HAYES-MacKENZIE REPORT ON WIND TURBINES – 2nd DRAFT

The development of wind energy within the UK has increased during the past 15 years. Within that time, 1598.55 megawatts of generating capacity have been installed of which 121 wind farms are located onshore.

In January 2004, the Daily Telegraph published an article which identified wind turbines at a Cornish wind farm as giving rise to health problems associated with low frequency noise emissions from the wind turbines. As a consequence of these articles, a study was commissioned to investigate infrasound and low frequency noise emissions from wind turbines and wind farms in general.

To undertake this study, measurements of noise levels have been undertaken at sites where low frequency noise has been identified by neighbours as a source of annoyance. Furthermore, additional noise measurements have been performed of a number of wind turbines to determine the level of infrasound noise emissions which have been measured from individual wind turbines and from wind farms.

The conclusions to these studies are as follows:

Infrasound

Infrasound noise emissions from wind turbines are significantly below the recognised threshold of perception for acoustic energy within this frequency range. Even assuming that the most sensitive members of the population have a hearing threshold which is 12 dB lower than the average hearing threshold, measured infrasound levels are well below this criterion.

The document *"Community Noise*" prepared for the World Health Organization, states that '*there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects'*.

As a result of this study, infrasound associated with modern wind turbines is not a source which will result in noise levels which may be injurious to the health of a wind farm neighbour.

Low Frequency Noise

The measurements performed at all three sites indicate that low frequency noise is measurable but below the DEFRA Night time Low Frequency Noise Criterion.

When assessed in accordance with the Danish Criterion of $L_{pA,LF}$ = 20 dB, internal levels do not exceed 20 dB when measurements are undertaken within rooms with windows closed.

However, wind turbine noise may result in internal noise levels which are just above the threshold of audibility, as defined within ISO 226. For a low frequency sensitive person, this may mean that low frequency noise is audible within a dwelling. At all the measurement sites, low frequency noise associated with traffic movements has been found to be greater than that from the neighbouring wind farms.

Aerodynamic Modulation

The common cause of complaints associated with wind turbine noise at all three wind farms is the audible modulation of the aerodynamic noise, especially at night. Although the internal noise levels associated with this noise source are not high enough to result in the awakening of a resident, once awoken the audibility of this noise results in difficulties in returning to sleep.

The analysis of the external and internal noise levels indicates that it may be appropriate to re-visit the issue of the absolute night-time noise criterion specified within ETSU-R-97. To provide protection to wind farm neighbours, it would seem appropriate to reduce the absolute noise criterion for periods when background noise levels are low. In the absence of high levels of modulation, then a level of 38 dB L_{A90} (40 dB L_{Aeq}) will reduce levels to an internal noise level which lies around or below 30 dB L_{Aeq} with windows open for ventilation. In the presence of high levels of aerodynamic modulation of the incident noise, then a correction for the presence of the noise should be considered. However, it is beyond the scope of this report to consider the issue of appropriate assessment and acoustic feature correction methodologies for this character within the noise as it lies outside the low frequency range.

Recommendation

The analysis of internal and external noise levels within dwellings neighbouring wind farms which have been identified as giving rise to problems associated with noise indicate that significant levels of infrasound and low frequency noise were not found. However, the presence of aerodynamic modulation which is greater than that originally foreseen by the authors of ETSU-R-97, particularly during the night hours, can result in internal wind farm noise levels which are audible and which may provoke an adverse reaction from a listener.

To reduce the potential for such situations with future wind turbines, it is recommended that consideration be given to a revision of the night-time absolute noise criterion proposed within ETSU-R-97 and the development of an assessment methodology to take account of periods when high levels of aerodynamic modulation are found at a neighbouring receptor location.

Sources of Noise Associated with Wind Turbine Operation

Aerodynamic noise associated with wind turbines is caused by the flow of air over the wind turbine blades as the rotor turns to generate electricity. Figure 1 1 below, is a schematic diagram of the flow around a turbine blade. Different aerodynamic effects result in noise being generated at varying levels over a range of frequencies from infra-sonic (<20 Hz; normally too low to be perceived by the human ear) to ultra-sonic (>20 kHz; normally too high to be heard by the human ear). These effects are outlined in Table 1 below.

[1] Wagner, S., Barieb, R., and Guidati, G., Wind Turbine Noise, Springer, Berlin, 1996

Table 1 - Sources of Aerodynamic Noise: from ref 1

Type or Indication	Mechanism	Main characteristics and importance
Low-frequency noise		
Steady 'thickness' noise Steady 'loading' noise	Rotation of blades or rotation of lifting surfaces	Frequency is related to blade passing frequency, not important at current rotational speeds
Unsteady loading noise	Passage of blades through tower velocity deficit or wakes	Frequency is related to blade passing frequency, small in cases of upwind turbines but possibly significant for large numbers of turbines acting together.
Inflow turbulence noise	Interaction of blades with atmospheric turbulence	Contributing to broadband noise; not yet fully quantified
Airfoil self-noise		
Trailing-edge noise	Interaction of boundary layer turbulence with blade trailing edge	Broadband, main source of high frequency noise (770 Hz < f < 2 kHz)
Tip noise	Interaction of tip turbulence with blade tip surface	Broadband; not fully understood
Stall, separation noise	Interaction of turbulence with blade surface	Broadband
Laminar boundary layer noise	Non-linear boundary layer instabilities interacting with the blade surface	Tonal, can be avoided
Blunt trailing edge noise	Vortex shedding at blunt trailing edge	Tonal, can be avoided

Noise from flow over holes, slits and intrusions	Unstable shear flows over holes and slits, vortex shedding from intrusions	Tonal, can be avoided

Infrasound and Very Low Frequency Noise Generation: < 20 Hz

Infrasound is noise at frequencies below the normal range of human hearing, i.e. < 20 Hz. Noise sources associated with these frequencies are generated by unsteady loading of the wind turbine blade. Such effects were noted by Hubbard & Shepherd[2] following measurements on 'downwind' turbines, i.e. turbines with blades downwind of the tower or other turbine support structures. The result of this configuration is that the blade passes through the wake caused by the presence of the tower in the air stream, generating high levels of acoustic energy at the blade passing frequency and associated harmonics. The size and rotational speed of the turbines resulted, in one case, in the perception of infrasound at distances of 10 miles from the source. However, with the development of upwind turbines, operating at lower rotational speeds, this source of noise has all but been eliminated. Measurements of infrasound noise emissions from modern upwind turbines indicates that at distances of 200 metres, infrasound is between 25 and 40 dB below recognised perception thresholds. The document "*Community Noise*" prepared for the World Health Organization [3], states that:

'*There is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above detection threshold may cause perceptual effects but these are of the same character as for "normal" sounds.*

Reactions caused by extremely intense levels of infrasound can resemble those of mild stress reaction and may include bizarre auditory sensations, describable as pulsation and flutter."

"Extremely intense levels of infrasound" refers to sound pressure levels in the range 130 – 150 dB. It should be noted that infra-sound levels from turbulent wind is a large source of infra-sound levels in itself, and it may be expected that at typical distances to community locations, infra-sound from a turbine source is likely to be significantly below that which would exist purely due to the presence of the wind.

[2] Hubbard, H. H. and Shepherd, K. P., "Wind Turbine Acoustics," NASA Technical Paper 3057 DOE/NASA/20320-77, 1990.

[3] Community Noise - Document Prepared for the World Health Organization, Eds. Bergland B. & Lindvall T., Archives of the Centre for Sensory Research Vol. 2(1) 1995: Section 7.1.4 : Page 41

Low Frequency Noise Sources: 20 – 250 Hz

Low frequency noise, between 20 and 250 Hz, is associated with inflow turbulence of air into the rotor disc. Increased inflow turbulence due to high wind shear, yaw error (turbine rotor not correctly aligning to the correct wind direction or wind direction varying with height) or wake effects (turbines in the wake from other turbines on the site), have been noted to increase low frequency noise emissions. These increased inflow turbulence effects have been noted where low frequency noise has caused complaint from those living nearby but is normally minimised by appropriate site design including careful wind flow modelling and appropriate turbine spacing.

Propagation of noise over long distances will reduce the high frequency content of a broadband noise source due to the frequency dependant nature of atmospheric absorption which reduces high frequency sounds more than low frequency sounds over long distances. This effect is more significant for larger wind farms (of the order 100 turbines) where the dominant frequency range may change from 500-1000 Hz at locations close to the site to 125-250 Hz for the increased separation distances associated with larger wind farms. However, the overall noise levels are still likely to be relatively low and it is only in extreme cases that problems will arise.

Figure 2 [4] below shows a range of typical signal sound pressure levels as a function of frequency and related to dB re 2.10^{-5} Pa, the threshold of human hearing (grey zone), and the absolute pressure in microbars. It may be seen from the figure that just the act of running will subject the runner to levels of infrasound around 90 – 95 dB at 2 – 6 Hz, the frequency depending upon how fast the runner is pacing. More extreme levels of infrasound may be experienced by a child for example who when playing on a swing can be subject to levels of 120 dB at 1 Hz, depending upon th e size and height of the swing.

Figure 2: Typical range of sound pressure levels in the infrasound/low frequency range: from ref 4

Introduction to the Physics of low frequency noise: From A Review of Published Research on Low Frequency Noise and its Effects: A Report for DEFRA by Dr Geoff Leventhall: May 2003.

The following are extracts from the DEFRA Report [5] on low frequency noise as they provide an overview of the subject and an introduction to the subject of low frequency noise. The full DEFRA report provides further detailed reading on the issue of low frequency noise.

Noise and sound:

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[4] Infrasonic and Near Infrasonic Atmospheric Sounding and Imaging: A. J. Bedard Jr NOAA/ERL/Environmental Technology Laboratory

[5] A review of published research n low frequency noise and its effects: Report for DEFRA by Dr Geoff Leventhall: May 2003.

Noise and sound are physically the same; the difference in their description arises in their acoustic quality as perceived by listeners. This leads to a definition of noise as undesired sound, whilst physically both noise and sound are similar acoustic waves, carried on oscillating particles in the air. Sound is detected by the ear in a mechanical process, which converts the sound waves to vibrations within the ear. Electrical signals, stimulated by the vibrations in the ear, are transmitted to the brain, in which perception occurs and the sensation of sound is developed. Response is the reaction to perception and is very variable between people, depending on many personal and situational factors, conditioned by both previous experiences and current expectations.

Frequency and wavelength:

The frequency of a sound is the number of oscillations which occur per second (Hertz: Hz), denoted, for example, as 100 Hz (100 cycles per second). Sound travels in air at about 340ms^{-1}, but this velocity varies slightly with temperature. Sound is transmitted through air as a compression and expansion of the air. Since each compression travels at about 340ms^{-1}, after one second the first compression is 340m away from the source. If the frequency of oscillation is, say 10Hz, then there will be 10 compressions in the distance of 340 m, which has been travelled in one second, or 34 m between each compression. This distance is called the wavelength of the sound, leading to the relation:

Velocity = wavelength × frequency

c = ÿ.f

Where c = speed of sound in air, metres / second
ÿ = wave length, metres
f = frequency of oscillation.

As an indication as to the potential relationship of wave length and frequency, Table 2 below provides an indication of the wavelengths for low frequency sound.

Table 2 detailing frequency and wavelengths for low frequency sound

Frequency (Hz)	1	10	20	50	100	150	200
Wavelength (m)	340.00	34.00	17.00	6.80	3.40	2.27	1.70

Noise character and quality:

Pleasant sounds convey pleasant associations, for example, music and birdsong. However, there are instants where bird song might give rise to complaints, for example, crowing cockerels early in the morning within an urban environment. Here, the "unwantedness" is determined by the cognitive environment in which each sound is detected, the character and quality of a noise, combined with our expectations and situation, both of which are important contributors to our response.

Low frequency noise and infrasound:

The frequency range of infrasound is normally taken to be below 20Hz and that of audible noise from 20 Hz to 20,000 Hz. However, frequencies below 20 Hz are audible, illustrating that there is some lack of clarity in the interpretations of infrasonic and audible noise. Although audibility remains below 20 Hz, tonality is lost below 16-18 Hz, thus losing a key element of perception.

Low frequency noise spans the infrasonic and audible ranges and may be considered as the range from about 10Hz to 200Hz. The boundaries are not fixed, but the range from about 10Hz to 100Hz is normally of most interest. When assessing infrasound and low frequency noise we shall consider each individually as will become clear within the results obtained from the measurements at the operating wind farms.

Infrasound:

There are a number of misconceptions about infrasound, such as that infrasound is not audible. As will be shown later, frequencies down to a few hertz are audible at high enough levels. Sometimes, although infrasound is audible, it is not recognised as a sound and there is uncertainty over the detection mechanism. Very low frequency infrasound, from one cycle in, say 1000 seconds (0.001Hz) to several cycles a second are produced by meteorological and similar effects and, having been present during all of our evolution, are not a hazard to us. Much of what has been written about infrasound in the press and in popular books is grossly misleading and should be discounted.

Low frequency noise.

The range from about 10 Hz to 200 Hz covers low frequency noise. For comparison, the lowest C note on a full range piano is at about 32 Hz whilst middle C is at about 261 Hz. All the low frequency noise range is audible, although higher levels are required to exceed the hearing thresholds at the lower frequencies.

Propagation.

The attenuation of sound in air increases with the square of the frequency of the sound and is very low at low frequencies. Other attenuating factors, such as absorption by the ground and shielding by barriers, are also low at low frequencies. The net result is that the very low frequencies of infrasound are not attenuated during propagation as much as higher frequencies, although the reduction in intensity due to spreading out from the source still applies. This is a reduction of 6dB for each doubling of distance. Wind and temperature also affect the propagation of sound. For large offshore wind farms the effect of wind and temperature may reduce the rate of attenuation from 6 dB per doubling of distance to 3 dB per doubling of distance. This will occur when sufficiently far from the turbines. This range is typically between 1.5 – 3.5 km depending upon wind speed, wind shear and the vertical temperature gradient.

