The noise characteristics of 'compliant' wind farms that adversely affect its neighbours

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ABSTRACT

In the UK many wind farms cause complaints of noise despite complying with control limits. Problems relate to reliance on the L_{A90} index, failure to consider or apply ratings on the context of the sound characteristics and actual human responses due to complex characteristics. In general in the UK low frequency and very low frequency sound effects are either ignored or denied. The complex interrelationship of features within this noise and difficulties in quantifying and qualifying noise impact and inappropriate comparison with other sources of noise renders the effects difficult to investigate or quantify with contradictory outcomes possible using the same data sets. Claim and counterclaim of health and adverse effects complicate the analysis. This paper explores some of the interrelating characteristics of wind farm noise measured and observed in the field that appear to influence complaints made by communities. Cumulative effects occurring in environments normally dominated by natural sounds and both audible and inaudible elements remain alien sounds which are not habituated to. It appears that sensitisation arises. The physical reason for the failure to appropriately identify modulating noise effects and in particular low frequency modulating noise problems are explored.

Keywords: Wind farm, Complaint, Noise character   I-INCE Classification of Subjects Numbers: 14.5.4, 63.7, 66.1, 66.2

1. INTRODUCTION

Human reaction to noise is influenced by a large number of objective and subjective factors. Perception and interpretation of these factors is highly individual and individual differences can be difficult to account for in any metric aimed at assessing the general population. As a result, analysis tends to focus on physical, easily measurable properties of sound. Subjective assessment of noise character is often neglected. The majority of guidance relates to noise that is considered benign and anonymous and does not contain specific character features. Where character is considered this tends to be limited to a simplistic, objective assessment of tonality and / or impulsivity.

In the UK noise nuisance assessment establishes whether a state of affairs exists where there are periods of intrusive noise that are unreasonable and excessive to the extent that they affect the use of enjoyment of a property in a material way. It requires a broader assessment approach that includes consideration of loudness, time of occurrence, duration, character of the noise, character of the area, message imparted by the noise, variation in noise over time, spectral content of the noise, frequency of occurrence, regularity / predictability of the noise, respite from the noise, length / duration of respite, how easily the noise can be avoided, impact of the noise on basic needs such as sleep or communication, the necessity of the noise in relation to greater society etc. That all these factors are deemed important for considering whether a noise constitutes a nuisance highlights the complexity of noise perception and impact, and arguably the oversimplification of these factors at the planning stage.

Noise assessment at the planning stage reduces assessment of acceptability to decibel levels and limits. In wind farm assessment in the UK, acceptability is for the most part judged against absolute limits or relative limits with an absolute lower threshold. Development can always be permitted if these lower thresholds are met, regardless of noise character or character of the area.

As wind farm noise is typically predicted at lower decibel levels than other industrial noise sources, comparisons are often made in noise impact assessments to 'contextualise' the level of impact being permitted. A wind turbine noise level of 35dB(A) is frequently asserted as equivalent to the noise level in a library or a quiet whisper (1). The 43dB L_{A90} UK night time limit is often compared to the noise level generated by a fridge (2). These comparisons and the focus on decibel levels can present a highly misleading impression of noise impact to the lay person.

An experienced acoustician always questions the noise levels and comparisons quoted, but this may not be obvious to a less experienced reader. A commonly quoted example in the media is that of the impact of military sonar on whales. "Sonar systems... generate slow-rolling sound waves topping out at around 235 decibels; the world's loudest rock bands top out at only 130" (3). Are the quoted figures sound power levels or sound pressure levels? At what distance were the noises measured? Are the figures A weighted? Do the figures account for the effect of propagation (speed of sound in water / air)? What is the frequency content? Is the noise level quoted a short term, average or maximum level? These same questions are relevant for assessment of wind turbine noise. A wind turbine may generate a noise level of 35dB(A) in average propagation conditions, but what about turbulent wind conditions and high wind shear? Is the noise constant or does it vary? What is the frequency content of the sound and does the dominant frequency vary? Is 35dB(A) the average level and does the sound vary significantly from this overall level? These questions are integral to perception and assessment of noise impact.

Perception of noise is complex and many factors influencing perception can be overlooked or oversimplified at the planning stage by reliance on absolute decibel limits and objective parameters. Inappropriate comparisons such as those given above are not only erroneous but the dogmatic oversimplification of wind farm noise assessment undermines the integrity of the acoustics profession. This paper investigates noise character and how these characteristics might contribute to the perception of wind farm noise. It compares detailed analysis of wind farm noise excerpts with other assessment metrics. It looks for explanation of why so many wind farms found to be compliant with noise limits generate significant complaints.

2. METHODOLOGY

2.1 Brief review of relevant UK guidance

UK wind farm noise is assessed using the guidance ETSU-R-97 (4). Wind farm noise is measured and assessed using the L_{A90} index of 10 minute periods. The guidance acknowledges a mid frequency 'swish' component to wind farm noise, 2-3dB(A) modulation around 800-1000Hz, but notes that as distance increases from the turbine this noise will decrease and masking of the background noise will therefore reduce any subjective impact (p.12). Tonality is noted in ETSU-R-97 as the main cause of noise complaints. In the event of complaints of tonal noise a maximum penalty of 5dB can be applied. The noise limits set in ETSU-R-97 therefore relate only to anonymous noise. Tonality is accounted for by penalty and amplitude modulation (AM) / blade swish is expected to reduce with distance to the point that it is not clearly discernible at residential dwellings. There is no further consideration of noise character.

Perhaps the most commonly used standard in the UK is British Standard 4142 'Method for rating industrial noise affecting mixed residential and industrial areas'(5). The standard is currently under review but the approach to noise impact assessment is similar both in the current and draft version of the standard. The background noise level, L_{A90}, is measured in the absence of the noise source. The noise source is measured, accounting for exclusion of extraneous noise, or calculated. A penalty is applied to the noise source for noise character, tonality, irregularity or any other feature that attracts attention. Currently the maximum penalty is 5dB but in the draft version this could be augmented with separate penalties for tonality and impulsivity. The background noise level is deducted from the source noise level plus any relevant penalty to give a complaint prediction level. If this complaint prediction level is around 5dB, noise impact is considered of marginal significance. If the complaint prediction level is 10dB or more then noise impact is considered likely to result in complaints. The important difference between this approach and that of other noise guidance is that it compares the source noise level to the background noise level occurring at the time of impact; it is not an average background noise level and there is no lower threshold of acceptability. BS4142 has proved to be a very successful and reliable judgment of noise impact.

2.2 Other objective assessments of noise character

International standards arguably consider noise character in greater detail than the UK's ETSU-R-97. The New Zealand Standard (NZS) 6808:2010 also measures wind farm noise using the

L_{A90} parameter but takes account of character under 'special audible characteristics' (6). It notes that wind farms should be designed so that no special audible characteristics arise, but where they do a maximum penalty of 6dB can be applied. This penalty is the maximum penalty to be applied regardless of the number of characteristics, e.g. tonality, amplitude modulation, impulsivity etc. The New South Wales draft wind farm guidance measures noise using the L_{Aeq} parameter and similarly to the NZS a maximum 5dB penalty is applied for the presence of tonality, low frequency noise or amplitude modulation (7). Danish guidance measures turbine noise using the L_{Aeq} parameter and has a separate limit for low frequency noise; tonal penalties are also applicable (8).

As with ETSU-R-97, international guidance tends to relate noise impact to absolute decibel levels, affording a maximum reduction of 5-6dB for noise character. Of note, amplitude modulation is recognised internationally as an adverse noise characteristic of wind farm noise, in the UK this is still a matter of debate. It is the authors' experience that amplitude modulation is the main cause of noise complaints from large wind farms in the UK.

At the end of December 2013 Renewable UK, a UK wind industry body, published the findings of research in to the cause and effects of amplitude modulation (9). Despite concluding that amplitude modulation was infrequent, attached to the main publication was a template noise condition for control of amplitude modulation. The current notion is that a maximum penalty of 5dB would be applied to the noise limit of a wind farm where amplitude modulation was found. The effectiveness and workability of the condition is still a matter of debate. Many working for the wind industry are still unwilling to accept controls on amplitude modulation, relying on assertions that it is a rare occurrence at a minority of wind farms.

Other methods for assessing wind farm noise character, specifically amplitude modulation, have been pursued independent of penalties and noise limits. A large study funded by the Japanese Ministry of the Environment resulted in three papers published in August / September 2013 (10) (11) (12). Recognising that amplitude modulation is a common feature of wind farm noise that causes serious annoyance, a method to evaluate the magnitude of AM was derived, D_{AM}. The onset of fluctuation sensation was confirmed at around 2dB modulation depth, equivalent to a D_{AM} of 1.7dB. Perceived noisiness increased as AM depth increased.

The Nordtest method is designed to assess the prominence of impulsive sounds and also proposes an adjustment criterion for the measured L_{Aeq} of an impulsive noise (13). This method was adopted by DiNapoli to investigate complaints from a single turbine in Finland (14). The Nordtest method derives a prominence value 'P' from the onset rate of the modulation peak and the difference in level between peak and trough. A graduated adjustment K_i based on the prominence, P, can be made to the L_{Aeq}. The standard also notes that when $K_i>3$ this can be used as support for application of a 5dB penalty made from subjective assessment of noise character.

