Low Frequency Noise and Annoyance

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Low frequency noise, the frequency range from about 10Hz to 200Hz, has been recognised as a special environmental noise problem, particularly to sensitive people in their homes. Conventional methods of assessing annoyance, typically based on A-weighted equivalent level, are inadequate for low frequency noise and lead to incorrect decisions by regulatory authorities.

There have been a large number of laboratory measurements of annoyance by low frequency noise, each with different spectra and levels, making comparisons difficult, but the main conclusions are that annoyance of low frequencies increases rapidly with level. Additionally the A-weighted level underestimates the effects of low frequency noises.

There is a possibility of learned aversion to low frequency noise, leading to annoyance and stress which may receive unsympathetic treatment from regulatory authorities. In particular, problems of the Hum often remain unresolved.

An approximate estimate is that about 2.5% of the population may have a low frequency threshold which is at least 12dB more sensitive than the average threshold, corresponding to nearly 1,000,000 persons in the 50-59 year old age group in the EU-15 countries. This is the group which generates many complaints.

Low frequency noise specific criteria have been introduced in some countries, but do not deal adequately with fluctuations. Validation of the criteria has been for a limited range of noises and subjects.

Keywords: Noise, low frequency noise, annoyance, subjective efforts, disturbance

Introduction

Low frequency noise, considered as the frequency range from about 10Hz to 200Hz, causes extreme distress to a number of people who are sensitive to its effects. The sensitivity may be a result of heightened sensory response, within the whole or part of the auditory range, or may be acquired. Onset of low frequency noise annoyance tends to occur in middle age. The noise levels are often low, in the region of a subject's hearing threshold, where there are large differences between individuals. The problem arises both in homes and in offices, or similar, premises. Whilst noise sources causing annoyance in the home may be unknown, in offices they are often fans or pumps in the building services. Similar plant, in those apartment blocks which have central services, may be the source of the noise in these premises, but a core of low frequency noise problems remain, of unknown origin, which continue to cause considerable annoyance. Low frequency noise problems also occur in industry, but generally at levels well above threshold, presenting a different noise problem to those in homes and offices.

Attempts to assess low frequency noise by conventional wide-band noise methods often fail, so illustrating the inadequacy of these methods for low frequencies. In particular, the regulatory dominance of A-weighted levels, leads to dismissal of valid problems of low frequency noise, so compounding the difficulties of some complainants

The World Health Organization recognizes the special place of low frequency noise as an environmental problem. Its publication on

Community Noise (Berglund et al., 2000) makes a number of references to low frequency noise, some of which are as follows

"It should be noted that low frequency noise, for example, from ventilation systems can disturb rest and sleep even at low sound levels"

"For noise with a large proportion of low frequency sounds a still lower guideline (than 30dBA) *is recommended"*

"When prominent low frequency components are present, noise measures based on A-weighting are inappropriate"

"Since A-weighting underestimates the sound pressure level of noise with low frequency components, a better assessment of health effects would be to use C-weighting"

"It should be noted that a large proportion of low frequency components in a noise may increase considerably the adverse effects on health"

"The evidence on low frequency noise is sufficiently strong to warrant immediate concern"

Annoyance

The meaning of annoyance

Annoyance has roots in a complex of responses, which are moderated by personal and social characteristics of the complainant. (Belojevic and Jokovljevic, 2001; Benton and Leventhall, 1982; Fields, 1993; Grime, 2000; Guski, 1999; Guski et al., 1999; Kalveram, 2000; Kalveram et al., 1999; Stallen, 1999).

For example, Guski (1999) proposes that noise annoyance is partly due to acoustic factors and partly due to personal and social moderating variables as follows:

Personal Moderators: Sensitivity to noise. Anxiety about the source. Personal evaluation of the source. Coping capacity with respect to noise.
Social Moderators: Evaluation of the source. Suspicion of those who control the source. History of noise exposure. Expectations

Noise annoyance in the home is considered as leading to a long-term negative evaluation of living conditions, dependent on past disturbances and current attitudes and expectations. Annoyance brings feelings of disturbance, aggravation, dissatisfaction, concern, bother, displeasure, harassment, irritation, nuisance, vexation, exasperation, discomfort, uneasiness, distress, hate etc, some of which combine to produce the adverse reaction.

Figure 1, modified from Guski (1999) in order to emphasise the central nature of the personal factors, summarises the interactions. The interpretation of Figure 1 is as follows. The noise load causes activity interference (e.g. to communication, recreation, sleep), together with vegetative reactions (e.g. blood pressure changes, defensive reactions). Interference with activity develops into annoyance and disturbance. Prolonged vegetative reactions may lead to effects on health. The personal factors interact with the outer boxes of Figure 1, moderating the complainant's complex of responses. The social factors moderate how the complainant interacts with external authorities in attempting to deal with the annoyance. Social factors may also interact with health effects, as some social classes may more readily seek medical assistance. The personal and social moderating factors are so variable that Grime (2000) questions the feasibility of developing a national noise policy.