There are a number of consequences of these physical effects. When standing close to a wind turbine/farm, the high frequency “swish” noise from the wind turbines will be dominant when standing within 200 – 300 metres of a wind farm. However, with increasing separation distances from the source, the high frequency noise will be absorbed by the atmosphere such that the spectrum will become biased towards the low frequencies. Figure 3 below provides an indication of this effect with increasing separation distance from the source using the algorithm within ISO 9613-2 [6].

[6] ISO 9613: Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation

Figure 3: Change in spectrum shape with increasing separation distance

This means that in very quiet environments, wind farm noise that is audible at greater distances will be heard more as a low frequency “rumble” rather than the more usually experienced “swish” heard when close to wind turbines. During the day, this is not such a problem but during the night, such noise may become noticeable over increased separation distances.

However, it has been indicated for all three of the wind farms which have been considered for these measurements that low frequency noise has been heard at distances of 400 – 1000 metres from the nearest wind turbines. Therefore, the change in spectral content with increasing distance from the source does not provide a simple solution to this issue, i.e. there may be other factors which increase the perception of low frequency noise.

Resonance:

Resonance occurs in enclosed, or partially open, spaces. When the wavelength of a sound is twice the longest dimensions of a room, the condition for lowest frequency resonance occurs.

From c = ÿ.f, if a room is 5m long, the lowest resonance is at 34 Hz, which is above the infrasonic range. However, a room with an open door or window can act as a Helmholtz resonator. This is the effect which is similar to that obtained when blowing across the top of an empty bottle. The resonance frequency is lower for greater volumes, with the result that Helmholtz resonances in the range of about 5 Hz to 10 Hz are possible in rooms with a suitable door, window or ventilation opening. For a room with a standing wave of the lowest room mode, the level is highest at the end walls and lowest in the centre of the room. It is often possible to detect the differences in level, at different room locations, within a room which has been driven into resonance by low frequency noise.

Control.

Low frequency noise and infrasound are steps along the same physical process of wave propagation, so that similar considerations apply to their control, although the shorter wavelengths of low frequency noise make control easier than that for infrasound. Infrasound is difficult to stop or absorb. Attenuation by an enclosure requires extremely heavy walls, whilst absorption requires a thickness of absorbing material up to about a quarter wavelength thick, ÿ 8 m thick for 10 Hz absorption. Low frequency noise may be controlled by a massive single partition, or a complex multiple partition with an insertion loss which improves as the frequency increases. Most walls in buildings are deficient in the low frequency region, so that noise transmission between rooms, and from outside to inside, may be a problem. This is associated with panel resonances of a wall such that there is a dip in the performance of the wall which is related to its mass and its thickness. Typically, for a brick wall this will occur between 150 – 250 Hz. Absorption of low frequency noise requires thick material, such that most sound absorbing linings, typically a few centimetres thick, are ineffective at the low frequencies.

Measurement of Sound

Noise Levels: the ’decibel’

Definition: The decibel is the logarithm of the ratio between two values of some characteristic quantity such as power, pressure or intensity, with a multiplying constant to give convenient numerical factors. Logarithms are useful for compressing a wide range of quantities into a smaller range. For example:

$\log_{10}10 = 1$

$\log_{10}100 = 2$

$\log_{10}1000 = 3$

and the ratio of 1000:1 is compressed into a ratio of 3:1.

This approach is advantageous for handling sound levels, where the ratio of the highest to the lowest sound which we are likely to encounter can be as high as 1,000,000:1. A useful development, many years ago, was to take the ratios with respect to the quietest sound we can hear. This is the threshold of hearing at about 1000 Hz, which is taken as 20ÿPa (2.10^{-5} Pa) of pressure for the average person. When the word “level” is added to the word that describes a physical quantity, decibels are implied. Thus, "sound level" is a decibel quantity. When the sound pressure is doubled, the sound pressure level increases by 6 dB. This is different from a doubling of the perceived loudness of a sound which is equivalent to a 10 dB increase in noise level at normal audible frequencies.

Measurements

Weighting networks.

The majority of noise measurements are made using sound level meters (IEC: 60651, 2001), which give numerical levels as a representation of the noise. For environmental noise it is normal to use the sound level meter A-weighting, which gradually reduces the significance of frequencies below 1000 Hz, until at 10 Hz the attenuation is 70 dB. The C-weighting is flat to within 1 dB down to about 50 Hz and then drops by 3 dB at 31.5 Hz and 14 dB at 10 Hz. Figure 4 shows the A and C weighting curves.

Figure 4: A-Weighting and C-Weighting Networks

The G weighting, (ISO 7196, 1995[7]), is specifically designed for infrasound and falls off rapidly above 20 Hz, whilst below 20 Hz it follows assumed hearing contours with a slope of 12 dB per octave down to 2 Hz. This slope is intended to give a subjective assessment to noise in the infrasonic range. A G-Weighted level of 95 – 100 dB(G) is close to the perception threshold level. G-Weighted levels below 85-90 dB(G) are not normally significant for human perception. However, too much reliance on the G-weighting, which is of limited application, may divert attention from problems at higher frequencies, say, in the 30Hz to 80Hz range. Figure 5 shows the G-Weighting curve.

Figure 5: G-Weighting Network

[7] ISO 7196: 1995 Acoustics – Frequency-weighting characteristics for infrasound measurements

There is a Linear Weighting, also known as Z-weighting, which has a flat frequency response from 10Hz to 20 kHz.

Frequency Analysis

The measurements of noise may be considered in greater detail by consideration of the frequency content of the noise under investigation. Frequency analysis may be undertaken using constant percentage filters, such as third octave or octave band analysis, and constant bandwidth filtering, also known as Fast Fourier Transform (FFT) analysis.

Measurements of sound pressure levels using filtering networks may be undertaken using a weighting network, such as A or C weighting. For the purpose of this study, measurements have been performed using a linear or Z-weighting, and then any weighting networks have been applied after data collection when considering spectral data. In parallel with the spectral measurements, overall A-weighted sound pressure level data was collected as well.

Narrowband analysis, using the FFT method, has been performed for some measurements to assess tonal noise emissions which might be related to wind turbine operations, and for investigations of noise associated with the blade passing frequency of the wind turbines under consideration.

Averaging

Sound level meters give a numerical representation of the noise. However, this is obtained by averaging over a period of time that, for fluctuating noises, is generally longer than the period of the fluctuations, leading to a loss of information on the fluctuations. The widespread use of the equivalent level discards important information on the quality of the noise, its spectral properties and corresponding perceived sound character.

The sound pressure level

This is defined as:

Where p is the RMS value unless otherwise stated of sound pressure in Pascal's and P_0 is 2 x 10^{-5} Pa for measurements in air. Sound incident at receptor (e.g. a neighbouring property) would normally be expressed as a sound pressure level (in dB).

The equivalent level: an energy average

This is defined as the value of the sound pressure level in decibels of continuous steady sound that within a specified time interval, *T*, has the same mean-squared sound pressure as a sound that varies with time. I t is given by the following equation:

Where:

$L_{eq,\,T}$ is the equivalent continuous sound pressure level determined over a time interval $T = t_2 – t_1$;
p_O is the reference sound pressure (20ÿPa);
p(t) is the instantaneous sound pressure (Pa).

L_{nn} percentile levels

The percentile levels L_{nn} may be defined as the sound pressure level which is exceeded for nn % of the time during the measurement time period, T. For the analysis undertaken within this study, we have considered the L_{05}, L_{90} and L_{95} sound pressure levels for the overall A-weighted sound pressure level and for each third octave band level which has been considered, i.e. L_{A90} for overall noise levels the total A-weighted sound pressure level exceeded for 90% of the time and $L_{05, 10Hz}$, the linear level exceed for 5% of the measurement period in the 10 Hz third octave frequency band.

Peak Levels

The peak sound pressure level is the maximum sound pressure level to be measured during a measurement period which represents that absolute peak sound pressure level. This has been used within the measurement set up to determine whether the measuring system has been overloaded during the data collection period. It has also been used to set the gain for each measurement channel to ensure good data collection during the unattended measurement process.

The Low Frequency Hearing Threshold and loudness

Average Thresholds

The aim of studies on the low frequency thresholds has been to determine the lowest levels which are audible to an average person, often a young person, with normal hearing. Thus, the threshold is a “quasi-objective” measurement in the sens e that it is free from emotional responses. Threshold studies have been carried out on relatively small groups, typically about 10 to 20 subjects, so that differences between experimenters are to be expected. However, the different studies follow the same trend, and the threshold region at low frequencies is now well established.

Current Threshold Values

The thresholds found by Watanabe and Møller [8] are very close to those contained within ISO 389-7[9] between the frequencies 20 – 125 Hz. At about 15 Hz, there is a change in the threshold slope from approximately 20 dB / octave at higher frequencies to 12 dB / octave at lower frequencies. This is a consistent finding by different experimenters, occurring within the range 15 – 20 Hz, depending upon which low frequency noise presentation frequencies have been used in the

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[8] Watanabe, T. and Møller, H.: Low Frequency hearing thresholds in pressure filed and free field. Jnl Low Freq. Noise Vibn 9, 106 - 115

[9] ISO 389-7: 2005 Acoustics -- Reference zero for the calibration of audiometric equipment -- Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions

measurements. This change in slope has not been fully explained but is thought to be due to a change in the aural detection process, occurring in the frequency region at which tonality of the auditory sensation is lost.

Figure 6 below details the thresholds found by Watanabe and Møller and also includes the limit of 85 dB (G) up to 20 Hz and a level of 20 dB(A) in the range 10 – 160 Hz.

Figure 6: Infrasound thresholds of audibility

Van den Berg and Passcheir-Vermmer 10 undertook a study of the 10% and 50% hearing thresholds for an otologically unselected 50 - 60 year old age group and compared this with that for otologically selected young adults. The older population is typically 6 – 7 dB less sensitive than the younger one, whilst the hearing sensitivity which is exceeded by 10% of the population is, typically, 10 -12 dB below the average 50% level. It was also estimated that the 5% hearing level was 2 dB below the 10% hearing level. This indicates that for the very select hyper-sensitive members of the general population, the threshold of audibility may be 10 – 14 dB below the average threshold of audibility for the general population.

Although a majority of the older population may be subject to an increase in the hearing threshold, there is still a proportion of the population who have low frequency hearing which is equivalent to a young adult and is more sensitive than the average person.

Individual Thresholds

The hearing thresholds which have been considered above are averaged over a group of subjects. However, the threshold of an individual may differ from the average hearing threshold. Frost 11 , for example, measured thresholds at 5 Hz intervals over the frequency range 20 – 120 Hz with results such as those detailed in Figure 7 below. It may be seen from this figure that one Subject was around 15 dB more sensitive at 40 Hz than another.

Figure 7: Individual thresholds showing regions of enhanced sensitivity: from Frost

This potential range in sensitivity between individuals will lead to occasions when one person may “hear” a low frequency noise and another may not. Such a difference in the hearing threshold may lead to some low frequency noise suffers becoming frustrated due to the disbelief by other observers that a low frequency noise is audible to them but not to anyone else.

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[10] Van den Berg, G. P., and Passcheir-vermeer, W.: Assessment of low frequency noise complaints. Proc. Internoise 99, Fort Lauderdale

[11] Frost, G. P.: An investigation into the microstructure of the low frequency auditory threshold and of the loudness function in the near threshold region. Jnl Low Freq. Noise: Vibn 6, 34 - 39

Walford [12, 13] showed that some hum complainants have a low frequency hearing which has been shown to be more sensitive than the average threshold, whilst others are less sensitive. This indicates that complainants do not necessarily have enhanced hearing acuity at low frequencies. These findings were borne out by the Salford Study [14] which investigated the hearing thresholds for three groups of persons. One of these groups were suffers of low frequency noise and it was found that their hearing threshold at low frequency was no more sensitive than any other group, allowing for the natural variation between subjects. However, the average hearing thresholds indicated that low frequency noise suffers were the least sensitive persons to low frequency noise, followed by the older group and then the younger group. These findings contradict the often held view that sufferers tended to be particularly sensitive. The Salford Study then considered the level above the hearing threshold at which low frequency sound would be considered acceptable. The averaged results indicated that suffers would set the acceptable level around 10 dB above the hearing threshold whereas the non-suffers set the acceptable level 20 dB above the hearing threshold. Hence, suffers appear to be more sensitive relative to their hearing threshold than non-suffers and might be considered to have been sensitised. It should be noted that only three suffers formed part of the test and the Salford Report indicates one should be cautious when considering this conclusion.

An additional finding from the acceptable level tests was that as frequency decreases, the level above which the low frequency noise may exceed the hearing threshold also decreases. This was considered significant within the Salford Report because it suggested that the optimum shape for a reference curve does not follow the threshold of audibility over the whole of the low frequency range but rather that it will tend to follow the hearing threshold curve for the lower bands and then move away from it above around 50 Hz. It is also indicative that as frequency decreases, the sensation of the change in loudness of a sound with increasing or decreasing sound pressure level will become greater for the same sound pressure level change with decreasing frequency. This may be seen from the equal loudness curves contained within ISO 226:2003 [15].

Figure 8 Normal equal-loudness-level contours for pure tones under free-field listening conditions: from BS ISO 226:2003 Acoustics – Normal equal-loudness-level contours

[12] Walford, R.E.: Acoustical aspects of some hum complaints DCC: Chelsea College, London University: 1978

[13] Walford, R.E: A classification of environmental “hums” and low frequency tinnitus. Jnl Low Freq. Noise Vibn 2, 60 – 84: 1983

[14] Proposed Criteria for the assessment of low frequency noise disturbance: Report for DEFRA by Dr Andy Moorhouse, Dr David Waddington, Dr Mags Adams, February 2005, Contract No. NANR45

[15] BS ISO 226:2003 Acoustics – Normal equal-loudness-level contours

The loudness level of a sound is the value in *phons* that has the same numerical value as the sound pressure level in decibels of a reference sound, consisting of a frontally incident, sinusoidal plane progressive wave at a frequency of 1000 Hz, which is judged as loud as the given sound. From Figure 8 above the sound pressure level at 1000 Hz for a sensation level of 20 phons is 20 dB. For the same sensation level at 20 Hz, the equivalent sound pressure level is 89.6 dB. If we now consider the sound pressure level required for a sensation level of 30 phons at 1000 Hz and 20 Hz, it will be seen that the levels are 30 dB and 94.8 dB respectively. For a doubling of the perceived loudness at 1000Hz, an increase in sound pressure level of 10 dB is required. However, at 20 Hz, this increase in sound pressure level is required to be only 5.2 dB for a doubling in loudness. The consequence of this change in sensitivity with frequency is that a smaller increase in sound pressure level at low frequencies will have a greater increase in perceived loudness . This leads to the potential effect that a relatively small increase in level above the hearing threshold being perceived as a large change in the loudness of the sound.