In the UK another metric for establishing reasonable / unreasonable AM has been widely debated. The method is detailed in the 'Den Brook AM condition' but essentially looks for a regular rise and fall in sound energy of 3dB (15). Sound energy levels investigated must be greater than 28dB L_{Aeq},1 min. If wind turbine noise modulates regularly by 3dB or more, at average levels more than 28dB L_{Aeq}, it can be deemed 'greater than expected' and considered unreasonable.

There are many other metrics proposed for assessing AM modulation depth. Review of the different methods to assess AM is outside the scope of this paper, which aims to look at some of the ways in which AM can be assessed and whether these methods can appropriately addresses the character of wind farm noise.

2.3 Subjective assessment of noise character

The importance of psycho acoustical factors in perception and assessment of wind farm noise was discussed in greater detail in a previous paper by the authors (16). In brief, the perceptual environment is constantly appraised and reappraised. Sensory information is judged against previous experiences and expectations. Much of this sensory information is ignored but there are other aspects that are either voluntarily or involuntarily focused upon. In relation to sound it is often sudden or unexpected sounds that attract attention, for example a door slamming. However, attention can also be drawn to subtle changes in our sound environment as well described in the extract below (17).

> *Suppose you hear the sound of a refrigerator pump – a series of noise bursts of a certain duration, spectral distribution, onset, offset envelope, location in space, cycle time, and so on. If the sound is not painfully loud, people will tend to lose awareness of it rather quickly, but they will tend to be conscious of the noise again as soon as any parameter of*

> *the sound changes: The noise can become louder or softer, the time between the noise bursts can change, the intensity envelope can change, or the noise bursts can just stop. Any of these changes will trigger a new OR [orientating reflex], just as we may become aware of the noisy refrigerator as soon as the noise stops.*

The capabilities of our hearing system are well exemplified by our ability to analyse music, even by the untrained listener. We can listen to a piece of music and ascertain the basic rhythm, regular 1, 2, 3, 4 counts or a dance, for example a waltz which counts 1, 2, 3, 1, 2, 3. We can make a judgement of the tempo, whether the music is fast or slow, and whether the tempo varies (accelerate / decelerate). Musical descriptors can be used to portray a message, emotion or character. The loudness of the music is a simple judgement and often conveys the energy of the music. Something that is loud or has sudden differences in loudness often represents lots of energy. The frequency content of music, differences of pitch, are also commonly used to convey a message. In Prokofiev's Peter and the Wolf the flute and oboe, higher frequency woodwind instruments, represent the bird and the duck as smaller docile animals. The hunters and the wolf are characterised by the timpani / bass drum and the French horns. These are lower frequency instruments with a harsher sound and represent more dangerous characters.

Simple messages portrayed by music can be extended to messages conveyed by noise. Many of the features used in music to attract attention, variance in loudness and pitch, may also explain why some noise is considered benign and other noise more annoying or difficult to habituate to. A more musical analysis of noise can highlight different aspects of sounds that are easily distinguished by the auditory system and colour our perception of the environment. Approaching analysis of noise with character from a musical perspective might enable better understanding of wind farm noise annoyance.

2.4 Assessment approach

The remainder of this paper presents several examples of wind farm noise that have been found to comply with the noise limits set according to UK guidance. The excerpts presented are judged 'compliant' and in many cases complaints and enforcement action has been dismissed as a result of this compliance. The character of the noise will be discussed and analysed from a musical perspective, exploring the interrelating features and how these might be perceived. Different assessment metrics described above have also been applied to the extracts. Where necessary a description of how metrics have been calculated is provided in footnotes accompanying the results table for each example. A prominence (P) value has been determined according to the Nordtest method for three representative modulation peaks in each example, these are marked 'P1', 'P2' and 'P3' in the figures and tables.

3. FINDINGS

3.1 Swaffham II - 30th September 2013 - 1 x 1.8MW turbine

The graph below shows clear amplitude modulation noise. With the exception of some insect noise (around 12.5kHz) the wind turbine noise is the only and dominant noise source. The noise level varies in loudness throughout the extract. The shape of the noise trace varies in waves but without regularity.

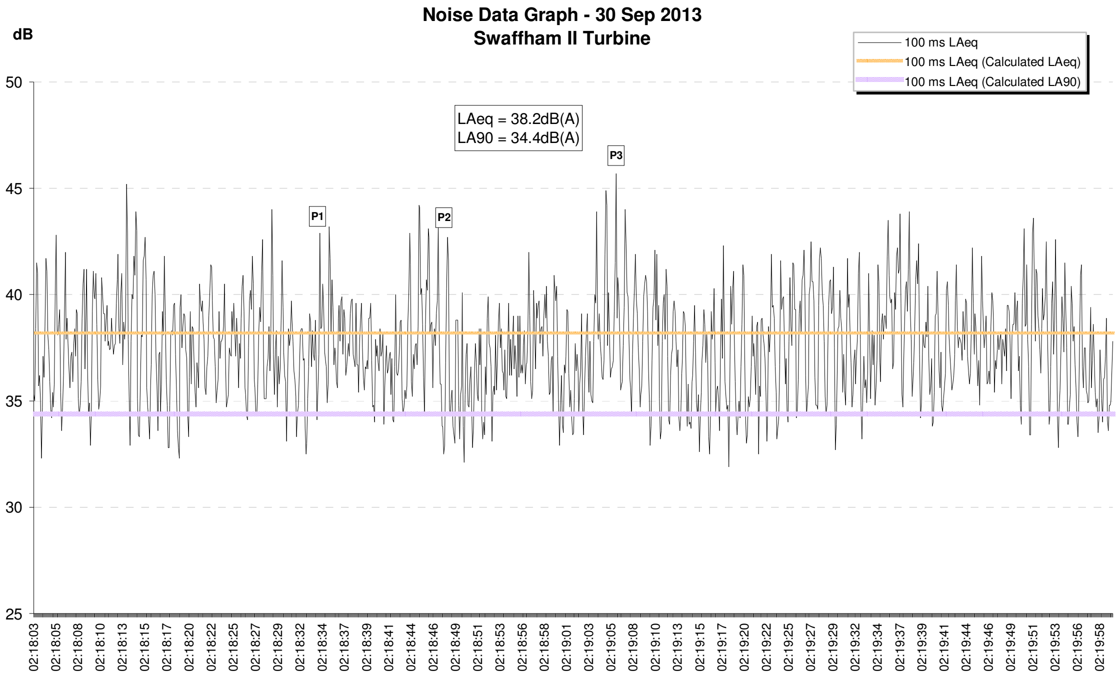

Figure 1: Swaffham II turbine - 30th September 2013

Increases and decreases in noise level and modulation peaks are followed by sudden reductions in noise level and modulation strength. The variances in loudness and clarity of modulation peaks can be compared to someone twisting the volume control on a music player or a radio station coming in and out of frequency range. The dynamics of the piece are very erratic and convey an image of something that has significant potential energy but is also highly changeable and unpredictable. Figure 2 below shows how the first minute of the above extract could be marked musically.

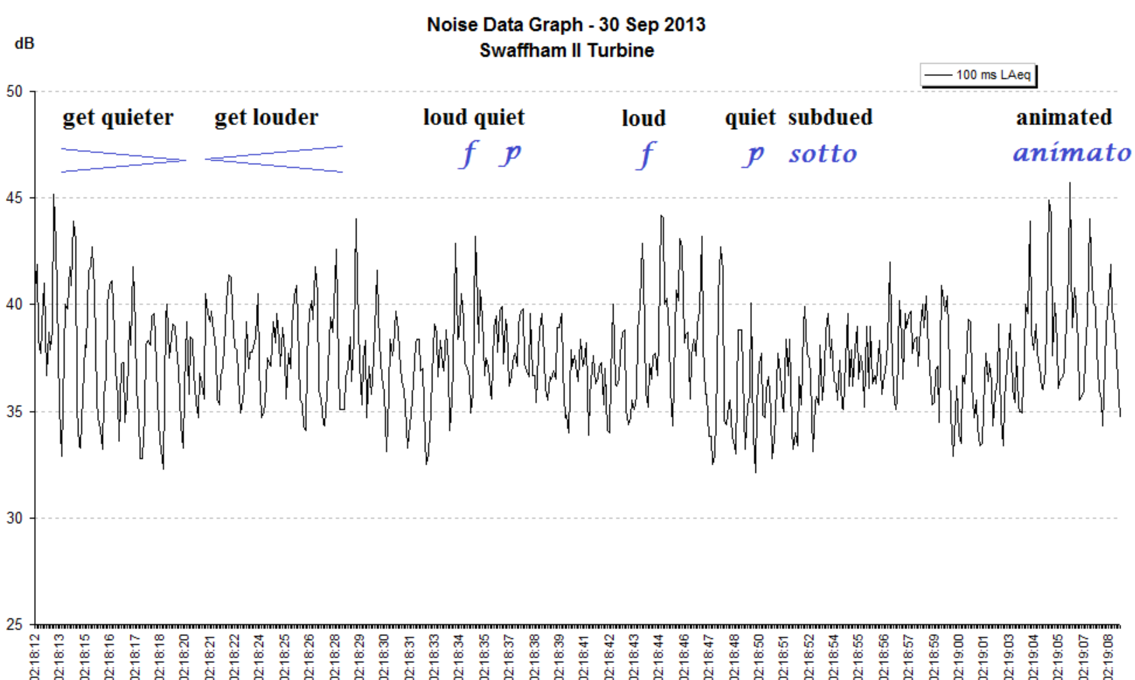

Figure 2: Musical description of first minute of figure 1

Where the listener is not in control of sudden or unpredictable change these changes are often ill perceived. The constant variance in clarity and loudness in the above extract could therefore attract attention and be perceived as annoying or unpleasant.

