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Amplitude Modulation analysis - now and in the future

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Summary

Over the past 10 years, significant progress has been made in the analysis of amplitude modulation in wind turbine noise. Several numerical analysis techniques have emerged and been refined by a number of authors. In particular, in 2016 a UK Institute of Acoustics working group published a proposed analysis methodology based on a hybrid frequency/time domain approach, which has been applied by a number of authors in the UK and abroad. The international community is now considering the assessment of this noise feature as part of an effort to standardise the measurement of wind farm noise in the far-field. It is therefore a good time to review the IOA method and its parameters, its application to a number of practical test cases, and perspectives for developing its scope further.

1. Introduction

Amplitude modulated (AM) sound can sometimes arise in proximity or in the far-field of wind turbines, the latter phenomenon being complex and sometimes pronounced to the extent that disturbance can arise. Following increased interest in this subject, different practitioners developed a number of comparable techniques to rate the level of modulation. However, the lack of a standard and robust assessment method made the research on this subject more difficult. Any such method needs to be useable on real-world recordings which are often corrupted by a number of other sources, particularly in the far-field.

The AM analysis method published in 2016 by the Institute of Acoustics [1] represents the outcome of the development of such a method by a UK-based working group, following a review of previous work on the subject. In summary, the procedure in Ref. [1] involves undertaking a frequency analysis of a band-filtered $L_{eq,100ms}$ signal separated in 10s blocks: if a clear peak is identified in the resulting modulation spectrum, at a rate expected for the turbines considered, then this indicates the presence of some AM. The identified modulation signal and its first two harmonics in the spectrum are retained and used to reconstruct a filtered modulated signal, whose variation is then rated using a simple statistical metric.

Results for individual 10s are then combined in groups of 10 minutes and a rating is given based on the top 10% of the individual 10s results (effectively representing a typical worst-case). Importantly, this rating is only given if sufficiently clear modulation (as defined using a “prominence” rating) is present for at least 50% of that 10-minute period. This last requirement

in particular has been found to be very effective at automatically identifying wind turbine noise, which tends to be relatively persistent in time, compared to other sources which may trigger apparent “modulation” which corrupts the analysis. Such is the effectiveness of that method that it often eliminates a large proportion of erroneous data in the analysis, even without restricting analysis to the quieter night-time periods. Nevertheless, a residual number of erroneous results can still remain in the processed dataset and further data-validation procedures will be discussed below based on our experience.

The IOA method has already been applied by a number of other practitioners [2,3] with some success. As part of the use of this method at a number of UK sites, the present paper illustrates practices that have emerged in the application of these techniques. The paper also considers specific application cases and possible extensions of these techniques that could be considered as part of international development work for AM techniques.

2. Applications

2.1 AM Data analysis

In practice, due to a number of different factors, levels of AM in the far-field of wind turbines can experience a wide range of variability. Furthermore, the specific weather conditions associated with specific disturbance may not occur regularly. This can therefore require noise measurements over long periods of weeks or months in order to capture representative data. The resulting large data volumes can be daunting to analyse directly through review of the instantaneous noise levels time history; in any case this rarely provides directly meaningful information and provides little indication of the prevalence of any particular data.

The first step in the analysis using the IOA method involves producing a modulation spectrum for each 10s period. By plotting this spectrum as a function of time, the presence of modulation and its variation is clearly apparent, as in the example of Figure 1 below. This allows to quickly identify trends in the data over the short to medium term. These spectrograms also represent a rapid tool for data validation which, with some experience, largely precludes in practice the time-consuming review of audio samples or measured noise frequency spectra.

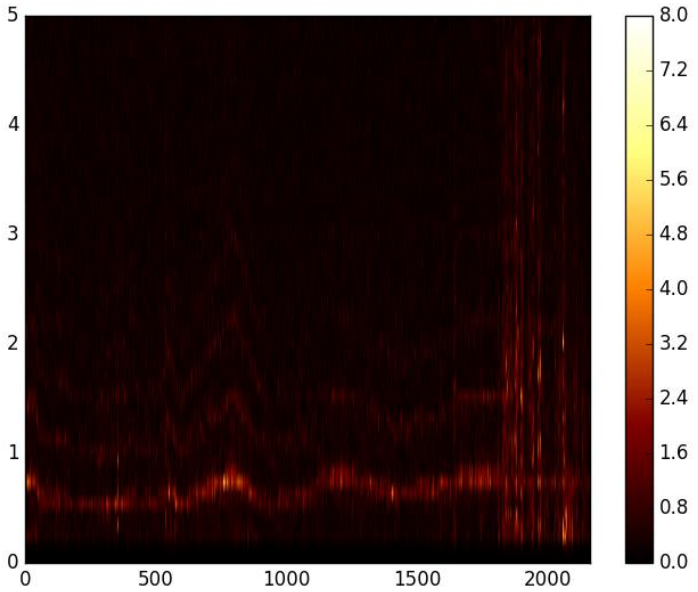

Figure 1 - Modulation spectrogram – scaled power spectral density of the modulation spectrum used in the IOA method analysis. Vertical axis: modulation frequency, horizontal axis: time, 10s blocks, representing a 6-hour period. Modulation from the turbines at variable rates is apparent as the varying but broadly horizontal spectral lines between 0 and 1 Hz (and harmonics); vertical lines represent corrupted data due to bird noise in this case.

