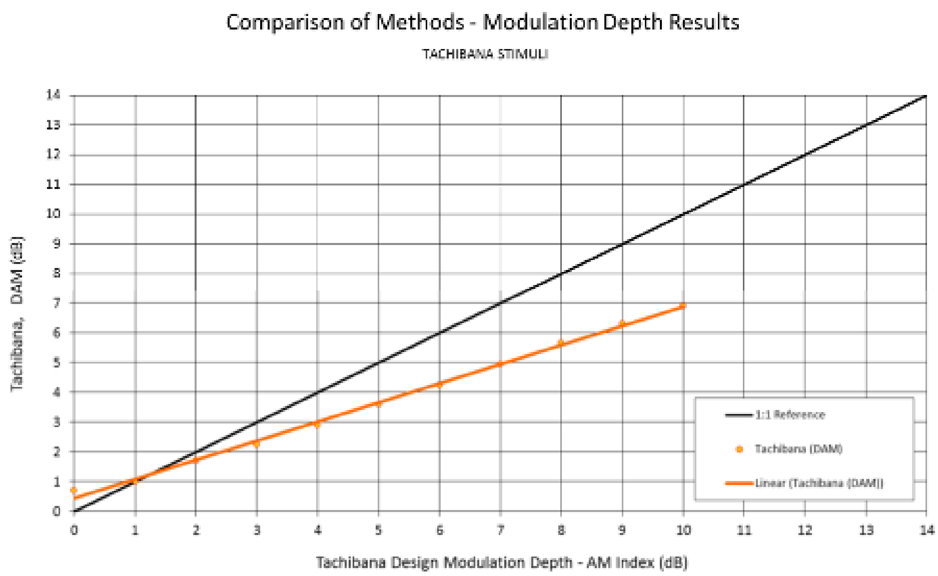


Figure 9.4 Analysis of the artificial stimuli used by the Japanese researchers using Method 1 (D_{AM}, vertical axis) as a function of the design level (horizontal axis). This highlights the difference between the AM Index used in the stimuli design and the output of the metric (D_{AM}) (see 4.3.3)

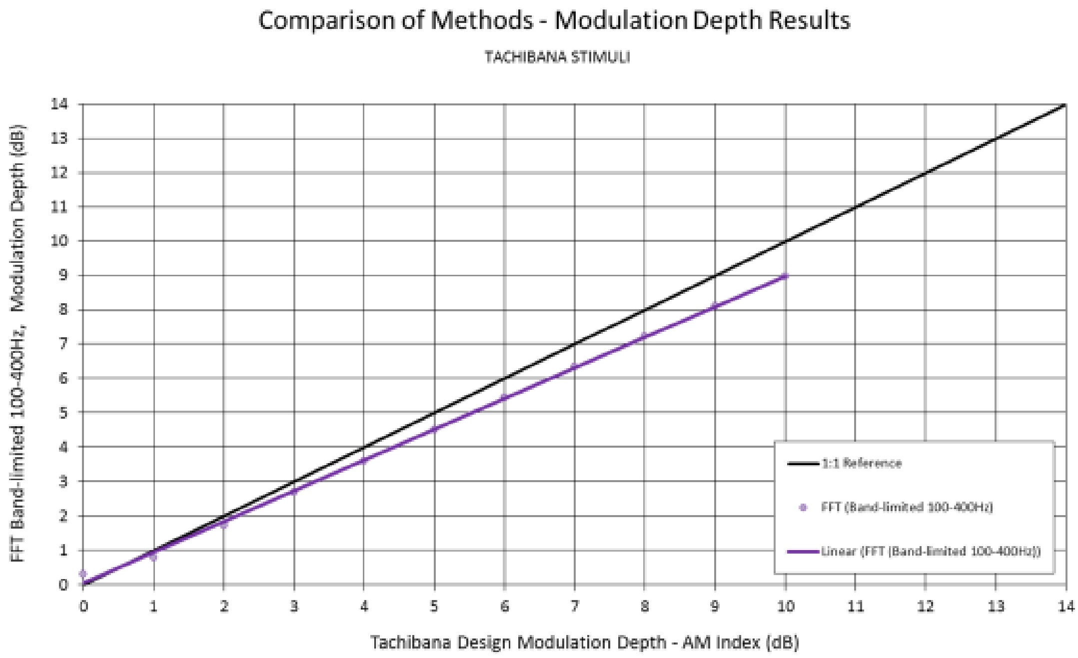


Figure 9.5 Analysis of the artificial stimuli used by the Japanese researchers using Method 2 (Band-passed FFT, vertical axis) as a function of the design level (horizontal axis)