The character of the modulation also varies throughout the extract. Both the shape and the rhythm of the modulation varies. At the beginning of the extract there is a single defined beat, the third modulation splits in to two and a double beat is heard in place of the single defined beat. The first 20s of the extract is shown below with the rhythmic element imposed at the top of the graph, ♩ indicates a single beat and ♫ a double beat. The varying beat is likely to attract and hold attention. The lack of pattern and regularity is likely to be perceived as annoying as patterns and expectations are broken and as the beat is difficult to ignore.

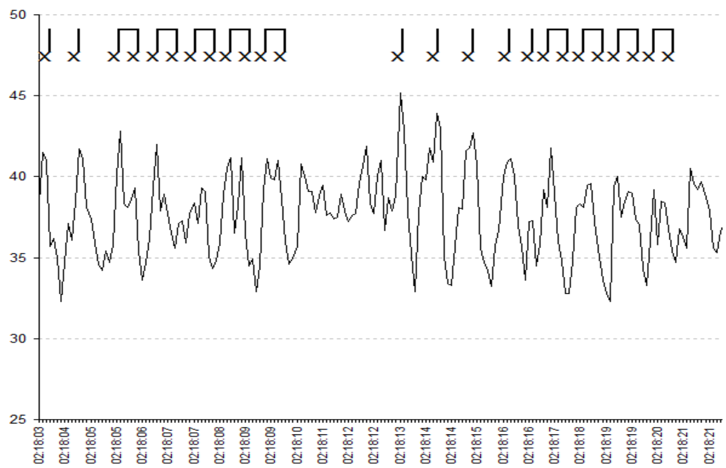

Figure 3: Extract of figure 1, variance of rhythm / beats shown

The table below assesses the example shown in figure 1 against five of the criteria discussed above.

Table 1: Assessment of turbine noise from Swaffham II turbine

Method	Criterion	Calculation	Result
ReUK / ETSU	5dB penalty to L_{A90}[1]	34.4[2] + 5 = 39.4dB L_{A90}	Compliant with ETSU-R-97 43dB lower night time noise limit
BS4142	L_{Aeq} (+5dB) - L_{A90}	(37.9[3] + 5) - 34.3[4] = 8.6dB	Complaints likely (see footnote)
Japanese D_{AM}	Fluctuation sensation when greater than 1.7D_{AM}	ΔL_{A5} (3.3) - ΔL_{A95} (-4.4)	7.7D_{AM}
Nordtest	Prominence, P	P=3log(onset rate/[dB/s]) + 2log (level difference /[dB])	P1 = 6.3 P2 = 6.5 P3 = 6.0
Den Brook	Regular 3dB modulation >28dB L_{Aeq}	L_{Aeq} = 38.2 Peak to trough range 4-11dB, regularly above 3dB	Greater than expected AM

1 It is assumed in each assessment that the maximum 5dB penalty would be applied. Separate long term tests have demonstrated this is not the case and at most even in extreme cases of AM it is likely a 3dB penalty would be applicable (see reference 19).
2 The 10 minute period including figure 1 is contaminated by nearby road traffic noise. This 2 minute period is representative of the turbine noise during the 10 minute period in the absence of road traffic noise.
3 This is based on a 5 minute period, which includes the 2 minute period shown in figure 1. All noise during this 5 minute period is dominated by wind farm noise.
4 Strictly this should be the background noise level in the absence of wind farm noise. In this case the turbine was operational throughout the measurements and a true background noise level could not be determined. As a best case the L_{A90} for the measurement period is used, background noise levels would be lower in the absence of wind turbine noise and the true complaint prediction level much higher.

3.2 Kessingland turbines - 10 June 2012 - 2 x 2.05MW turbines

The noise data graph below is taken from two turbines at Kessingland. The beginning and end of the extract show clearly defined modulating noise which also has a strong rhythmic element. Modulation is still apparent in the middle of the extract but has a less clearly defined, muddied modulation sound similar to a tumble dryer noise, a descriptor often used by residents to describe the noise character of wind farm noise. The noise in the middle of the extract is more continuous and undulating compared to the defined modulation that fades in and out (at the end and beginning of the extract) as if the turbines were moving in and out of synchronisation with each other. That the noise is less variable during the middle period and its likeness to a common noise source (tumble dryer) could suggest that this middle period is less intrusive, more easily habituated to. However, the change in noise character to a strongly rhythmic, irregular noise just after half way through the period creates a stark and noticeable change that draws attention. A listeners attention might wander from the wind farm noise as it becomes less prominent and more subdued but refocus on the noise when the strong modulation returns.

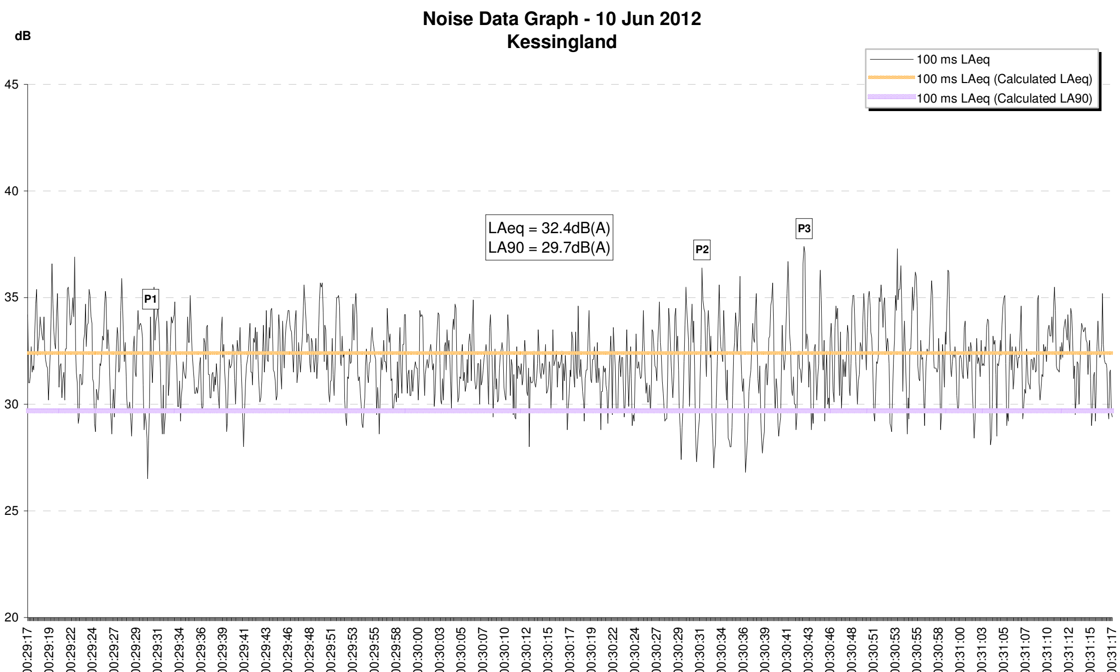

Figure 4: Kessingland turbines - 10th June 2012

The frequency content of the noise also varies throughout the extract. The dominant frequencies are centred around the 315Hz, 400Hz and 500Hz third octave bands. The dominance of these frequencies are constantly changing and increases and decreases in loudness are not necessarily perfectly synchronised, thus creating a 'Mexican wave' type effect through the third octave bands. Some of the dominant frequencies of the modulation peaks are labelled on figure 5 below to demonstrate the variability. There is also variable low frequency content, indicated by the 125Hz and 100Hz third octave band content in figure 5 below. Periods of lower frequency rumble are particularly noticeable during the middle section of the extract, though there are no obvious difference in low frequency content compared to the beginning or end of the extract. The increase in low frequency content contributes to the changeable character of the noise. Subjectively the noise varies between a whoosh, swish and tumble dryer type noise. The range of different and varying pitches adds body to the sound and creates a broader multi-dimensional sound, for example the difference between a strong quartet and the string section of an orchestra. This feature could be attributed to descriptions from affected residents that they feel surrounded by the noise.