Annoyance and the "meaning" of noise

Kalveram (2000) points out that much psychoacoustical noise research has limitations, because it is based upon the correlation between annoyance ratings and physical measurements of sound energy, often equivalent level, leading to noise dose. But equivalent level, A-weighted or linear, is only a part of the total process. Noise level and noise dose approaches neglect the "meaning" of a noise and are contrary to the interactive model in Figure 1. The noise level / noise dose assessment reduces Figure 1 to Figure

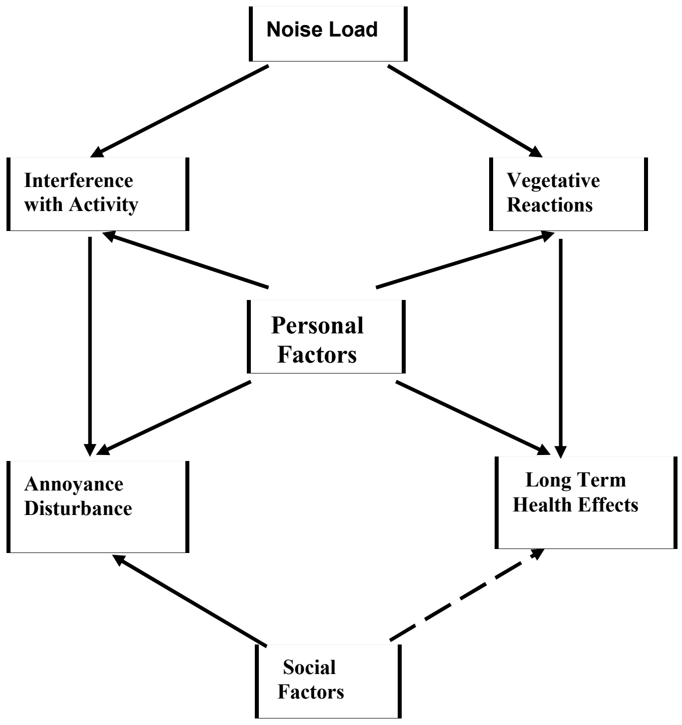

Figure 1. Factors moderating noise annoyance

2, in which the personal factors are constrained to those of the average person, so that only a limited number of subjects are protected by criteria which are developed from the assessment.

Kalveram proposes an "ecological" approach, which emphasises the psychological functions of sounds. Annoyance originates from acoustical signals which are not compatible with, or which disturb, these psychological functions. In particular, disturbance of current activities is a primary effect of noise exposure, producing a potential loss of fitness in the subject with respect to those behaviour patterns which permit coping with changes in the environment. Presence of a harmful sensory variable in the environment leads to actions which interrupt current behaviour, in an attempt by the subject to reduce the sensory input. This tests the coping capacity of the individual.

Those who have experienced long-term exposure to low frequency noise may recognise this within themselves. However, a few persons are known to have modified their responses to low frequency noise, thereby removing it from the category of a challenge and threat.

Most field work on noise annoyance has been where there is a known source, for example air or road transport. The particular circumstances of some low frequency noise problems, where the noise source is not known, adds an additional element to annoyance. Those affected suffer extreme frustration and may find it necessary to assume a source, thus enabling themselves to cope through provision of a focus for anger and resentment. Assumed sources have included neighbours, gas pipelines, radio transmissions and defence establishments.

Annoyance Measurements

Annoyance measurements are generally of the type described by Kalveram (2000), an attempt to relate annoyance ratings directly to measured noise levels. As described above, these measurements are limited in their results, since they deal with only part of the annoyance complex.

Laboratory determinations

There have been a large number of laboratory determinations of annoyance of low frequency sounds, mainly measurements using either 'normal' or 'sensitive' subjects. Stimuli have included tones, bands of noise or specially

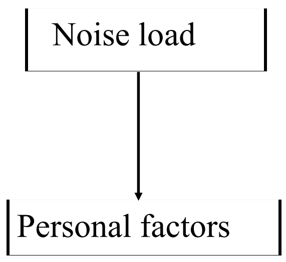

Figure 2. Noise dose interaction

developed spectra. There is, of course, a wide range of possible stimuli, which experimenters have chosen according to their experience of what is required (Adam, 1999; Andresen and Møller, 1984; Broner and Leventhall, 1978; Broner and Leventhall, 1984; Broner and Leventhall, 1985; Goldstein, 1994; Goldstein and Kjellberg, 1985; Inukai et al., 2000; Kjellberg and Goldstein, 1985; Kjellberg et al., 1984; Møller, 1987; Nakamura and Inukai, 1998; Persson and Bjorkman, 1988; Persson-Waye, 1985; Poulsen, 2002; Poulsen and Mortensen, 2002). Some of the laboratory studies have used recordings of real noises as stimuli, whilst others have worked with recordings of the actual noises as experienced by subjects in their own work places or homes. (Holmberg et al., 1993; Landström et al., 1994; Manley et al., 2002; Mirowska, 1998; Mortensen and Poulsen, 2001; Poulsen and Mortensen, 2002; Tesarz et al., 1997; Vasudevan and Gordon, 1977; Vasudevan and Leventhall, 1982).