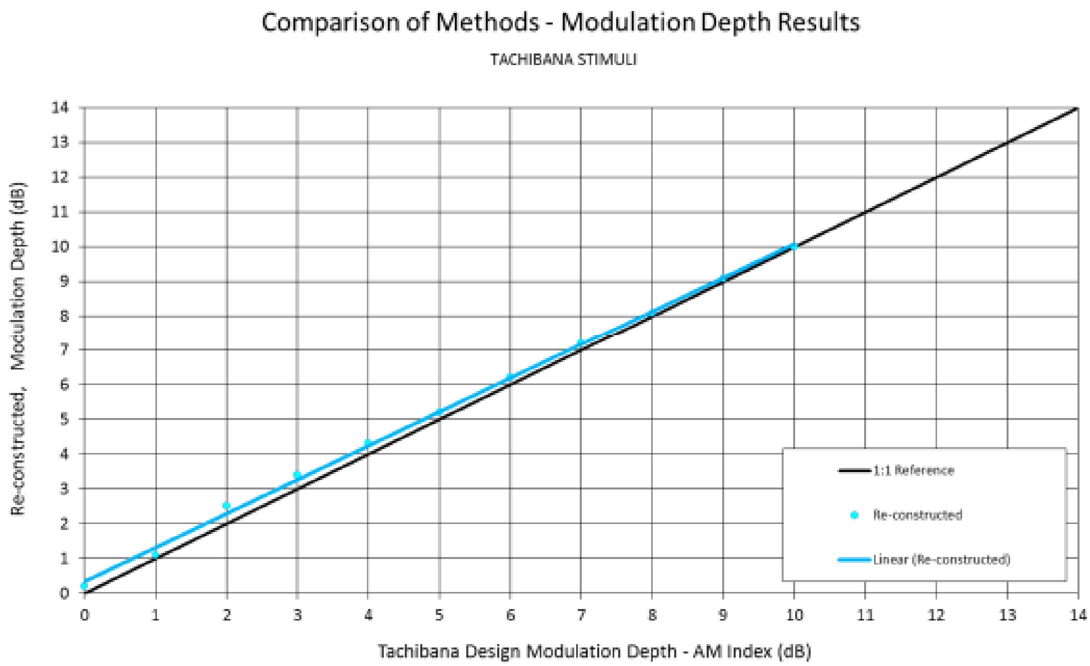


Figure 9.6 Analysis of the artificial stimuli used by the Japanese researchers using Method 3 (reconstruction method, vertical axis) as a function of the design level (horizontal axis)

9.2 Example of on-site measured data

The following charts are based on the analysis of data measured at a free-field location adjacent to an operational wind farm ('Site B'). The period analysed represents 6 hours of data with varying levels of modulation, some of them marked. The site is considered relatively quiet and the period analysed comprises mostly core night-time hours but also includes a period affected by bird noise.

