THIRTY FIVE YEARS OF LOW FREQUENCY NOISE

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1 INTRODUCTION

It is first necessary to define low frequency noise. Infrasound is considered as sound at frequencies below 20 Hz. However, there is no logical reason for terminating a continuous process of hearing at this arbitrary frequency and from about 10Hz to 100Hz could be taken as the low frequency range. It may be argued that there is no logical reason for terminating at 100 Hz, and the range is sometimes extended to about 200Hz. However, there do seem to be same interesting phenomena in the range of 10 Hz to 100 Hz.

2 EARLY WORK

Early work on low frequency noise and its subjective effects was stimulated by the American space programme. It was realised that very large launch vehicles produce their maximum noise energy in the low frequency region. Furthermore, as the vehicle accelerates, the crew compartment is subjected to boundary layer turbulence noise for about two minutes after lift off. Experiments were carried out in low frequency noise chambers on short term subjective tolerance to bands of noise at levels of 140 to 150dB in the range up to 100Hz (1). It was concluded that subjects who were experienced in noise exposure, and who were wearing ear protection, could tolerate both broadband and discrete frequency noise in the range 1Hz to 100Hz at sound pressure levels up to 150dB. Later work suggests that, for 24 hour exposure, Levels of 120-130dB are tolerable below 20Hz (2) These limits were set to prevent direct physiological damage. It is not suggested that the exposure is pleasant, or even subjectively acceptable, for anybody except those who have a personal interest in the noise.

3 INFRASOUND

The early American work was published in the mid 1960's and created no great sensation, but a few years later ***infrasound*** entered upon its mythological phase, echoes of which still occur. The main name associated with this phase is that of Gavreau from CNRS Marseille. He developed high intensity sources, but made some unwise statements which confused harmful effects of very high levels at higher frequencies with the effects of infrasound.(3) These were picked by the press and embellished further, including a statement that 7Hz was fatal.

Infrasound was blamed for anything for which some other explanation had not yet been found (e.g., brain tumours, cot deaths, road accidents). A selection of some press headlines from the early years is:

The Silent Sound Menaces Drivers - Daily Mirror, 19th October 1969
Does Infrasound Make Drivers Drunk - New Scientist, 16th March 1972
Brain,Tumours 'caused by noise' - The Times, 29th September 1973
Crowd Control by Light and Sound - The Guardian, 3rd October 1973
Danger in Unheard Car Sounds - The Observer, 21st April 1974
The Silent Killer All Around Us - Evening News, 25th May 1974
Noise is the Invisible Danger - Care on the Road (ROSPA) August 1974

On the 20th September 1977, the London Evening News published an interview with David Bowie, giving his views on life, including the following:

"He also expresses fears about America's new Neutron Bomb. 'It was developed along the lines of the French sound bomb which is capable of destroying an area 25 miles around by low frequency vibration'. According to Bowie, plans for such a bomb are readily available in France and any minor power can get their hands on a copy. Low frequency sounds can be very dangerous. The 'sensurround' effect that accompanied the film 'Earthquake°' was achieved by a noise level of nine cycles per second. Three cycles per second lower is stomach bleeding level. Any lower than that and you explode".

Public concern over infrasound was one of the stimuli for a growth in complaints about low frequency noise during the 1970's and 1980's and may still have lingering effects..

Incorrect claims were made in the book 'Supernature' by Lyall Watson, first published in 1973 as 'A natural history of the supernatural' and which had large sales as a paperback. This book includes an extreme instance of the nonsense which has been published about infrasound. It states that the technician who gave the first trial blast of Gavreau's whistle "fell down dead on the spot". A post mortem showed that "all his internal organs had been mashed into an amorphous jelly by the vibrations". It continues that, in a controlled experiment, all the windows were broken within a half mile of the test site and further, that two infrasonic generators "focussed on a point even five miles away produce a resonance that can knock a building down as effectively as a major earthquake".