Most determinations have been aimed at relating the A-weighted level, or some other derivative of the spectrum of the low frequency noise, to its annoyance. Whilst they are adequate studies, and have shown some general factors in low frequency noise annoyance, they are limited in that their results apply only to the particular noises investigated, often with a small number of subjects. It is unlikely that continued studies of this kind will result in step changes in our understanding of low frequency noise annoyance. However, Poulsen and Mortensen (2002) are an advance on previous work, as they compare subjective assessments with criteria, which have been developed in some European countries, specifically for assessment of low frequency noise.

Experimental methods

The responses required from subjects vary with experimental method. In laboratory investigations, subjects may be asked to "“imagine” themselves relaxing in their homes in the evening and to rate annoyance by, for example, choice on a semantic scale ranging from ‘Not Annoying’ to ‘Extremely Annoying’. Other methods include marking the level of annoyance on an unnumbered linear scale at a point between ‘Not at all annoying’ and ‘Very annoying’, or assigning a number to a reference noise and appropriate numbers to other noises in order to estimate their magnitudes. These psychological techniques are well established, but need care in their performance, as they are sensitive to experimental factors.

Equal annoyance contours

The main results of this work are as follows. Møller (1987) investigated contours of equal annoyance for pure tones in the frequency range 4Hz to 31.5Hz. The annoyance contours are influenced by the narrowing of the range of equal loudness contours at low frequencies. Møller’s results are shown in Figure 3. The vertical scale is the annoyance rating in terms of the distance marked for the tone along a 150mm linear scale. The lowest frequencies must be at a higher level than other frequencies in order to become audible but, once they are audible, their annoyance increases rapidly. For example, the scale rating range at 4Hz is about 10dB between extremes of annoyance. 8Hz and 16Hz have a 20dB range, whilst 31.5Hz has nearly 40dB range. The 1000Hz comparison, which is for an octave band of noise, has a range of nearly 60dB. These findings are important, as they confirm that the hearing contours are reflected in annoyance, although loudness and annoyance are not necessarily the same. Figure 3 gives averages for 18 subjects with normal hearing.

Individual annoyance functions

Broner and Leventhall (1978) measured individual annoyance functions for 20 subjects using ten low frequency noise stimuli. The

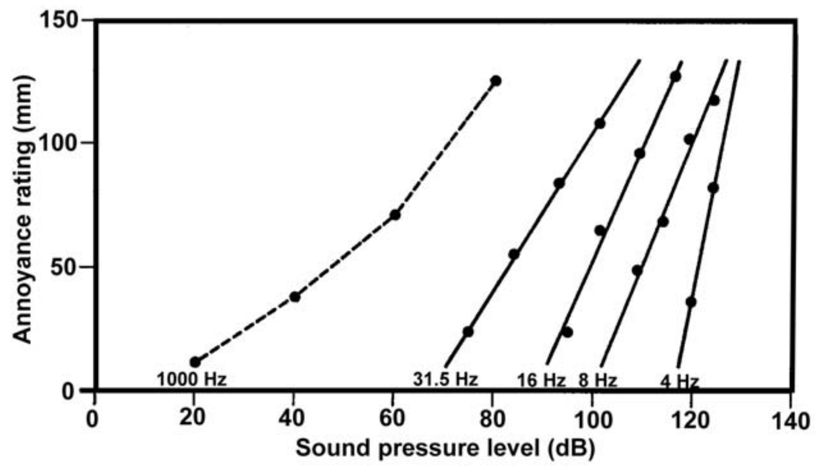

Figure 3. Annoyance rating, showing rapid growth at low frequencies

psychophysical function was assumed to be a simple power function

$$\psi = k\varepsilon^{\beta}$$

Where ψ represents the estimation of psychological magnitude, ε is the stimulus intensity and β a subject-specific exponent. It was shown that there was a wide range of individual exponents, β, from a low of 0.045 to a high of 0.4 and three groupings of individual differences were identified. Previous work at higher frequencies had also shown individual loudness functions (Barbenza et al., 1970) and had posed the question of whether one set of regulations should be applied to all people (Bryan and Tempest, 1973).

Annoyance and the dBA

A comparison of a band of noise peaking at 250Hz with a band peaking at 100Hz, whilst both were adjusted to the same A-weighted level, showed that the annoyance from the low frequency noise was greater than that from the higher frequency noise at the same A-weighted level (Persson et al., 1985) . This work was subsequently extended (Persson and Bjorkman, 1988; Persson et al., 1990) using a wider range of noises, for example, peaking at 80Hz, 250Hz. 500Hz and 1000Hz, leading to the following conclusions:

* There is a large variability between subjects.

*The dBA underestimates annoyance for frequencies below about 200Hz.

For broadband low frequency noise, the underestimate was found to be 3dB for levels around 65dB(Linear) and 6dB for levels around 70dB(Linear). Similar results had been obtained in earlier work (Kjellberg et al., 1984). Two broadband noises were investigated, in which one was dominated by energy in the 15-50Hz range. Twenty subjects compared the two noises within the dynamic range 49-86dBA. At equal A-weighted levels, the noise dominated by the low frequency component was perceived as 4-7dB louder and 5-8dB more annoying.