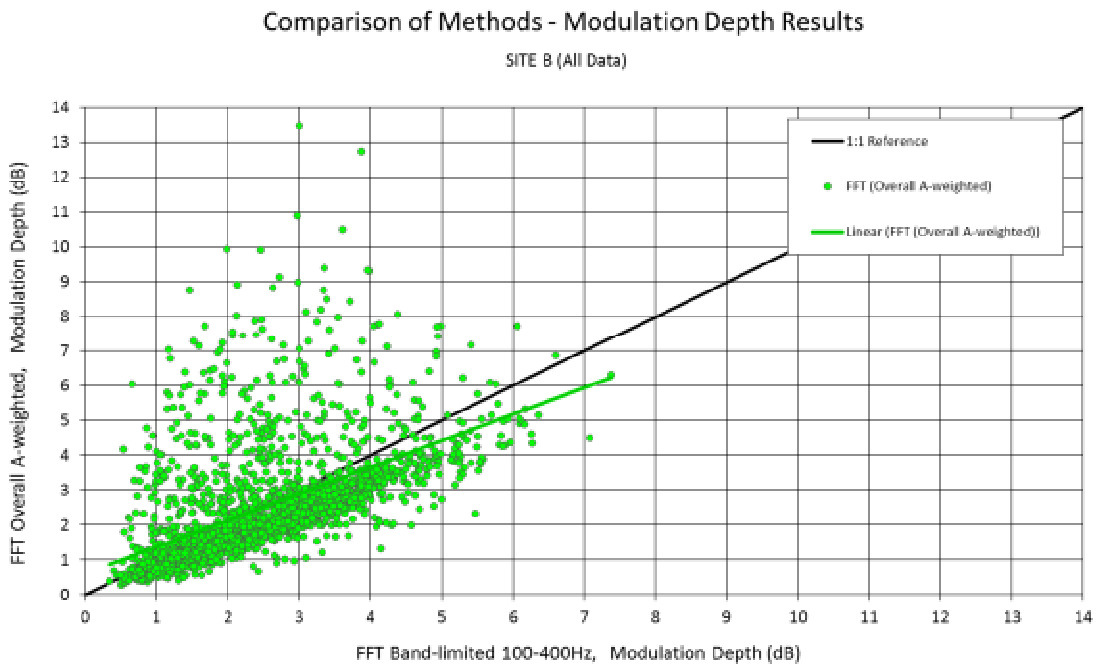


Figure 9.7 Comparison of Method 2, with the FFT applied to data band-filtered in the range 100-400 Hz (horizontal axis), and also if applied to A-weighted data (vertical axis). This chart shows all data, with in particular a large number of erroneous "false positive" results

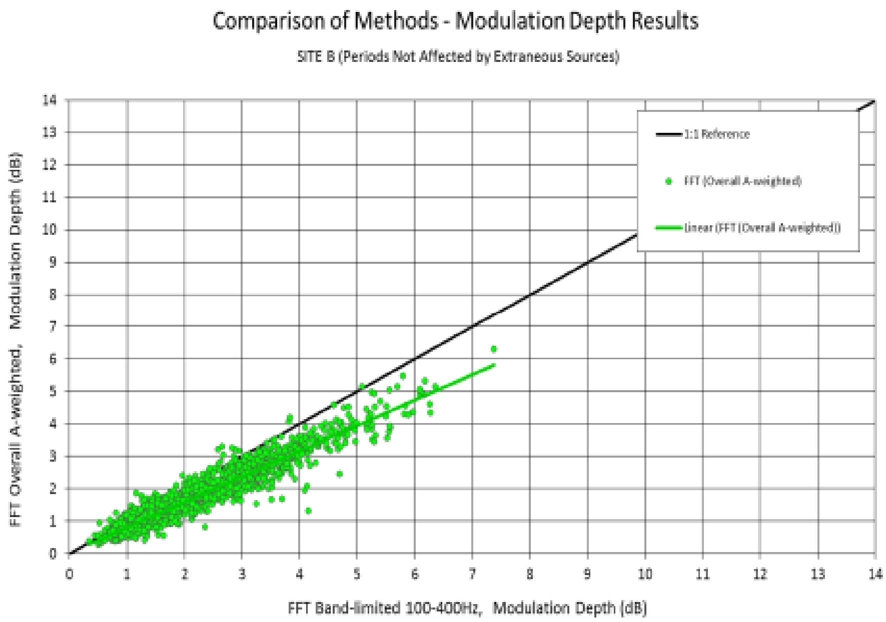


Figure 9.8 Same comparison as Figure 9.7, but in this case most of the spurious periods were manually excluded; this shows that, on valid data, the filtered analysis provides generally higher ratings