Measurements of the equal-loudness-contours at frequencies below 20 Hz have been investigated by Møller and Andresen [16] and Whittle et al. [17] and Figure 9 below, from Møller and Andresen, compares the results. These measurements indicate good agreement between the two papers and indicate a continuing tendency for the contours to become closer as the frequency reduces. Therefore, it the infrasonic range, an increase of the sound pressure level by 10 dB may be perceived as an 8 - 16 fold increase in loudness as compared to a doubling, 2 fold increase, at 1 kHz..

Figure 9Infrasound equal loudness contours: from Møller and Andresen

The result of this change in perceived loudness with change in sound pressure level in the low frequency region is that small changes in the pressure level may be experienced as a large change in perceived loudness. Therefore, when infrasound and low frequency are of sufficient level to be detected, then a small change in pressure level above this threshold will quickly become perceived as a large change in loudness which may be considered unacceptable.

The experience of the low frequency sufferers within the Salford Study indicate that once the subject has been “sensitised” to low frequency noise then only a small increase in pressure level above the hearing threshold is required to be considered unacceptable.

Methods for the Assessment of Infrasound and Low Frequency Noise

It has been described above that infrasound may be considered to be acoustic energy which is contained within the frequency spectrum below 20 Hz and that low frequency sound is considered to be between 20 – 160 Hz. As such, the two frequency ranges are assessed using different

[16] Møller, H. and Andresen, J.: Loudness of pure tones at low and infrasonic frequencies. Jnl Low Freq. Noise Vibn 21, 53-65

[17] Whittle, L.S., Collins, S.J., and Robinson, D.W.: The audibility of low frequency sounds. Jnl Sound Vibn 21, 431 - 448

methods. We shall discuss these different methods and determine which methods we shall use to assess measurements of infrasound and low frequency noise at the measurement locations neighbouring the three wind farms.

Infrasound Assessment Methods

The method of assessment of low frequency noise within the UK is described within the Salford Report. The noise criterion proposed within this document covers a frequency range from 10 Hz up to 160 Hz. The criterion covers the higher frequencies of the infrasound range and the accepted low frequency range. However, the Salford Report does not provide any criteria for frequencies below 10 Hz.

To supplement the criterion within the Salford Report we have considered additional noise criteria that are contained within other European National Standards.

Denmark

For low frequency noise, the "A" weighted level of the noise in the frequency range 10 – 160 Hz is considered, the symbol used is $L_{pA,LF}$. The recommended limits are 5 – 15 dB lower than the ordinary noise limits, and the lowest recommended limit, $L_{pA,LF}$ = 20 dB, has a close connection with the infrasound limit, L_{pG} = 85 dB. An environmentally acceptable infrasound level must be below the hearing threshold, which occurs for tones in the frequency range between 1 – 20 Hz at a level L_{pG} = 96 dB. It can be assumed that a sensitive individual’s hearing threshold might be 10 dB lower than the average threshold, so the recommended limit for environmental infrasound has been set at an L_{pG} = 85 dB.

Danish Infrasound and Low Frequency Noise Limits	Infrasound, L_{pG}	Low frequency noise, $L_{pA,LF}$	Usual noise limit, L_{pA}
Dwelling, evening & night	85 dB	20 dB	30 dB / 25 dB
Dwelling, day	85 dB	25 dB	30 dB (day & evening)
Classroom, office etc.	85 dB	30 dB	40 dB
Other rooms in enterprises	90 dB	35 dB	50 dB

Table 3. Recommended limits for infrasound (L_{pG}), for low frequency noise ($L_{pA,LF}$), and the normal noise limit for noise from enterprises (L_{pA} , used when the enterprise and the dwelling are in the same building). All levels in dB re 20 µPa.

Low Frequency Noise Criterion

To assess the acceptability of low frequency noise associated with the operation of wind turbines, noise measurements have been performed following the principles outlined within the Salford Report.

The recommendations within the Salford Measurement Procedure Report [18] propose a methodology for the assessment of low frequency noise complaints.

[18] Procedure for the assessment of low frequency noise complaints: February 2005: Contract No. NANR45: Prepared for DEFRA by Dr Andy Moorhouse, Dr David Waddington, Dr. Mags Adams

Within the Section Measurement it is preferable for the measuring sound level meter to have third octave band filters from 10 Hz to 160 Hz, which covers the criterion curve range. The equipment used for the measurements undertaken within this project fully meets these requirements as measurements are to be made into the infrasound region, down to 1 Hz.

The measurement locations used for these assessments were within the dwellings, where the residents reported that the low frequency sounds were greatest. Measurements were made at these locations and, for one series of measurements, at a corner location to minimise the potential influence of room boundaries and modes within the room.

The Procedure Report indicates that for most low frequency noise problems, unattended measurements may be required to determine the presence of any low frequency noise. If suggests that recordings should be made continuously for a minimum period of three days since "*the complainants response can be affected by the presence of the equipment and is often untypical immediately after it is installed*."

The Measurement Parameter suggested to be monitored within the Procedure Report is the $L_{eq,T}$ in the third octave bands 10 – 160 Hz to allow comparison with the criterion curve. An average time, T, of 5 minutes is usually considered appropriate. It is suggested that other measurement periods may be appropriate for specific situations but no indication is given as to what these may be.

It is also considered advisable to record the L_{10} and L_{90} in the same bands since these will provide information about the character of the sound and how it fluctuates.

When undertaking measurements for this study, we have used a data logging system which logs the L_{eq}, $L_{p,fast}$, $L_{p,impulse}$ sound levels every 50 mSecs. The L_{eq} data has been used when assessing the level of low frequency noise at a receptor location.

The Criterion Curve proposed within the Measurement Procedure Report is provided within the table 4 below.

Table 4: DEFRA Night-time Low Frequency Noise Criterion

Third Octave Band Centre Frequency (Hz)	10	12	16	20	25	31.5	40	50	63	80	100	125	160
DEFRA LFN Criterion Curve: Night	92	87	83	74	64	56	49	43	42	40	38	36	34

Assessment Criteria for Infrasound and Low Frequency Noise

Figure 10 below details the criterion curves which have been adopted to determine the audibility of infrasound and low frequency noise. These curves detail the following:

The equivalent 85 dB(G) sound pressure level in each third octave band for frequencies between 1 – 20 Hz;
The hearing thresholds according to Wanatabe and Møller from 4 – 20 Hz;
The DEFRA Low Frequency Noise Criterion Curve from the Salford Report from 10 – 160 Hz;
The hearing threshold curve defined within BS ISO 226:2005 from 20 – 500 Hz.

Figure 10: Detailing infrasound and low frequency noise assessment criterion curves

Infrasound and Low Frequency Noise Emissions from Wind Turbines

The generation of infrasound from wind turbines is associated with the movement of the blades through, and their interaction with, the air. Infrasound noise emissions were identified within a paper by Shepard and Hubbard 19 which provided field data for a number of Upwind and Downwind rotor configuration wind turbines. The generation of blade passage frequency (BPF) energy and associated harmonics were found to be more dominant for down wind rotor configurations. This was due to the effect of the supporting tower wake interaction as the blade passed behind the tower and would experience a sudden and significant change to the airflow.

Figure 11: from ref: 16

Machines A and B represent measurements from two-bladed down wind rotor wind turbines, whereas, Machines C and D represent measurements from upwind rotor, two bladed wind turbines. It may be seen from the above data that the downwind rotor configuration has resulted in an increased level of noise within the infrasound region of the spectrum. The spectra obtained for Machines C and D are representative of upwind wind turbines which exhibit a high level of infrasound energy and are not typical of the sorts of spectra available from most modern wind turbines. It is indicated within Shepherd and Hubbard that the spectra provided within the above figures for Machines C & D are representative of the results from high inflow distortion believed to be caused by the effects of terrain irregularities in the upwind direction 20, 21.

Measurements performed and reported in 1997 22 at a modern wind farm indicate that the acoustic signal in the infrasound frequency range is below accepted thresholds of perception. Measurement of ground borne vibration associated with wind turbine operations were detectable but below accepted thresholds of perception, even within the wind farm.

[19] Physical characteristics and perception of low frequency noise from wind turbines: Noise Control Engineering Journal: Jan-Feb 1991: Vol.36/Number 1.

[20] Kevin. P Shepherd and Harvey H. Hubbard. Noise radiation characteristics of the WWG-0600 (600kW) wind turbine generator. NASA TM-101576. June 1989

[21] Kevin P. Shepherd and Harvey H Hubbard. Environmental noise characteristics of the MOD5-B (3.2MW) wind turbine generator. NASA TM-101567 March 1989

[22] Low frequency noise and vibrations measurement at a modern wind farm: ETSU W/13/00392/REP: D Snow: 1997

Measurements of infrasound were also undertaken as part of the study of ground borne vibration from wind turbines and which was reported by Styles et al. [23], [24]. These studies indicated that, although infrasound energy was detectable at considerable distance and that this was associated with the operation of wind turbines, the levels were significantly below the recognised thresholds of perception.

Figure 12 details measurements made at the Eskdalemuir Infrasound Array: Kelphope 1 which was located some 2400 metres from the nearest wind turbine (26 Vestas V-47 wind turbines at Dunlaw). This data indicates that although infrasound blade passage frequency harmonics were detectable, they are significantly below the perception threshold for such a noise, by 50 – 60 dB. At this location, no wind farm noise was audible during the measurements.

Figure 12: Infrasound Measurements at Eskdalemuir Array Location: Kelphope 1

Measurements of the infrasound emissions from a Nordex N80 wind turbine are reported by Betke [25] using a correlated pair of measurement microphones to reduce the inherent low frequency noise from wind turbulence. These measurements are summarised in Table 5 which details the G-weighted sound pressure level for the operating wind speed range during the tests. It may be seen from this data that measured levels are at least 20 dB below the infrasound noise criteria adopted within Denmark, a level of 85 dB(G).

Table 5: detailing G-weighted sound pressure levels measured at 200 metres downwind of a Nordex N-80 wind turbine: from Ref 25

Jakobsen [26] undertook a critical survey of published measurement results of infrasound from wind turbines. The conclusions of which are as follows:

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[23] A detailed study of the propagation and modelling of the effects of low frequency seismic vibration and infrasound from wind turbines: Peter Styles, Richard England, Ian G. Stimpson, Sam Toon, David Bowers, Malcolm Hayes: First International Meeting on Wind Turbine Noise: Perspectives for Control: Berlin 17th – 18th October 2005.

[24] Microseismic and Infrasound Monitoring of Low Frequency Noise and Vibrations from Windfarms: Recommendations of the siting of windfarms in the Vicinity of Eskdalemuir, Scotland: Professor Peter Styles, Dr Ian Stimpson, Mr S Toon, Mr R England, Mr M Wright: Applied and Environmental Geophysics Research Group

[25] Messung der Infraschall-Abstrahlung einer Windenergieanlage des Typs Nordex N-80: ITAP – Insitut für technische und angewandte Physik Gmbh: 20th June 2003

[26] Infrasound emission from wind turbines: Jørgen Jakobsen: 11th International Meeting on Low Frequency Noise and Vibration and its Control: Maastricht: 30th August – 1st September 2004.

From a critical survey of published measurement results of infrasound from wind turbines it is found that wind turbines with the rotor placed upwind produce very low level of infrasound. Even quite close to these turbines the infrasound level is far below relevant assessment criteria, including the limit of perception. Such low infrasound level are unimportant for the evaluation of the environmental impact of wind turbines.

Wind turbines with a downwind rotor generate considerably higher infrasound levels, which may violate relevant assessment criteria in distances up to several hundred metres. At longer distances the level drops below these criteria, and it is questioned if the infrasound can be the cause of reported negative public reactions to large downwind turbines.

Jakobsen noted that where adverse reaction had been received due to the operation of the wind turbines, the overall A-weighted noise levels exceed the Danish noise limits for wind turbines, levels of 40 dB L_{Aeq} for suburban and urban areas and 45 dB L_{Aeq} for single dwellings in the countryside.

Van den Berg 27 concludes the following with respect to infrasound noise emissions from wind turbines:

Infrasound harmonics of the Blade passing frequency from modern, tall wind turbines must be considered inaudible. Low frequency in-flow turbulence sound may be audible, but wind turbine sound is loudest at medium to high frequencies. This readily audible sound is caused by atmospheric and induced turbulence at the blade surface. The level of this medium/high frequency turbulent sound varies at the rate of the blade passing frequency, which causes the typical swish sound of a modern wind turbine.

Measurements of infrasound noise immissions have been undertaken by Hayes McKenzie Partnership at a location 420 metres downwind of a wind farm that was comprised of 12 No. 1.65 MW wind turbines. The measured data indicates that wind turbines do increase the level of infrasound acoustic energy within the environment but that this energy is below the perception threshold. The measured data, a sample of which is contained within Figure 13, indicates that infrasound emissions from the wind farm are 20 – 60 dB below the hearing thresholds in the frequency range 1 – 20 Hz. This is indicative that infrasound is not of sufficient level to be audible.

Figure 14 below provides the G-Weighted sound pressure level of the measured data during a night-time period during which the wind farm was parked. It may be seen from this data that levels are below the Danish Infrasound Noise Criteria of 85 dB(G) and around 15 dB below the hearing threshold of 96 dB(G) even during periods of wind turbine rated power wind speeds and above.