2.2 Systematic analysis in relation to weather parameters

The short-term variations in noise or AM levels can be difficult to explain in themselves, but considering long-term results of the AM analysis against weather and operational data allows further analysis. Trends then often become more apparent which allows evaluating the situation at a particular site, either to consider the prevalence of this feature against any adverse comments from wind farm neighbours or to help consider mitigation of the feature if required.

Hoare Lea developed the use of representing the variation of AM through a type of "wind rose" showing the distribution of AM as a function of wind speed and direction, as shown in the example of Figure 2. This shows a particular case of AM present over a relatively wide range of conditions. This type of plot requires a single wind speed and wind direction, representative of the site, to be determined as in most wind farm assessments: either from a site anemometer mast or as measured from one or more turbines. In this case, the wind speed was "standardised" to 10 m height as per IEC 61400-11:2006.

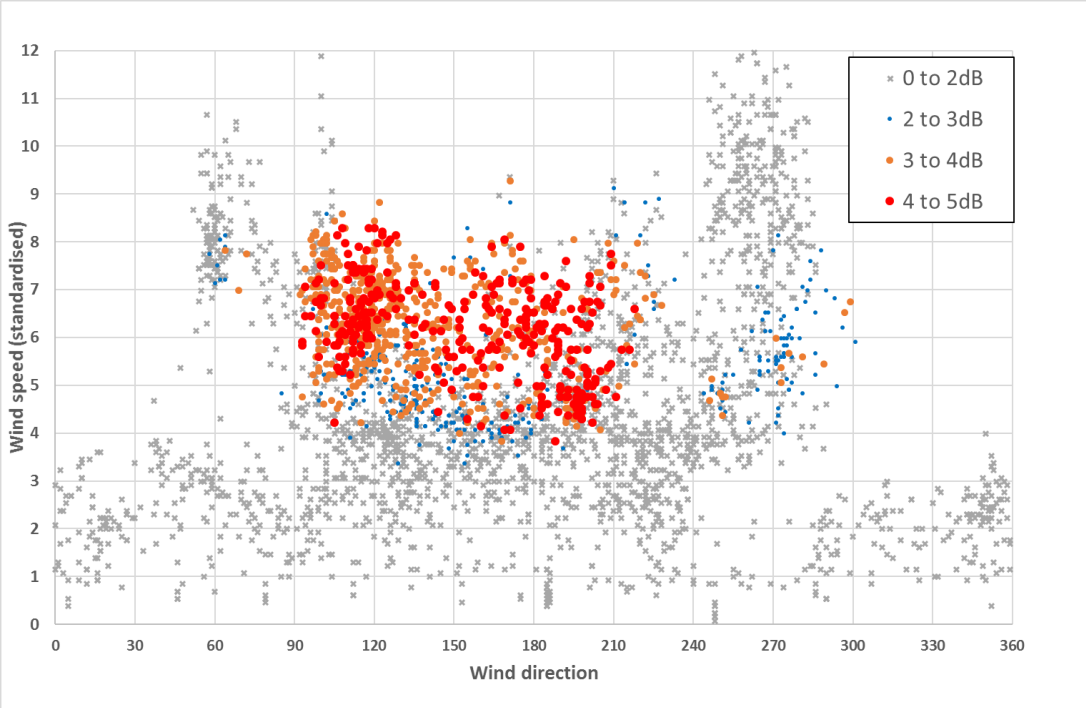

Figure 2 – Plot of AM ratings (10-minute values, IOA methodology [1]) determined over a long-term survey at a residential location in the far-field of a wind farm – values were separated into different bands and related to a representative wind speed and direction (average 10-minute values) for the site.

Provided a representative wind speed/direction is used, a clear pattern is often apparent. Furthermore, any outliers in this pattern will usually become clearly apparent in the chart and can be selected for further review and analysis: this can show if it is an atypical event or due to corruption from noise events not related to the wind farm. As this data is plotted as function of wind direction, a *radial* plot can also represent a useful graphical representation of the situation: this and other examples are included in Ref. [4].

The IOA method requires analysis in three frequency ranges: 50-200 Hz, 100-400 Hz and 200-800 Hz, to represent different turbine/site characteristics that may occur in different cases. The band that *"tends to give the highest modulation values over a representative range of valid data measured"* [1] should be use, and Ref [1] suggests a scatter plot is used. Additional experience suggests that this may be more complex on certain sites, for example if one band gives higher results for low modulation levels but the opposite is true for higher values.

In some cases, different frequency bands may give different results depending on the wind direction: for example, for the data in Figure 2, a different band-pass analysis gives much lower values in the 90-150 wind direction sector, but comparable values in the 150-220 sector. This suggests different AM generation effects at play, corresponding to other generation and/or propagation characteristics. This should be the focus of further research as this complex aspect of AM behaviour is currently poorly understood.

2.3 Binned analysis

Another way of represent the data such as that shown in Figure 2 is to undertake a “binned analysis”. Table 1 shows the result of averaging the ratings obtained by the IOA method in each bin, with the data split in bins of 30 degrees for wind direction and 1 m/s for wind speed.

Table 1 - Average AM rating as a function of binned wind speed (1m/s) and wind direction (30°) – Figure 2 data.