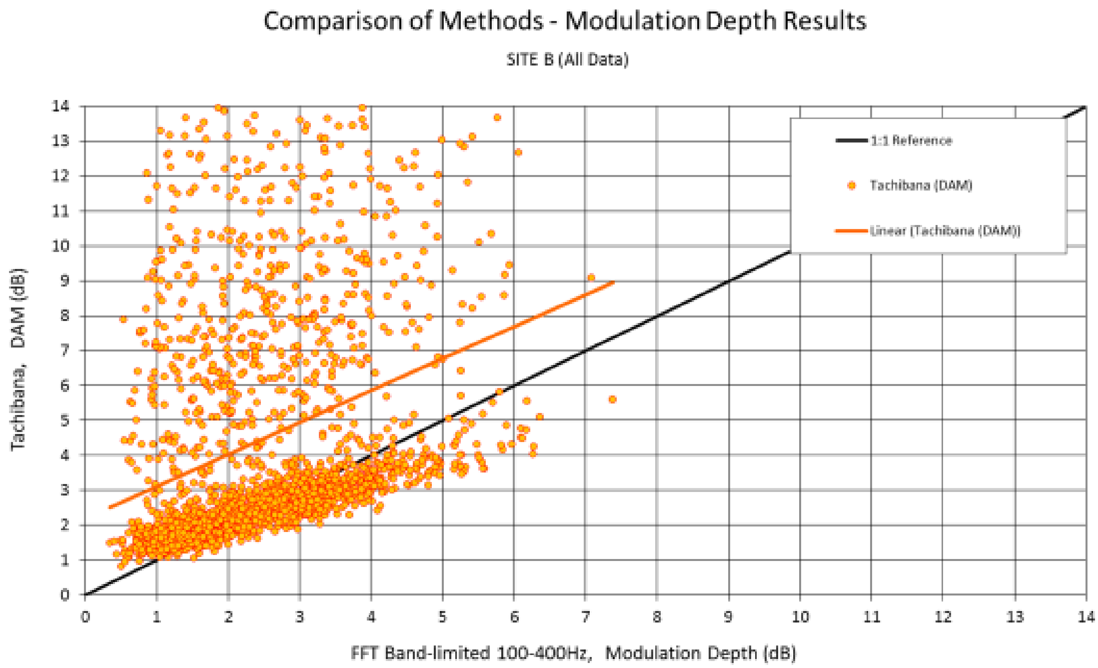


Figure 9.9 Comparison of Method 2 (FFT, horizontal axis) with Method 1 ("Tachibana" method, vertical axis). This shows all data, with in particular a large number of erroneous, "false positive" results

