Initial findings of the UK Cotton Farm Wind Farm long term community noise monitoring project.

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ABSTRACT

This paper provides early results of a long term study of community impact from wind farm noise and uses of the data obtained. A continuously recorded database of noise collected under different meteorological conditions has allowed detailed analysis of particular characteristics such as amplitude modulation and also the reliability of assessment methodologies for predicting and quantifying impact. Surprising outcomes are explored including upwind impact. In 2013 MAS Environmental established a permanent monitoring station to record and publish data online located 600m from the nearest turbine to correlate the impact upon the community and provide an extensive database. This paper maps the evolution of the project. Online data enables a wider study of the effect of meteorological change on noise immission in a flat eastern area of the UK. Anyone can independently observe and listen to the audible elements of the noise that people complain about. This tool aids understanding as well as predicting times of likely adverse impact. The database has enabled testing of proposed controls, particularly in relation to audible amplitude modulation and demonstrated the recent Renewables UK proposed control mechanism fails. Data obtained challenges blade stall research claims as the primary cause of far field AM and wind farm noise prediction methodologies.

Keywords: Wind farm, Community impact, data analysis, database, control mechanisms, prediction

I-INCE Classification of Subjects Numbers: 14.5.4, 63.7, 66.1, 66.2

1. INTRODUCTION and DISCUSSION

This paper outlines the Cotton Farm Wind Farm community noise monitoring project where real time sound and weather data is continuously gathered at a representative community location and provided on-line for anyone to research, evaluate and improve their understanding of wind farm noise. The Cotton Farm WF project compliments measurements made by MAS Environmental (MAS) of amplitude modulation (AM) and other elements of wind farm noise at over 18 sites.

The provision of the equipment was funded by local community donations. The community were cognisant of the likely adverse impact. MAS undertook all the research, software development, system installation, maintenance and calibration, data processing and analysis. As the funding is limited substantial potential analysis and research remains to be undertaken. In particular there is extensive complaint evidence that can be correlated with noise measurements and compared to the audio.

MAS have made some of the data available to others to test responses to AM and / or test potential control mechanisms. MAS looked at automated test processes and found none to be a suitable replacement for manual inspection of the audio. Difficulty arises as two periods of data can provide noticeably different outcomes and a procedure or algorithm designed to trigger for a certain criteria based on one particular dataset, for example with a regular or single modulation peak, may not trigger when processed using a different level and type of AM, for example an erratic or double peaked modulation.

In the same way two forms of music may have the similar energy levels or beat patterns; one form of music may not be objectionable to some at a specified level but is to others. AM is viewed by some as related to the total sound energy emitted. This paper explores our findings which differ from this view and identify it is more a response to the psycho-acoustical characteristics contained within the noise.

1.2. **Cotton Farm Wind Farm and its locality.**

Cotton Farm WF comprises 8 Senvion (formerly REpower) MM92 2.05MW turbines with a total capacity of 16.4MW located between the villages of Graveley to the east, Great Paxton to the west and Toseland to the south in Cambridgeshire UK. The nearest dwellings are approximately 600 metres. See Figure 1 below.

The permanent monitoring station was established on the outskirts of Graveley. We have now collected over 17 months data and consider the research unique as we are able to test noise level and character against community response as it occurs. Much of the data is presented online so that all can see what impact arises, experience itunderstand the regularity of impact and its degree. In particular this allows analysis of meteorological conditions related to impact.

Web link **www.masenv.co.uk/~remote_data/**

1.3. The Monitoring Station.

This includes a 10 metre meteorological mast recording wind speed, wind gusts, wind direction, temperature, barometric pressure, humidity and rainfall in 10 minute periods within 20m distance of the noise measurement location. Measurements are made using a Vantage Pro system. This has a small solar panel and battery and transmits data to a base station located within a nearby dwelling.

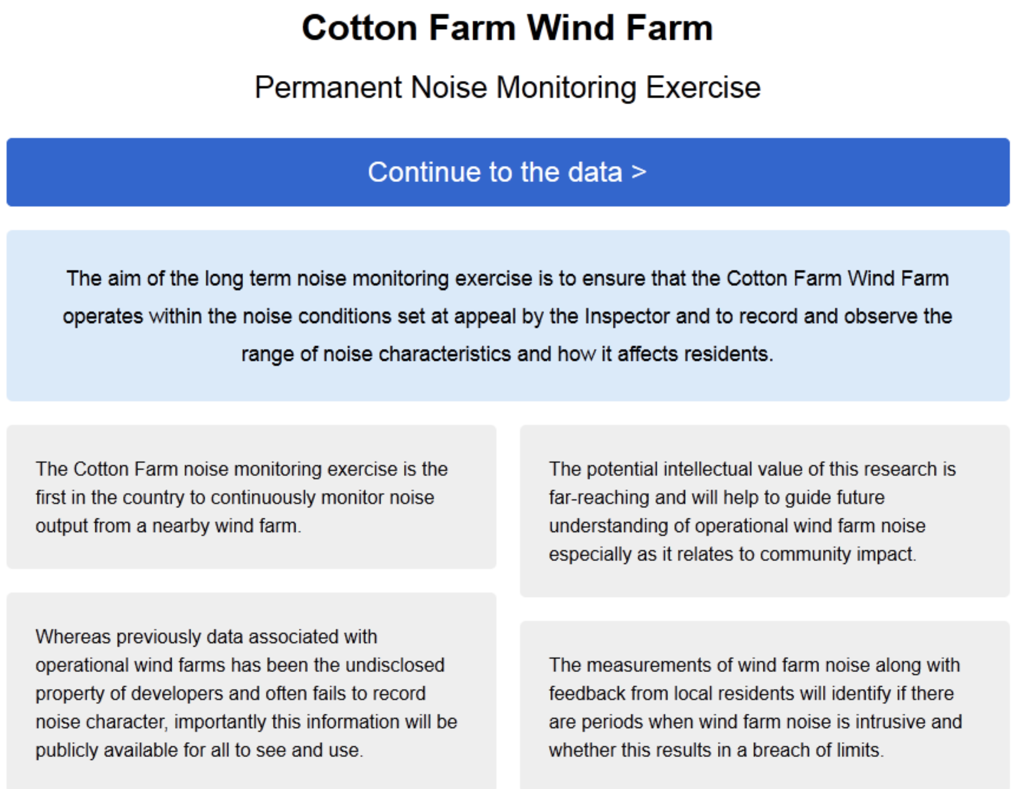
Noise is recorded in a free field location at the boundary of residential property at a height of 1.5m above ground level using a Larson Davis double skin external microphone enclosure. The microphone has a noise floor of 17dBA and is connected via a 30m cable to an internally located Larson Davis LXT sound level meter.

100ms L_{Aeq} and 1/3rd octave data is recorded along with 10 minute values and statistical parameters. Audio is also recorded which can be post processed to undertake narrow band analysis if required. Data is directly streamed to a laptop computer which processes the information and uploads via a wireless internet link using the resident's broadband connection. Data is also backed up to a hard drive and manually downloaded on a monthly basis. It is output in CSV format and converted into tables and graphs using in-house programs constructed on an Excel platform.

Figure 1 showing turbines & monitoring station. 1-8 = turbines & blue dot = station

Figure 2 – Pre- wind farm with dwelling to right where station now located.

Figure 3 – Post-wind farm showing anemometer (arrowed blue) & microphone location (red) in rear garden of dwelling.



Cotton Farm Wind Farm

Permanent Noise Monitoring Exercise

Continue to the data >

The aim of the long term noise monitoring exercise is to ensure that the Cotton Farm Wind Farm operates within the noise conditions set at appeal by the Inspector and to record and observe the range of noise characteristics and how it affects residents.

The Cotton Farm noise monitoring exercise is the first in the country to continuously monitor noise output from a nearby wind farm.

The potential intellectual value of this research is far-reaching and will help to guide future understanding of operational wind farm noise especially as it relates to community impact.

Whereas previously data associated with operational wind farms has been the undisclosed property of developers and often fails to record noise character, importantly this information will be publicly available for all to see and use.

The measurements of wind farm noise along with feedback from local residents will identify if there are periods when wind farm noise is intrusive and whether this results in a breach of limits.

Figure 4 – Start of website front page.