Wind speeds	Wind directions (bin centred on…)											
	0	30	60	90	120	150	180	210	240	270	300	330
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.2	0.3	1.1	0.8	0.5	0.1	0.3	0.0	
5		0.0	0.0	1.6	2.2	2.7	2.0	2.1	1.0	1.1	1.5	
6			0.0	2.7	3.3	3.6	4.0	1.3	0.0	1.6	2.6	
7			0.7	2.6	3.6	3.9	3.6	1.9	1.0	0.6	2.5	
8			0.7	2.0	3.8	3.4	2.9	1.3	0.0	0.2	1.1	
9			0.2	0.5	3.2			1.1	0.1	0.0		
10			0.0	0.0					0.0	0.0		
11			0.0	0.0					0.0	0.0		
12				0.0					0.0	0.0		

Calculating an average AM value in each of the bins is only illustrative in this case. Depending on the local applicable regulations and/intended use, other approaches may be more relevant. In the UK, a potential penalty regime has been proposed for AM. Several UK practitioners have concluded [5] that, to determine the rating adjustment applied to wind turbine noise to reflect the presence of AM, the corresponding penalty value (up to 5dB for AM levels above 3dB) is determined for each 10 minute periods, and an average penalty is calculated over the range of conditions of interest. Some example applications of this approach are set out in Ref. [4].

Ref. [4] also notes that although a finer resolution with 10 degree-wide bins were also investigated, this resulted in scarcity of data in many bins and excessive variability which made the analysis less clear. The use of 30 degrees/1 m/s bins as in Table 1 therefore represents a good starting point for a systematic analysis of the statistical behaviour of the data, in the absence of more specific information, and can indicate trends which may not be obvious at first glance. It is important to acknowledge that lack of data in some conditions does not mean that AM would not potentially be present in these conditions, as sufficient data may not be present.

Figure 4 shows the results of the variation in average AM with wind speed for different wind direction sectors, from very wide to very focused. This illustrates that averaging over too wide or too narrow a range of wind directions can understate the average levels in other conditions. This may also suggest a more detailed statistical analysis could be of value. Caution should also be taken when averaging over limited quantity of data, which can throw spurious trends.

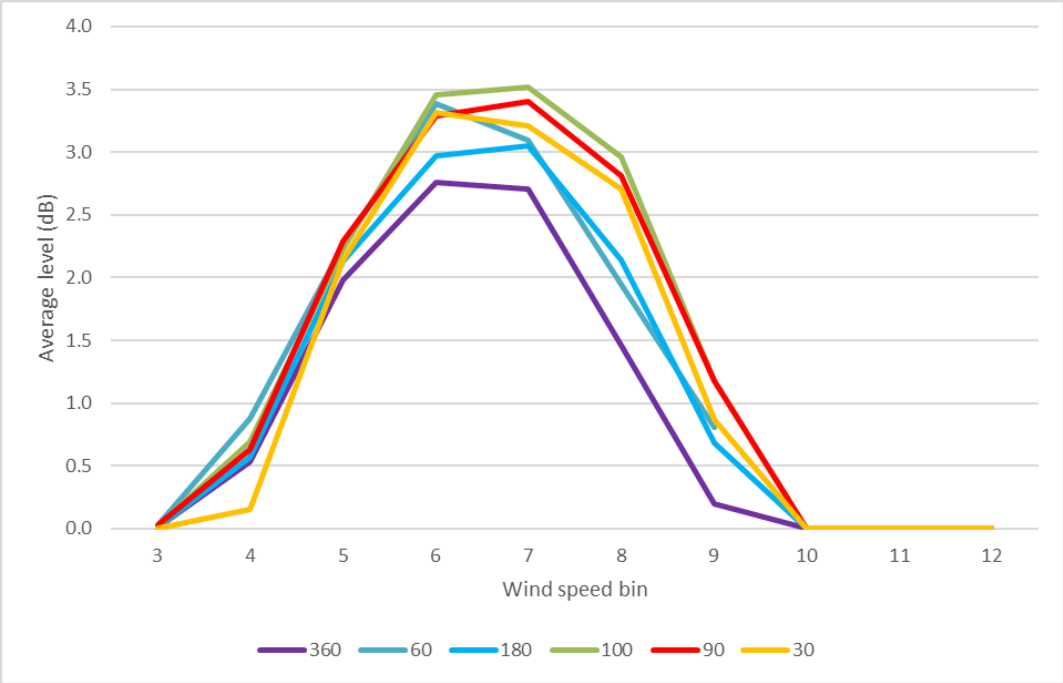

Figure 4 - variation of calculated average AM rating (IOA method) as a function of the width (degrees) of the wind direction sector for averaging: 360 degrees = all directions, 180 = 180 degree sector centred on DW conditions, etc. in In this case each direction sector was centred on the downwind direction.

Any distribution of AM obtained from this analysis, such as that of Table 1, is obviously only representative of the conditions obtained during the survey period, and whilst efforts should be made to make it as representative as possible, the wind conditions may differ from those observed in the long-term for any particular site. However, these results can allow identifying a particular set of wind conditions corresponding to relatively elevated AM (for example, in Table 1, wind directions of 105-195 degrees and wind speeds of 6 m/s and above). Reference can then be made to a long-term wind rose for the site which would allow determining the average prevalence (% of the time) in which these conditions arise, and therefore more elevated AM could occur. This can also help to target operational mitigation measures if relevant, either through targeted shutdowns or more advanced measures [6].

2.4 Use of turbine parameters

It is also useful to consider the AM analysis data against operational data from the wind farm control system (SCADA). In a first instance, of course, controlling for periods when turbines were not operating represents a good test.