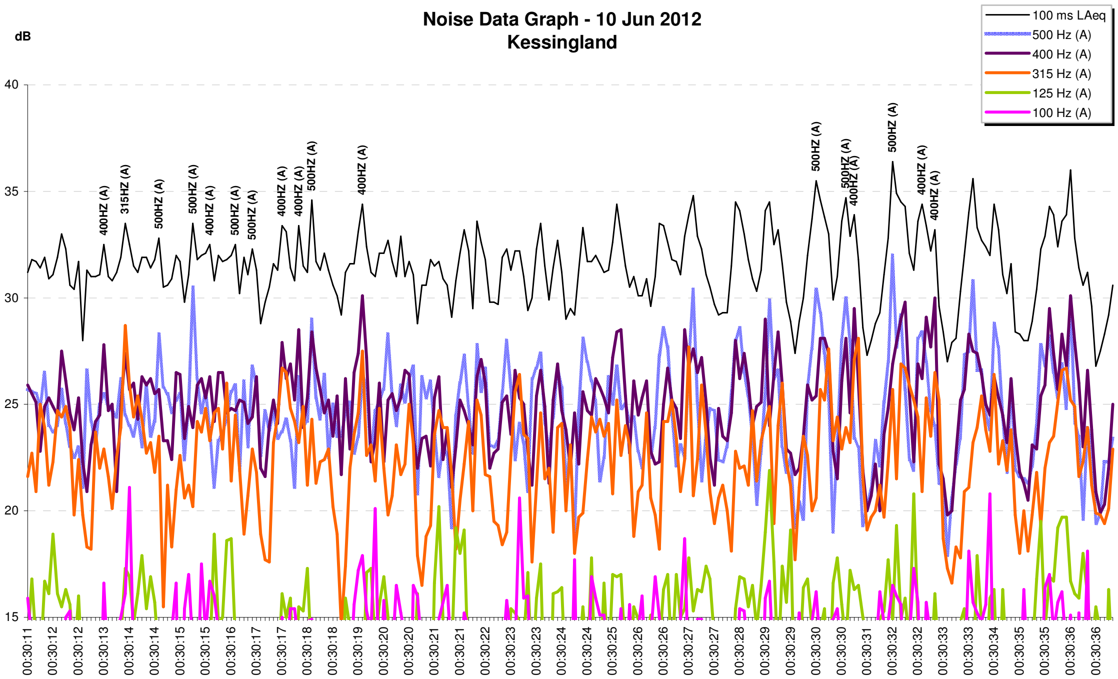

Figure 5: Kessingland turbines - 10th June 2012, frequency analysis and dominant frequencies

As noted above there are very strong rhythmic qualities to the turbine noise. This is shown in figure 6 and 7 below. In western music there is a preference to hear sound with meter, an alternation between strong and weak beats. Entrainment describes the interaction of two rhythmic processes combining to a common phase. Human entrainment to rhythms is observed from an early age (18). The emphasis of strong and weak beats in the excerpt below changes within the modulation peak and creates two distinct rhythms in the extract.

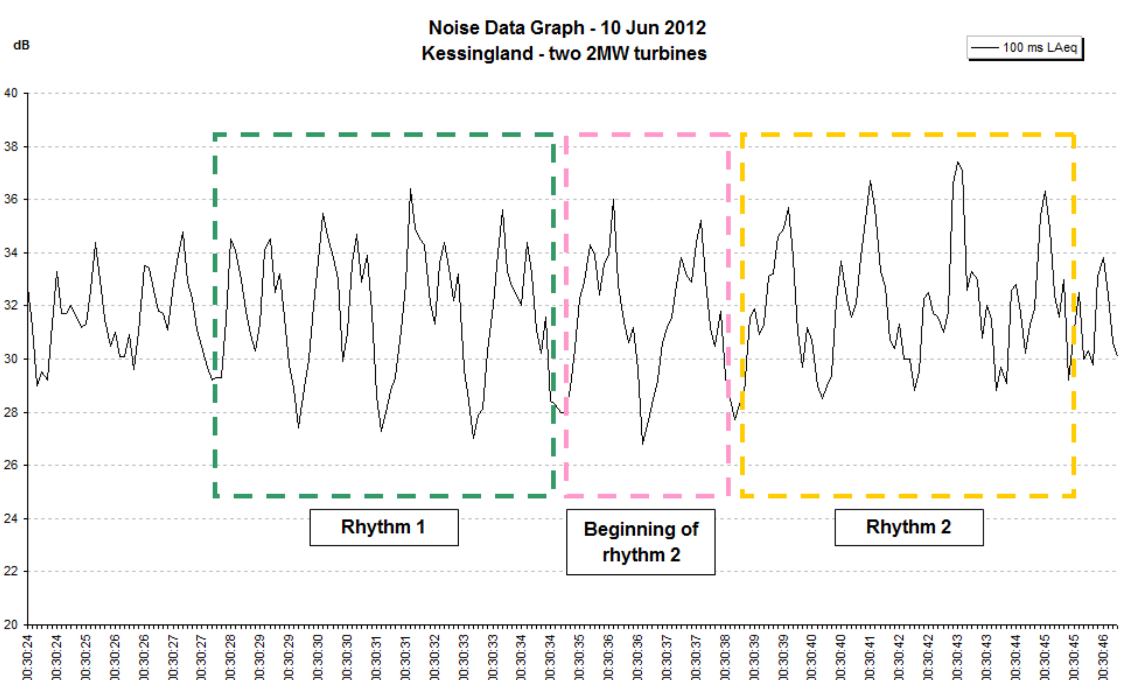

Figure 6: Extract from figure 3, strong rhythmic elements

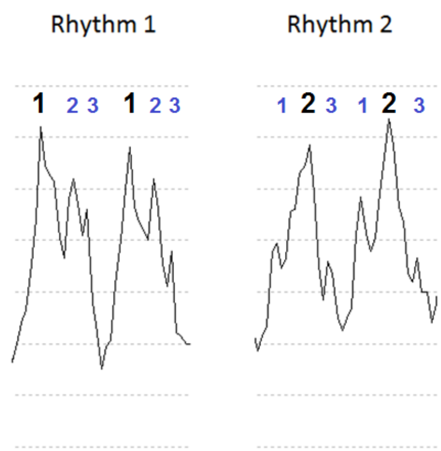

Figure 7: Dominant rhythms in figure 6

Whilst rhythmic attributes of noise are not uncommon the rhythm is usually regular, constant and predictable, in this case it is randomly variable. This could create a subjectively unpleasant noise character as the noise lacks pattern or symmetry and so is not consistent with expectations. The changes in rhythm and / or the attempt to try and look for a rhythmic pattern could make this character feature annoying, intrusive or difficult to ignore.

Numerous complaints have been received from the turbines at Kessingland. Despite the Council admitting that the noise is a statutory noise nuisance they refuse to take action against the turbines.

The table below assesses the extract shown in figure 4 against five of the criteria discussed above.

Table 2: Assessment of turbine noise from Kessingland turbines

Method	Criterion	Calculation	Result
ReUK / ETSU	5dB penalty to L_{A90}	29.7[5] + 5 = 34.7dB L_{A90}	Compliant with ETSU-R-97 43dB lower night time noise limit (**NB** also compliant with simplified 35dB L_{A90} ETSU limit)
BS4142	L_{Aeq} (+5dB) - L_{A90}	(32.4[6] + 5) - 26.2[7] = 11.2dB	Complaints likely (see footnote)
Japanese D_{AM}	Fluctuation sensation when greater than 1.7D_{AM}	ΔL_{A5} (2.2) - ΔL_{A95} (-2.8)	5.0D_{AM}
Nordtest	Prominence, P	P=3log(onset rate/[dB/s]) + 2log (level difference /[dB])	P1 = 6.0 P2 = 5.6 P3 = 5.8
Den Brook	Regular 3dB modulation >28dB L_{Aeq}	L_{Aeq} = 32.4 Peak to trough range 4-9dB, regularly above 3dB	Greater than expected AM

[5] This is based on a 2 minute period. It is assumed the 2 minute period continued in a similar manner for 10 minutes. The four minute L_{A90} covering this extract was 29.8dB, at the beginning and end of the four minute extract the noise trace is affected by road traffic noise.

[6] This is based on a 2 minute period. It is assumed the 2 minute period continued in a similar manner for 5 minutes. The four minute L_{Aeq} covering this extract has an L_{Aeq} of 33.2dB, at the beginning and end of the four minute extract the noise trace is affected by road traffic noise.

[7] The turbine was operational throughout the measurement period. The L_{A90} is taken from a five minute period approximately 20 minutes prior to extract shown in figure 4 when the turbines are still operational but at a slightly lower level. True background noise levels would be lower in the absence of wind turbine noise and the likelihood of complaints higher.

3.3 Site F - 31 December 2013 - 1 x 275kW turbine

Site F remains anonymous due to potential nuisance action. It is a single 275kW turbine that operates in two different gears. The extract below, figure 8, is a 10 minute period which shows the operation of the turbine in the lower gear at the start of the period, a change up to the higher gear in the first third of the period and change back down to the lower gear just after half way through the period.