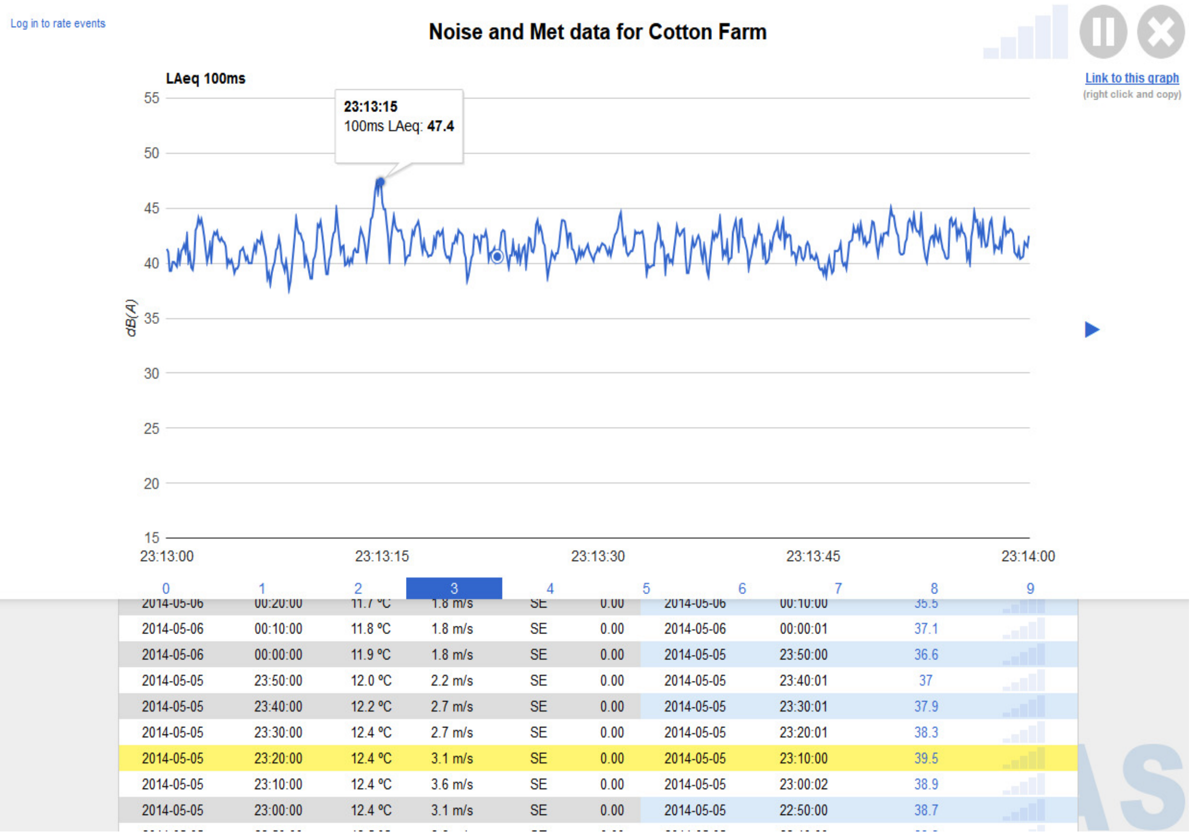


Figure 5 **–** Website data page open with interactive graph at top and data tables below.

1.4. Development difficulties with the monitoring system and data uploading.

Very occasionally the sound level meter crashes and requires resetting. When this occurs individuals within the community have been trained how to reset the meter and recordings continue. Calibration is undertaken through monthly site visits when the entire equipment is checked. The meteorological mast is on a pivot and can be lowered to the ground to clean and adjust the anemometer as necessary. The microphone wind shield does not have bird spikes in order to avoid extraneous noise that some types can generate but does suffer bird pecks from time to time leading to the need to replace the outer foam screen. The Vantage Pro weather station has shown to be stable with few difficulties or problems.

The audio output on the LxT sound level meter has a hardware limited dynamic range resulting in clipping distortion during moments of high decibel level, for example during gusts of wind. This has no effect on the decibel levels calculated by the device. The audio is primarily for identification and this is not considered an impediment to analysis.

As time has progressed the site has collected a vast amount of data. In order to speed up page loading time, the site has a rating system allowing visitors to mark periods of significance. Insignificant periods are periodically removed from the site index but kept locally.

1.5. **Future systems under development – low cost systems.**

We are currently trialing low cost iOS platform software with an interface to a type 1 precision microphone and posting equipment ready for recording to be installed under remote video (Skype) supervision to ensure correct calibration and location. The hardware enables recording for up to 3 months without download but equally data can be automatically uploaded to “Cloud” storage for viewing and interrogation. Costs are expected around 10-20% of the existing system making it widely available. The main technical problem is obtaining a suitable external weatherproof microphone enclosure / wind shield.

Positive outcomes of the work include:

- The ability to research the actual impact arising under various meteorological conditions.
- Evidence based tests of predictions and theoretical concepts proposed for wind farm noise.[1]
- Comparison of community responses with measured sound energy values and sound character.
- Determination of contributions from extraneous noise sources.
- Immediate evidence correlating with complaints at the time of occurrence.
- Development of an online subjective rating of the AM which is moderated.[2]
- Transparency of actual impact versus decibel parameters.
- Statistical evidence of occurrence of a range of noise characteristics.
- Refinement of meteorological relationships with noise immission.[3]
- Raised awareness of the extent, frequency and duration of noise problems.
- Development of an extensive database to test metrics that are used to try to control wind farm noise characteristics such as excess amplitude modulation.
- Development of processes to differentiate wind farm noise from other sources.
- Development of simplified cost effective community monitoring procedures and equipment that can be used in other localities.

1.6. **Renewables UK (ReUK) research into Amplitude Modulation published December 2013.** (14)

The Cotton Farm WF database has been instrumental in testing the theories and ideas put forward in the ReUK research program that was itself based on smaller data sets. Whilst the ReUK research is extensive in text, it is based on limited data and field analysis. Some simple checks were able to test some of the theories put forward in their research but they are not supported by the field data suggesting false assumptions. This requires a separate paper but some findings are addressed in this paper.

2. BACKGROUND to the Cotton Farm Wind Farm project.

The Cotton Farm Wind Farm development was permitted at a public inquiry in December 2010. The local authority concluded there would not be excess noise and did not support objections based on noise. MAS concluded from investigations at a number of other sites that AM was a common and serious problem and sought its control. Additionally MAS were of the opinion the prediction methods applied, as now adopted by the UK Institute of Acoustics (IoA), understated noise impact and the pre-development assessments also overstated the background noise environment.

In the UK the positive decision of the Cotton Farm public inquiry not to control AM was used in other decisions to foster the conclusion there was not a need to control excess AM and also that the prediction methodology adopted in the UK was fit for purpose. The position on AM persists at the current time with reliance on a Salford report in 2007 which understated impact still being quoted. The Cotton Farm comments are still relied on despite extensive evidence that the inspector erred.

The government inspector in 2010 deciding the case rejected arguments for control and stated:

"I place greater weight on the results of [the Salford study] than on the research carried out by Mr Stigwood … it is simply not possible to predict in advance … statistically the odds are very much against it being a problem at Cotton Farm. I appreciate that some similarity with problem sites … but not to the extent that it can reasonably be regarded as a distinct possibility, let alone a probability"

The wind farm's acoustician[4] who gave evidence at the Inquiry stated:

"Given the very small number of occurrences of increased levels of 'blade swish' or AM, it is my view that an appropriate way to control the potential for the noise from a wind farm to contain

1 Example findings discussed in this paper include support for Lee et al 2013 and convective amplification as a primary cause of AM and ReUK work on 'Other' AM which is contradicted by the Cotton Farm and other data.
2 Most residents/ site visitors rate the impact worse than the acousticians / researchers moderating the site.
3 The site is frequently used to judge appropriate times to visit and monitor at other sites.
4 Dr Andrew Bullmore of Hoare Lea.

increased levels of AM is by way of statutory nuisance action".[5]

MAS stated:

"the risk of AM was high and has long been under-estimated. A condition to control the noise was essential."

Post operation of the wind farm the community response is:

"A considerable number of noise complaints by residents have been made to the Environmental Health Officers. Each village appears to be affected at different times depending on the wind direction and speed ...The Action Group is also aware of residents who have been affected by turbine noise but have not formally complained"

The industry acoustician's erroneous view prevailed and has been commonly repeated and adopted by decision makers in the UK up to the current time and post work in 2013 showing AM was a common and serious problem (1). Acceptance of the need for controls is evolving in the UK but arguments that it is rare persist despite the strength of evidence globally.