In addition, the rotational rate of each turbine is generally available. The analysis of the AM modulation rate against this data also allows further filtering of the data. The IOA method requires as input a range of modulation frequencies which are potentially related to the turbines being considered (f=3*RPM/60 for a three-bladed turbine). However, this remains a broad criteria, particularly for modern variable-speed machines which can have strong variations in rotational rate at moderate wind speeds. So, even if a modulation “peak” is identified, this may not be valid if the AM frequency observed is inconsistent with that produced by the turbine(s).

Whilst determining a rotational rate is trivial for a site comprising a single turbine, this can be more complex for a larger wind farm. Our experience is that several turbines may be contributing to the AM in different individual 10s periods. This may therefore be at slightly different rates, particularly in sites with complex terrain where significant variation in the wind speed and therefore rotational speed can be experienced between different turbines. It may therefore be relevant to consider a range of RPMs for the relevant turbines potentially

contributing to noise at the receiver rather than a single value. The case of different turbine types is considered below.

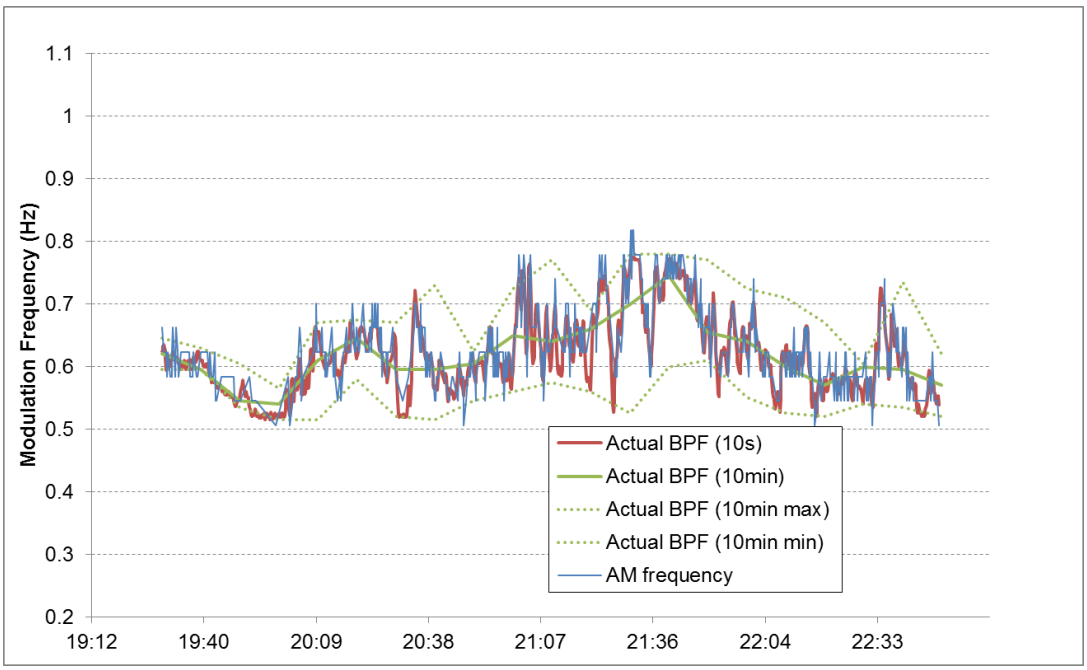

Figure 5 - Comparison of modulation frequency determined from the AM analysis with the frequency corresponding to the rotational speed of the closest turbine to the measurement location (both in 10s resolution and min/max/average over 10 minutes) – from [7] (based on a precursor of the IOA method)

Furthermore, the RPM data is generally available at 10-minute resolution rather than 10s, although in some cases a minimum and maximum value is recorded in addition to the 10-minute average. See Figure 5 for example: in this study [7], more detailed 10s data was recorded on one of the turbines and this showed an excellent match with the measured modulation rate (in cases of clear AM).

Another consideration is that the IOA method [1] defines a modulation frequency for each 10s period not over 10 minutes, as this frequency can vary slightly. There is no single frequency value as output from the algorithm directly usable for comparison with the turbine information. Possible candidates can be selected from a statistical analysis of the frequencies obtained over each of the 10s periods: in our experience the mode (most common value over each 10-minute) is usually representative, but alternatively the range of values may be considered instead. See next section for further discussion.

A data validation check is then to compare the frequency value or range determined from the AM analysis with the range of operational values determined from the rotational rates of the turbine(s). If the absolute difference is more than the tolerance of the method (0.1 Hz in the case of the IOA method) then these periods are flagged for further review.

2.5 Presence of turbines operating at different rates

The potential performance of the IOA method in complex modulation scenarios has been questioned. An example period was studied in which measurements were influenced by noise from two wind farms, with different turbine technologies: one with smaller turbines operating at 24-30 RPM (fast modulation around 1.3Hz) and one with larger machines operating at 13-18 RPM (slow modulation around 0.8 Hz). In the example period shown in Figure 6, modulation at both frequencies is apparent over a 30-minute period (with 3 separate 10-minute blocks of data with valid results).