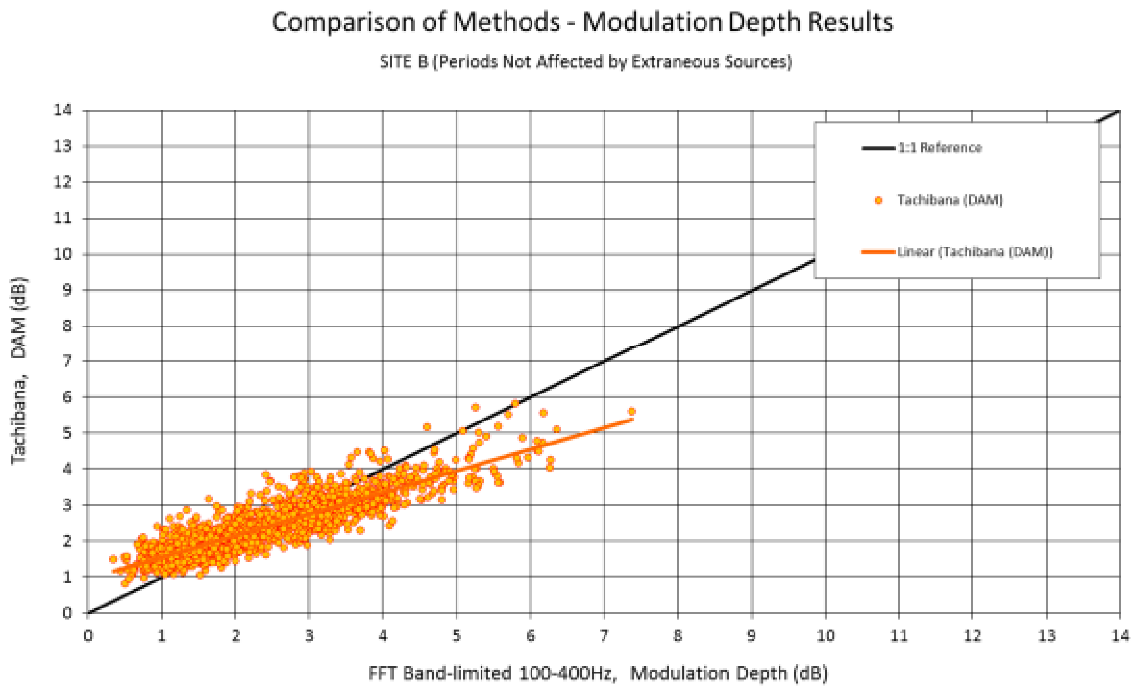


Figure 9.10 Comparison of Method 2 (FFT, horizontal axis) with Method 1 ("Tachibana" method, vertical axis). This excludes spurious periods as in figure 9.8 above

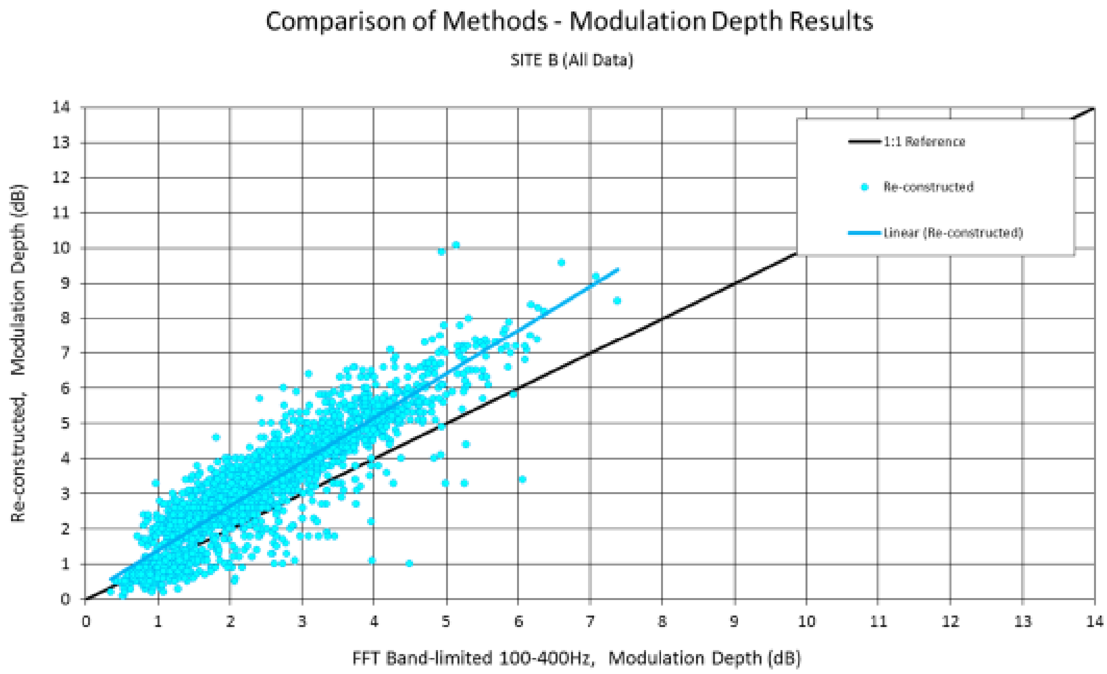


Figure 9.11 Comparison of Method 2 (FFT, horizontal axis) with Method 3 (reconstructed time series, vertical axis). This shows all data, illustrating the relative robustness of both methods