2.1. Decision to continuously monitor the noise.

The local community were unhappy with the decision after funding the presentation of detailed evidence showing the need for AM control and decided to fund the installation of a permanent monitoring station. At MAS we saw this as an opportunity to expand our research and dedicated resources into the project.

Despite the Cotton Farm daily on-line data provided by MAS and continuing complaints of residents for over 17 months, no action to address the main problems have been implemented or are apparently being considered. Cotton Farm WF is owned by Greencoat UK Wind PLC a company that is invested in by UK Government.

3. RESULTS and detailed data analysis

This paper includes data analysis from the first 10 months of measurements and additional detailed analysis of a 2 month period from December 2013-January 2014. The primary focus of the research at this stage is on amplitude modulation occurrence compared to its characteristics and predictions versus actual noise levels.

3.1. Methods of data processing and analysis.

Various algorithms have been considered and produced to analyse the data and these have been compared to see how well they determine amplitude modulation including those procedures developed by ReUK which is reliant on FFT[6] analysis to determine blade passing frequency. We have also compared the method with those used by Tachibana et al, comparing the differences in the historical "fast" and "slow" processing meter settings of 125ms and 1 second respectively.

3.2. Method of data analysis adopted by MAS.

We have found the quickest and most effective method of analysis remains the processing of 100ms L_{Aeq} data into 2 minute graphs of a suitable scale. Identifying the periods unaffected by significant extraneous noise depends on the time of day and season of the year. In the UK MAS have primarily focused on 21:00-05:00 hours as an initial period for analysis when extraneous noise is infrequent. As with many processes involving complex effects, visual examination of graphical data is commonly the quickest method of identifying relevant patterns.

The original goal of the analysis was to ascertain an approximation of the occurrence of AM at the site. The approach needed to balance processing months of data quickly with the requirement to rule out any false positive indications of AM. This process resulted in scanning through 2 minute graphs looking

[5] The statutory nuisance procedure in the UK has failed every case so far and appears administratively incapable of addressing the issues and such an approach leaves communities unprotected.

[6] A number of methods have been developed using the Fast Fourier Transfer approach, potentially with the hope of automating data analysis.

for clear signs of AM in each 10 minute period and verifying the absence of false positives by checking irregularities in the graph pattern using the audio recordings.

Adopting this approach means a single night period can be visually scanned in less than 10 minutes and commonly half that time. A secondary filter then is sometimes applied to identify dominant third octave bands that are also recorded every 100ms in order to assess their modulation. Where specific community complaints are recorded, these periods are scrutinised and where a clear AM trace is not obtained then spectrographs may be used or the audio checked. Spectrographs have been found particularly helpful for modulating tones or drones that span a number of frequencies or where harmonic frequencies are measured. In this manner we have been able to check long periods of data in a short period of time, before deciding what other processing might be relevant. Visual checks have also rapidly identified periods of AM impact missed by automated processes such as that proposed in the ReUK mechanism.(2)

The MAS analysis also attempted to quantify the degree of AM monitored without the need for exact peak to trough level analysis. Therefore positive periods were divided into 3 sub-categories. Any periods with clear modulation of approximately 5dB and above were indicated as positive results. Periods where the AM appeared momentary or there was any doubt over the modulation being 5dB or above for a significant amount of time, were indicated as "borderline". Periods where AM had regular peaks of 10dB were recorded as "severe". Periods were always verified by audio and categorised conservatively. Many periods were disregarded completely due to other environmental activity or extremely irregular behaviour. This will have resulted in some periods of occurrence being recorded as an absence of AM. There were times where it would appear the turbines were switched off; without confirmation these periods were included as periods with absence of AM.

3.3. **Limit of unacceptable AM.**

Scientific discussion continues over what is an appropriate trigger point of unacceptability for AM in terms of modulation depth. This is discussed further in our second paper at Internoise 2014.(3) Reliance only on modulation depth (MD) is considered a misleading approach to describing acceptability as a range of intrusive characteristics arise that do not necessarily relate to modulation depth or are not within the "A" weighted values. Impact relates also to frequency of occurrence, duration, times of impact and the consequences / effects of the intrusion.

Since 2009 MAS have used a criterion of repetitive 3dBA modulation depth impact values as an indicator there is likely to be adverse impact from AM on the basis it is clearly noticeable at these levels and changes the noise to one with character. It also means the soundscape is dominated by wind turbine noise and effectively is equivalent to an industrialised sound environment. There are no longitudinal studies of the effects on communities of AM at the boundary of acceptability and this would be impractical due to the scale of such a study and because levels at the boundary are only one component of impact.

There is repeated evidence that except in locations more distant from a wind farm where AM impact is of reduced regularity and has a smaller peak to trough range, occurrence of 3dBA modulation depth will also mean significant periods of much greater modulation depth arises for much of the time. Similarly, periods arise when modulation depth is not substantial but impact is greater. This occurs either because of the frequency content and how unusual the noise is, its rate of change or changes in pitch that are not reflected in the corresponding changes in the "A" weighted decibel levels. It is not possible therefore to segregate long term impacts according to modulation depth.

The AM immisions relating to Cotton Farm WF have some different characteristics to the AM observed at other sites for much of the time and also many common features. For example, the AM measured adjacent Cotton Farm WF could reasonably be described as erratic in nature with continuous changes in character. At many other sites prolonged periods of similar pitch and character AM can arise or AM with a different character to that found at Cotton Farm can arise. Historically it is our finding that when 3dBA modulation depth is commonly experienced communities will experience adverse impact to varying degrees.

3.4. **Use of >5dBA modulation depth data.**

In order to avoid problems of including AM that other researchers may consider acceptable or less intrusive, most analysis of excess amplitude modulation for this paper is focused on periods where peak to trough levels commonly and regularly exceed 5dBA.[7] This approach ensures arguments of extraneous noise inclusion are minimised. Our approach to data analysis is therefore considered conservative.

3.5. Data availability for research by others.

MAS have made some of the Cotton Farm WF data available to others for responsible research; however, in view of the on-going costs to the local community there is now a need to charge for data except for exceptional research projects of merit which are considered on a case by case basis.

3.6. PRELIMINARY DATA FINDINGS

Analysis of 10 months data including shut down periods is considered. This resulted in 10,030 ten minute periods analysed and included. Overall during that period 54% of nights were significantly affected by periods of AM with MD of +5dBA. A further more detailed analysis of 2 months (2/12/13-3/02/14) 56 days provided the following results:

82% of nights occurrence MD+5dBA (46 nights) of which:
30% nights occurrence of classed severe AM (17 nights)
10% nights occurrence of classed borderline MD+5dBA (6 nights)
18% nights little or no occurrence of MD+5dBA (10 nights)
4 continuous nights prolonged of severe MD+5dBA[8]

Table 1 - Cotton Farm: Total periods MD+5dBA v wind direction @ 600m

	% of AM occurring for each wind direction (Degrees from North)															
Wind Speed 10m	0	22.5	45	67.5	90	113	135	158	180	203	225	248	270	293	315	338
0		0%	8%	0%	22%	0%		25%	67%		0%				4%	
0.4	0%	4%	0%	5%	17%	17%	17%	25%	29%	15%		11%	29%	0%	11%	9%
0.9	19%	11%	10%	17%	48%	23%	28%	16%	7%	10%	23%	36%	4%	20%	0%	15%
1.3	15%	20%	28%	28%	54%	35%	39%	38%	20%	19%	20%	19%	26%	24%	6%	0%
1.8	24%	36%	35%	91%	87%	85%	60%	53%	20%	29%	19%	11%	9%	32%	15%	22%
2.2	21%	50%	23%	90%	93%	86%	65%	43%	28%	37%	39%	20%	4%	18%	56%	55%
2.7	34%	71%	30%		88%	100%	81%	66%	45%	57%	58%	28%	7%	16%	22%	53%
3.1	46%	74%			90%	95%	87%	90%	55%	64%	60%	38%	19%	18%	31%	60%
3.6	52%	78%	13%		86%	100%	89%	80%	70%	73%	86%	44%	20%	16%	42%	
4	11%	97%	50%		94%	100%	81%	93%	73%	84%	80%	88%	31%	33%	39%	
4.5	0%	100%			76%	100%	97%	85%	81%	89%	70%	63%	48%	30%	44%	
4.9	0%				50%	100%	93%	80%	64%	88%	67%	80%	30%	53%	63%	
5.4	0%					100%	87%	76%	43%	77%	73%	82%	45%	78%	11%	
5.8	0%					83%	80%	65%	41%	53%	79%		65%		7%	
6.3	0%	Cells with less than 6 records					81%	56%	14%	36%	83%	83%	63%		0%	
6.7	0%	of data (1 hour) are ignored.					29%	70%	36%	44%	78%		62%		0%	
	UPWIND						><			DOWNWIND						

[7] An added point is that the ReUK research suggests convective amplification which they call "normal" AM does not exceed 5dBA modulation depth and that this only occurs under cross wind conditions close to the turbines. Thus their theory suggests this form of AM should not be experienced other than rarely, close to the turbines and with sideways directionality. This was not the reason for comparing above 5dBA but is a coincidental benefit.