The energy input to the subjects was, of course, greater for the low frequency noises due to the attenuating effect of A-weighting, and it might be expected that there would be a greater effect, perhaps suggesting that loudness, assumed related to the A -weighting, differs from annoyance at low frequencies.

Unpleasantness

The "unpleasantness" of low frequency noise has also been estimated (Inukai et al., 2000; Nakamura and Inukai, 1998). Nakamura and Inukai used a stimulus sound of a pure tone in 20 conditions from 3Hz to 40Hz and sound pressure levels from 70dB to125dB, with evaluation by 17 subjects. There were four main subjective factors in response to low frequency noise: auditory perception, pressure on the eardrum, perception through vibration of the chest and more general feeling of vibration. Analysis of the responses showed that auditory perception was the controlling factor. That is, although high levels of low frequency noise may produce other sensations, the ear is the most sensitive receptor.

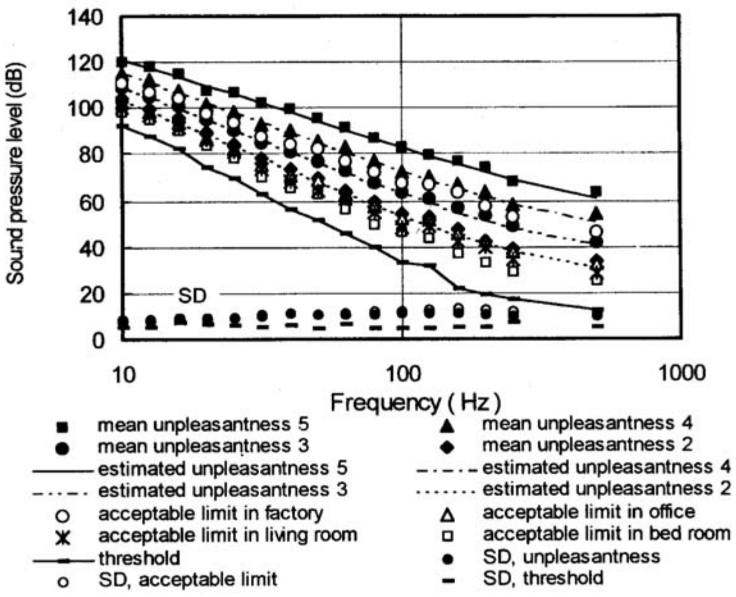

Figure 4. Equal unpleasantness contours and acceptable limits (Inukai)

Inukai et al (2000) determined "equal unpleasantness" contours for 39 subjects over a tone frequency range of 10Hz to 500 Hz. A verbal scale was used ranging through: *Not at all unpleasant (1) - somewhat unpleasant (2) – unpleasant(3) – quite unpleasant(4) – very unpleasant(5)*. Subjects in a test chamber were asked to assume different home and work situations and adjust the level of a tone to match a level on the scale, as requested by the experimenter. For example if instructed to match to level 4 (*quite unpleasant*), subjects would adjust the tone until they judged that this level was reached. Results are shown in Figure 4. The numbers 1,2,3,4,5 refer to the unpleasantness level. All levels of unpleasantness are approximately linear with a negative slope of 5 - 6dB per octave. The acceptable limits for different locations are all above the hearing threshold in this laboratory setting. For example, the self-adjusted acceptable limit in an assumed bedroom is more than 10dB above threshold, but this might not be replicated for long term exposure at night in a real bedroom.

Spectrum balance

The work by Inukai et al (2000) was for single tones. Spectrum balance has also been considered a factor in noise annoyance of a wideband spectrum. Correlation of a number of complaints with the corresponding spectra (Bryan, 1976) led to the conclusion that, for spectra which averaged as shown in Figure 5, a fall off above 32Hz of 5.7dB/octave was acceptable, whilst a fall off from 63Hz at 7.9 dB/octave was unacceptable. Work on acceptable spectra of air conditioning noise in offices led to similar conclusions (Blazier, 1981). Blazier found that, on average, acceptable office environments had a fall off of 5dB/octave. An excess of low frequency noise led to rumble, an excess of mid frequency noise led to roar, whilst an excess of high frequency noise led to hiss. Later work (Blazier, 1997) developed a "Quality Assessment Index" for an HVAC noise through the balance of low, mid and high frequencies.

(dBC – dBA) weighting.