Figures 13 & 14 also provide a clear indication that for this particular measurement series, noise associated with the operation of the wind turbines resulted in an increase in the infrasound to be

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[27] Do wind turbines produce significant low frequency sound levels?: G.P.van den Berg: 11th International Meeting on Low Frequency Noise and Vibration and its Control: Maastricht: 30th August – 1st September 2004: Page 367 - 375

found at the measurement location. This compares with some recent results reported in USA [28] which indicated that at high wind speeds, wind turbines might help to reduce the level of atmospherically induced infrasound due to the energy capture of the wind turbines.

Figure 13: Measured Infrasound and Low Frequency Noise Levels: External Location on Ground Board

The data presented in Figure 13 shows a clear change in the infrasound noise levels when the wind farm is operating as compared to when the wind farm is parked. In the frequency bands 3.15 Hz – 20 Hz, there is a 16 – 18 dB level increase between the low wind speed spectrum and the parked wind farm spectrum. The change in level associated with the high wind speed sound pressure levels ranged between 23 – 25 dB. The parked condition ambient infrasound noise levels were obtained at 23:35hrs from within the data reported within Figure 14. The measurements were performed in the external environment, with the microphone located on a ground board with a large secondary wind shield (= 650 mm) to reduce the influence of wind turbulence.

Figure 14: Time History Figure of G-Weighted Sound Pressure Levels for a Wind Farm

Low frequency noise emissions from a wind turbine are associated with the aerodynamic noise from the wind turbine blades as they pass through the air. Specifically, the effect of inflow turbulence has been identified as the main source of low frequency noise emissions from a wind turbine blade. Van den Berg, within reference 27, indicates that low frequency inflow turbulence sound may be audible at a receptor location; however, little data exists of low frequency noise measurements within dwellings associated with the operation of modern wind turbines. Some measurements have been reported within Ref 2, but they relate to turbines which are not installed within the UK or, for that matter, anywhere else in the world.

Transmission of Wind Turbine Noise into Living Spaces

Most guidance for wind turbine noise assessment is based on a noise criterion applied externally to a dwelling house or receptor location. However, low frequency noise complaints are often associated with the perception of the noise within buildings, specifically bedrooms and living rooms.

For a sound incident on a building structure to be heard within, the acoustic energy must be transmitted through the structure and into the living spaces. The level of acoustic energy transmission into the building depends upon the level sound insulation provided by the structure.

[28] Infrasound from Wind Turbines: Observations from Castle River Wind Farm: Howard Hepburn and Jason Edworthy: 18th October 2005: Canadian Wind Energy Conference Toronto Canada

Figure 15 below details the expected performance of single panels, i.e. single leaf walls and glazing. It should be noted that the actual performance of a wall is dependent upon its construction method and its mass. However, the general shape of the curve detailed below holds true for most building elements.

Figure 15 - Indication of sound insulation performance of single leaf structures.

The sound insulating performance of a panel is determined at very low frequencies by the stiffness of the structure. Thick walls, for example, are very stiff and will perform well in reducing transmission at very low frequencies. In the mid frequency band, typically 200 – 2 kHz, the sound insulating performance of the structure is mass controlled, i.e. for every doubling of the mass of the panel, the sound insulating properties will increase by around 6 dB.

In the region between stiffness and mass control, additional effects associated with panel resonance’s can significantly compromise the performance of the structure. These resonance’s fall into the region of the low frequency range of the noise spectrum. Additional resonance can be introduce into a structure by the use of double skin panels, i.e. caravan lightweight structures and double glazed windows. Such materials introduce resonant effects, mass-spring-mass, that can amplify the level of noise within a room as compared to the energy impinging on the external surfaces of the structure.

The geometry of a building may also have an effect on the perceived level of noise within a room. Room modes, the presence of nodes (low) and anti-nodes (high) of acoustic intensity, occur that are related to the size of the room. Locations such as corners of rooms and doorways may experience an increase in level over the room average of 9 + dB. For a room of 4 by 5 metres, the first mode frequency will be around 32 Hz; i.e. in the region of the expected minimum sound insulation performance of most building structures.

In addition, the lack of wind induced masking noise, which would normally result from wind induced turbulence in the external environment, serves to make the ear more sensitive to low frequency sources when indoors.

The combination of low frequency resonant effects due to the building structure, the presence of room modes and low levels of masking noise all combine to maximise any potential audibility of low frequency noise within a bedroom, for example. Suggested transfer functions are contained within Kelly 29 who indicates an increase in levels from external to internal environments of between 1 – 6 dB in the frequency range 25 – 125 Hz. Infrasound (<20Hz) noise levels, however, are extremely unlikely to be significant due to the low levels of such noise signals even on the wind farm site itself.

Wind Farm Noise Measurements

[29] Kelley N.D. A proposed metric for assessing the potential of community annoyance from wind turbine low frequency noise emissions AWEA Windpower ‘87

To assess the potential levels of infrasound and low frequency noise exposure a t receptor locations neighbouring three wind farms, measurements were undertaken using a measuring system capable of measuring across the frequency range from 1 Hz up to 20 kHz.

The data logging device used was a 01dB 4-channel Harmonie System with the use of low frequency microphones and preamplifiers and a 01dB 2-channel Symphonie System. Measurements were performed at internally and externally locations at each of the receptor locations. Where low frequency noise has been described by the occupants, then the microphones were located at positions where it was considered it to be most audible when the noise occurred. The calibration certificates for the measuring equipment are provided within Appendix 9.

In addition to the sound pressure level measurements, ground borne vibration in the vertical axis was measured at one location. These vibration measurements were to determine whether any vibration associated with the operation of the wind turbines was detectable. The occupants at this specific dwelling described the sound as coming up through the floor. Ground vibration measurements were not undertaken at any other locations. It should be noted that vibration associated with the operation of wind turbines has been considered in considerable detail within references 23 & 24 and indicate that this is not of concern to human perception or health due to the very low levels of vibration measured.

Free-field noise measurements were also performed, in accordance with the requirements of ETSU-R-97 30. These free-field measurement locations allow an assessment of the noise incident at the receptor location, external to the building. However, due to the potential problems associated with wind induced noise in the infrasound region, these measurements only logged frequencies above 10 Hz.

Low noise microphones were employed for measurements of the internal sound pressure levels in the “free-field” locations. These microphones (GRAS 40EN) have a limit to their low frequency response, quoted as ± 2dB @ 2.6 Hz and ± 1 dB @ 4 Hz. However, the sensitivity of the low noise microphone to pressure fluctuations caused by the wind on the building structure or internally generated noise, i.e. closing of doors within the buildings, would result in overloads to the measuring system. To eliminate these effects, the lowest frequencies measured when using this microphone arrangement was 10 Hz. This 10 Hz high pass frequency limit was set within the 01dB measuring system set-ups and was not due to the microphone/preamplifier system.

Site 1: Location 1

The existing wind farm at Site 1 was commissioned in July 1999. Seven pitch regulated wind turbines are installed at the site. Since the operation of the wind farm, complaints associated with noise have been received. One of the specific descriptions of noise associated with the operation of this wind farm was the presence of low frequency and infrasound noise.

The measurement location selected for the investigations into this noise were complainants who described the noise as “*thumpe d and resulted in us experiencing headaches and pressure sensations within my head. It is like a heart beat and appears to come through the floor into our bedroom. Even with the windows closed we can still hear this noise.*”

[30] The assessment and rating of noise from wind farms: ETSU-R-97: September 1996

Initial investigations of the property indicated the following:

that the main facades of the building faced away from the site;
an en-suite bathroom had windows facing the wind farm;
that double glazing had been installed in a conservatory area facing southwards away from the site;
double glazing existed between the main bedroom and conservatory area;
double glazing was installed within the living room windows facing towards the south;
the double glazing was thermal double glazing with no special acoustic properties;
that the noise was most audible within the conservatory and living room areas which were connected via an access door;
within the living room the noise was most audible at the end of the room closest to the conservatory;
that the noise was audible within the bedroom but that the levels were most noticeable within the conservatory and living room;
that following the implementation of a Noise Reduction Management System(NRMS) the low frequency noise had been substantially reduced at this property and that, in general, the need to complain had been greatly reduced;
wind turbine noise was audible within the garden areas of the property even when the NRMS was operating;
when low frequency noise was most intrusive, an easterly wind condition would exist at the site.

The internal measurement locations selected for assessment at this property were within the conservatory area, external to the internal windows to the main bedroom of the property. A microphone location in the corner of the room was selected and a sitting position within the conservatory, away from the room boundaries.

External measuring locations were a façade measurement location to the eastern façade of the building facing towards the wind farm, and a “free-field” measurement location in accordance with the requirements of ETSU-R-97. This ETSU-R-97 measurement location was logged using a Larson-Davies LD824 Sound Level Meter of a Type I specification.

An additional measurement channel of the 01dB Harmonie system monitored the vertical acceleration within the foundation slab of the conservatory to determine whether any detectable vibration associated with the operation of the wind turbines could be detected.

It has been indicated above that, in general, the implementation of the NRMS at the wind farm had greatly reduced the potential for noise disturbance at the dwellings. Therefore, to increase the potential likelihood of the noise occurring, the NRMS system was turned off for the period of the noise measurements when weather conditions were expected to cause the noise which caused complaints. For this location, this was an easterly wind condition..

Measuring equipment was installed on the 24th February 2005. The equipment was downloaded on the 2nd March 2005. It was reported by the occupants that although noise was audible at external locations to the dwelling, noise was not heard within the dwelling. However, the greatest problem that was experienced during this survey period was the failure of the sound level equipment which failed to log any noise data.

Following a period of review of the data logging equipment and receipt of new software drivers for the data card, the equipment was re-installed on the 12th May 2005 and operated through to the

17th May 2005. During the early morning of 14th May 2005, a Saturday, noise associated with the wind farm was described as *"intolerable"* and the following comment was logged:

"Woke us 4 AM. Unable to get back to sleep. Between Thurs. 12th and Wed. 18th May the windfarm was audible on the patio during the afternoon on several occasions but as the weather was cold we were not working or sitting outdoors, otherwise it would have been a nuisance."

The analysis of the noise data for this location during this period is assessed below. It should be noted that the occupant refers to 4 am BST (British Summer Time) whereas all the measurements reported are undertaken relative to GMT (Greenwich Mean Time).

Infrasound

The measurements which are detailed within the figures below, Figures 15 – 20, detailed the measured L_{eq}, L_{05} , L_{10} and L_{90} third octave band sound pressure levels. The presentation of the data using the L_{nn} sound pressure levels provide an indication of the potential period that wind farm noise may exceed the Criteria thresholds which have been adopted for this assessment of internal noise levels.

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

Figure 21

The measurements detailed within Figures 16 – 21 above, detail the third octave band sound pressure levels measured in the corner of the Conservatory within the receptor dwelling. It will be noted that all times within the figures are GMT. The reported time of the noise is 04:00 hours BST which is equivalent to 03:00 hours GMT.

Acoustic energy at 20 Hz is 20 dB below the threshold of hearing, 20 dB below the DEFRA LFN Criterion and 28 dB below the threshold of perception defined by Watanabe and Møller.

Figure 22: Time History of G-Weighted Sound Pressure Levels: 14th May 2005

Figure 22 above, details the G-Weighted sound pressure levels for the early morning period of 14th May 2005. The internal "free-field" and "corner" locations have been plotted as well as the external façade noise levels. It may be seen that the internal G-Weighted sound pressure levels are significantly below (25 – 30 dB) the Acceptability Criterion of 85 dB(G) and 30 – 35 dB below the Threshold of Perception Criterion of 96 dB(G). This is a positive indication that infrasound is not of sufficient level as to be audible at this location.

Low Frequency Noise

Low frequency noise has been assessed by comparing the measured third octave band levels with the DEFRA Night-time LFN Criterion and the Danish $L_{pA,LF}$ Criterion of 20 dB(A).

The measurements within Figures 16 – 21 above indicate that at 02:50 Hours (Figure 16) internal noise levels are below the

DEFRA Night-time LFN Criterion. At 50 Hz, the measured L_{05} levels are within 4 dB of the criterion curve with an increasing level difference above and below this frequency. At frequencies above 100 Hz, the measured noise levels exceed the ISO 226 Threshold of Audibility Curve by 4 – 6 dB up to 315 Hz, whereupon, the measured noise levels then increase above the ISO Threshold of Audibility by 10 – 14 dB at 500 Hz. The sounds which can be heard at this moment in time are the breathing/snoring of the occupants within the neighbouring bedroom and some aerodynamic higher frequency noise. The overall A-weighted sound pressure levels during this period are between 21 – 24 dB L_{Aeq}.

At 02:55 hours (Figure 17), measured sound pressure levels have increased at 50 and 63 Hz, such that the measured L_{05} noise levels are within 2 dB of the DEFRA Night-time LFN Criterion. Listening to the audio recordings for this time period indicates that the increase in levels within these frequency bands is associated with the movement of a vehicle along the A-class road located to the south-west of the dwelling, approximately 250 metres away. This increase in sound pressure level results in LFN L_{05} exceeding the ISO Threshold of Audibility Curve by 4 – 5 dB at 63 Hz. Between 125 – 500 Hz, measured noise levels exceed the ISO Threshold of Audibility Criterion by 4 – 15 dB, respectively.

At 03:00 Hours (Figure 18), Measured L_{05} noise levels are within 2 dB of the DEFRA LFN Criterion Curve at 50 Hz. At 100 Hz, the measured L_{eq} sound pressure level just falls below the DEFRA Night-time LFN Criterion Curve, whereas the L_{05} levels are 6 – 8 dB below this level. This indicates that the source of the LFN at 100 Hz is associated with a short period transient event. Listening to the recordings of the noise for this time period, it is clear that a vehicle passage results in an increase in the internal noise levels from 23 dB(A) to 34 dB(A). At this moment in time, one of the occupants is noted to awaken and move from their bedroom.

At 03:05 Hours (Figure 19), the occupant returns to their bed. Some vehicle movements occur during this period. As a consequence, measured LFN L_{05} noise levels at 50 and 63 Hz are at the ISO Threshold of Audibility (ToA). Measured LFN noise does not exceed the DEFRA Night-time LFN Criterion. At 125 Hz and frequencies above, measured internal noise levels exceed the ISO ToA by 1 – 5 dB. At 400 – 500 Hz, the measured levels are 10 – 12 dB above the ISO ToA Criterion.