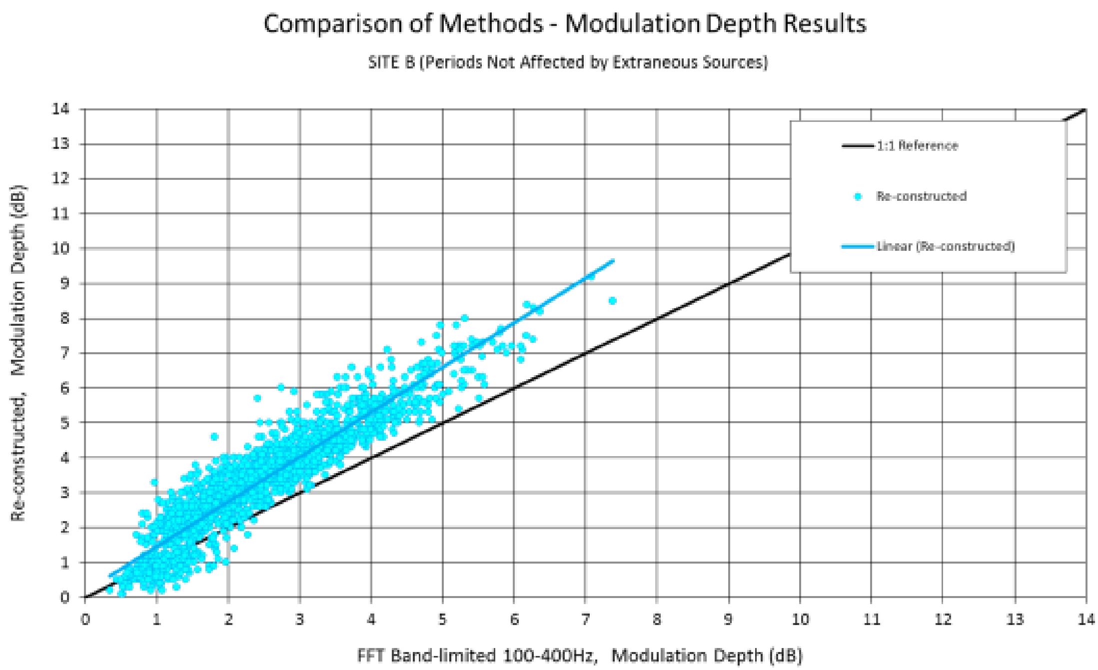


Figure 9.12 Comparison of Method 2 (FFT, horizontal axis) with Method 3 (reconstructed time series, vertical axis). This excludes spurious periods as in figure 9.8 above.

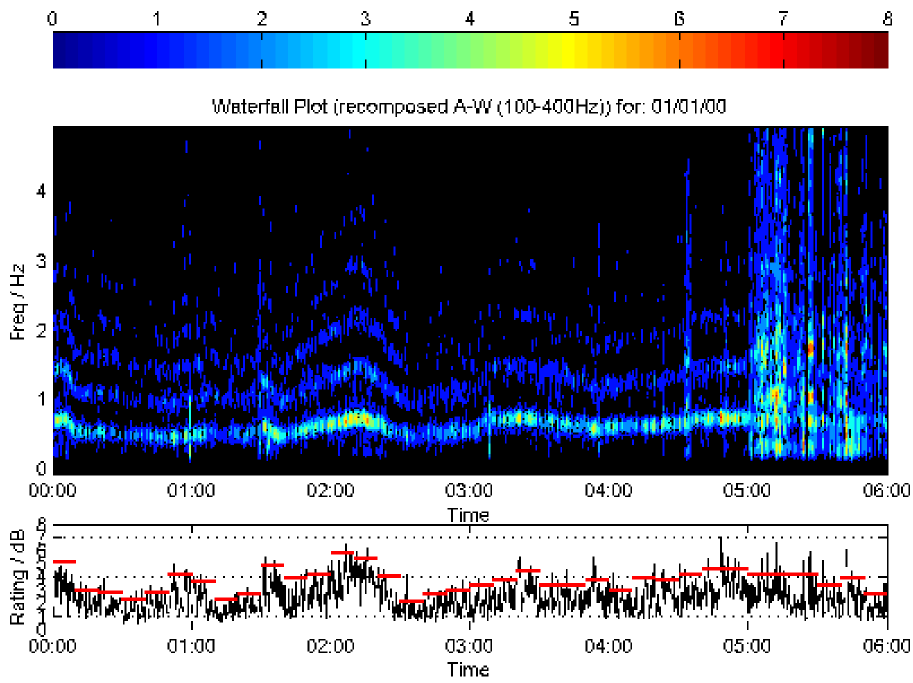


Figure 9.13 Chart showing a detailed time history of the output of method 2 as a function of time (horizontal axis) for site B: the top chart (colour) shows all the modulation spectra for each 10 s interval (waterfall *plot); the bottom chart shows the modulation magnitude at the BPF for each 10 s (black line) and the 10 minute level (90th percentile, red line). Contaminated periods are visible as vertical lines in the waterfall chart.*

10 INSTRUMENTATION

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.