[8] Note the background noise level during this period and as influenced by the wind farm noise was 31dB L_{A90}(10 minutes) and modulation peaks were up to 50dBA.

Table 1 compares the percentage of time excess AM with a modulation depth greater than 5dBA commonly occurred for different measured 10m height wind speeds and directions. The extent of upwind AM was unexpected as was the modulation depths and overall L_{Aeq} values. Commonly decibel levels were of similar magnitude when upwind and downwind when AM was occurring.

When considered along with previous field measurements by MAS (4) the Cotton Farm data indicates a directionality pattern to AM that fits reasonably with the theory of Lee et al (5) for convective amplification. When factoring in the refraction effects, the variable pitch and shape of blades and that convective amplification is generated by different parts of the rotor disk in different directions, a pattern is produced that approximates in an illustrative form to the diagram in Figure 6 below.

The Cotton Farm WF and data for other sites confirms a directionality effect which has been tested by moving measurement locations around turbines when the wind direction is relatively steady. [9] This pattern is not entirely clear in Table 1 which is due to the array of turbines meaning the monitoring station is always at different angles to different turbines.

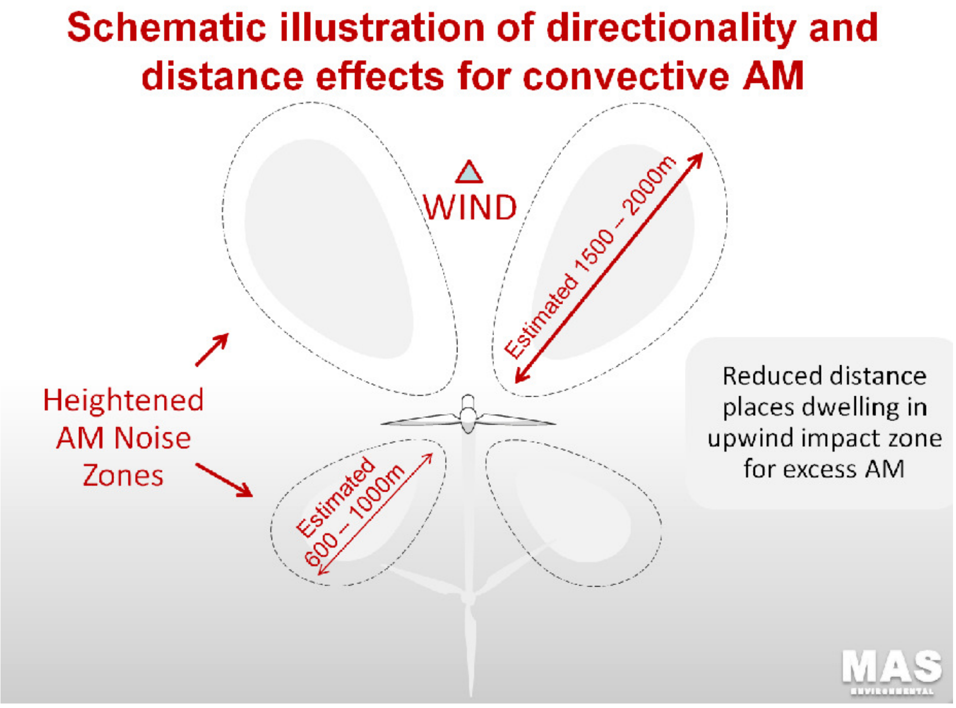


Figure 6 – Schematic representation of apparent wind turbine AM due to convective amplification.

3.7. **Analysis of sound energy changes during switch off tests.**

As a consequence of the community complaints, operational checks were undertaken and turbines were switched off for periods to enable measurement of the background noise contribution. These switch off tests were recorded by our continuous monitoring and provided valuable data on the changes to the sound environment. Examples are included below with some of the findings discussed. Above each main graph is an expanded section of the varying sound showing the MD and its variations.

[9] Directionality was tested at a number of sites including Delabole, Kessingland and Wadlow as well as Cotton Farm.

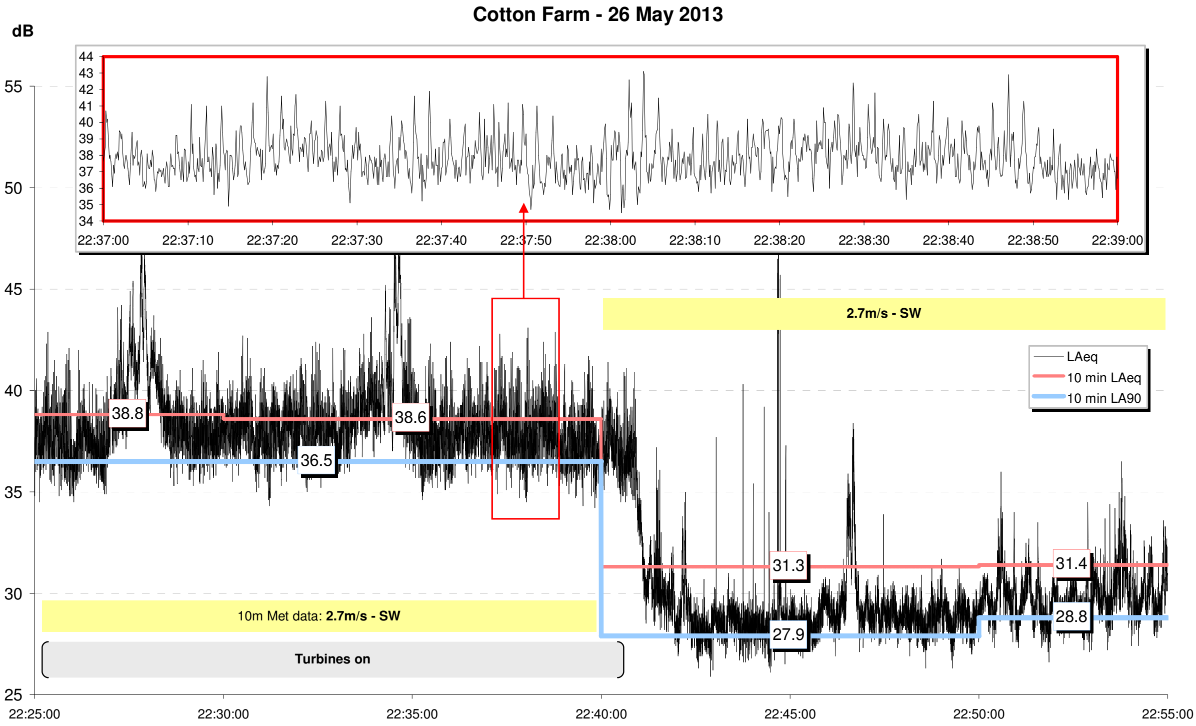


Figure 7 – Example 1 - Cotton Farm 26[th] May 2013 – Switch off effect

- Change in L_{A90} value = 9dB
- MD 3-6dBA and erratic in nature.
- The minimum headroom before any penalty applied to the ETSU-R-97 limits would start to curtail the noise = 7.1dB.
- This noise is not prevented by the ReUK proposed penalty.
- This noise is prevented by the Den Brook AM procedure (6).