At 03:10 Hours (Figure 20), the occupant has returned to bed. During this 5 minute measurement period, no vehicle movements are audible on the recording. As such, the levels measured at 50 and 63 Hz are reduced and fall below the ISO ToA Criterion. The measured levels do not exceed the DEFRA Night-time LFN Criterion Curve. Between the frequencies 125 – 250 Hz, there is a rise in noise levels which is associated with the sleep of the occupants and movements in bed. Particularly, snoring was clearly audible during this period as at 03:11 – 03:12, one of the occupants begins to snore which is the cause of the increased level. At 400 – 500 Hz, measured noise levels exceed the ISO ToA Criterion by 10 – 15 dB.

At 03:15 Hours (Figure 21), a similar shaped spectrum is found as that for 03:10 hours. One of the occupants is still snoring and there is a little additional vehicle noise during the measurement period. The increased levels between 125 – 250 Hz are associated with the snoring of the occupant. Again, at 400 – 500 Hz, it may be seen that measured internal noise levels exceed the ISO ToA Criterion by 15 – 17 dB. Measured internal noise levels do not exceed the DEFRA Night-time LFN Criterion.

The data which was collected during this period was when the wind turbine noise was described as awakening the occupants and then keeping them from falling asleep. Our analysis of the recordings would indicate that rather than the wind farm awakening the occupant, the occupant was awoken by the passage of a vehicle along the A-class road. However, once awoken, the sounds from their partner and the audibility of wind farm noise in the 400 – 500 Hz region may have caused the occupant who has been awoken to have difficulty in returning to sleep.

It should be noted that the description of the noise by the awoken occupant was that the noise was "*intolerable*". The range in noise levels in the 400 – 500 Hz third octave bands was measured to lie between 9 – 10 dB and to be 17 dB above the ISO ToA Criterion Curve. In this event, the perceived change in level in this frequency range would be a doubling of the perceived loudness, with levels potentially rising in and out of the Threshold of Audibility. This would give rise to the description of a heart beat type sound as the sound would only be audible for part of the time, i.e. as the noise associated with the wind farm is aerodynamic in origin and is associated with the rotation of the blades, then this will appear at 3 times the rotational speed also know as the blade passage frequency.

Figure 23: Time History of $L_{pA,LF}$ Internal Noise Levels

Figure 23 details the assessed $L_{pA,LF}$ noise levels in accordance with the method described within the Danish Guidelines for the assessment of low frequency noise. In general, the calculated $L_{pA,LF}$ falls below 20 dB even for the corner located measurement position. Where the $L_{pA,LF}$ exceeds the 20 dB criterion, this is associated with the passage of motor vehicles rather than noise from the wind farm. The level associated with wind farm operations falls in the range 10 – 15 dB for the "free-field" internal measurement location and 12 – 17 dB for the corner location.

The occupants of the dwelling clearly indicate that they have been subject to noise within their property which they describe as being low frequency in nature. However, the measured levels when the noise was described as "*intolerable*" indicate that noise associated with the operation of the wind farm was below the DEFRA Night-time LFN Criterion even when assessed using the levels that occur for 5% of the measurement period. However, the measured levels are at or just above the ISO Threshold of Audibility. As the Threshold of Audibility is considered to represent the average hearing for a normal hearing person, it may be expected that a more sensitive listener may be able to detect low frequency noise at even lower levels. It has been suggested by van den Berg and Passcheir-vermeer (ref 10) that the most sensitive 10% of the population may have a Threshold of Audibility in this low frequency region which is as much as 10 dB lower, and 12 dB lower for the most sensitive 5% of the population. If one assumes that the occupants fall into this more sensitive population then wind farm noise will be audible in this low frequency region.

It has been observed from the recordings that the awakening of the occupants coincides with the passage of a motor vehicle along the neighbouring A-class road. At this point, one of the occupants moves within the dwelling and then returns to bed a few minutes later. After this point, it is indicated within the log that the occupant was no longer able to sleep. This is indicative that the noise associated with the operation of the wind turbines was audible within the bedroom. Without a hearing test of the occupants it is not possible to determine whether the occupants are low frequency hearing sensitive. However, this may not be relevant as noise in the 400 – 800 Hz region was audible within the conservatory. This may be seen within Figures 16 – 21 where the measured noise levels exceed the ISO Threshold of Audibility by as much as 12 – 13 dB. The recordings made within this period also exhibit the characteristic amplitude modulation of the aerodynamic noise in this frequency range. Low frequency noise is audible using an audio replay system if the gain of the system is increased such that internal noise levels are 20 dB higher than actual levels within the dwelling.

Within Appendices 1 - 4 (A-D) summarise all the data collected at this location between the hours of 00:00 – 06:00. It will be seen from these measurements that on a number of different days, measured noise levels were higher than those found at 03:00 GMT (04:00 BST) on the 14th May 2005. In these circumstances, the occupants have either not awoken or the noise is associated with traffic movements or the wind on the building itself, i.e. it is noise which is not associated with the operation of the wind turbines. Furthermore, these measurements were collected when the wind was from a direction other than the east and did not, therefore, exhibit the level of amplitude modulation of the aerodynamic noise which is experienced for an easterly wind direction.

External Noise Levels

Measurements were performed at two locations external to the dwelling. A façade mounted measurement location at which recordings on the incident noise were made and a free-field measurement at a location in accordance with the requirements of ETSU-R-97. The measurements performed at the façade indicate that amplitude modulation of the noise was clearly audible. Figures 24 - 27 detail the measured levels over a short period between 02:58:29 to 03:00:19 hours on 14th May 2005. It may be seen from this data that short term levels of amplitude modulation of 5 - 6 dB peak to trough occurs during this period.

Figure 24: 400Hz

Figure 25: 500 Hz

Figure 26: 630 Hz

Figure 27: 800 Hz

The measurements within the third octave bands centred at 400, 500, 630 and 800 Hz indicate that a significant proportion of the modulated acoustic energy is associated with in these frequency bands. This noise is associated with trailing edge noise from the wind turbine blades and is aerodynamic in origin.

Measured $L_{A90,\ 10}$ minute noise levels at the ETSU-R-97 measurement location ranged from 37.8 – 38.1 dB during the period when this data set was collected. The façade noise levels during this measurement period were 39.8 – 40.9 dB $L_{A90,\ 10\ minute}$. This may be compared with background noise levels when the wind turbines are not operating for an easterly wind direction, which range in level from 26 – 32 dB $L_{A90,\ 10minute}$ for the wind speeds 6 to 10 $m.s^{-1}$ at the hub height of the wind turbines, respectively.

Following the guidance within ETSU-R-97, when background noise levels are below 38 dB L_{A90}, then the absolute noise level proposed for night-time operations is 43 dB L_{A90}. Therefore, the noise associated with the operation of the wind turbines meets the requirements of ETSU-R-97 for night-time operation.

The assessed levels of low frequency noise within the dwelling, when compared with the DEFRA Night-time LFN Criterion and Danish $L_{pA,LF}$ Criterion, indicate that external noise levels at this dwelling of 37 – 38 dB L_{A90} free-field will result in an internal noise environment which meets both these criteria. However, wind farm noise within the dwelling is likely to be audible as internal noise levels associated with the operation of the wind turbines exceed the threshold of audibility as defined within ISO 226. Furthermore, the dominant audible noise associated with wind turbine operation is acoustic energy within the 250 – 800 Hz frequency region which originates from the aerodynamic modulation of the wind turbine noise. This noise is outside the normal range considered for low frequency, i.e. frequencies below 160 Hz.

Site 2: Location 1

The existing wind farm at Site 2 was commissioned in September 2001. Sixteen stall regulated wind turbines are installed at the site. Since the operation of the wind farm, complaints associated with noise have been received and specifically low frequency noise has been identified by neighbouring receptors to the development.

The measurements at this location were undertaken by the site operator as part of an extended measurement series to evaluate the issues associated with the noise emissions from the wind farm. The measured data made available for this analysis covered the period from 25th May 2005 – 29th June 2005.

The occupant of the dwelling was instructed in the method by which the 01dB Symphonie system could record the sound which was causing them to complain. Two measurement locations were used, an external measurement location which satisfied the requirements of ETSU-R-97 and an internal measurement location within a bedroom facing the existing wind farm. The installation of the equipment within the building followed the Draft Guidelines which were available from the DEFRA LFN Report. This was to ensure that measurements were compatible with the requirements of the DEFRA Night-time LFN Criterion.

The building is of a detached, brick construction with double glazed windows. The dwelling also had the ability for the installation of secondary glazed panels (triple glazing) which is not installed by the occupants due to their desire for fresh air. The dwelling is located within a shallow hollow which provides some shelter from the prevailing wind. The dwelling is down wind of the wind farm in the prevailing wind direction. The tip of the closest wind turbine is visible from the dwelling.

Descriptions of the noise experienced by the occupant include: *thumping and roaring; sounds like a number of piston engines with a roaring furnace; woken trying to sleep, thumping during the second half of the night; thumping not much roaring; whoosh whoosh; bumping, thumping; whirring whoop whoop; headaches and feeling tired due to lack of sleep.*

The occupant was instructed to record the noise when it was considered to be a problem. However, during the course of the measurement period, the record mode was activated only twice in a month. Furthermore, when the recordings were undertaken, the bedroom window was opened. The recordings indicate that aerodynamic wind turbine noise was audible at the external and internal locations when the window was open. However, there are no recordings when the window was shut. Third octave band levels were logged during the survey period and periods when the windows were shut can be detected due to the decrease in the measured internal noise levels. Internal noise measurements were undertaken incorporating a low noise microphone with a high pass filter incorporating a 10 Hz cut-off frequency.

Infrasound

The measurements which are within the figures below, Figures 28 – 31, detail the measured L_{eq}, L_{05}, L_{10} and L_{90} third octave band sound pressure levels.

Figure 28 provides the measured levels from 10 Hz and above which were collected within the dwelling, with the window open, when the noise was considered intrusive by the occupant during the day. It may be seen from this data that infrasound levels below 20 Hz are below the DEFRA Night-time LFN Criterion and the Threshold of Audibility published by Watanabe and Møller. It should be noted that the DEFRA Night-time LFN Criterion measurement method should be undertaken when windows are closed. If windows are closed, then internal noise levels associated with the operation of the wind turbines will fall still further below the various criteria.

Figure 28: Site 2: Internal: 12:15: 2nd June 2005

Figure 29: Site 2: External: 12:15: 2nd June 2005

Figure 30 presents noise data collected during the night at 23:55 hours on 14th June 2005. Again, this period of turbine operation was identified as a period when wind farm noise was unduly audible. The recording was made with the window open. These measurements again indicate that acoustic energy in the infrasound region is below the DEFRA Night-time LFN Criterion and the Threshold of Audibility published by Watanabe and Møller.

Figure 31 presents noise data collected at the external location on the 14th June 2005. Again, acoustic energy in the infrasound region is below the DEFRA Night-time LFN Criterion and the Threshold of Audibility published by Watanabe and Møller.

Low Frequency Noise

Low frequency noise between 20 Hz and 160 Hz, when measured within the dwelling with the windows open is below the DEFRA Night-time LFN. The measured noise levels

Figure 32: Representative internal noise data with windows closed

An assessment of the low frequency noise within the room in accordance with the Danish method indicates that internal noise

Figure 29 provides the measured levels external to the dwelling. It may be seen from this figure that even external noise levels meet the DEFRA Night-time LFN Criterion and the Threshold of Audibility published by Watanabe and Møller in the infrasound region.

Figure 30: Site 2: Internal: 23:55: 14th June 2005

Figure 31: Site 2: External: 23:55: 14th June 2005

are below the ISO Threshold of Audibility Curve up to 125 Hz for the measurements performed on 2nd June 2005 and 100 Hz for the measurements in the late evening on the 14th June 2005. Above these frequencies, internal noise levels associated with the operation of the wind turbines exceed the ISO Threshold of Audibility. The recordings made by the occupant clearly indicate that wind turbine noise is audible within the dwelling. A sample of the analysis of the internal noise levels measured within the bedroom before the opening of the window is detailed within Figure 31 below. Further data is presented within Appendices 5(A-B) and 6(A-C). These measurements indicate that with the window closed, infrasound energy has been reduced by 5 – 10 dB at frequencies below 20 Hz. Levels are reduced by 5 - 7 dB between the frequencies 25 – 500 Hz with the exception of the frequency band 125 Hz where internal noise levels are around 12 dB lower.

Figure 33: Time History of internal $L_{PA,LF}$ noise levels

levels do not exceed a level of 17.5 dB $L_{pA,LF}$. This analysis is detailed within Figure 33 above.

The analysis of the measured noise data with windows closed indicates that internal levels of low frequency noise are below the Danish Low Frequency Noise Criterion of 20 dB $L_{PA,LF}$ and below the DEFRA Night-time LFN Criterion. However, internal noise levels do exceed the ISO Threshold of Audibility above the third octave frequency band of 100 Hz. Between 160 Hz and 500 Hz, internal noise levels range between 2- 18 dB above the Threshold of Audibility with the greatest exceedence occurring at 250 Hz. Although no recordings have been made for the closed window situation, the spectrum shape which has been measured indicates that wind turbine noise is likely to be audible even with windows closed.

The sound which is audible within the room when the windows are open is the modulation of the aerodynamic noise associated with the movement of the turbine blades through the air. The measurements indicate that for this location, the greatest potential audibility of the noise occurs at 250 Hz, which is outside the range of accepted low frequency noise. External noise measurements indicate levels ranging between 36 – 39 dB $L_{A90,\ 10\ minute}$ (37 – 42 dB $L_{Aeq,\ 10\ minute}$) which meets the requirements of ETSU-R-97 for night-time operations. Internal noise levels range between 22- 24 dB $L_{Aeq,10\ minute}$ and 31 – 33 dB $L_{Aeq,10\ minute}$ for windows closed and open, respectively.