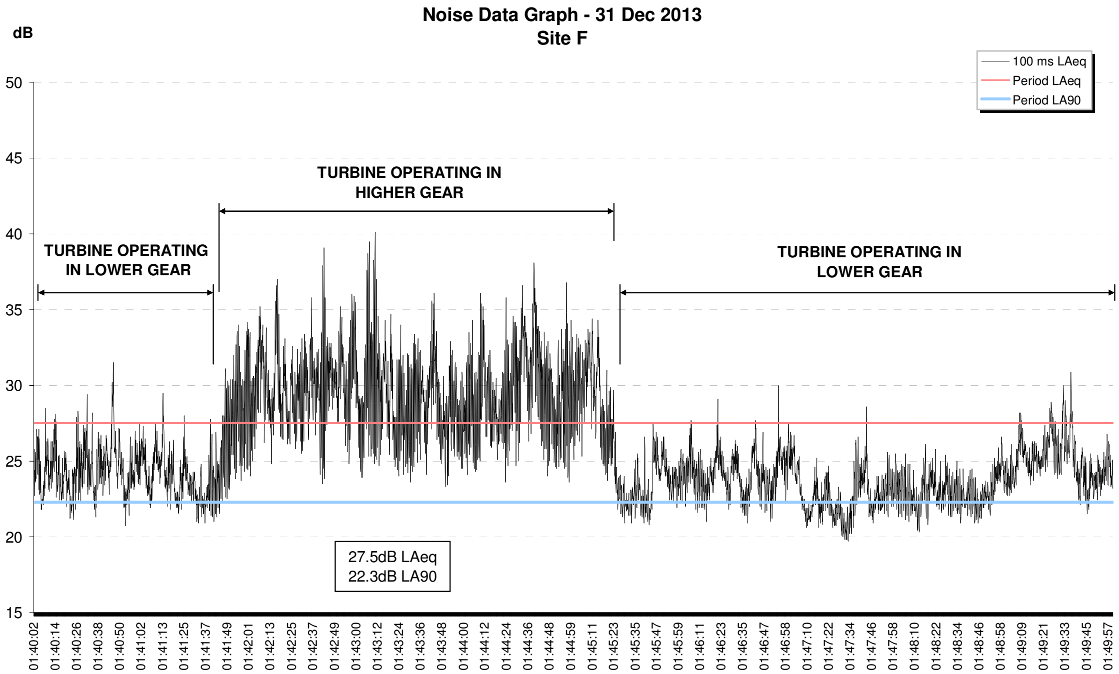

Figure 8: Site F - 31 December 2013

The turbine noise is highly tonal and an element of tonality is always present when the turbine is operating. When operating in the lower gear the turbine produces a humming noise which is mid frequency in pitch though there is also a quieter higher frequency tonal whine. In the higher gear mode the tonality of the turbine is much stronger and is better described as a dominant high pitched whine. The turbine also generates AM. In the lower gear blade swish modulates at a reasonable pace and has a more subdued character. The modulation of noise is much greater in the higher gear and this is caused both by variances in the tonality but also by a harsh whipping / scraping blade swish noise. The operation of the turbine in the higher mode generates a much harsher sound resulting from a combination of a highly tonal high pitched whine and violent (whipping / scraping) modulating blade noise. Noise generated by the turbine in the higher gear is likely to be perceived as unpleasant and disturbing due to the harsh characteristics. These characteristics are unlikely to be accustomed to because of the constant variability both in noise level and character and also due to frequent unpredictable gear changes.

Periods of tonal 'resonance' also occur in the data. This is when the tonal noise generated by the turbine becomes louder and more dominant, for example when resonance is reached from running a finger round the rim of a wine glass. The noise is comparable to the sound of a distant train passing. The similarity and dissimilarity to an existing environmental noise source could create a negative reaction to the sound. Whilst the turbine noise sounds familiar it does not behave as expected, tonal resonances return without warning, they do not appear and disappear as would be expected if the noise was caused by a distant train. This aspect of the noise is also likely to draw attention back to the noise.

Figure 9 below shows an excerpt from figure 8 as the turbine changes from the lower gear operation to the higher gear operation. There is an increase in loudness, modulation, tonality and blade swish noise as described above. Inset in the left hand corner of figure 9 is an A weighted frequency analysis of the lower and higher gear operation of the turbine shown in figure 9. It confirms the mid frequency and higher frequency tonality of the lower gear operation (blue trace at 01:40:53.600) and the strong higher frequency tonality of the higher gear operation (red trace at 01:41:48). Changes in gear occur throughout entire night time periods. They occur often but with no predictability or regularity.

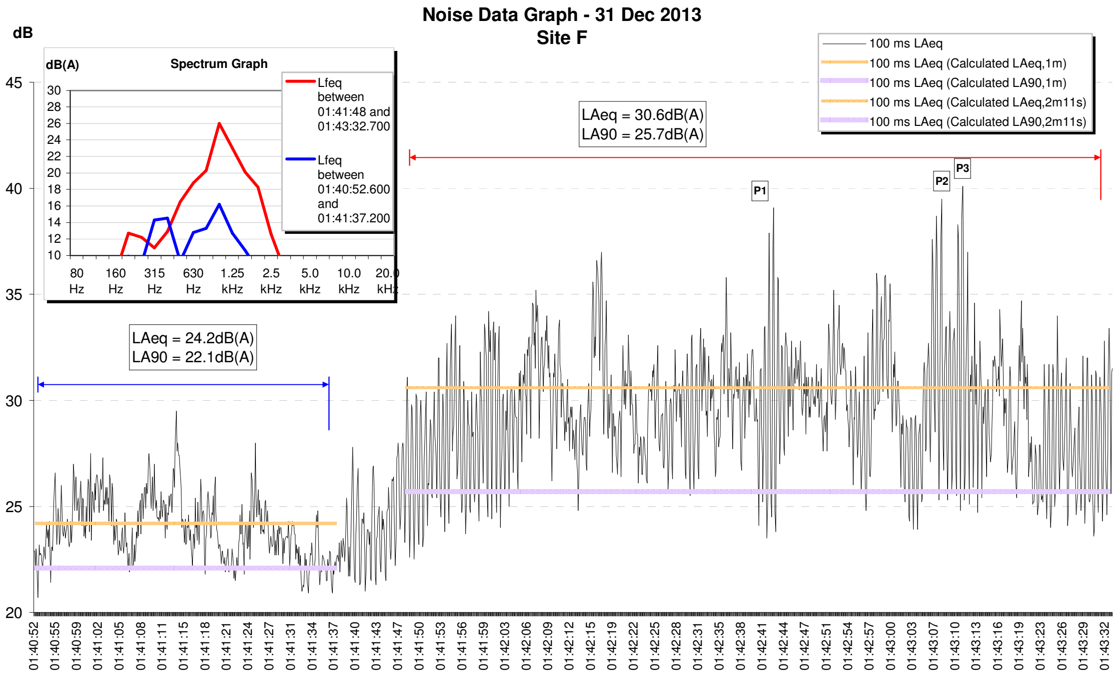

Figure 9: Site F - 31 December 2013, extract showing character and frequency content

The table below assesses the noise from the turbine at site F against five of the criteria discussed above. The D_{AM}, Nordtest and Den Brook assessment are based on the period shown in figure 9 above, 3 minutes in length.

Table 3: Assessment of turbine noise from site F turbine

Method	Criterion	Calculation	Result
ReUK / ETSU	5dB penalty to L_{A90}	10 minute period: 22.3. + 5 = 27.3dB L_{A90} High gear operation only[8]: 25.8 + 5 = 30.8dB L_{A90}	Compliant with ETSU-R-97 43dB lower night time noise limit (**and** simplified 35dB L_{A90} ETSU limit)
BS4142	L_{Aeq} (+5dB) - L_{A90}	(29.3[9] + 5) - 23.0[10] = 11.3dB	Complaints likely
Japanese D_{AM}	Fluctuation sensation when greater than 1.7D_{AM}	ΔL_{A5} (2.5) - ΔL_{A95} (-3.9)	6.4D_{AM}
Nordtest	Prominence, P	P=3log(onset rate/[dB/s]) + 2log (level difference /[dB])	P1 = 7.4 P2 = 7.0 P3 = 7.5
Den Brook	Regular 3dB modulation >28dB L_{Aeq}	L_{Aeq} = 24.2 / 30.6 Peak to trough range 3-15dB, regularly above 3dB	Greater than expected AM caused by higher gear only

[8] Worst case assumption that the higher gear operation, see figure 9, occurs for an entire 10 minute period.
[9] Based on a 5 minute period which includes the lower and higher gear operation shown in figure 9. Strictly BS4142 cuts off at a rated level of 35dB(A); however, it also advises that the principles are generally applicable and as the elevated period of noise gives a rating above 35dB it is considered appropriate for use in this case.
[10] The L_{A90} is taken from the same 5 minute period as the L_{Aeq}; it is determined by the lower gear turbine noise, background noise in the absence of turbine noise would be lower and complaint prediction levels higher than indicated in the table.

3.4 Cotton Farm Wind Farm - 3rd February 2014 - 8 x 2.05MW turbines

MAS have set up a permanent monitoring station with significant help from local residents to measure community noise levels from the Cotton Farm Wind Farm. Residents complain of a loud 'whoomp' / 'whoosh' noise, which is prevalent in much of the data. The excerpt below is taken from a night time period entirely dominated by wind farm noise. Whilst the noise trace is consistently affected by AM, the shape of the noise trace does not vary in a wave-like shape to the same extent as the examples above. For example, a flat line can be drawn underneath the troughs of the data whereas the excerpts above follow waves of increases and decreases in the trough level. The number of turbines at Cotton Farm is much greater than the above examples and this flat lower level is likely the 'general' wind farm noise level[11]. The noise is far from characterless and significant variation is still observed and heard.