Observations – The impact recorded was under downwind conditions. Near ground winds were low with background noise levels of 28-29dB L_{A90}. The area is relatively quiet absent the wind farm noise which increased the L_{A90} almost double that intended by ETSU-R-97. The AM impact was on top of this increase. Thus the impact from AM was not just its modulation depth, with an average value of 3-6dBA and average energy value of 39dB L_{Aeq} but other wind farm noise exceeding the background by 9dBA, with the AM greater than this and both completely dominant.

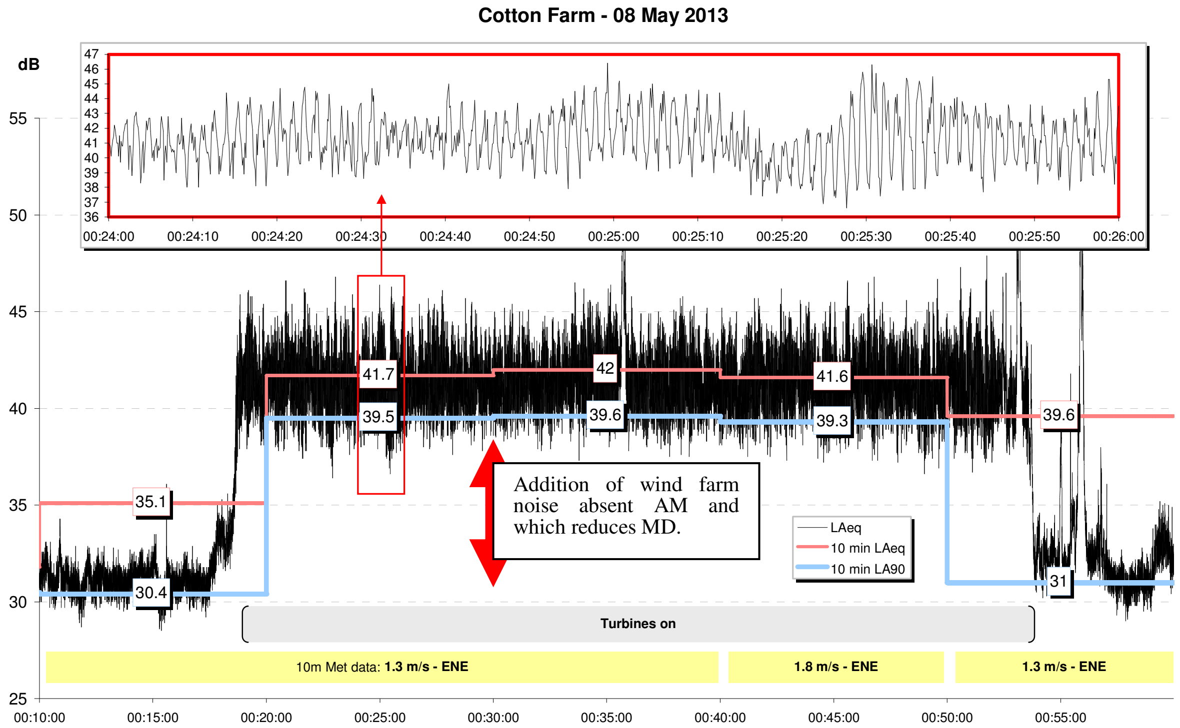


Fig 8 - Example 2 Cotton Farm 8th May 2013 – Switch on/off effect

- Change in L_{A90} value = 9dB
- MD 4-8dBA and classic in nature.
- The minimum headroom before any penalty applied to the ETSU-R-97 limits would start to curtail the noise = 4.1dB.
- This noise is not prevented by the ReUK proposed penalty.
- This noise is prevented by the Den Brook AM procedure.

Observations – The impact on this occasion occurred under upwind conditions. Note: average decibel values are higher than in example 1 and wind speeds are lower. Near ground winds were very low with background noise levels of 30dB L_{A90}. As before it shows the area would normally be relatively quiet absent the wind farm. The wind farm noise increased the L_{A90} almost double that intended by ETSU-R-97. There was a 9dBA increase in the underlying noise due to the wind farm noise. The AM impact was on top of this. Thus the AM modulation of 4-8dBA was on top of a 9-10dBA increase in levels with an overall energy value of 40dB L_{Aeq}. As previously in example 1, there is complete dominance and change in the sound environment.

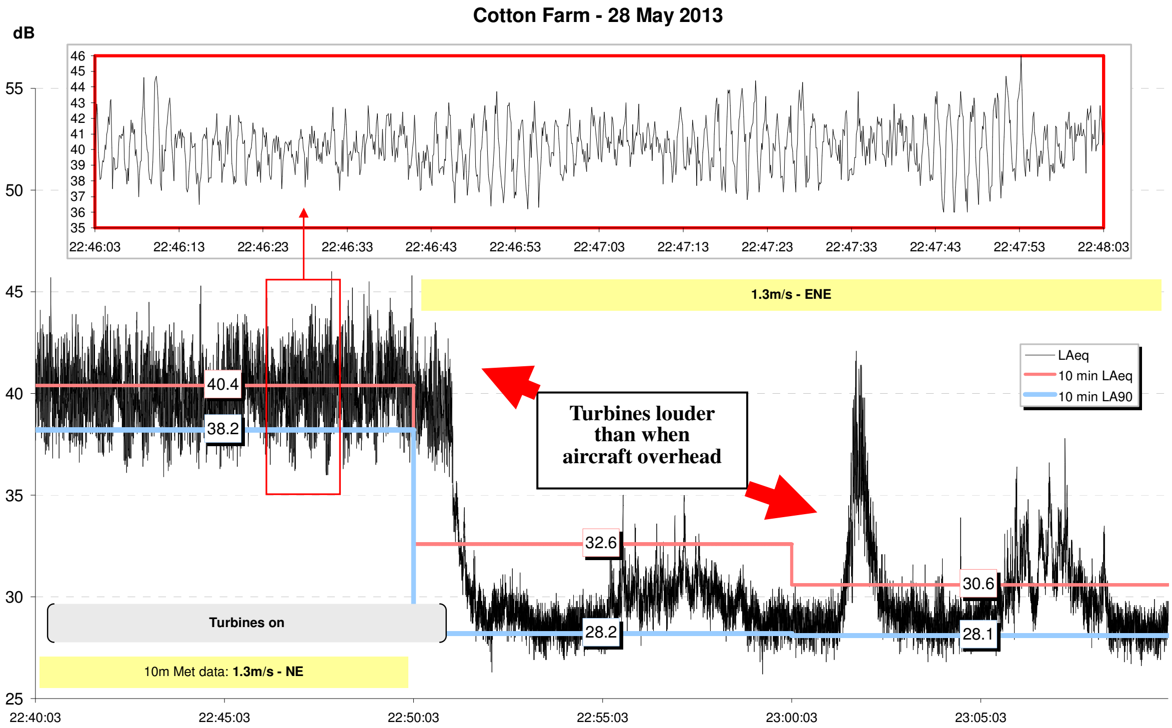


Figure 9 - Example 3 - Cotton Farm 28th May 2013 – Switch off effect

- Change in L_{A90} value = 10dBA double intended by ETSU-R-97
- MD 3-7dBA. Classic and erratic in nature.
- The minimum headroom before any penalty applied to the ETSU-R-97 limits would start to curtail the noise = 5.4dBA.
- Controlled by the ReUK proposed penalty = No
- Controlled by the Den Brook wind farm penalty = Yes

Observations – The impact on this occasion occurred under upwind conditions. Near ground winds were very low with background noise levels about 28dB L_{A90}. This shows consistently it would normally be relatively quiet absent the wind farm. The wind farm noise increased the L_{A90} double that intended by ETSU-R-97. There was a 10dBA increase in the underlying noise due to the wind farm noise. The AM impact was on top of this increase. As in the other examples the impact from AM was not just its modulation depth, with an average value 3-7dBA and overall energy value of 40dB L_{Aeq}, but its exceedance of the background noise by 10dBA. The complete dominance and change of the sound environment is particularly stark. It is notable that in this example aircraft in flight which is normally an intermittent characteristic of the sound environment would be masked by the wind farm noise.

The three examples above are typical, although under conditions of less atmospheric stability the differential between the normal sound environment absent the wind farm noise and that with it are less.