Site 3: Location 1

The existing wind farm at Site 3 was commissioned in July 2002. Three stall regulated wind turbines of 1.3 MW generating capacity are installed at the site. Since the operation of the wind farm, complaints have been received by the Local Authority that relate to noise associated with the operation of the wind turbines. One description of the noise is that of low frequency noise being audible within a neighbouring dwelling. An additional complaint from another dwelling has been associated with potential tonal noise from the turbines. Two sets of measurements were performed at this site. The first set involved the measurement of wind farm noise both externally and internally for the location where low frequency noise was described as a concern. The other location, Location 2, was monitored only at an external location to the dwelling as internal noise levels were described as “ not a problem”.

The dwelling at Location 1 is of stone/brick construction with single and double glazed units. The main façade of the building faces towards the south west, towards the wind turbines. A steep bank exists to the rear of the property into which the building sits. A lawn area exists to the front of the building with a picnic table. A C-class road passes adjacent to the building to the north but there is very little traffic along this road. To the west, a B-class road, located some 500 – 600 metres away provides the source of any traffic noise. The location of the dwelling is within a valley, at 180m AOD, which affords a high degree of shelter from the wind during easterly wind conditions and a relatively high degree of shelter during westerly wind directions. The wind farm is located at a height of 300 – 320 m AOD. Mature trees exist to the west and south-west of the property such that it is difficult to see the wind turbines when they are in leaf. Standing within the southern end of the garden area results in the wind turbines becoming visible through the trees. There is insufficient tree cover or depth to provide any beneficial attenuation of noise from the wind farm as it propagates through the tree canopy, i.e. this will have little effect upon the incident noise at the property. Within the valley is a stream which, depending upon the flow of water, may become the dominant noise source within the vicinity of the dwelling.

To investigate the potential for low frequency noise within the dwelling, measurements were undertaken at an external location to the dwelling and at the top of the access stairs within the building to the upper floor area. This internal location was originally on the window ledge within very close proximity to the window. At a later date, the internal location was moved to a corner location within the landing. Both these locations were external to the bedroom to the property but it was considered representative of the location where low frequency and wind turbine noise was audible within the dwelling.

Initial investigations of the property indicated the following:

that the main facades of the building faced towards the site;
that the landing area with a window in the gable end wall had views towards the site was a representative location to experience wind turbine noise;

Location 2 where only external noise measurements were performed is positioned due east of the wind farm. This property is located higher up the valley sides and is more exposed to wind from all directions, with the dwelling located at 255m AOD. The dwelling is therefore around 75 – 95 m below the bases of the wind turbines. The measurement location used was to the west of the dwelling, facing the wind turbines. The garden is to lawn, falling away from the house towards the site. At a distance of around 100 metres further to the west from the dwelling, the ground falls away steeply into the valley within which Location 1 is positioned.

The closest turbine to Location 1 is 1030 metres to the south-west and for Location 2, 740 metres WNW.

Measurements undertaken at Location 1 began on 14th October 2005 and ran through until 1st December 2005. During this time recordings were made during the night hours for a majority of nights with the exception of periods when equipment malfunctioned. However, during this lengthy survey period, only one occasion was reported by the occupants to experience low frequency noise associated with the operation of the wind turbines. This was one morning on 25th October 2005. On this occasion, the house holders noted that the noise was audible within the dwelling. Analysis of the recordings made during this time indicated that clearly a source of low frequency noise was audible at both measurement locations but that this was associated with the operation of a washing machine within the conservatory. Figure 34 below details the measured levels in the morning for both the external and internal locations, Channels 1 and 2 respectively. It may be seen from Figure 34, which details the measured L_{eq} noise levels at 160 Hz for both channels that a source of noise in this frequency range starts to operate at 06:48:25 for the external measurement location. This continues until 07:05:25. The internal measurements indicate the presence of low frequency noise at the start of the data logging period, at 06:47:15, which falls in level at 06:55:00 due to the closure of the window and door to the conservatory located at the bottom of the stairs from the landing area. The source is noted to stop at 07:05:25 at both measurement locations. Listening to the recordings of the measured sound indicates that the external measurement location experiences a sudden increase in noise levels associated with a change in the operational mode of the washing machine whereas the internal levels are dominated by noise from the washing machine and other domestic sources including a discussion by the occupants as to whether to shut the window. This is the cause of the higher levels measured around 06:56 and the overloads (marked in red within the figure) caused by the microphone system being touched and the sudden momentary pressure increase due to closure of the window and doors to the bedroom and conservatory.

Figure 34: Measured sound pressure levels on morning of 25th October 2005, 160 Hz third octave band

The operation of the wind turbines will not result in the sort of signature which has been experienced at this location. At this time, the wind turbines were all operating, with an average generating capacity of 1 MW, a hub height wind speed of 11.47 – 12.86 $m.s^{-1}$ and with a wind direction from the south-west when the dwelling would be directly down wind of the site. Analysis of the tonal content of the sounds indicates that no tones are present which can related to the operation of the wind turbines.

Measurements undertaken on the 20th October 2005 indicate that during the morning, modulation of the aerodynamic noise is audible at the external measurement location to the dwelling. Listening to the internal location recordings indicates that this modulation is just audible above the sound of water in the stream within the neighbouring valley bottom. Figures 35 - 40 below detail the period when this modulation is most noticeable within the recorded data at the external measurement location.

Figure 35: 200 Hz

Figure 36: 250 Hz

Figure 37: 315 Hz

Figure 38: 400 Hz

Figure 39: 500 Hz

Figure 40: 630 Hz

Infrasound

The measurements which are detailed within the figures below, Figures 41 – 42, detailed the measured L_{eq}, L_{05}, L_{10} and L_{90} third octave band sound pressure levels over a 1 minute measurement period from 06:43 – 06:44 hours, the period when the highest level of modulation of the aerodynamic noise was noted.

Figure 41: External Level: 06:4 3

Figure 42: Internal Level: 06:43

Figure 43: Internal Level: 06:42: No footfall Noise

The measurements indicate that levels of acoustic energy in the infrasound region are below the recognised perception thresholds for such a source. The high internal sound pressure levels measured in the 16 – 25 Hz range are associated with the rising of one of the residents who exits the bedroom in haste and descends the stairs. This caused low frequency noise through foot fall noise of the suspended wood floor. Figure 43 provides an indication of the internal noise levels when no footfall is experienced during the data collection period, i.e. the minute before. This indicates that acoustic energy in the infrasound region is below the DEFRA Night-time LFN Criterion and the Threshold of Audibility published by Watanabe and Møller.

Low Frequency Noise

Low frequency noise has been assessed by comparing the measured third octave band levels with the DEFRA Night-time LFN Criterion and the Danish $L_{pa,LF}$ Criterion of 20 dB(A).

Figures 42 & 43 detail the internal noise levels measured within the dwelling. The initial reaction is that the low frequency noise level is above the DEFRA Night-time LFN Criterion Curve. However, comparison of the measured internal and the external noise levels indicate that the levels are very comparable and that there is little difference between internal and external levels. The cause of this reduce level difference is associated with the position of the microphone during this period of the survey. The window had a clear view down towards the stream running at the bottom of the valley which greatly influenced the noise levels measured at this location. The increased levels between 200 – 400 Hz within Figure 42 are the result of coughing and sneezing as the occupant passed the microphone.

Following a review of the data, the measurement location was moved to reduce the influence of the noise entering the window which was adjacent (within 300mm) of the microphone. Figure 4 4 below details measurements of the internal noise levels at the new microphone location. The data represents the internal noise levels measured when wind speeds at site were 9.13 ms^{-1}, average generating capacity of the site was 632 kW and the wind was from the SW, i.e. the dwelling was downwind of the site.

Figure 44: Sample of internal noise levels when downwind of wind farm

The data collected during the evening of 11th November 2005 was not an occasion when the occupants indicated that noise was audible within the dwelling. However, the recordings indicate that the occupants were not in residence when the data was collected, although a washing machine was operating and the house dogs were barking on occasion. The external recordings indicate that wind turbine noise is just audible through the masking provided by the wind in the trees and water flowing in the neighbouring stream.

The low frequency noise levels are below the DEFRA Night-time LFN Criterion Curve. The measured data indicates noise levels exceed the ISO Threshold of Audibility between 100 – 500 Hz. It should be noted that the data selected is representative when the washing machine was not clearly audible within the general noise. Therefore, the data presented within Figure 44 must be considered to be indicative of the levels associated with the operation of the wind turbines. However, when listening to the internal recordings, even with high gain, it is difficult to discern any noise associated with the operation of the wind turbines. It is likely, however, that some the level exceedence about the ISO Threshold of Audibility is associated with the operation of the wind turbines and that, in the event of less tree noise and/or less water noise, that wind turbine noise may become more audible within the building. The frequency range at which wind turbine noise may just exceed the ISO Threshold of Audibility is between 100 – 500 Hz.

Figure 45: Low Wind Speed Sound Pressure Levels

Site 3: Location 2

Measurements were undertaken at Location 2 as part of studies to assess noise levels at this property. The survey period for these measurements covered the period 8th – 26th March 2006. The occupants had not complained about low frequency noise associated with the operation of the wind turbines at the house but had identified tonal noise and low frequency noise within forestry located 250 metres away as being their main concern. This valley location is within the same valley as Location 1: Site 3.

As the complaints were associated with the noise which was experienced external to the dwelling, a measurement location was used which represented an external location used for relaxation. This was a close to a patio area to the south-west of the dwelling with direct views to all three wind turbines.

Figure 46: High Wind Speed Sound Pressure Levels

Figures 45 and 46 detail the measured noise levels at Location 2. The data has been filtered to include only data where all wind turbines are generating; the dwelling is directly downwind of the nearest turbine ± 45°; and no rain fell during the measurements. The installed wind turbines are two-speed in operation, therefore, the data has been separated into low speed operation and high speed operation.

Figure 45 details the measured levels for low speed operation. In this operating mode, incident noise levels at Location 2 are below 30 dB $L_{A90, 10 minute}$.

Figure 46 details the measured noise levels for normal mode or high speed operation. It may be seen that as the average hub height wind speed across the site reaches 11 – 12 ms^{-1}, the incident noise at the measurement location increases at a greater rate than that found between 6 – 11 ms^{-1}. The significance of the increase in noise levels at 11 – 12 ms^{-1} is associated with operating characteristics of the wind turbines. As the turbines are stall regulated, when rated power is achieved by the wind turbines, the turbines blades will enter a stall condition. As wind speed increases, this stall condition will also increase. This stall condition increases the level of noise emitted by the wind turbines.

This increase in noise levels when rated power is achieved can result in an increase in noise at a receptor location of 5 dB for a 2 ms^{-1} wind speed increase. Such an increase would be clearly audible for a sheltered location where no change in background masking noise may be expected with increasing wind speed. Location 1: Site 3 may, for certain wind directions be such a location.

Another potential source for the increase in noise levels during high wind speed conditions is the noise generated by the wind in the trees or wind induced noise around the microphone assembly. A review of the recordings was undertaken and they indicate this was not a significant source of increase in the measured levels.

Discussion of Findings

A number of clear conclusions may be drawn from the measurements undertaken at the three wind farms.

Infrasound

Infrasound noise emissions from wind turbines are significantly below the recognised threshold of perception for acoustic energy within this frequency range. Even assuming that the most sensitive members of the population have a hearing threshold which is 12 dB lower than the average hearing threshold, measured infrasound levels are well below this criterion, even when the noise is being experienced within the dwellings.

The document "*Community Noise*" prepared for the World Health Organization, states that '*there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects'*.

As a result of this study, infrasound associated with modern wind turbines is not a source which will result in noise levels which may be injurious to the health of a wind farm neighbour.

Low Frequency Noise

The low frequency noise measurements undertaken at the three sites indicate that even with windows open for some complainants, measured low frequency noise levels are below the DEFRA Night-time Low Frequency Noise Criterion.

When assessed in accordance with the Danish Criterion of $L_{pA,LF}$ = 20 dB, internal levels do not exceed 20 dB when measurements are undertaken within rooms with windows closed.

However, compliance with both low frequency assessment criteria does not mean that noise associated with the operation of the wind turbines will be inaudible. Comparison of the measured levels at all locations indicates that wind turbine L_{eq} noise levels are below the Threshold of Audibility defined within ISO 226 for frequencies below 80 – 100 Hz within a dwelling. However, at higher frequencies, depending upon whether windows are open or closed, noise associated with the operation of the wind turbines may be as much as 10 – 20 dB above the threshold of audibility.

In the frequency region between 20 – 100 Hz, although the measured L_{eq} wind farm third octave noise levels are below the Threshold of Audibility as defined within ISO 226, if a receptor has particularly sensitive hearing in this frequency region then it is possible for noise in this frequency range to be audible. The analysis for Site 1: Location 1 indicates that the L_{05} third octave sound pressure levels are close to or at the Threshold of Audibility. In this event, it is quite possible that for 5% of the time, the low frequency noise is above the Threshold of Audibility of the listener. This would give rise to the description of "a beating heart" sound which would be related to the higher levels of the noise exceeding the Threshold of Audibility briefly at the blade passage frequency of the turbine. Furthermore, the Salford Study indicated that low frequency noise suffers are less tolerant of any low frequency noise which exceeds the threshold of audibility. Therefore, any small exceedence that might occur for a complainant may be considered an exceedence which is not acceptable, i.e. the occupant has become sensitised to the noise.

It is important to note, however, that for Site 1: Location 1, the occupant complained of wind turbine noise only after being woken by the passage of a motor vehicle on the nearby A-Class road. As such, this indicates that, rather than wind turbine noise resulting in noise which is of sufficient level as to awaken a sleeping person, it is the inability to return to sleep associated with some audible wind turbine noise within the bedroom which is of more concern to that occupant. A difficulty in returning to sleep will result in tiredness the next day and all the associated descriptions of ill health which might be associated with a lack of sleep.

When the wind is blowing from another direction, rather than the easterly wind direction which causes the problems experienced at Site 1: Location 1, the character of the noise associated with the operation of the wind turbines is significantly different. Specifically, there is little modulation of the aerodynamic noise associated with the operation of the wind turbines. The occupants, during this wind condition consider that the internal noise levels associated with the operation of the wind turbines is satisfactory, although they still consider the external noise environment undesirable.