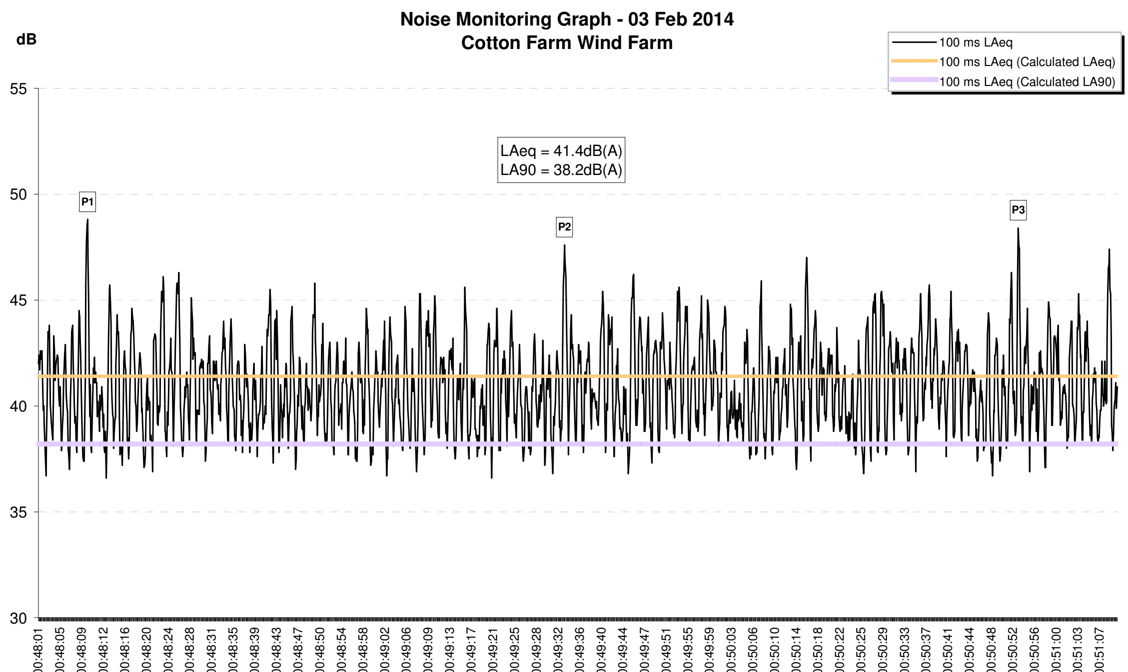

Figure 10: Cotton Farm Wind Farm - 3rd February 2014

The character of the noise at Cotton Farm is quite different to the above examples. Modulation is slower paced but has a 'big' 'roar' like sound and lower pitched in character. The main variable in the noise trace is the constant change in loudness. When there are higher modulation peaks this generates an unexpected element to the noise as the noise level continues to rise above that expected, more noise for longer.

Figure 10 below shows the first minute of figure 9 above. Changes in loudness and modulation depth continue without regularity throughout the extract. As with the first example of wind turbine noise at Swaffham the dynamics of the noise are highly variable. The beginnings of patterns can be observed in the data, increases in loudness (crescendo) and decreases in loudness (diminuendo) are marked on the figure.

[11] This has been separately confirmed by switch off tests where the turbines were stopped and is reported by the authors in a separate paper (19).

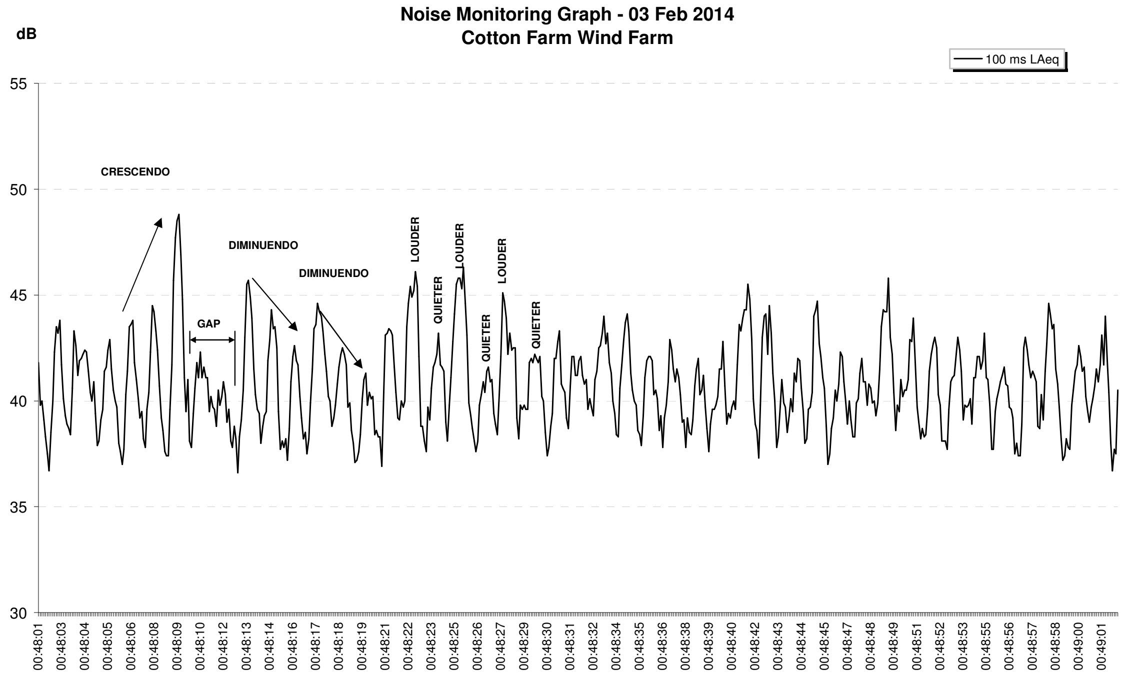

Figure 11: Extract of figure 9 showing patterns and changes in loudness

Figure 12 below demonstrates the varying frequency content of the wind farm noise. Most of the modulation is broadband and mid frequency, perhaps causing the 'big' sound, though a definite lower frequency rumble is also present. As with Kessingland, this could cause residents to feel 'surrounded' by the noise. Some peaks have a definite lower pitched / frequency 'whoomph' character, see for example the end of the period peaks 2 (blue) and 4 (black) evaluated in figure 12 below. The spectrum graph inset in figure 12 shows the presence of the rumble at around 100Hz, more 400Hz content in peaks 2 and 4 ('whoomph'), and more 630Hz noise in peaks 1 (red) and 3 (green).

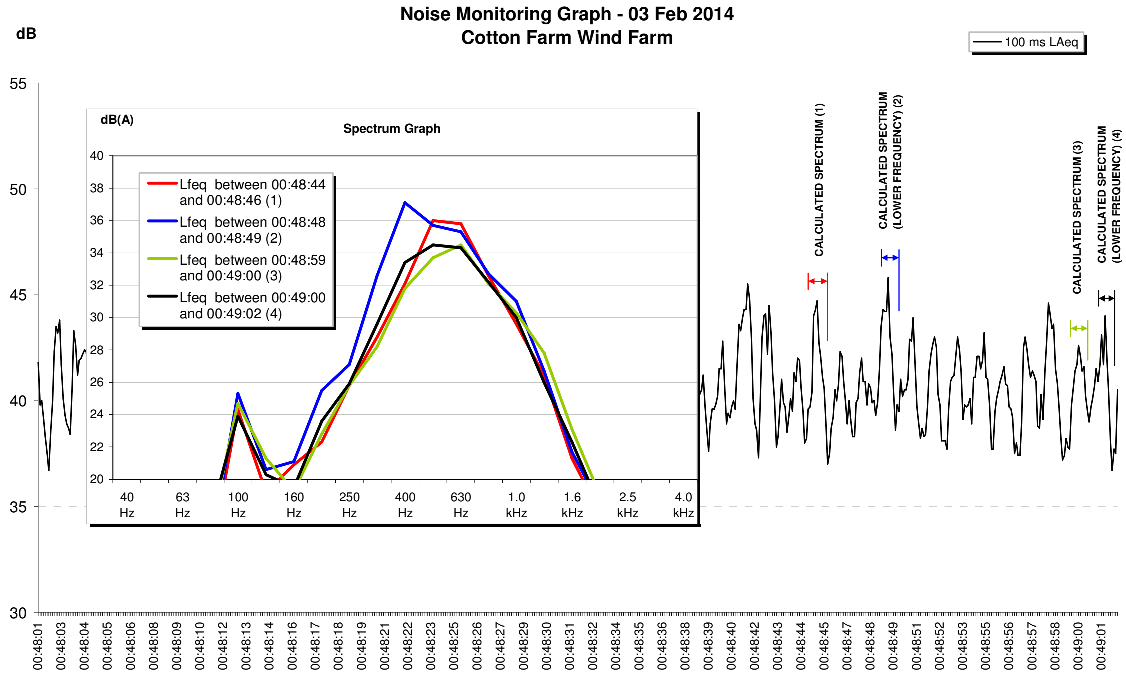

Figure 12: Extract of figure 9 showing differences in frequency content (pitch)

The table below assesses the noise from the turbine at Cotton Farm against five of the criteria discussed above. The ReUK / ETSU-R-97 assessment is based on the 10 minute period from which figure 10 is taken. The BS4142 assessment is based on background noise levels measured prior to the erection of the wind farm. The 10m height wind speed measured at the monitoring location (Toseland Road, Gravely) during the above noise measurements, figures 10 - 12, was 4m/s. The prevailing background noise level at 4m/s as measured at the application stage at 97 Toseland Road was 27dB(A).