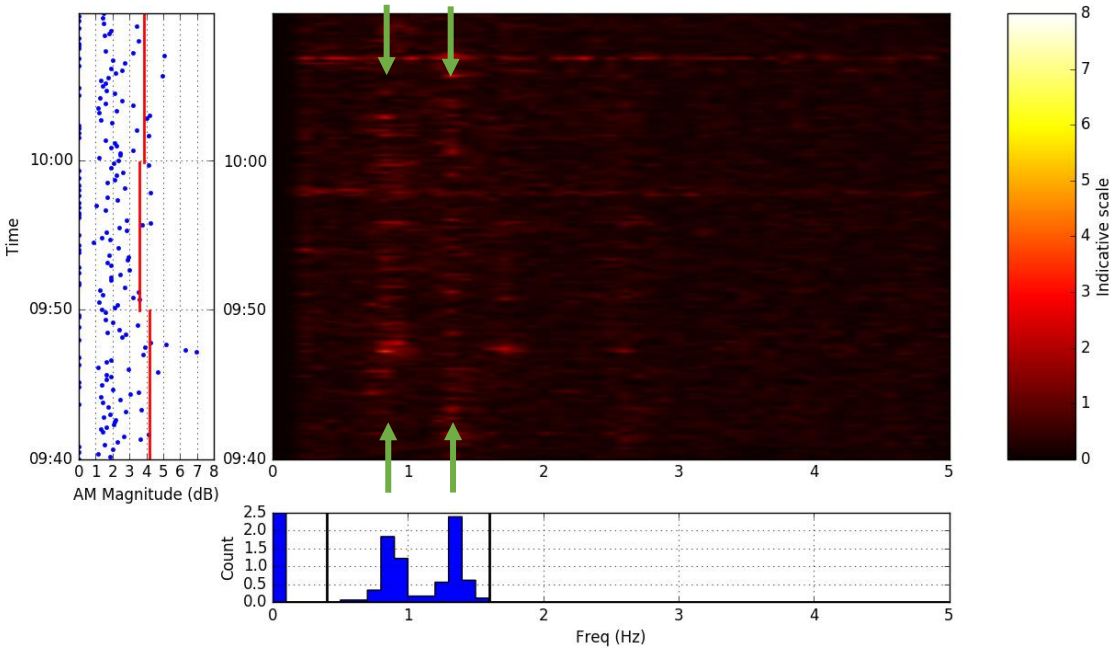

Figure 6 – Modulation spectrogram for a 30-minute period (central chart); left: time history of 10s AM rating values (blue) and 10-minute rating (red lines): this shows 3 x 10 minute blocks of data with valid AM ratings; below: histogram of the individual (10s) modulation frequencies determined. Arrows highlight the two frequency trends at 1.3Hz and 0.8Hz.

Figure 6 shows two clear trends for modulation at both rates throughout the period, with a double distribution in the histogram of frequencies obtained. To allow this analysis to work, the input range of valid frequencies for the method was set to 0.4 to 1.5 Hz. Whilst, in theory, a double modulation could create difficulties for the method, in practice, the variability of AM means that, for most of the periods analysed, only the modulation for one site is effectively dominant at any one time. In these cases, the strongest modulation peak in the input range specified was selected by the method.

A more detailed analysis showed that for some individual periods, the faster modulation was taken as the first harmonic of the lower modulation, or only one modulation component was analysed. But overall, the output of the method provided a good representation of the modulation values experienced throughout, despite the complex situation.

The question of determining a single output modulation frequency for each 10-minute period can then be considered in this case. Two clearly separate distributions are apparent in the graph below Figure 6. Calculating an average of the frequencies would yield a value in the middle of the two separate distributions which would not correspond to a real frequency for either site measured. If the most frequently occurring frequency (or mode) is used instead, excluding zero values, the result is 1.3Hz for all three periods in the example shown above. However, this does not necessarily represent the highest AM values which were experienced over this period. A more complex alternative is selecting the frequency of the 10s block with the AM rating *closest* to the 90th percentile value determined (red lines). This yields frequencies of 1.3Hz, 0.8Hz and 0.8 Hz respectively for each of the three 10-minute blocks shown. This is therefore more representative of the worst-case periods in each 10-minute block.

Analysis over 30s data blocks (see below) did not seem to yield good results as the modulation peaks were often too spread out, due to variable modulation, leading to poorly resolved peaks with poor apparent “prominence”, even if increasing the prominence criteria to account for the increased duration.

3. Future development

3.1 Varying the analysis parameters

The IOA method was developed with a focus on modern large commercial-scale turbines, with rotational rates (in full operation) corresponding to BPFs of 0.7 to 1.2 Hz (RPM of 14 to 24). Consideration can be given to expanding the remit of the method to faster or slower turbines. This means considering the parameters and approach of the method and if it could be extended.

In any Fourier-type analysis, there is a necessary compromise between frequency and time resolution that need to be balanced, but always involves trade-offs. In the IOA methodology [1], it was decided to separate the data into 10s blocks as this provided a good representation of the variability of far-field AM which was experienced from different site measurements, with individual "bursts" of modulation sometimes lasting only a few seconds. This corresponds to a frequency resolution[1] of 0.1Hz for the modulation spectrum. As discussed below, an increased analysis period could increase the frequency resolution some of the temporal detail can be lost.

Simplicity of approach is also a consideration: it was determined [8] that by using a 10s block, a simple measure of average modulation in each block provided a robust representation of individual modulation peaks and troughs over a 10-minute period. The working group concluded that it was reasonable to characterise the level of AM in each 10-second interval by a single value of the difference between L5 and L95 of the filtered dataset, which effectively represents the average of the different peak-to-trough values.