All three wind farms clearly experience occasions when aerodynamic noise is subject to high levels of modulation. The measurements of noise during these conditions, in association with the comments from the occupants, indicate that when wind farm noise is at its most intrusive, it is this aerodynamic modulation which gives rise to their complaints associated with the operation of the wind turbines.

Modulation of Aerodynamic Noise

The identification of increased, modulated aerodynamic noise from wind turbines giving rise to complaints is experienced at other sites in Europe. The issue of the modulation of aerodynamic noise has been discussed within a number of papers by van den Berg. Within his paper *"Do wind turbines produce* *significant low frequency sound levels?"* [31], the conclusions state the following:

Infrasound harmonics of the blade passing frequency from modern, tall wind turbines must be considered inaudible. Low frequency in-flow turbulence sound may be audible, but wind turbine sound is loudest at medium and high frequencies. This readily audible sound is caused by atmospheric and induced turbulence at the blade surface. The level of this medium/high frequency turbulent sound varies at the rate of the blade passing frequency, which causes the typical swishing sound of a modern wind turbine.
When the atmosphere becomes more stable, which is usual at night when there is a partial clear sky and a light to moderate wind (at ground level), there is an important change in wind profile affecting the performance of a modern, tall wind turbine. The airflow around the blade then changes to less than optimal, resulting in added induced turbulence. This effect is strongest when the blades pass the tower, causing short lasting, higher sound levels at the rate of the blade passing frequency. In a wind park, these pulses can synchronise, leading to still higher pulse levels for an observer outside the park. The resulting repetitive pulses change the character of the wind park sound and must be expected to cause added annoyance.

The presence of high levels of amplitude modulation has been identified with operating wind farms where this character has been described as giving rise to complaints. However, the suggestion by van den Berg that the effect is associated with the passage of the blade in front of the tower is more debateable.

An existing project [32] for which some of the source identification studies have been published [33] provides an indication as to the main sources of aerodynamic noise associated with the operation of wind turbines. Figure 47 below details the identification of the location of the major contribution to the noise measured at a location directly upwind of a Gamesa G52 pitch regulated wind turbine. The data indicates that a significant proportion of the noise heard upwind of the turbine at the measurement location is associated with the downward sweep of the blade as it approaches the observer. Van den Berg showed, within ref 31, that the more dominant audible part of the spectrum at a receptor location lay between 200 – 1600 Hz at the façade of a dwelling.

Figure 47: from Localisation and Quantification of Noise Sources on a Wind Turbine: Oerlemans and Lopez

The data within Figure 47 shows that there is a small effect of the tower at the tip of the blade as it passes the tower, but as the dynamic range of the data is 12 dB, it may be seen that this is not of significance as compared to the downward movement of the blade.

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[31] Do wind turbines produce significant low frequency sound levels?: 11th International Meeting on Low Frequency Noise and Vibration and its control: Maastricht, The Netherlands:

[32] SIROCCO, Silent Rotors by Acoustic Optimisation (ENK5-CT-2002-00702) part funded by the European Commission's Fifth Framework Programme and by Netherlands Organisation of Energy and the Environment.

[33] Localisation and Quantification of Noise Sources on a Wind Turbine: Oerlemans and Lopez: First International Meeting on Wind Turbine Noise: Perspectives for Control: Berlin 17th – 18th October 2005.

The movement of the observer relative to the hub of the turbine will result in the movement of the dominant location of the sound heard at the observer position. Figure 48 provides an indication as to how the noise moves in the described disk with a movement off-axis from directly upwind of the turbine. It may be seen that a shift to the right, when looking at the wind turbine from an upwind location (ÿ = +11°) results in the dominant noise source location moving upwards, whereas a movement to the left, (ÿ = -12°), results in a movement of the dominant noise source location downwards.

Figure 48: from Localisation and Quantification of Noise Sources on a Wind Turbine: Oerlemans and Lopez

However, from which ever location the noise is observed from there is no clearly discernable effect caused by the tower/blade interaction. This indicates that the noise is being generated by the trailing edge of the wind turbine blade and that the observed movement of the dominant source location with movement on the ground indicates that the directivity of the noise generated at the blade accounts for this effect.

Movement of the observer up to the same height as the hub of the turbine should result in the noise being more evenly distributed around the described disk of the rotor. In these circumstances, the effect of the tower/blade interaction may be greater. However, a similar effect can be obtained through movement away from a wind turbine which reduces the modulation of the noise. If blade/tower interactions were the dominant source of this increased modulation noise, then it might be expected that more wind farms would experience this effect and significantly more complaints might be expected as a result.

Within a more recent paper [34], van den Berg relates this increase in modulation to increased wind shear during stable atmospheric conditions. However, the presence of high levels of modulation at Site 1: Location 1 is associated with wind direction and the inappropriate aerodynamic conditions seen by the closest three wind turbines to the dwelling. Van den Berg has described a potential means by which aerodynamic modulation may occur, but measurements reported within ref 33 do not necessarily support this argument. In an attempt to determine whether such an effect is measurable, the authors of ref 33 have been contacted to assess whether any data was collected during stable atmospheric conditions and for conditions where high yaw error may exist for the wind turbine. It is reported that little data was collected during the night when stable atmospheric conditions may be expected to occur with limited data collected during the evening when such conditions may be expected to start to appear [35]. As the analysis for these specific atmospheric conditions did not form part of the original study no analysis has been performed to date. However, it might be expected that an acoustic array would allow identification of effects such as blade/tower interactions to be identified.

Measurements reported within ETSU W/13/00391/REP *Wind turbine measurement for noise source identification* [36] provides

[34] The Beat is Getting Stronger: The Effect of Atmospheric Stability on Low Frequency Modulation Sound of Wind Turbines: G.P. van den Berg: Journal of Low Frequency Noise, Vibration and Active Control

[35] Personal communication with Oerlemans

[36] Wind Turbine Measurements for Noise Source Identification: ETSU W/13/00391/REP: Flow

an evaluation of blade swish. Within the Executive Summary the following is stated with respect to investigations into blade swish.

Blade Swish
Frequencies below the 250 Hz octave band do not show modulation. Modulation is sometimes seen in the 500 Hz octave band, with typical peak to peak amplitude of 1 to 2 dB. Modulation is most marked in the 1 kHz and 2 kHz octave bands where a typical peak to peak modulation is 2 to 4 dB, but maximum modulations of 10 dB are sometimes seen.
Modulation of noise in the 1 kHz is not strongly correlated with wind speed. The 2 kHz band exhibits a stronger correlation, but this correlation usually decreases with increasing wind speed at a rate of approximately 0.5 dB (A)/m/s. No significant correlation of modulation with either wind profile exponent or turbulence intensity had been identified.
Modulation of noise in both the 1 kHz and 2 kHz octave bands are significantly correlated with yaw error, at up to approximately 1 dB per 10 degree of yaw error.
The effects of blades passing the tower and preferential directional noise radiation have been modelled theoretically and the results compared with the experimentally observed results. However, the predicted modulation is both cases was lower than the measured level. The analysis suggests that the experimentally observed modulation is due to a combination of tower shadow effects as the blades pass the tower plus the preferential radiation of noise into some directions in preference to others.

The reference to the tower shadow effects is related to the shielding of the measurement locations from the aerodynamic blade noise as the blade passes behind the tower when observed from the noise measurement position, i.e. it is described as a shielding effect and not a blade/tower aerodynamic interaction as described by van den Berg. The type of turbine which was considered for this ETSU study, a Windane/Vestas W34 400kW, is a relatively small turbine as compared to those which have been considered by van den Berg and it may be expected that wind shear effects during atmospheric conditions for such a turbine are considerably less than those found for tall, larger wind turbines.

Therefore, there are a number of potential mechanisms which may be the cause of these high levels of aerodynamic modulation. Whatever the cause of this character to the noise, it should be considered that there is a risk of its occurrence for sites where stable atmospheric conditions may occur at night.

ETSU-R-97 Noise Criteria

Planning Policy Statement 22: Renewable Energy [37], issued in 2004, identifies the document ETSU-R-97 *The assessment and rating of noise from wind farms* [38] as the appropriate method for the assessment of noise from wind turbines. Paragraph 22 of the PPS22 states the following with respect to renewable energy developments:

Noise
22. Renewable technologies may generate small increases in noise levels (whether from machinery such as aerodynamic noise from wind turbines, or from associated sources – for example, traffic). Local planning authorities should ensure that renewable

Solutions Ltd, Hoare Lea & Partners Acoustics: Renewable Energy Systems Ltd.: 1999

[37] Planning Policy Statement 22: Renewable Energy: 2004

[38] The assessment and rating of noise from wind farms: ETSU-R-97: Sept 1996

energy developments have been located and designed in such a way to minimise increases in ambient noise levels. Plans may include criteria that set out the minimum separation distances between different types of renewable energy projects and existing developments. The 1997 report by ETSU for the Department of Trade and Industry should be used to assess and rate noise from wind energy development.

The guidelines within ETSU-R-97 have also been adopted within PAN45 [39] and TAN8 [40] issued by the Scottish Executive and the National Assembly for Wales, respectively.

The Companion Guide to PPS22 [41], within The Technical Annex: Section 8 Wind, considers the issue of wind farm noise at paragraphs 41 – 46. It clearly indicates that the method described within ETSU-R-97 should be considered as "*Recommended good practice on controlling noise from wind turbines*". This method provides a means by which the noise from a wind farm may be assessed that offers a reasonable degree of protection to wind farm neighbours. However, the method does not mean that wind turbines are inaudible at neighbouring properties nor, for certain circumstances, inaudible within a neighbouring dwelling.

Separate noise limits are applied for daytime and night-time. ETSU-R-97 indicates that the purpose of these different noise limits is that for night-time periods, the emphasis is on the prevention of sleep disturbance, whereas, the daytime noise limits are to protect the amenity value of the area and of a property in particular.

The noise limits take the form of a fixed level for periods when background L_{A90} noise levels are very low and a margin above the background once background noise levels increased due to wind effects. The amenity hour' s noise criterion is defined as "the greater of 35 – 40 dB L_{A90} or background + 5 dB " and for the night-time period "the greater of 43 dB L_{A90} or background + 5 dB".

In general, the occupants of Site 1: Location 1 and Site 3: Location 1 & 2 have described wind farm noise as being most intrusive within the dwellings during the night-time or early morning periods. The occupants have also indicated that the amplitude modulation of the aerodynamic noise is a character that draws their attention to the noise and which makes it readily identifiable when heard within an internal living space. The levels of external noise when the wind farms were considered to give rise to audible noise within the dwellings and specifically identified by the occupants ranged as follows:

Site 1: Location 1: 38.5 – 41.0 dB $L_{Aeq, 10 minute}$: 36.3 – 38.7 dB $L_{A90, 10 minute}$

Site 2: Location 1: 37.5 – 40.2 dB $L_{Aeq, 10 minute}$: 36.2 – 38.1 dB $L_{A90,10 minute}$

Site 3: Location 1: 40.4 – 45.5 dB $L_{Aeq, 10 minute}$: 39.0 – 39.8 dB $L_{A90, 10 minute}$

Irrespective of the existing background noise level at the time of the measurements, the external noise levels associated with the operation of the wind turbines meets the requirements of ETSU-R-97 for night-time operations, i.e. noise levels are lower than 43 dB L_{A90}. However, the current situation

[39] Planning Advice Note 45: Renewable Energy: January 2002: Scottish Executive

[40] Technical Advice Note 8: Planning for Renewable Energy: 2005: National Assembly for Wales

[41] Planning for Renewable Energy: A Companion Guide to PPS22: 2004

which has not taken account of any distinguishing characteristics within the incident noise at the properties has given rise to complaints associated with noise disturbing the occupants of the neighbouring dwellings.

ETSU-R-97 has considered the issue of blade swish/aerodynamic modulation and this is summarised within the Executive Summary as follows:

27. The noise levels recommended in this report take into account the character of noise described as blade swish. Given that all wind turbines exhibit blade swish to a certain extent we feel this is a common-sense approach given the current level of knowledge.
Page X of Executive Summary to ETSU-R-97

Within the discussion of Blade Swish (page 68 ETSU-R-97), the following is stated:

The modulation or rhythmic swish emitted by wind turbines has been considered by some to have a characteristic that is irregular enough to attract attention. The level and depth of modulation of the blade noise is, to a degree, turbine-dependent and is dependent upon the position of the observer. Some wind turbines emit a greater level of modulation of the blade noise than others. Therefore, although some wind turbines might be considered to have a character that may attract one's attention, others have noise characteristics which are considerably less intrusive and unlikely to attract one's attention and be subject to any penalty.

This modulation of blade noise may result in a variation of the overall A-weighted noise level by as much as 3 dB(A) (peak to trough) when measured close to a wind turbine. As distance from the wind turbine/wind farm increases, this depth of modulation would be expected to decrease as atmospheric absorption attenuates the high frequency energy radiated by the blade. However, it has been found that positions close to reflective surfaces may result in an increase in the modulation depth perceived at a receiver position remote from a site. If there are more than two hard, reflective surfaces, then the increase in modulation depth may be as much as ± 6 dB(A) (peak to trough).
Page 68: ETSU-R-97

The level of external noise modulation which has been measured at the façade of Site 1 and in free-field conditions at Site 2 indicate a peak to trough depth of 3 – 5 dB(A) and individual third octave band modulated levels of 6 – 10 dB. These levels are indicative of the level of modulation which is discerned within the dwellings which range from 5 – 6 dB at Site 1: Location 1 and 4 – 6 dB at Site 2: Location 1 for the third octave bands between 315 – 800 Hz. The depth of modulation of the overall A-weighted sound pressure levels range between 2 – 3 dB(A), however, this measured depth of modulation may be limited by the noise floor of the measuring equipment and other internal noise sources within the dwellings.