Table 4: Assessment of turbine noise from Cotton Farm Wind Farm

Method	Criterion	Calculation	Result
ReUK / ETSU	5dB penalty to L_{A90}	10 minute period: 38.8. + 5 = 43.8dB L_{A90}	0.8dB breach of 43dB L_{A90} limit. At most de-minimis breach: unactionable.
BS4142	L_{Aeq} (+5dB) - L_{A90}	(41.4[12] + 5) - 27.0 = 19.4dB	Complaints likely - significantly exceeds onset point of complaints (+10dB)
Japanese D_{AM}	Fluctuation sensation when greater than 1.7D_{AM}	ΔL_{A5} (2.3) - ΔL_{A95} (-3.5)	5.8D_{AM}
Nordtest	Prominence, P	P=3log(onset rate/[dB/s]) + 2log (level difference /[dB])	P1 = 6.0 P2 = 5.6 P3 = 6.1
Den Brook	Regular 3dB modulation >28dB L_{Aeq}	L_{Aeq} = 41.4 Peak to trough range 4-11dB, regularly above 3dB	Greater than expected AM

[12] The 5 minute L_{Aeq}, which includes the extract shown in figure 10, was 41.8dB L_{Aeq}.

NOTE: Whilst the ReUK / ETSU approach does indicate a breach, the current approach to application of this metric is to average this result with a longitudinal study of noise impact. The averaging effect combined with a minor exceedance results in easy compliance. It is also noted that this assessment assumes that the maximum 5dB penalty would be applicable whereas research has shown this is unlikely to be the case (19).

3.5 Summary

The table below summarises the assessments of the four examples above.

Table 5: Summary of assessments at four examples

Method	Swaffham II	Kessingland	Site F	Cotton Farm
Subjective	Waves of noise, erratic dynamics, highly changeable / unpredictable, changeable modulation beats / rhythm	Strongly rhythmic, changes between defined modulation (swish / whoosh) and muddied tumble dryer sound, unpredictable patterns, 'big' sound, changes in pitch	Highly variable, highly tonal, subdued modulation, hum, violent whipping / scraping modulation, harsh, whine, resonance (distant train), highly changeable	Constant lower level of noise (constant din), 'big' sound, 'roar' like, lower pitch rumble, variable dynamics and pitch
ReUK / ETSU	Compliant	Compliant	Compliant	Borderline
BS4142	Complaints likely (8.6dB +)	Complaints likely (11.2dB +)	Complaints likely (11.3dB +)	Complaints likely (19.4dB)
Japanese D_{AM}	7.7 D_{AM}	5.0 D_{AM}	6.4 D_{AM}	5.8 D_{AM}
Nordtest	P = 6.3 / 6.5 / 6.0	P = 6.0 / 5.6 / 5.8	P = 7.4 / 7.0 / 7.5	P = 6.0 / 5.1 / 6.1
Den Brook	Greater than expected AM (4-11dB)[13]	Greater than expected AM (4-9dB)	Greater than expected AM (3-15dB)	Greater than expected AM (4-11dB)
dB $L_{Aeq,T}$	38.2	32.4	27.5 (24.2 / 30.6)	41.4
dB $L_{A90,T}$	34.4	29.7	22.3 (22.1 / 25.7)	38.2

4. DISCUSSION

This paper looks primarily at the character of wind farm noise and how this relates to assessment of impact, particularly where noise has been found compliant with limits but causes complaints. The above analysis raises many questions that relate to this assessment as outlined below.

4.1 Is it appropriate to compare wind farm noise levels to other noise source levels?

As noted in the introduction, wind farm noise levels are often compared to other noise sources, the noise level in a quiet library or the noise level of a fridge. WHO guidelines are similarly often quoted. Assessors commonly state that as noise is below either 40dB $L_{night,outisde}$ (lowest observed effect level) or 30dB $L_{night,outisde}$ (no observed effects level) the noise cannot be considered an adverse impact (20). With reference to the summary table above, the noise levels from the four examples evaluated are similar to the noise level that might be measured in a quiet library / office or the noise of a refrigerator hum in the kitchen. The majority of levels are below an $L_{night,outisde}$ of 40dB and some below 30dB $L_{night,outisde}$. Are these comparisons fair?

The noise in a quiet library will typically be dictated by heating and ventilation units. A steady,

[13] Modulation level, peak to trough.

broadband generally anonymous noise. As there is little variance in this type of noise it is easily pushed to the back of consciousness. There may be intermittent noises from those using the library, footsteps, page turning, coughing. These tend to be single, isolated events. They do not occur frequently and in many cases they are predictable with visual and audible cues that inform that the noise will happen, when it will happen and when it will cease. In contrast, and as demonstrated above, wind farm noise is constant but highly changeable and variable, without predictability or regularity. At night time, inside the dwelling and when trying to sleep there are no visual cues for wind farm noise. Audible cues can often be misleading, for example periods of lower modulation and lower wind farm noise levels indicate that the noise is going away, but quieter periods are often followed by increases in noise / modulation or sudden louder modulation peaks, see the above examples.

The noise level of a fridge might also be similar to wind farm noise level, but as with the library it is entirely different in character. The noise from a fridge might have a tonal element, but this is unlikely to modulate to the extent that wind farm noise tonality modulates, particularly in third octave band analysis. The noise from a fridge is often constant and regular with limited variation or change. It is also important to consider the context of each noise in the surrounding environment. A fridge, presumably located in the kitchen, is likely to be the least dominant noise source in this location. Other noises will either mask the fridge noise or attract attention away from the noise. Fridge noise is similar to other noises likely to be found in a kitchen, it is not unexpected or alien and usually within the control of the occupant. Wind farm noise is typically the dominant noise source where there are no other dominant man made or industrial noises. Particularly at night time there are few other sources that could either mask or divert attention from the wind farm noise. Wind farm noise is typically obtrusive in what is otherwise a quiet rural environment, dominated by wildlife sounds which are entirely different in character to that of wind farm noise.

Whilst the average L_{Aeq} or L_{A90} level of wind farm noise might be similar to the average L_{Aeq} or L_{A90} level of noise from a fridge or in a quiet library, this is demonstrably the end of any likeness.

It is clear from review of the WHO night time noise guidelines that the vast majority of research upon which effect levels are based relates to transportation noise. Can transportation noise be fairly compared to wind farm noise? As above, the character of the noises are entirely different. Studies have already shown that wind farm noise is perceived as more annoying (21). Transportation noise is predictable and much less variable. It does not contain changing rhythmic or tonal features. Transportation noise is typically found in urban areas, wind farms are more often located in quiet rural environments.

The focus on decibel level again draws focus away from the noise character and noise context. Such comparisons are at best tenuous and the appropriateness of such comparisons is seriously questioned.

4.2 Is a single figure parameter appropriate for assessing impact? Would multiple parameters be more appropriate?

The L_{Aeq} of the excerpt from Cotton Wind Farm is 41.4dB and the L_{A90} 38.2dB. This is considerably louder than the excerpt of the two turbines at Kessingland, 32.4 dB L_{Aeq} and 29.7dB L_{A90}. The noise at Kessingland should supposedly be half as loud as that from the Cotton Farm Wind Farm. Does this mean that those complaining of noise from Kessingland have half the right to complain, or half as strong a case as those complaining of noise from Cotton Farm? Would the Cotton Farm residents accept twice as much of the Kessingland noise before they complained?

Whilst there is clearly a significant difference in decibel level between the two sites, assessment based on different metrics leads to different conclusions on acceptability than review of decibel level alone. The prominence rating, P, of modulation peaks is very similar both at Cotton Farm and at Kessingland, P = 6.0 / 5.1 / 6.1 and P = 6.0 / 5.6 / 5.8 respectively. The noise modulates with a similar peak to trough range, 4-11dB and 4-9dB, both would be considered to generate unreasonable, greater than expected amplitude modulation. The D_{AM} rating of the noise from Cotton Farm and Kessingland, 5.8 D_{AM} and 5.0 D_{AM} respectively, is also not dissimilar. These metrics suggest that impact of noise character from Cotton Farm and Kessingland is comparable.

Review of decibel levels suggests Kessingland impact to be considerably more tolerable than Cotton Farm impact. Review of prominence, P, modulation peak to trough level and D_{AM} rating suggest that impact is comparable at both locations. Detailed examination of the noise character might again change the decision.

Noise from Cotton Farm wind farm and from the Kessingland turbines is highly variable in dynamic and there are unpredictable changes in peak to trough level. However, the Cotton Farm modulation is a single modulation peak with one beat or modulation pulse per peak and this is generally consistent throughout the data. The Kessingland modulation is highly rhythmic and randomly alternates between different rhythms throughout the extract. There are often two or three beats or pulses within each modulation peak. Subjectively the Kessingland noise might be considered more likely to attract attention, more difficult to ignore and potentially more annoying.