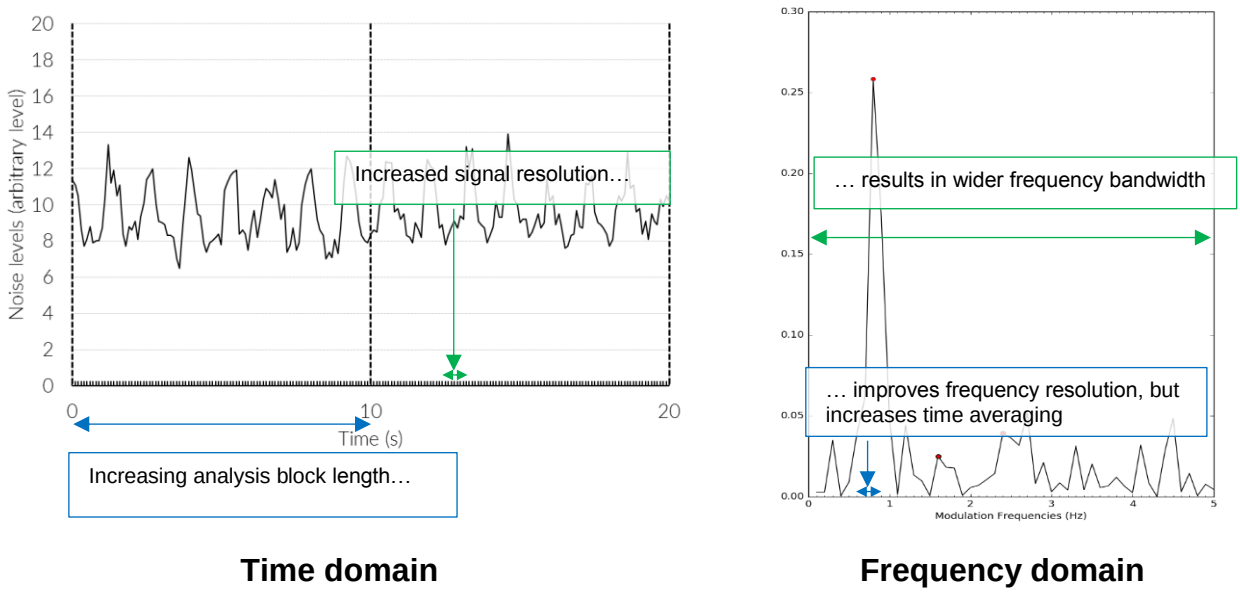

Figure 7 – representation of the main parameters affecting the time and frequency resolution of the analysis.

Practical considerations are also a factor: noise levels, particularly with 1/3 octave band data, are typically only available on most sound level meters at 100 ms resolution (10 Hz). This means the modulation spectrum can only extend up to 5 Hz. As the method is based on accounting for the first three harmonics of the signal, this limits the frequency of the main peak to 1.6 Hz [1], which corresponds to a turbine operating at 32 RPM for a three-bladed turbine. A

[1] Although zero-padding the data can appear to increase the frequency resolution, this is only an artefact and does not represent a true increase in the actual resolution of the analysis.

higher signal sampling rate would be required in order to represent faster-rotating turbines, which will tend to be smaller models. Alternatively, less harmonics could be retained.

More generally, a balance has to be made when deciding how many harmonics to include – using too many will increase the noise floor while including too few will result in missing the true amplitudes of the peaks and troughs when harmonic energy is present. The use of the first three harmonics in the IOA method was found to provide a good representation of the original time-series in the large majority of measured data test cases, whilst maintaining a reasonably low noise floor.

3.2 Analysis over longer periods

During the development of the IOA method, consideration was given to a longer analysis time (30 s to one minute). This would provide not only more frequency resolution but also error reduction, through additional averaging of the turbine signal (which tends to persist in time), and averaging out spurious sources such as wind and animal noises which tend to be more short-lived. It was determined that 1-minute could be too long for variable-speed machines whose rotational speed can vary even over this period, but a 30s-period represented a potential alternative.

Figure 8 shows an example of the resulting spectrogram for the same period as Figure 1, demonstrating the cleaner signal and increased frequency resolution obtained. To obtain a comparable analysis, the parameters of the IOA method were modified as follows:

- Where one spectrum line was used before when inverting the Fourier analysis, three are used instead;
- In a similar way, the prominence of the spectral peak is calculated by ignoring three lines either side of peak and then calculating the average over six lines either side of this;
- The prominence criteria was increased from 4 to 12;
- The search for harmonics was done over wider area (2-3 lines either side of the exact multiple of the main spectral peak)