3.8. **Cotton Farm – Switch on/off tests - Findings.**

There was typically a 9dBA increase in the sound environment due to the turbines equating to a major change even without the presence of AM. The range identified was between 5-10dBA. The typical or most common modulation depth was in the region of 3-7dBA but at times has reached 13dBA. Excess AM was very common and an additional impact to the stark increase in sound energy and dominance of wind farm noise. The change experienced at switchover provided a good method for perceiving the difference in the soundscape caused by the wind farm noise and it is recommended such periods are used in any listening tests, where available, to enable judgment of impact.

The ReUK research approach and their proposed penalty permitted all the periods of AM experienced or tested including the periods of most extreme AM recorded from Cotton Farm WF. In most cases there was substantial headroom below the limits and none of the periods of noise causing complaint would be reduced in level or stopped. In contrast a metric built on the Japanese procedure (1) would be more effective provided it did not link to the ETSU-R-97 limits, but addressed it as standalone procedure. The Den Brook condition would prevent the impact experienced. Upwind and downwind L_{A90} values were similar at the measurement distance (600m) but the upwind AM presented different character in the noise compared to the downwind AM.

3.9. Further evaluation of AM Metrics

A procedure based on the Japanese method (1) appeared to most closely map actual impact as it varied well with variations in modulation depth. The ReUK method missed significant periods and forms of AM. The attached graph presents an example of this. This is outlined in Figure 10 below.

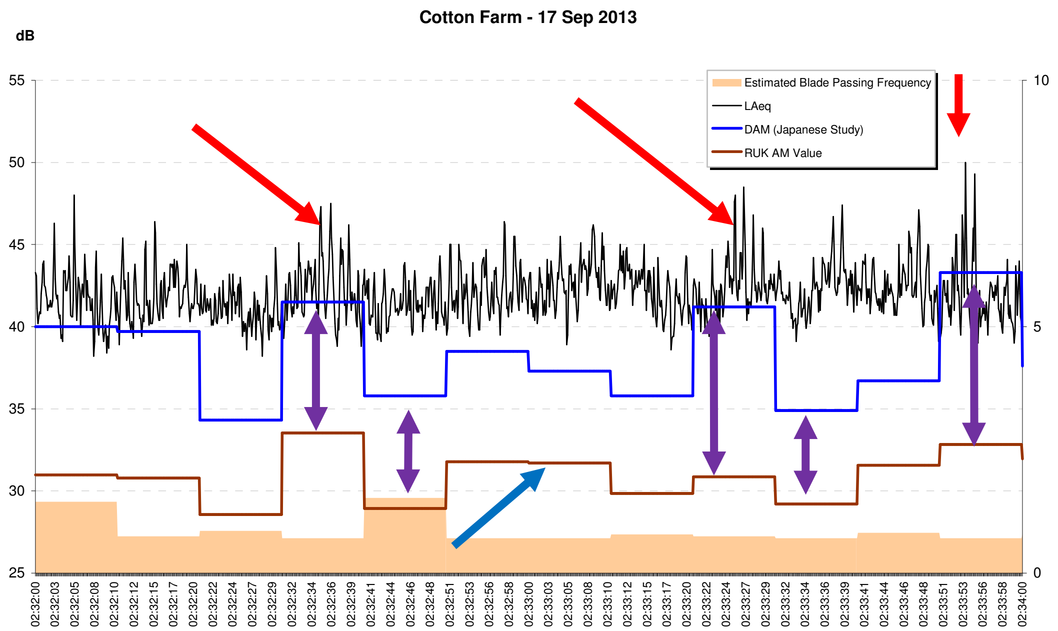


Figure 10 - Example analysis of ReUK condition versus Japanese method for 2 minute period of AM – 100ms LAeq (black), Japanese study D_{AM} (blue), ReUK AM value (brown), Calculated blade passing frequency (solid beige).

In the absence of SCADA data, the ReUK method value is based on the scenario that gives the highest figure, that which is the blade passing frequency matching the peak in modulation indicated on the graph as "Estimated Blade Passing Frequency". Even at this highest possible value, the ReUK method understates periods of increased AM and changes in noise are excessively damped. Compare the brown horizontal lines produced by the ReUK method every 10 seconds with the blue horizontal lines using the Japanese method[10]. The latter reflects the sudden changes in AM modulation depth not found with the ReUK method.

The graph shows a typical period of AM that has erratic elements of change. Three periods are identified by red arrows where the modulation depth suddenly increases, potentially due to synchronicity of the noise immissions from turbines. Not only are there differences in scale of change but the ReUK method does not always map increasing or reducing AM with an increased or reduced value. The blue arrow shows a period where one method increases its value when the other reduces. Subjectively the impact was reducing at this point.

[10] The method is slightly adapted to enable comparison with the ReUK method.

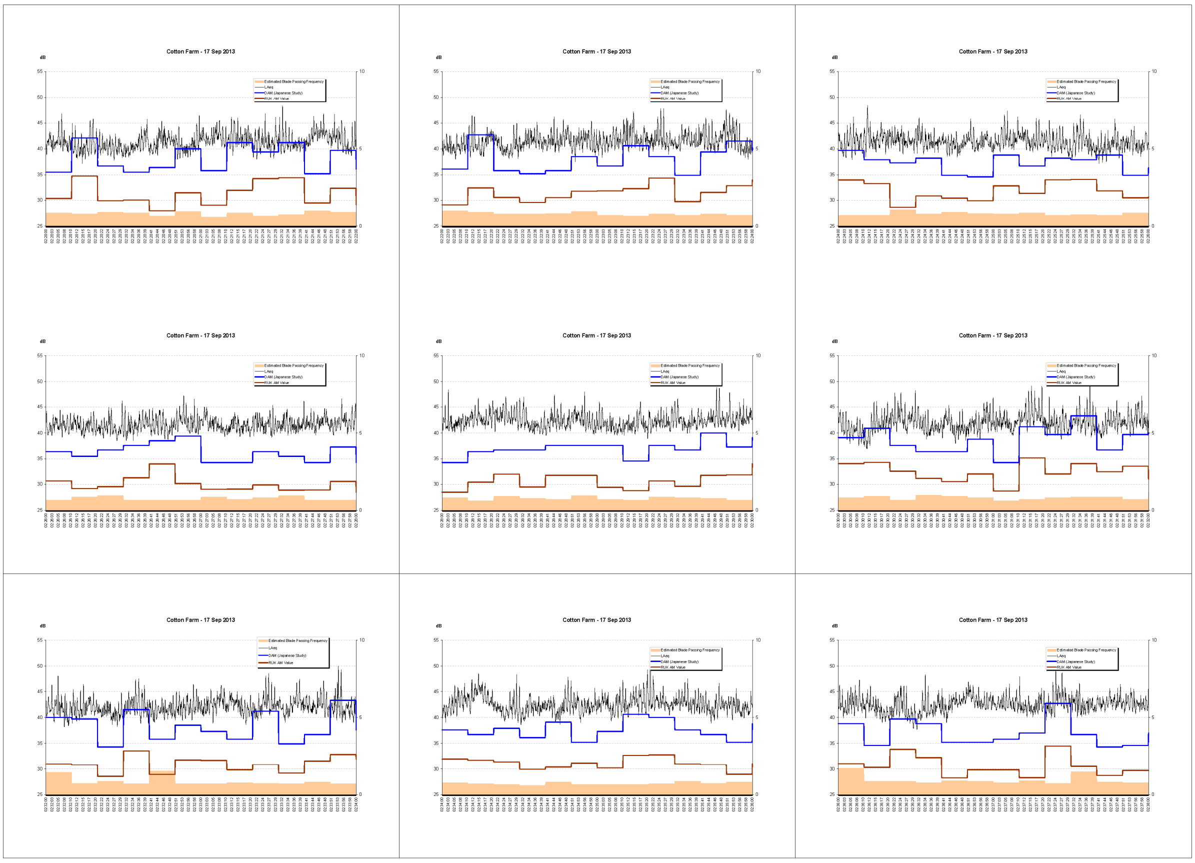


Figure 11 - Example tests.

Figure 11 – Reflects the fact extensive comparative tests have been undertaken using algorithms which consistently showed the ReUK procedure understated impact and regularly presented spurious results which did not reflect the AM experienced. This was rarely found with the Japanese procedure. Neither method can give full weight to changes in character such as changes in pitch, discontinuity and rhythm in the noise.