Where noise has character a single number parameter cannot adequately describe impact. Even if multiple parameters are used this can often result in conflicting conclusions of impact. There are situations and character features which, as demonstrated by the rhythmic quality of the Kessingland turbines, would be entirely neglected from assessment even if using multiple assessment parameters.

4.3 Do noise readings reflect human perception?

It is asserted above that a single noise level cannot adequately assess the impact of noise character. Description of noise using multiple parameters can also be contradictory. Does even a detailed assessment of noise character presented by noise readings accurately reflect human perception?

The four examples above were recorded external to the dwelling. The above assessment metrics also relate to externally recorded noise levels. How is impact perceived internally? Complaints of wind farm noise are commonly received at night time and residents often complain of sleep disturbance. To reflect this in noise measurements there is a strong argument to require internal noise measurements. Notwithstanding the potential difficulties of access, there are also difficulties with instrumentation. Most type 1 / class 1 sound level meters have a noise floor of around 18-20dB(A). Specialist low noise microphones are needed to accurately measure internal noise levels, which in rural areas can be as low as 12dB(A).

The accuracy of A weighting to reflect the human hearing sensitivity might also be questioned, particularly in very low noise environments or where noise, especially low frequency noise, is close to perception thresholds. There may be internal room effects that further influence the perception of noise, but how could such a variable be accounted for in a general assessment of impact?

Self reported health effects can also prove problematic when assessing noise solely using recorded noise levels. Residents affected by wind farm noise often report ear pressure effects or liken impact to other hearing impairments such as tinnitus or ringing; they often question whether they are hearing, feeling or imagining the noise. These reports can lead assessors to dismiss impact as a hearing defect rather than a feature or symptom of the wind farm noise. This is particularly the case where there are no obvious identifiable causes in the data, where low frequency noise levels are below thresholds or where low frequency noise is at lower levels than other sources of environmental low frequency noise. The middle section of figure 5, Kessingland, has a lower pitched character but there are no obvious changes in the third octave band frequency data. In many cases residents leave their homes either temporarily or permanently to find respite elsewhere, action that does not suggest imagined effects.

Rather than question the reliability of those reporting annoyance and health effects assessors should perhaps be questioning the reliability of the data to accurately portray what is being heard by those affected.

4.4 Can short term assessments of noise level and character represent long term impact?

The above examples review only short periods of wind farm noise. The examples are generally representative of the noise generated at each site and can give an indication of the main character features, but they do not represent the duration of impact and how character manifests for longer periods (to which residents are subjected). Can short term analysis fairly reflect what the resident is exposed to on a daily basis and / or the reaction and perception of the noise after long term exposure?

It is highly likely that residents will become sensitised to noise when they hear it and are affected by it on a day to day basis. Residents will be able to pick out the source noise where those assessing it, who are not as familiar with the noise, may struggle to do so. Similarly, the resident will be acclimatised to the background noise levels in the area whereas the assessor may not be familiar with the typical noise sources in the area or simply used to louder, busier environments. Is this assessors judgement therefore fair and representative of what the resident experiences?

4.5 Should character be considered as a single feature of noise or do different features interrelate and cumulatively impact perception?

The four examples examined above contain a number of noise features that contribute to distinct noise character. Should each feature be considered in isolation and then assessed cumulatively, should each feature be considered in isolation and assessed independently or should all features be combined in a single 'character' assessment? For example, does the modulation of the Cotton Farm noise make it immediately unacceptable? Would it be equally unacceptable if there was only low frequency noise and no modulation? Does the addition of low frequency noise to the modulation make the modulation more intrusive and is this more or less intrusive than adding a rhythmic component such as that found in the Kessingland data?

At site F there is a very strong tonal character and significant amplitude modulation, but the character features are different depending on the operating gear. As such there is not a single feature of noise that describes both operating modes of the turbine. How could these differences be accounted for as a single character feature? Complaints from the resident affected by site F focus mainly on tonal noise. Perhaps reported annoyance focuses on the tonal noise as it is more prevalent, it is perceived as always present compared to the variable presence of amplitude modulation noise. Should annoyance from amplitude modulation therefore attract less of a penalty than the tonal noise? Alternatively, does the amplitude modulation noise simply draw the residents attention back to the tonal turbine noise? Perhaps in the absence of amplitude modulation noise the tonal noise would be more easily forgotten? In this case the amplitude modulation noise is the driver of annoyance and so would perhaps warrant a harsher penalty than the tonal noise. Can the two features be separated? Perhaps the intrusiveness of the tonal noise is heightened when it 'resonates', which most often occurs in conjunction with periods of erratic and violent blade swish noise. Is the tonal noise more or less annoying in the presence of amplitude modulation noise? How can these complex interactions be accounted for as a single feature of noise impact?

Very little is known about how different character features interrelate and are perceived by those affected. Assessment is problematic as each case is so variable both in terms of the noise, see for example the different character features of the four examples above, and in terms of individual differences of residents affected.

4.6 Should wind farm noise character be assessed separately or as part of a total noise dose?

Many international guidelines for assessment of wind farm noise propose a penalty for prominent character features that is applied to the overall noise limit. The assessment of the four examples above shows wind farm noise with highly discernible character features that have resulted in noise complaints but comply with noise limits even with the maximum afforded penalty deducted from the noise limit. This demonstrates that the current penalty approach is ineffective.

The average L_{Aeq} level or L_{A90} rarely represent the high variability of the noise within the extract and as such do not fairly represent noise character. If the noise level itself does not reflect noise character can a penalty applied to this level fairly account for noise character either? If the noise level was reduced by 5dB would this render the noise acceptable? Comparison of noise levels from the Cotton Farm Wind Farm and the Kessingland turbines suggests that noise level is not the deciding factor and noise would still be intrusive at levels 10dB lower. Noise levels from the turbine at site F are a further 5dB lower than the Kessingland noise levels, yet site F has the highest prominence (P) value and still generates complaints.

A comparison of the penalty method (ReUK / ETSU) and the penalty / rating method of BS4142 shows a stark difference in acceptability. Complaints were deemed likely from all of the above four examples using the BS4142 approach whereas the ReUk / ETSU penalty approach only indicated a borderline situation at Cotton Farm, assuming the full penalty was applied, thus rendering all examples acceptable, not in need of control. If a penalty approach is favoured, the above examples indicate that this should only be applied in a context type approach such as that of BS4142.

If the character of wind farm noise is to be considered separately to the overall limits then which metric is most appropriate and is acceptability decided on a graduated scale or as a simple pass or fail? The Den Brook condition states that all greater than expected amplitude modulation is unacceptable. The Nordtest prominence method is proposed as a graduated penalty to be applied to the L_{Aeq}. Whilst the Japanese D_{AM} method offers no guidance on acceptability, the papers do suggest that as soon as fluctuation is perceived adverse impact arises and that noisiness increases as fluctuation strength increases. The above examples indicate that each metric will give a slightly different result on acceptability.

Whilst it is the authors' opinion that a separate assessment of noise character is favourable, the assessment metrics used above account only for modulation and fail to consider other factors contributing to adverse noise character such as low frequency noise, unpredictability of the noise and changes in noise character. A separate noise character assessment would certainly help assess the above examples but considerable thought is still needed to ascertain how this might be approached, which character features it would include and what metric is most appropriate and effective.

5. CONCLUSIONS

Wind farm noise character is largely neglected at the planning stage. This appears to be exacerbated by inappropriate comparisons with noise sources that have a similar noise level but an entirely different noise character. Noise limits rarely account for noise character and where they do assessment is typically limited to application of a maximum 5-6dB penalty to the existing noise limits. In cases where noise complaints have been received from wind farm noise there are distinctive intrusive character features in the noise, but the noise is found to be compliant with decibel limits. This is demonstrated in the examples above and is evidence that the current approach to assessing impact is ineffective.

The above four examples show that wind farm noise character can be unique to each development and highly variable within each development. Different assessment metrics result in contradictory outcomes of acceptability at each site. Whilst one aspect of noise character might be well characterised by a modulation index another noise characteristic might be better defined by a prominence rating, other characteristics, such as rhythm, are ignored by all assessment parameters.

The analysis and comparison of assessment methods for each of the four examples confirms that a single assessment parameter does not reflect impact. The worst metric of assessment for noise character is that of a penalty applied to a noise limit, as currently proposed in the UK. Even where multiple assessment parameters are adopted significant character features can still be neglected. The ability of noise measurements to accurately reflect the perception of the listener, including within the dwelling, is further questioned.

It is concluded that assessment of character in wind farm noise is in need of serious review by the acoustics community. The current methods adopted to assess noise impact fail those affected and suggest compliance where significant adverse impacts exist. The above analysis suggests that metrics assessing amplitude modulation in isolation will help to provide an indication of intrusive noise character but still neglect many important characteristics. It is noted that the above examples focus only on short extracts of wind farm noise. Long term exposure to noise is likely to heighten perception and annoyance of specific characteristics. Studies investigating how multiple character features interrelate to judgement of impact and the longitudinal impact of noise with character are recommended.

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