In order that the AM measurements are resistant to the effects of wind turbulence, the existing guidance regarding windshields should be followed. If data is available regarding the effect of the used windshield on frequency response, it shall be used to correct the measurement.

Similarly, any correction required for microphone orientation shall be used.

However, it is unlikely that either of these corrections will be significant in the frequency range proposed for AM metrics.

The main difference with standard wind farm noise measurements is the requirement to capture data at sufficient resolution in order to capture the variations in levels associated with modulation. A resolution of a fraction of a second[14] is required rather than the 10 minute averaging used in ETSU-R-97.

10.1 Noise measuring equipment

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.

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.

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.

10.2 On-line AM measurement

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

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.

10.3 Sound level logging equipment

Instruments for storing sound level with time shall meet the requirements of BS EN 61672-1: 2003 to Class 1 accuracy.

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

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

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

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[14] It is common to use 8 or 10 times per second sampling (100 or 125ms resolution) as this is the basic data capture rate of several sound level meters.

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

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).

Regardless of the post-processing method used for calculating the AM rating, the stored data must be made available in a format easily readable by text editors or spreadsheets

10.4 Audio recording equipment

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

Recordings shall 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.

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

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

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 651 Type 1), including frequency response, linearity and dynamic range. The onus is on the user to verify these requirements are met.

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

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 background noise surveys, or for noise compliance measurements, can be used to capture suitable data for AM analysis. (IOA 2013) (IOA 2014)

The sound level meter should be set-up to measure at least the following:

- the L_{Aeq} index for consecutive 100 ms periods within each 10 s period, for every 10 min interval considered

and, optionally:

- the L_{Aeq} & L_{A90} indices in 10 min intervals
- the L_{Aeq} & L_{A90} indices for consecutive 10 sec periods within each 10 min intervals
- in each 1/3-octave band from 63 Hz to 8000 Hz, the L_{eq} index for consecutive 100 ms periods within each 10 s period, for every 10 min intervals
- at least 2 min of audio for every 10 min interval considered
- audio shall be recorded as uncompressed WAV file in mono with a sample rate of at least 12 kHz and a bit depth of at least 16 bits.

Alternatively, where it is possible to record audio for the entire period of interest, it is also possible to calculate the above statistics directly from the audio data using suitable software, for example 01dB's 'dBFA'. In this event, careful consideration should be given to obtaining calibration recordings so that all data can be converted into absolute units.

11 SOFTWARE

Software will be provided when available.

12 REFERENCES

Bass, J. (2011). "Investigation of the 'Den Brook' Amplitude Modulation Methodology for Wind Turbine Noise " Acoustics Bulletin **36 Nov/Dec 2012 and 37 Jan/Feb 2012**.

Cooper, J. and T. Evans (2013). "Automated detection and analysis of amplitude modulation at a residence and wind turbine " Proceedings of Acoustics 2013 – 17-20 November 2013, Victor Harbor, Australia.

di Napoli, C. (2009). "Case Study: Wind Turbine Noise in a small and quiet community in Finland." Proc Third International Conference Wind Turbine Noise. Aalborg.

di Napoli, C. (2011). "Long distance propagation of wind turbine noise." Proc 4th International Meeting Wind Turbine Noise, Rome.

ETSU-R-97 (1996). "THE ASSESSMENT AND RATING OF NOISE FROM WIND FARMS The Working Group on Noise from Wind Turbines
Final Report."

Fukushima, A., et al. (2013). "Study on the amplitude modulation of wind turbine noise: Part 1 – Physical investigation " Proc Internoise 2013.

Gabriel, J., et al. (2013). "Ampliude modulation and complaints about wind turbine noise." Fifth Intenational Confernce Wind Turbine Noise, Denver.

Hayes, M. (2006). "The measurement of low frequency noise at three UK wind farms. DTI Report - 06/1412."

http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/energy/sources/renewables/explained/wind/onshore-offshore/page31267.html.