3.10. Summary findings from initial data analysis of the Renewables UK proposed condition.

a. Even when looking at the worst case AM recorded at night, however extreme it was permitted to continue uncontrolled by the ReUK condition. Analysis included 10 months of Cotton Farm data plus data from two other sites. The results were consistent.
b. Manipulating the data to apply the most extreme 10 seconds ever recorded as if continuous, with modulation depths up to 13dBA and an average modulation depth of 9.6dBA, it was still permitted by the ReUK method.[11]
c. There was a lack of transparency with the ReUK process preventing any ability to relate the results to actual impact.
d. Promotion of a procedure following research has led to an assumption by some that it works and it has been recommended and applied in cases. It is understood ReUK accept there are difficulties with the control.
e. The procedure remains highly technical preventing any means of easily isolating and addressing the areas where it fails.
f. The process is cumbersome and requires judgment checks at several stages. Software has been released to assist but this similarly renders the process cumbersome and open to judgment at several stages.
g. The procedure remains reliant on manual checks and notwithstanding its failure to be triggered it has rendered the process far more labour intensive than manual data checks.
h. The primary problem is the method understates modulation depth and in any event cannot assess other character.

[11] In this example the ReUK procedure produced an AM value of 6.5dB (3.1dB lower than actual) and applied a penalty of 3.8dB adjusting the limit to 38.5dBA. This still left headroom of 0.7dB before any reduction was required. Even then it would only require a reduction in overall level and not the modulation depth.

i. The procedure ignores harmonic noise at blade passing frequency which has varying significance depending on the type and character of AM being checked.
j. The procedure's error rate changes depending whether wind farm noise is dominated by one turbine at a location or contributed to by several turbines producing noise of similar magnitude. It falls substantially short of any level of obvious protection and is partly based on the erroneous idea principles for benign anonymous noise are transferable to noise with psycho-acoustic character.
k. Averaging effects of the ReUK approach indicate modulation depths of 10-13dBA result in a penalty of less than 4dBA.
l. Work by the UK Renewable Energy Foundation similarly found significant errors with the ReUK approach[i] and effectively recommended the Den Brook condition. (7)

3.11. **Analysis of some ReUK general findings using Cotton Farm data.**

The key conclusions in the ReUK report of interest to this research are the suggestions that:

- "Normal" AM (convective amplification) has a maximum value of 5dBA MD close to the turbines and occurs mainly in a crosswind situation.
- AM greater than 5dBA is caused by what ReUK term "Other" AM which they mainly attribute to "blade stall" effects.
- "Blade stall" is an infrequent condition and possibly rare but when it occurs it has quaquaversal emission such that it will impact equally in all directions, subject to wind refraction.
- AM impact increases with increasing energy level (L_{Aeq}) and not modulation depth increase.

Whilst the ReUK study provides some useful work helping progress, the Cotton Farm data and other data sets suggest some erroneous conclusions. In particular the common incidence of AM found at Cotton Farm WF and in various studies including the previous MAS paper (4) does not fit with the ReUk finding that AM above 5dBA modulation depth is infrequent. The directionality found in data is also contrary to the ReUK work which considers OAM as omnidirectional. [12] The Cotton Farm data and other study suggests most AM impact is convective amplification and this is not limited to 5dBA in a cross wind direction. In these circumstances the ReUK study of "blade stall" assists with one possible mechanism adding to the occurrence of AM but erroneously concludes this is the main cause of impact and that overall it is infrequent.

Complaints of AM appear to relate more to the audibility of specific intrusive characteristics and not its average energy level as implied in the ReUK study. The Cotton Farm data shows the tests undertaken in the ReUK study do not reflect what noise impact is received at community locations. Disregarding the short periods of exposure used in the ReUK study, their comparison was made by elevating the sound energy of AM in an otherwise quiet environment rather than testing it in context with the actual effects found in communities.[13]

The Cotton Farm data shows that higher sound energy AM (increased L_{Aeq}) occurs on top of the increased characterless wind farm noise that serves to mask the troughs in the AM reducing its MD. Comparatively the addition to impact from AM on top of the reasonably steady wind farm noise is relatively the same even when the average sound energy is greater. This addition is shown by the red arrow in Figure 8 above. It is likely this context change with the emerging AM fluctuations on top of the overall wind farm noise is a cumulative effect which generates the community responses and not its average energy level in isolation which would be much lower absent other wind farm noise contribution.

Complainants appear to object as much when AM is low in level and without it the environment would be tranquil. The evidence also suggests increased low frequency content can arise when average energy levels are lower and this change in character is a further factor to be considered but which was excluded in the ReUK response tests. Testing of response to noise in very short bursts in a laboratory is unrepresentative of human response in the field, especially when impact response commonly relates to weeks and months of impact and in some cases it is a matter of years. In our study (4) we found significant response differences to wind turbine AM listening experiences when they were conducted in an office compared to a home environment and when conducted daytime compared to late evenings. We also concluded exposure for a period in excess of an hour was typically required to elicit an appropriate reaction. Critically we considered it important to use actual AM with background noise such as bird calls to place it in context and so create a realistic environment. Changes in characteristics over time are also a common

[12] Closer examination of the ReUK field work enables alternative explanation for a number of their findings.
[13] 20 second bursts of artificially generated AM were used.

AM feature that was not tested by ReUK but are found with actual field data.[14]

3.12. **Predicted wind farm noise versus measured levels - ISO9613-2 based predictions.**

Data from Cotton Farm indicates procedures adopted in the UK to predict wind farm noise understate decibel levels at far field locations. In the UK prediction methods rely on a modified ISO9613-2 procedure developed primarily from research by Bullmore et al in 2009 (8) and latterly by research in 2011 by Cooper and Evans (9). A number of spot checks by MAS previously found actual levels under high wind shear conditions higher than those predicted by Bullmore et al. Concern also arises as the predictions rely on averaging, but compliance under ETSU-R-97 requires selection of specific circumstances of complaint. These conditions, normally relating to high wind shear, were not factored into the Bullmore et al study.

MAS has separately concluded the research did not sufficiently support its conclusions long before the Cotton Farm project commenced due to anomalies within the work; however, Cotton Farm WF's predicted noise was decided on the basis of the current ISO9613-2 method following the Bulmore et al work. It is considered the work by Cooper and Evans (9) indicates higher levels than the adopted UK method as when differences in use of L_{A90} and height are accounted for to compare the UK methodology, for flat sites, it suggests the UK method understates values up to 2dBA.

Criticisms arose over the Bullmore et al (8) research due to the high level of filtering of the data that was not transparent and not all the reported data supported its conclusions. Requests by others to obtain the data to enable peer review were refused and this remains the position to date (10). A request by MAS to review the data of the Cooper and Evans study was similarly refused in 2013.

The data expert who requested the Bullmore et al data reverse engineered some of the published information and concluded downwind angles were incorrectly reported in the study (10). The sites used in that study remain anonymous but their descriptions have enabled their identification. No response has been received from the authors. In these circumstances and in light of the findings from Cotton Farm WF reported below and at other sites, it is concluded little weight should be given to that research and additional study is required.

Long term Cotton Farm WF measurements compared to predictions are presented in Figure 12 below.[15] Compare the purple predicted level for the turbines actually installed with the grey circles showing wind farm noise and the green line showing the average wind farm noise for a standardised wind speed. The values indicate average levels were typically 3-4 dBA higher than those predicted and during periods of worst impact levels were of the order of 5-9dBA higher than predicted. More than 85% of the calculated wind farm noise levels exceeded the predicted values.[16]

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[14] The lead researcher has confirmed acceptance their analysis understates likely responses when presenting the evidence at an IoA seminar March 2014.

[15] The measurements reported in this section were obtained independently from the operator's acousticians to avoid any dispute as to the findings based on 10m height wind measurements and they relate to standardised wind speeds.

[16] After deducting background noise contribution.