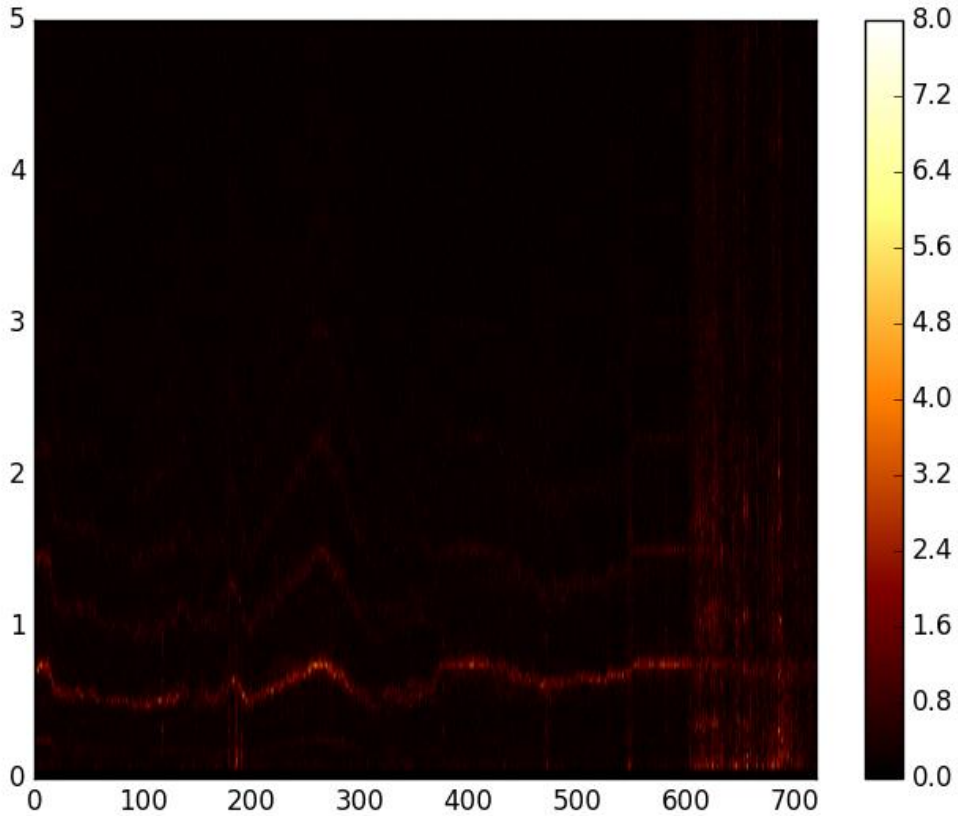

Figure 8 - Modulation spectrogram – same data and presentation as Figure 1 (6-hour period) but with the analysis undertaken in 30s blocks.

Figure 9 illustrates an example of analysis of one individual 30s period: this shows a relatively clear spectrum but illustrates two points: the variability of the reconstructed signal is much larger over the 30s, which was found to be often the case. This means that the simple L5-L95 variability metric used is too coarse to represent the signal variation over 30s. However, the filtered signal generated through inverse Fourier transform does include this time history element, and a more detailed analysis of the peaks/troughs is possible (as discussed in the next section). This however means the method then becomes more complex.

Figure 9 also illustrates a case where higher harmonics of the signal are more clearly visible, and it would be possible to consider these upper signal harmonics when reconstructing the signal. This tended however to represent a marginal effect on the analysis, with the exception of very isolated periods with strong harmonic content. For these reasons, the working group concluded that a 10s analysis period represented a better approach overall (at least for the modulation rates considered).

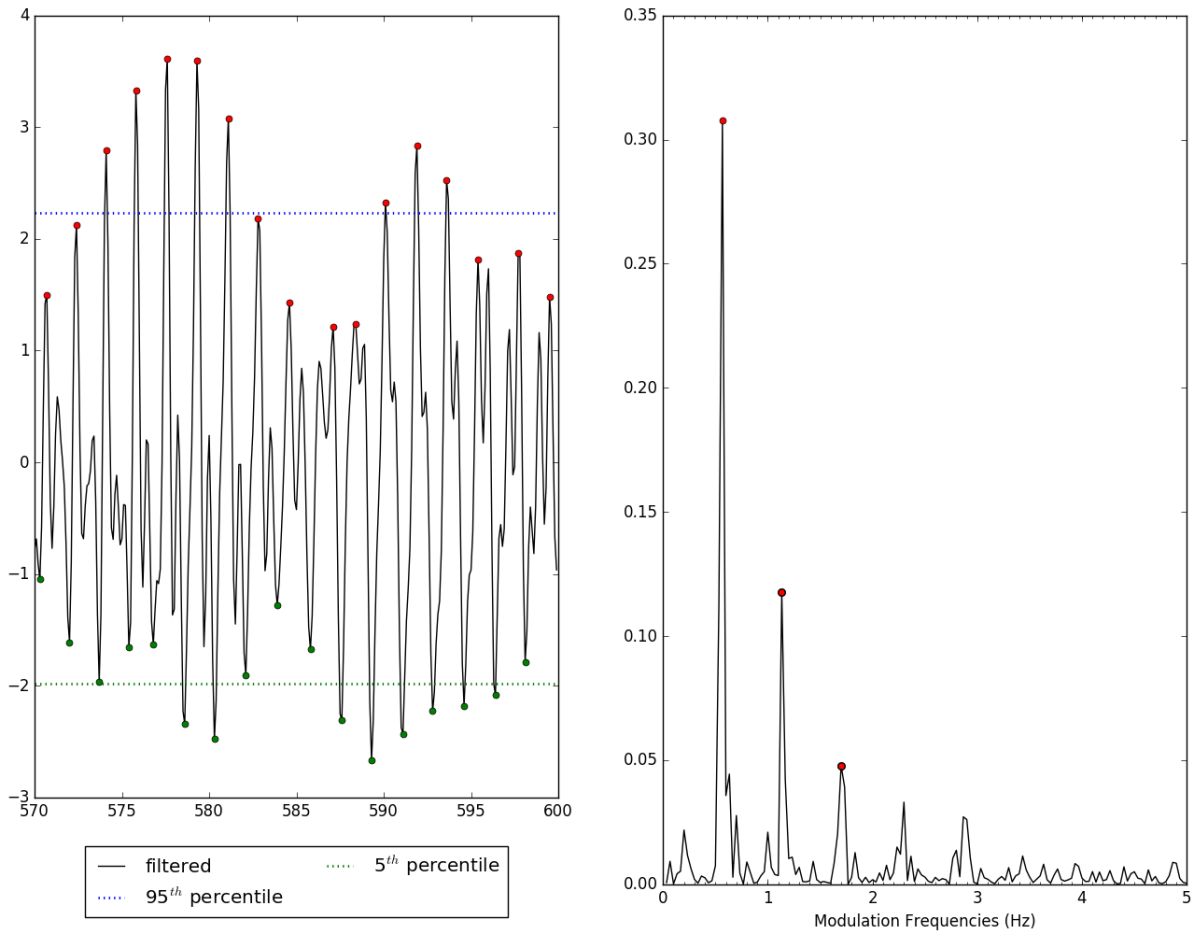

Figure 9 - Modulation signal and spectrogram analysed over one 30s period – left: filtered signal generated, 95th and 5th percentile values and individual peak/troughs marked by red and green circles respectively. Right: corresponding modulation power spectral density, with the red circles highlighting the three harmonics identified.