The difference between C- and A-weightings has also been considered as a predictor of annoyance (Broner, 1979; Broner and Leventhall, 1983; Kjellberg et al., 1997), as this difference is an indication of the amount of low frequency energy in the noise. If the difference is greater than 20dB, there is the potential for a low frequency noise problem. Kjellberg et al used existing noise in work places (offices, laboratories, industry etc) with 508 subjects. Three sub- groups were obtained with a maximum difference in low and high frequency exposure. The conclusions on correlations of (dBC – dBA) difference and annoyance were that the difference is of limited value, but, when the difference exceeds 15dB, an addition of 6dB to the A-weighted level is a simple rating procedure. However, the difference breaks down

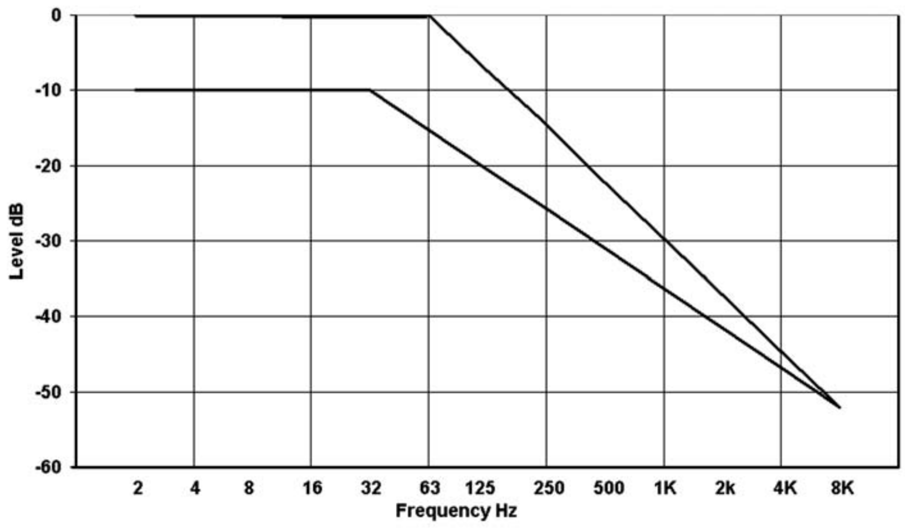

Figure 5. Acceptable and unacceptable spectrum slopes

when the levels are low, since the low frequencies may then be below threshold. The (dBC – dBA) difference cannot be used as an annoyance predictor, but is a simple indicator of whether further investigations may be necessary.

Home and work environments

Other studies, have assessed low frequency noise in real or assumed work environments or in the home (Bryan, 1976; Cocchi et al., 1992; Holmberg et al., 1997; Holmberg et al., 1993; Holmberg et al., 1996; Landström et al., 1993; Landström et al., 1994; Lundin and Ahman, 1998; Mirowska, 1998; Vasudevan and Gordon, 1977; Vasudevan and Leventhall, 1982).

Homlberg et al (1996 and 1997) assessed noise in real environments. The 1996 paper compared responses of about 240 subjects with the noise measures which might be available on a sound level meter i.e. dBLIN, dBA, dBB, dBC and dBD and the difference (dBC-dBA). Additionally, Zwicker loudness (ISO532, 1975) and Low Frequency Noise Rating (LFNR) (Broner and Leventhall, 1983) were calculated. There was poor correlation between the sound level meter weightings and annoyance. Similarly, the loudness in sones and the difference (dBC – dBA) did not correlate well.

The LFNR did separate out annoying and not annoying noises, but no more effectively than the (dBC – dBA).

Level variations

Holmberg et al (1997) investigated noise in workplaces, using the (dBC – dBA) difference as an indicator. Low frequency noise exposure was found in a group of 35 out of a total of 337 persons. Measurements of temporal variation of the levels of low frequency noise at the workplaces, averaged over 0.5, 1.0 or 2.0 seconds, was correlated with subjective annoyance. Significant correlation was found between the irregularity of the noise levels and annoyance.

This work represents an advance, in that it shows the importance of fluctuations in noise level. A limitation of much work on assessment of low frequency noise has been that long term averaged measurements were used and, consequently, information on fluctuations was lost, although complaints of low frequency noise often refer to its throbbing or pulsing nature. Broner and Leventhall(1983) had noted the importance of fluctuations and suggested a fluctuation penalty of 3dB in the Low Frequency Noise Rating Assessment. The importance of fluctuations has also been assessed in laboratory experiments (Bradley, 1994). Subjects listened first to steady wideband noises which peaked at 31.5Hz and adjusted the overall level of these to be equally annoying to a reference spectrum which fell at 5dB/octave. It was found that the more prominent the low frequency noise, the greater the reduction in level required for equality of annoyance with the reference spectrum. The test spectra were now amplitude modulated, in the low frequency region only, at modulation frequencies of 0.25, 0.5, 1.0, 2.0 and 4.0Hz and depths of 10dB and 17dB. Subjects again adjusted the level of the noises to produce equal annoyance with the unmodulated reference noise. The reductions varied with modulation frequency and modulation depth. An example is that, for the highest modulation depth at 2.0Hz modulation frequency, the level was reduced by 12.9dB averaged over the subjects. This work confirms the importance of fluctuations as a contributor to annoyance, and the consequent limitation of those assessment methods which do not include fluctuations .

Field investigations

Vasudevan and Gordon (1977) carried out field measurements and laboratory studies of persons who complained of low frequency noise in their homes. A number of common factors were shown:

* The problems arose in quiet rural or suburban environments
* The noise was often close to inaudibility and heard by a minority of people
* The noise was typically audible indoors and not outdoors
* The noise was more audible at night than day
* The noise had a throb or rumble characteristic
* The main complaints came from the 55-70 years age group
* The complainants had normal hearing.
* Medical examination excluded tinnitus.