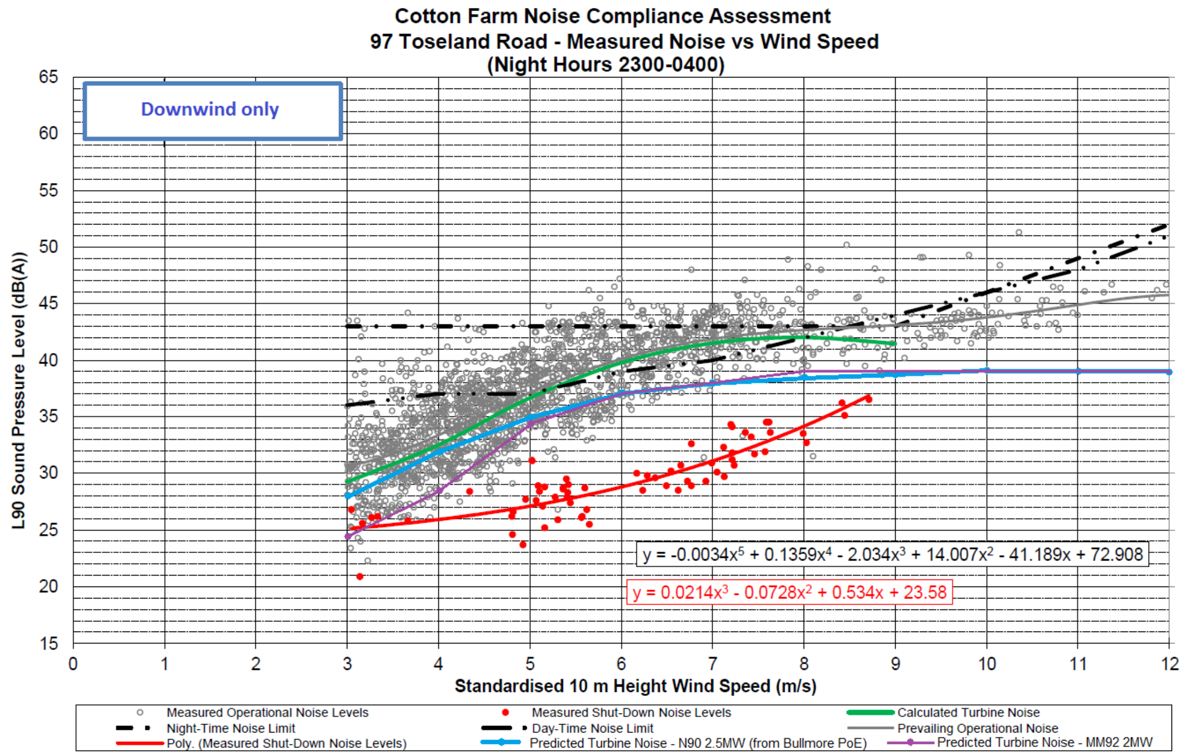

Figure 12 - Predicted turbine L_{A90} v actual L_{A90}

The findings in relation to Cotton Farm WF data compared to predictions are also supported by data obtained at the Swaffham II turbine, an Enercon E66. The data was collected by MAS and reported at the Shidham public inquiry (10). In that case predicted levels using the ISO9613-2 procedure adopted in the UK understated levels by on average 5.7dBA. No explanation has been provided for this significant exceedance. Similar exceedances have been found by others (11).

It is concluded the typical individual complaint event caused by wind turbine noise, which occurs under high wind shear conditions, may be of the order of 5-8dBA higher than the predicted noise for those conditions. This outcome is contrary to the intent of ETSU-R-97, which was designed to limit exceedance of the background noise as measured using the L_{A90} index to 7dB L_{Aeq}. It is concluded the increase in impact compared to historical wind farms in the UK arises as a result of the adoption of hub height wind speeds standardised to 10 metres rather than comparison with measured wind speeds at 10 metres as originally identified in ETSU-R-97 and this follows published research by MAS and others comparing the two methods (12) (13). The adoption of what is effectively hub height wind speeds as found in the UK IoA Good Practice Guide 2013 is a deliberate change effectively increasing the level of noise permitted near residential property through change of procedure. It is considered this is partly the reason for an increase in problems and complaints in the UK and especially excess AM problems as they now impact dwellings under upwind as well as downwind conditions partly because separation distances are reduced. Propagated levels increase with wind shear increase and they exceed the UK predicted levels by large margin.

MAS are unaware of any cases where predictions have overstated impact once adjusted for the turbine operational mode, complaint conditions and appropriate wind direction. It is concluded a review of the procedure is warranted. It is of note that had the higher sound energy levels identified post development of the Cotton Farm WF been predicted it is likely the development would have been recommended for refusal on noise grounds.

4.0. SUMMARY FINDINGS - What the Cotton Farm WF data shows

a. Far field AM follows predictions of convective amplification most of the time.

b. Far field AM with a modulation depth of 5dBA and higher is very common. It is not infrequent as suggested by ReUK and is not found mainly under cross wind as they state but at downwind angles. It is not normally experienced directly downwind of a turbine. [17] The spread of turbines in a wind farm usually means a receptor is at an appropriate downwind angle to be affected by convective amplification for a wide range of wind directions.
c. Convective amplification AM theory as explained by Lee et al 2013 (5) is supported and the concept that modulation depth can be much greater than 5dBA at distant receptors is also supported by the measurements.
d. "Other" AM, primarily related to blade stall, in the ReUK research December 2013 is not the primary cause of far field impact, albeit important, but an extra mechanism leading to impact.
e. Findings of ReUK of increasing impact with increasing average noise (L_{Aeq}) fail to address context / ambient change and therefore rely on incorrect assumption.
f. Excess audible amplitude modulation is the primary characteristic causing complaint. Where tonal noise also arises it sometimes also modulates.[18] Impact appears less related to average sound energy but its relative loudness considered in context and other wind farm noise contributions that are cumulative and separately its characteristics.[19]
g. AM exhibits a range of features and characteristics that constantly vary and are different from site to site and under different meteorological conditions.
h. AM impact can be as great under upwind conditions at distances of 600m as it is under downwind conditions.
i. Upwind and downwind AM characteristics differ.
j. Predictions using ISO9613-2 understate sound energy levels when applied using the procedure as set out in the UK IoA Good Practice Guide 2013. This finding is also supported by independent evidence. The understated average level is typically 3-5dBA at 600m and under certain conditions is much greater. This outcome follows similar findings at a range of other sites including the Swaffham II wind turbine where detailed comparisons were made with the turbine operational data.
k. AM impact occurs under a wide range of wind directions as illustrated in terms of distance and direction resulting in heightened noise zones. The actual spread of these zones can be complicated by the spread of turbines producing overlapping zones.
l. AM with regular peak to trough greater than 5dB occurred more than 54% of the time at 600m from the nearest turbine.
m. During a 2 month period 82% of nights experienced AM with modulation depth in excess of 5dBA and up to 13dBA. Severe AM occurred for 30% of nights, four of them consecutively.
n. At a distance of 600m, in the case of Cotton Farm WF AM in excess of 5dBA modulation depth occurred more commonly under upwind angles than downwind angles but both incidences were high.
o. Incidence of objection to the noise appears to increase with time with increasing awareness and an apparent sensitisation over time.

4.1. Additional findings indicated by the Cotton Farm data and its analysis

p. Propagated levels increase with wind shear increase and exceed those predicted by the IoA adopted prediction method by a significant margin. These increased values follow the science and what has been found by some other researchers.
q. As wind shear increases masking noise reduces (WT and non-WT) leading to greater context differences and impact as a result.
r. As masking noise reduces modulation depth increases. This is logical as the troughs in the noise are no longer masked. This indicates any proposed control based on LA90 values reduce protection as modulation depth increases.
s. Modulation depth is mainly limited by other wind turbine noise and not the background noise in an environment.
t. Switch off tests should be closely monitored and provide a good method of measuring the true change in a sound environment.
u. There are a wide range of characteristics where subtle differences change the impact. It can be highly erratic, repetitively similar or with repetitive changes. Variations can occur rapidly. Character change moment by moment is a significant factor. These are all significant factors in the intrusiveness of the noise.
v. Community monitoring is a valuable assessment tool empowering the community, can be achieved at reasonable cost and operated by the community in many cases.

[17] Zero degrees to the wind direction or 90 degrees to the angle of the turbine where there is no yaw error.
[18] This is thought to be due to the noise radiating from specific blades.
[19] Relative loudness was not examined in the ReUK study.

w. The occurrence of when and where AM will impact is reasonably predictable depending on the particular circumstances relating to a site.
x. The defining factor as to the level of impact is meteorology and the extent of upward or downward atmospheric refraction. Small changes can lead to large differences in effects.
y. Nearby locations can experience wholly different noise levels and character depending whether they are in a heightened noise zone.
z. Complaints are unrelated to individual attitudes to wind farms and have arisen due to actual impact and not perceived impact.

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