3.3 Individual peaks/troughs

In cases such as that of Figure 9 where the analysis period becomes relatively long compared to the modulation period T (which depends on the main modulation frequency), then the variability in modulation over the data "block" becomes significant. In these cases, considering the overall statistics (5 to 95th percentiles) of the signal may not necessarily provide a sufficiently robust estimate of the AM variability. But since the time series is reconstructed using knowledge of its frequency content, this allows the peaks and troughs to be identified and

characterised individually, as illustrated in Figure 9. This means that a more detailed statistical analysis of variations of individual consecutive peak-trough differences is possible.

Ref. [9] also used a similar approach of identifying peaks/troughs directly, but the advantage of the hybrid approach used in the IOA method is that the frequency analysis undertaken guides the detection of peaks and troughs in the reconstructed signal. This was in fact the approach used in one of the earlier draft methods [10] proposed by the IOA working group, but not retained in the final document, to limit the complexity of the method. Additional steps such as these can also introduce errors and “edge cases” which makes the method less robust.

Specifically, a version of the reconstructed signal is obtained based only on the fundamental modulation peak in the spectrum (see Figure 4.5.2 in [1] or Figure 10 below). It is trivial to identify local maxima and minima in that signal (which has a fixed period) and these provide a guide as to the likely locations of peaks and troughs in the full reconstructed signal. The fundamental modulation frequency also provides the basic modulation period: a window of half this length is used to seek for a local maximum/minimum in the reconstituted (filtered) signal, starting from each peak/trough in the fundamental.

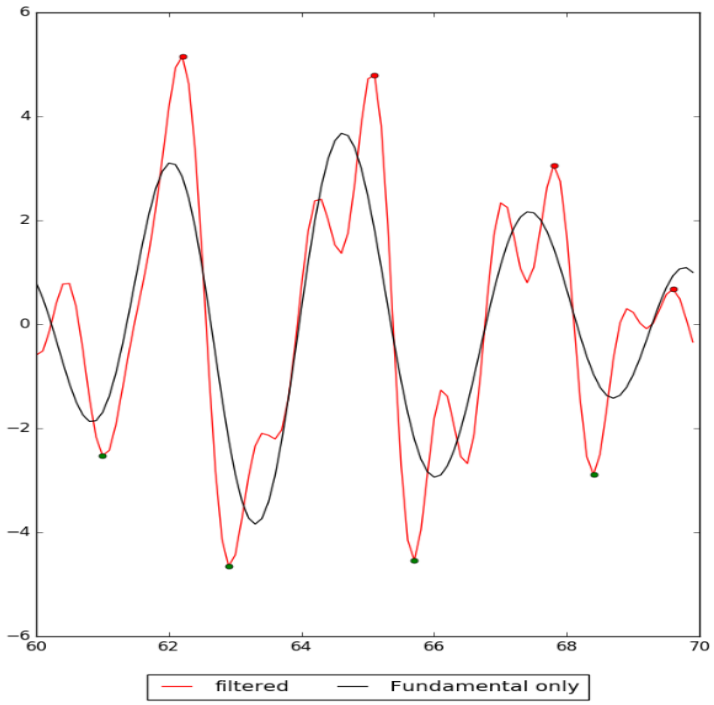

Figure 10 – filtered signal generated by the IOA methodology (red line), as well as first harmonic signal only (black). Individual peak/troughs identified are marked by red and green circles respectively.

Consecutive peaks/troughs provide individual AM results which can then be processed for further analysis. The 90th percentile of the individual peak-to-trough values provides a useful metric. It can be shown that, for data such as that in Figure 9, the average of the 90th percentile of peak-to-trough values in 30s blocks over a 10-minute period is equivalent to the IOA metric, *i.e.* the 90th percentile of (what is effectively) the average AM in each 10s block.

3.4 Slower turbines

As the move to larger and larger turbine rotors continues apace, consideration should perhaps be given to turbines operating at a slower rate (less than 10 RPM) and how any AM method could be extended to deal with this.

The first requirement would probably be to increase the time period for analysis, to capture more modulation periods and better capture this slower signal. This would also increase the

frequency resolution, which would help to resolve the lower frequency area of the modulation spectrum (below 0.5 Hz) where the main modulation peak is likely to be found.

Despite this, initial investigations suggest that the prominence calculation in the standard IOA method can run into difficulties: the calculation of a “masking level” relies on averaging frequency lines either side of the main modulation peak and this could in theory decrease below the lowest spectral lines. In these cases, the calculation of the masking level can be modified to only consider spectral lines at higher frequencies (above the main peak) and still result in an effective procedure. Initial investigations using simulated data suggest this approach could be effective but the dynamics of actual 5-10 RPM turbines may be very different in practice and this would require further investigations.

References

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