These are now recognised as classic descriptors of low frequency noise problems.

Further work in the laboratory showed that gradually falling spectra, as measured in the field and simulated in the laboratory, possessed a rumble characteristic. Figure 6 compares a measured noise on the left with a simulated noise on the right. Both fell at 7 – 8 dB/octave and had similar rumble characteristics. It is also known that a rapidly falling spectrum, such as one which follows the curve of the NR or NC ratings has an unpleasant quality. This was one reason for the development of the PNC rating as an improvement of the NC rating (Beranek et al., 1971). Further work (Vasudevan and Leventhall, 1982), confirmed that levels close to threshold caused annoyance, which increased if the noise also fluctuated. This work included spectra with tonal peaks and emphasised that the nature (quality) of the noise was important. Fluctuating noises are more annoying than predicted by their average sound levels.

Recent work on annoyance to people in their homes has been by Mirowska (1998) and Lundin and Ahman (1998). Both these papers considered annoyance due to plant or appliances, installed in, or adjacent to, living accommodation. Mirowska found problems from machinery, including transformers in electricity substations, ventilation fans, refrigeration units and central heating pumps. Lundin and Ahman investigated a husband and wife who experienced typical symptoms of aversion to low frequency noise. Refrigerators and freezers were suspected as the source of the offending noise which, in some parts of the building, was high at 50Hz. The time varying pattern of the noise, due to equipment cycling, was considered to add to its annoyance. However, there was no totally convincing link between effects on health and the noise.

Development of enhanced susceptibility.

It is known that different regions of the brain are responsible for different functions. The brain also possesses "plasticity", in the sense that parts within the same region may change their function. For example, extensive training in a frequency discrimination task in small mammals leads to improved discrimination ability and an expansion of the cortical area responsive to the frequencies which were used during training. (Schnupp and Kacelnick, 2002).

In humans, there is considerable plasticity in the brain during its early development, requiring appropriate stimuli for proper growth. Plastic adaptation is slower in the adult brain. Two examples of plastic adaptation are:

London taxi drivers are required to memorise many routes through London. Magnetic resonance imaging showed that the part of the brain associated with spatial navigation, the posterior hippocampus, enlarged at the expense

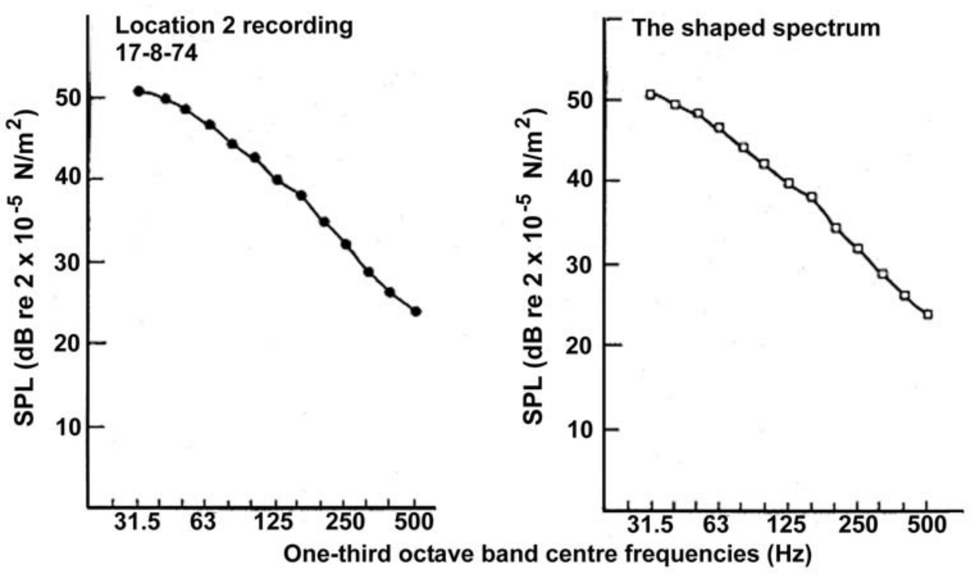

Figure 6. Measured spectrum (left) and simulated spectrum (right)

of neighbouring regions.(Maguire et al., 2000). There has been a similar finding for skilled musicians (Pantev et al., 1998). Cortical reorganisation was greater the younger the age at which music training began.

The significance of these findings for low frequency noise annoyance is:
There is clear evidence that the brain is able to adapt to stimuli.
If complainants spend a great deal of time listening to, and listening for, their particular noise, it is possible that they may develop enhanced susceptibility to this noise.

Enhanced susceptibility is therefore a potential factor in long-term low frequency noise annoyance.