This measured level of modulation is greater than that expected or assumed within ETSU-R-97 for the derivation of the noise criteria suggested within the document. In these specific, high modulation conditions, the application of a penalty for the character of the noise may be appropriate. British Standard 4142:1997 [42] *Method for Rating industrial noise affecting mixed residential and industrial areas* advises in paragraph 8.2 the following:

Apply a 5 dB correction if one or more of the following features occur, or are expected to be present for new or modified noise sources:
the noise contains a distinguishable, discrete continuous note (whine, hiss, screech, hum, etc.);
the noise contains distinct impulses (bangs, clicks, clatters, or thumps);

[42] BS 4142:1997 Method for Rating industrial noise affecting mixed residential and industrial areas: BSi 1997

the noise is irregular enough to attract attention;

During periods of high modulation of the aerodynamic noise which occur during the night-time period when the potential for stable atmospheric conditions is greatest, then it may be appropriate to consider the application of a 5 dB penalty to the incident noise from the assessed wind farms.

Van den Berg has indicated that during normal daytime neutral atmospheric conditions, the predicted modulation of aerodynamic noise will be little different from that assumed within ETSU-R-97. In these circumstances, unless high levels of modulation occur, there is no need to consider the potential for this character for a daytime noise assessment. However, during the night-time periods when high levels of modulation have been measured, it may be appropriate to apply a 5 dB penalty to the incident noise from the wind farms. This would bring the assessed rated noise levels associated with the three wind farms at which measurements have been made to lie between 41.2 – 44.8 dB L_{A90}. For Sites 1 & 2, the assessed level of wind farm noise, even with the application of this penalty, would result in the wind farm noise meeting the requirements for night-time operation outlined within ETSU-R-97. It is clear from the occupants of the dwellings at Sites 1 & 2 that such a situation would still be considered unacceptable.

Measured internal noise levels for the same measurement periods detailed above are as follows:

Site 1: Location 1: 22.7 – 24.6 dB $L_{Aeq,\ 10\ minute}$: 21.8 – 22.5 dB $L_{A90,\ 10\ minute}$

Site 2: Location 1: 27.6 – 36.7 dB $L_{Aeq,\ 10\ minute}$: 25.9 – 30.1 dB $L_{A90,10\ minute}$

Site 3: Location 1: 42.5 – 53.1 dB $L_{Aeq,\ 10\ minute}$: 41.6 – 42.0 dB $L_{A90,\ 10\ minute}$

The internal noise levels which have been measured within the living spaces indicate the differences between the locations, window conditions (open or shut) and microphone locations. Site 1: Location 1 is within a double glazed conservatory with no windows open, Site 2: Location 1 is within a room with windows open, and Site 3: Location 1 is within a room with windows open with the internal measurement location having a direct line of sight down to the stream in the valley below and the microphone placed within 0.3 m of the open window. In fact, due to the direct line of sight, internal noise levels at Site 3: Location 1 were generally 3 dB higher than the external noise levels due to water noise from the neighbouring stream.

When windows are closed within Site 2: Location 1, the internal noise levels when the wind turbines were operating was reduced to 22.1 – 24.2 dB $L_{Aeq,\ 10\ minute}$ and 20.7 – 22.9 dB $L_{A90,\ 10\ minute}$. This is a level comparable with that found at Site 1: Location 1. The noise floor of the measuring systems used for these measurements is estimated to lie between 12 – 16 dB(A) as they incorporated the use of a GRAS 40EN low noise microphone (self noise=9.6 dB(A)) and a GRAS Preamplifier Type 26AK-S1 (A-Weighted noise floor < 2.5μV) giving an estimated noise floor of 14.8 dB(A). During periods of no wind and with windows closed and the dwelling empty, noise levels as low as 12 dB(A) were measured within Site 2: Location 1.

The averaged measured noise reduction from free-field A-Weighted to internal “free-field” A-Weighted sound pressure levels was found to be as follows:

Site	Location	Window Closed	
		Level Difference	Std Dev.
1	1	15.5	0.6
2	1	14.5	0.4

Table detailing measured A-weighted level difference

These calculated level differences may be compared with the suggested insertion losses within PPG24 [43] and PAN 56 [44](10 – 15 dB for an open window) and the assumed 15 dB reduction within WHO Guidelines for Community Noise.

The levels measured at Site 1: Location 1 indicate that, even with windows closed, that this level of performance is just achieved. Measurements at Site2: Location 1 indicate that with windows wide open, a level reduction of 10 dB(A) is achieved and 14.5 dB(A) with windows closed.

An assessment of the low frequency performance of the two structures was undertaken which indicates that Site 1: Location1 increases at a relatively constant insertion loss with increasing frequency, with an average insertion loss of 2.8 dB at 20 Hz rising to 18.8 dB at 500 Hz. Whereas the performance at Site 2: Location 1 indicates a rapid increase in the insertion loss from 20 HZ (12.7 dB) up to 24.4 dB at 31.5 Hz., and then a levelling off with a small dip between 100 – 250 Hz. This dip is associated with the resonant effects of the building (i.e. room modes, glazing panel resonance) and the coincidence dip due to the reflected wave off the ground for the external measurement location, which results in a reduction of the measured levels at 200 – 250 Hz.

[43] Planning Policy Guidance 24: Planning and Noise: PPG24: ODPM

[44] Planning Advice Note: PAN 56 Planning and Noise: April 1999: The Scottish Office

Figure 49: Insertion Loss of Site 1: Location 1: ETSU-R-97 Location to Internal Location

The assessment of the building envelope acoustic performance leads to the following conclusions:

Infrasound

The insignificant levels of infrasound noise emissions associated with the operation of modern, upwind rotor, wind turbines will result in measurable infrasound well below the accepted threshold of perception for such noise;

Low Frequency Noise

The measurements performed at all three sites indicate that low frequency noise is measurable but below the DEFRA Night time Low Frequency Noise Criterion. However, wind turbine noise may result in internal noise levels which are just above the threshold of audibility, as defined within ISO 226. For a low frequency sensitive person, this may mean that low frequency noise is audible within a dwelling. At all the measurement sites, low frequency noise associated with traffic movements has been found to be greater than that from the neighbouring wind farms and for one location, traffic noise was the noise which woke a sleeping resident.

Aerodynamic Modulation

The common cause of complaints associated with wind turbine noise is the audible modulation of the aerodynamic noise, especially at night. Although the internal noise levels associated with this noise source are not high enough to result in the awakening of a resident, once awoken the audibility of this noise results in difficulties in returning to sleep. The WHO *Guidelines for Community Noise* indicate internal noise levels that will protect against sleep disturbance, with levels of 30 dB L_{Aeq}

Figure 50: Insertion Loss for Site 2: Location 1: ETSU-R-97 Location to Internal Location

(continuous) and 45 dB L_{Amax} for single noise events being proposed. The WHO also state that:

Lower noise levels may be disturbing depending upon the nature of the noise source.

Internal noise levels within the dwellings at which measurements have been performed indicate that internal levels of 22.7 – 24.6 dB L_{Aeq} (Site 1: Location 1) and 27.6 – 36.7 dB L_{Aeq}, (Site 2: Location 1) gave rise to complaints.

If one takes the guidance within the WHO for the protection against sleep disturbance of 30 dB L_{Aeq}, and apply a 5 dB correction for the presence of high levels of modulation within the incident noise, then this gives rise to an internal noise criterion of 25 dB L_{Aeq}. Based upon the measured building attenuation performances at Site 1 & 2, then an external level between 35 – 40 dB L_{Aeq} (33 - 38 dB L_{A90}) would provide sufficient protection to neighbouring occupants to minimise the risk of disturbance from the modulation of the aerodynamic noise.

Implications to ETSU-R-97 Night-time Criterion

The internal noise level measurements, even when wind turbine noise is audible within a bedroom, falls in the range 22 – 24 dB L_{Aeq} with windows closed. With windows open, this rises top 27 – 29 dB L_{Aeq}. This indicates that internal noise associated with the wind farms is below the sleep disturbance threshold proposed within the WHO Guidelines.

The recordings of wind farm noise indicate that this noise does not result in the awakening of the neighbours to the developments; other noise sources are the cause of this. However, once awake, it is found that returning to sleep is more problematic. If the sound also contains an acoustic character which attracts attention of the listener, then returning to sleep becomes a greater problem to the individual.

The increased period of returning to sleep of a room occupant is not a direct effect of the noise levels which are in themselves very low, but a response to the noise by the occupant. This response to the noise is what prevents a person falling asleep. Some help to occupants may be provided by the development of coping strategies for such situations where wind farm noise is audible. One of the potential subject dwellings which were considered within the potential list of original wind farms which were considered for this study had developed such a strategy to distract them from the noise when audible within a bedroom at night. To avoid reducing or removing the benefits of this coping strategy, measurements were not performed at this location following discussion with Dr Geoff Leventhall.

The presence of high levels of amplitude modulation is not associated with all wind farms or all wind turbines. However, some wind farms clearly result in modulation at night which is greater than that assumed within the ETSU-R-97 Guidelines. Furthermore, the basis of the ETSU-R-97 external night-time guidelines it to protect the processes of sleep with an internal noise level limit not to exceed 35 dB L_{Aeq}. Such an internal noise level could be anywhere between 5 – 10 dB higher than the existing internal noise environment within an occupied bedroom at night, i.e. clearly audible to the average listener who is awake.

The measured external noise levels during the high modulation conditions ranged between 36 – 40 dB L_{A90}. If an incident noise is not subject to high levels of amplitude modulation, then internal noise levels will range between 20 – 30 dB L_{A90}, (for a 10 – 15 dB insertion loss from outside to inside). However, if the noise does contain a high level of modulation, then the "rated" internal level will range between 25 – 35 dB $L_{A90,r}$, equivalent to 27 – 37 dB $L_{Aeq,\ r}$. In the worst-case a reduction in the external criterion level by 7 dB would ensure that 30 dB $L_{Aeq,r}$ is not exceeded with windows open.

The current ETSU-R-97 Night-time Absolute Noise Criterion is a level of 43 dB L_{A90}, equivalent to 45 dB L_{Aeq}. A reduction of 7 dB(A), to 38 dB L_{Aeq} (36 dB L_{A90}) will, on the basis of the measurements, give rise to an internal noise environment of less than 30 dB L_{Aeq}, with windows open and with a 5 dB acoustic feature correction for high levels of aerodynamic modulation. Actual internal noise levels will range up to 25 dB L_{Aeq}, which is close to the unoccupied internal noise levels within the dwellings. Even so, with windows open and during periods of high aerodynamic modulation, there is still the potential for this noise to be heard but at a greatly reduced level. With windows closed, it should be expected that wind farm noise is likely to be reduced to close to inaudibility for a majority of the time.

The risk of high levels of aerodynamic modulation is believed to be greatest for sites where stable atmospheric conditions occur or where high levels of wind shear exist at a site. In general, this is likely to occur at flatter sites to be found in the UK, i.e. the eastern side of England for example. Site specific effects in hillier terrain, due to topographical effects, might also result in such modulation.

This discussion indicates that it may be appropriate to re-visit the issue of the absolute night-time noise criterion specified within ETSU-R-97. To provide protection to wind farm neighbours, it would seem appropriate to reduce the absolute noise criterion for periods when background noise levels are low. In the absence of high levels of modulation, then a level of 38 dB L_{A90} (40 dB L_{Aeq}) will reduce levels to an internal noise level which lies around or below 30 dB L_{Aeq} with windows open for ventilation. In the presence of high levels of aerodynamic modulation of the incident noise, then a correction for the presence of the noise should be considered. However, it is beyond the scope of this report to consider the issue of appropriate assessment and acoustic feature correction methodologies for this character within the noise.

Conclusions

A number of clear conclusions may be drawn from the measurements undertaken at the three wind farms.

Infrasound

Infrasound noise emissions from wind turbines are significantly below the recognised threshold of perception for acoustic energy within this frequency range. Even assuming that the most sensitive members of the population have a hearing threshold which is 12 dB lower than the average hearing threshold, measured infrasound levels are well below this criterion, even when the noise is being experienced within the dwellings.

The document "*Community Noise*" prepared for the World Health Organization, states that '*there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects'*.

As a result of this study, infrasound associated with modern wind turbines is not a source which will result in noise levels which may be injurious to the health of a wind farm neighbour.

Low Frequency Noise

The measurements performed at all three sites indicate that low frequency noise is measurable but below the DEFRA Night time Low Frequency Noise Criterion.

When assessed in accordance with the Danish Criterion of $L_{pA,LF}$ = 20 dB, internal levels do not exceed 20 dB when measurements are undertaken within rooms with windows closed.

However, wind turbine noise may result in internal noise levels which are just above the threshold of audibility, as defined within ISO 226. For a low frequency sensitive person, this may mean that low frequency noise is audible within a dwelling. At all the measurement sites, low frequency noise associated with traffic movements have been found to be greater than that from the neighbouring wind farms.

Aerodynamic Modulation

The common cause of complaints associated with wind turbine noise at all three wind farms is the audible modulation of the aerodynamic noise, especially at night. Although the internal noise levels associated with this noise source are not high enough to result in the awakening of a resident, once awoken the audibility of this noise results in difficulties in returning to sleep.

The analysis of the external and internal noise levels indicates that it may be appropriate to re-visit the issue of the absolute night-time noise criterion specified within ETSU-R-97. To provide protection to wind farm neighbours, it would seem appropriate to reduce the absolute noise criterion for periods when background noise levels are low. In the absence of high levels of modulation, then a level of 38 dB L_{A90} (40 dB L_{Aeq}) will reduce levels to an internal noise level which lies around or below 30 dB L_{Aeq} with windows open for ventilation. In the presence of high levels of aerodynamic modulation of the incident noise, then a

correction for the presence of the noise should be considered. However, it is beyond the scope of this report to consider the issue of appropriate assessment and acoustic feature correction methodologies for this character within the noise.

Recommendation

The analysis of internal and external noise levels within dwellings neighbouring wind farms which have been identified as giving rise to problems associated with noise indicate that significant levels of infrasound and low frequency noise were not found. However, the presence of aerodynamic modulation which is greater than that originally foreseen by the authors of ETSU-R-97, particularly during the night hours, can result in internal wind farm noise levels which are audible and which may provoke an adverse reaction from a listener.

To reduce the potential for such situations with future wind turbines, it is recommended that consideration be given to a revision of the night-time absolute noise criterion proposed within ETSU-R-97 and the development of an assessment methodology to take account of periods when high levels of aerodynamic modulation are found at a neighbouring receptor location.