IoA (2013). " A good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise."

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

Ioannidou, C. (2014). "Amplitude Modulation of Wind-Turbine Noise and its Effect on Annoyance." MSc Thesis Danish Technical University.

ISO:15666 (2003). " Acoustics- Assessment of noise annoyance by means of social and socio-acoustic surveys."

Large, S. and M. Stigwood (2014). "The noise characteristics of 'compliant' wind farms that adversely affect its neighbours " Proc Internoise 2014, Melbourne.

Larson, C. and O. Ohlund (2012). "Variations of sound from wind turbines during different weather conditions." Proc Internoise 2012.

Larsson, C. and O. Ohlund (2014). "Amplitude modulation of sound from wind turbines under various meteorological conditions." Jnl Ac Soc America **135 (1)**: 67-73.

Lee, S., et al. (2011). "Annoyance caused by amplitude modulation of wind turbine noise." Noise Control Eng Jnl **59**: 38 - 46.

Lee, S., et al. (2009). "An estimation method of the amplitude modulation in wind turbine noise for community response assessment." Proc Third International Meeting on Wind Turbine Noise, Aalborg:

Legarth, S. V. (2007). "Auralisation and Assessments of Annoyance from Wind Turbines." Proc Second International Conference on Wind Turbine Noise. Lyon.

Lenchine, V. (2009). "Amplitude modulation in wind turbine noise." Proceedings of ACOUSTICS 2009 23-25 November 2009, Adelaide, Australia.

Levet, T. and M. Craven (2014). "Initial findings using RUK AM assessment methodology." Inst Acoustics Conference "Wind Turbine Noise. AM, and where to next for ETSU-R-97"( ).

Lundmark, G. (2011). "Measurement of swish noise. A new method." Proc Fourth Int Mtg. Wind Turbine Noise Rome.

McCabe, N. (2011). "Detection :and Quantification of AM in Wind turbine Noise." Proc Fourth Int Mtg. Wind Turbine Noise Rome.

McLaughlin, D. (2011). "The measuremnt of amplitude modulation frequency spectrum." Proc. Fourth International Meeting Wind Turbine Noise, Rome.

Moroney, L. and J. Constable (2011). "The Den Brook Amplitude Modulation Noise Condition " Renewable Energy Foundation - Information Note.

NZS (2010). "NZS 6808:2010 Acoustics – Wind farm noise "

Persson Waye, K. and E. Ohrstrom (2002). "Psycho-acoustic Characters of Relevance for Annoyance of Wind Turbine Noise." Jnl Sound Vibration **250(1)**: 65-73.

RenewableUK (2013). "Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect." Work package B2.

Seong, Y., et al. (2013). "An experimental study on rating scale for annoyance due to wind turbine noise " Proc Internoise 2013,.

Siponen, D. (2011). "Noise annoyance of wind turbines " RESEARCH REPORT VTT-R-00951-11.

Tachibana, H., et al. (2014). "Nationwide field measurements of wind turbine noise in Japan." Noise Control Eng Jnl **62**(2): 90-101.

van den Berg, F. (2005). "The Beat is Getting Stronger: The Effect of Atmospheric Stability on Low Frequency Modulated Sound of Wind Turbines." Jnl Low Freq Noise Vibn and Active Control **24**(1): 1-24.

Van den Berg, G. (2006). "The sound of high winds." Thesis.

Vogl, S. (2013). "Detection and Rating of Amplitude Modulation of Wind Turbine Sound (in German)." Thesis Jade Hochschule (University of Applied Sciences).

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

Zwicker, E. and H. Fastl (1999). "Psychoacoustics. Facts and models." Springer.

APPENDICES

Appendix A Terms of Reference Paper

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 5 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 2 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 5 months from the Inception meeting to the publication of a consultation draft and software. A 6 week consultation is envisaged, followed by a further 4 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 AM WG
- 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 AM WG 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
- Sam Miller, Xi Engineering
- 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 & 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 Dec 2013 and recent modifications to the RenewableUK method which would correct some of the shortcomings – see Tom Levet (metric) & 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:
    - methods based in the time domain
    - methods based in the frequency domain or
    - 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
- 1/3-octave 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 & 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.