Low frequency noise annoyance and stress
Stresses may be grouped into three broad types: cataclysmic stress, personal stress and background stress. Cataclysmic stress includes widespread and devastating physical events. Personal stress includes bereavements and other personal tragedies. Cataclysmic and personal stresses are evident occurrences, which are met with sympathy and support, whilst their impacts normally reduce with time. Background stresses are persistent events, which may become routine elements of our life. Constant low frequency noise has been classified as a background stressor (Benton, 1997; Benton and Leventhall, 1994). Whilst it is acceptable, under the effects of cataclysmic and personal stress, to withdraw from coping with normal daily demands, this is not permitted for low level background stresses. Inadequate reserves of coping ability then leads to the development of stress symptoms. In this way, chronic psychophysiological damage may result from long-term exposure to low-level low frequency noise.

Changes in behaviour also follow from long-term exposure to low frequency noise. Those exposed may adopt protective strategies, such as sleeping in their garage if the noise is less disturbing there. Or they may sleep elsewhere, returning to their own homes only during the day. Others tense into the noise and, over time, may undergo character changes, particularly in relation to social orientation, consistent with their failure to recruit support and agreement from the regulatory authority that they do have a genuine noise problem. Their families, and the investigating officer, may also become part of their problem. The claim that their "lives have been ruined" by the noise is not an exaggeration, although their reaction to the noise might have been modifiable at an earlier stage.

The HUM
Occurrence
Hum is the name given to a low frequency noise

which is causing persistent complaints, but often cannot be traced to a single, or any, source. If a source is located, the problem moves into the category of engineering noise control and is no longer "the Hum", although there may be a long period between first complaint and final solution. The Hum is widespread, affecting scattered individuals, but periodically a Hum focus arises where there are multiple complaints within a town or area. There has been the Bristol Hum (England), Largs Hum (Scotland), Copenhagen Hum (Denmark), Vancouver Hum (Canada), Taos Hum (New Mexico USA), Kokomo Hum (Indiana USA) etc. A feature of these Hums is that they have been publicised in local and national press, so gathering a momentum which otherwise might not have occurred, possibly increasing the number of adverse reactions. Although the named Hums, such as Kokomo, have gained much attention, they should not be allowed to detract from the individuals who suffer on their own.

Hum character

The sound of the Hum differs between individuals. Even in the areas of multiple complaints, the description is not completely consistent, although this may be because people use different words to describe the same property of a noise. Publicity tends to pull the descriptions together. The general descriptors of the sound of the Hum include: a steady hum, a throb, a low speed diesel engine, rumble and pulsing. A higher pitch, such as a hiss, is sometimes attributed. The effects of the Hum may include pressure or pain in the ear or head, body vibration or pain, loss of concentration, nausea and sleep disturbance. These general descriptions and effects occur internationally, with close similarity.

Unsympathetic handling of the complaint leads to a build-up of stress, which exacerbates the problems. Hum sufferers tend to be middle aged and elderly, with a majority of women. They may have a low tolerance level and be prone to negative reactions. The knowledge that complaints are being taken seriously by the authorities helps to reduce personal tensions, by easing the additional stresses consequent upon not being believed. This is particularly so when, as is often the case, only one person in a family is sensitive to the noise. Whilst some Hum sufferers may have tinnitus, they will, of course, also be troubled by intruding noise at a different frequency from their tinnitus. Tinnitus should not be used as a reason to reject a complaint of low frequency noise annoyance.

Psychological aspects of the Hum

Psychosocial factors affect the physiological impact of noise (Hatfield et al., 2001). Adverse physiological consequences may be mediated by psychological factors related to the noise exposure. It is plausible that excessive noise exposure promotes negative psychological reactions, leading to adverse physiological effects, as was shown by Hatfield et al.(2001). Therefore, psychological factors must be addressed to help ameliorate the annoyance of low frequency noise.

Some Hum sufferers have achieved this for themselves, saying that they have "learnt to live with the Hum" so that it no longer worries them. Others are "cured" by prescription of relaxant drugs. For a few, the Hum goes away after a time. Some escape the Hum by moving house. One long term sufferer, and leading campaigner for official help with low frequency noise problems, decided that it was time to leave the low frequency forest of chaotic emotions and now has no problem, remaining detached from low frequency noise and of the opinion that to become involved with other sufferers heightens ones awareness of the noise. Some sufferers accept that the noises are not at a high level, but that their reactions are equivalent to those which might be expected from a high level of noise – "As soon as I hear the noise, something builds up inside me". This is a similar response to that of hyperacusis sufferers, although more specialised in its triggers. A form of hyperacusis may be indicated.

Combined acoustical and psychological studies (Kitamura and Yamada, 2002) have explored involvement of the limbic system of the brain in annoyance responses[1]. The limbic system commands survival and emotional behaviours, which we cannot always control, although we may learn to do so.

The Hum remains a puzzling aspect of low frequency noise. No widespread Hum has been unequivocally traced to specific sources, although suspicion has pointed at industrial complexes, especially fans.

In the absence of known sources, Hum sufferers often search their neighbourhoods for a source, walking or driving around at night. It is important for them to find a target for their frustrations. Some general ones include their neighbours, the main gas pipelines, radio transmissions (particularly pulsed signals for navigation), defence establishments etc.

Auditory sensitivity

Special difficulties arise when, despite persistent annoyance, there is no "measurable" noise or, as might occur in urban areas, the noise levels at low frequencies are in the 40 - 50dB range, well below the average threshold (ISO:226, 1987). Van den Berg supports tinnitus as an explanation in these circumstances (van den Berg, 2001). With respect to audibility, the average ISO:226 threshold levels must be interpreted carefully. Van den Berg's choice of a limit criterion is the low frequency binaural hearing threshold level for 10% of the 50 – 59 year old population, which is 10-12 dB below their average hearing level (van den Berg and Passchier-Vermeer, 1999a). This may be too restrictive a cut off, since 10% of the age group has more sensitive hearing. For example, the population of the EU-15 countries is 379,000,000. There are differences between north and southern European countries, but approximately 10% of the population is in the 50 – 59 year age group. Thus, about 3,800,000 of the 50 – 59 year age group of the European population (10% of 10% of the total) will be more sensitive than the suggested cut-off for assessment of low frequency noise for this age group. A smaller number will have greater sensitivity. Yamada found one subject to be 15dB more sensitive than the average (Yamada, 1980), whilst recent work (Kitamura and Yamada, 2002), gives two standard deviations from the average threshold as about 12dB. However, the average threshold of the complainants in this work is somewhat higher than the ISO 226 threshold, as might be expected for older people. A range of two standard deviations covers 95% of people. Of the remaining 5%, half are more sensitive than two standard deviations from the average and half are less sensitive. In the EU-15 countries, 2.5% of the population is about 10,000,000 persons of whom around 1,000,000 are in the 50-59 year old age group, who might have very sensitive low frequency hearing and be prone to annoyance from sounds which are not heard by most people and which are difficult to measure. The unfortunate association of one of these people with a low level, low frequency noise leads to considerable distress for the person concerned. A "rule of thumb" may be to take 15 - 20dB below the ISO 226 threshold as the cut off for perception, but this may be a generous level, depending on the complainants' individual threshold at low frequencies.

The preceding deductions on numbers of persons are clearly approximate, but are sufficient to give an "engineering" indication of the extent of the problem.

Criteria for low frequency noise control.

A number of criteria have been developed for assessment of low frequency noise. (Broner and Leventhall, 1983; Challis and Challis, 1978; Inukai et al., 1990; Vercammen, 1989; Vercammen, 1992).

In recent years, some European countries have adopted national criteria for low frequency

[1] The human brain has three layers representing its three stages of development. The primitive (reptilian) brain is connected with self preservation. The intermediate (old mammalian) brain is the brain of the inferior animals and related to emotions. This is the limbic system. The superior (new mammalian) brain is related to rational thought and intellectual tasks. The limbic system is activated by perceived threats.

Table 1. Test noises

No	Name	Description	Tones, characteristics
1	Traffic	Road traffic noise from a highway	None – broadband, continuous
2	Drop forge	Isolated blows from a drop forge transmitted through the ground	None – deep, impulsive sound
3	Gas turbine	Gas motor in a CHP plant	25 Hz, continuous
4	Fast ferry	High speed ferry; pulsating tonal noise	57 Hz, pass-by
5	Steel factory	Distant noise from a steel rolling plant	62 Hz, continuous
6	Generator	Generator	75 Hz, continuous
7	Cooling	Cooling compressor	(48 Hz, 95 Hz) 98 Hz, continuous
8	Discotheque	Music, transmitted through a building	None, fluctuating, loud drums

noise, including Sweden ((Socialstyrelsen-Sweden, 1996)), Denmark (Jakobsen, 2001) Netherlands ((N S G, 1999) Germany (DIN:45680, 1997) , Poland (Mirowska, 2002). Some of these methods assume a threshold curve for limitation of annoyance, based approximately on the ISO226 threshold, or a curve parallel to this threshold, but extended to frequencies below 20Hz.

The criteria have been compared under laboratory conditions for some specific noises (Poulsen, 2002; Poulsen and Mortensen, 2002). Noises used were eight recorded samples of different types as shown in Table 1.

The noises were judged by 18 otologically normal young listeners and by four older people (41-57 years) who had made complaints of annoyance by low frequency noise. Judgements were made under assumed listening circumstances of day, evening and night. The complaint group rated the noises to be more annoying than the other group did. Overall, the Danish method gave highest correlation between objective and subjective assessments, but only when a 5dB penalty for impulsive sounds was included.

Conclusions

Regulatory authorities must accept that annoyance by low frequency noise presents a real problem which is not addressed by the commonly used assessment methods. In particular, the A-weighted level is very inadequate, as are the NR and NC criterion curves. Assessment methods specific to low frequency noise are emerging, but a limitation of existing methods is that they do not give full assessment of fluctuations. It is possible that application of noise quality concepts, in particular fluctuation and roughness (Zwicker and Fastl, 1999), may be a way forward.

Acknowlegement

This paper is partly based on extracts of a report, prepared by the author for the UK Department of the Environment, Food and Rural Affairs (Defra),(Leventhall, 2003).

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