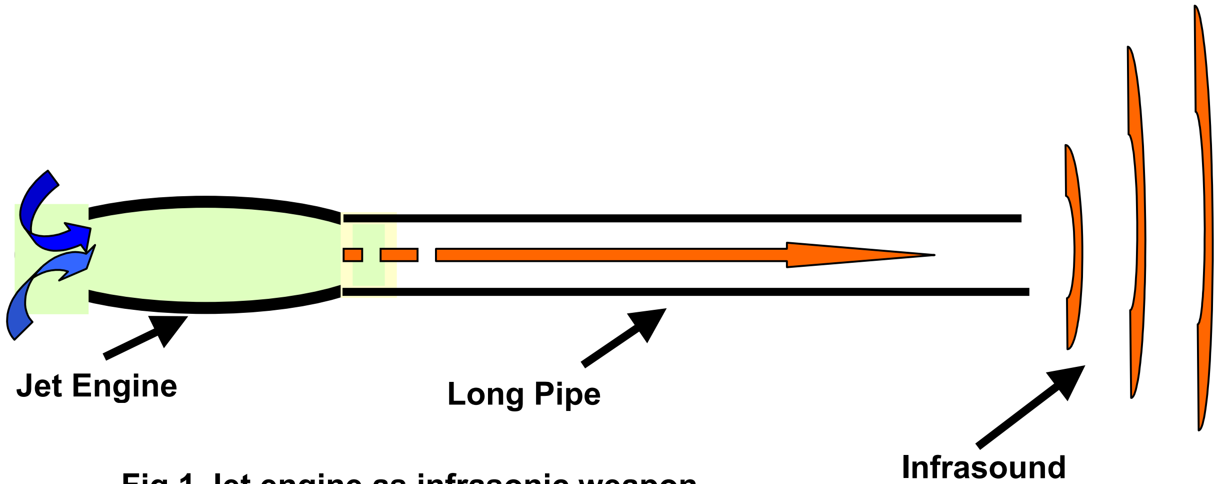

Fig 1 Jet engine as infrasonic weapon

The infrasonic weapon had a resurgence a few years later during the cold war, after Chairman Brezhenev made a reference to "new and terrible weapons", so causing alarm amongst the Western powers. At this time there was a Conference of the Committee on Disarmament, which sat for a considerable time in Geneva and may still be sitting. The Committee received a working paper on infrasonic weapons from the Hungarian People's Republic (GCD/575, 14th August 1978), with the request that there should be an agreement to ban the development of these weapons. An example given in the working paper is illustrated in Fig 1, in which a jet engine fires into a long resonant pipe. However, a little thought shows that the fast gas flow will destroy the resonance, as the wavelengths of the waves travelling in opposite directions will be different.

Suppose we wish to develop a weapon to produce 150 dB at 100m. Assuming hemispherical spreading over the ground and only geometrical attenuation, the source sound power level required is 198 dB or about 6×10^7 watts of acoustic power. This is only a few decibels lower than the Saturn rocket launcher. One could reduce the power requirement by a suitably immense reflector, several wavelengths long - the wavelength at 10 Hz is about 34 metres - or with an array of sources.

Of course, one way to produce high levels of infrasound is to do knee bending exercises. Application of *p=hρg* shows that peak to peak change in head height of 0.5m produces a pressure change of 6N, which is about 110dB.

Despite the awesome mythology, infrasound has long been a respected area of study in meteorology. Large infrasound arrays detect low frequencies originating in explosions, atmospheric and other effects. There is also a worldwide system of about 60 infrasound arrays, which are part of the monitoring for the Nuclear Test Ban Treaty.

As so much that is written about infrasound and low frequency noise in popular presentations is incorrect, we have to consider what is known. Infrasound is audible. It can be heard at fairy moderate levels and the levels required to produce significant effects are well above threshold. Fig. 2 illustrates the hearing threshold, showing the average of a number of threshold determinations. It is seen that, at high enough levels, the hearing sensation continues in some form down to a few Hertz .(4) Equal loudness contours come closer together as the frequency is reduced, such that, say, a 5dB increase leads to doubling of loudness, rather than the 10dB which is often quoted for higher frequencies

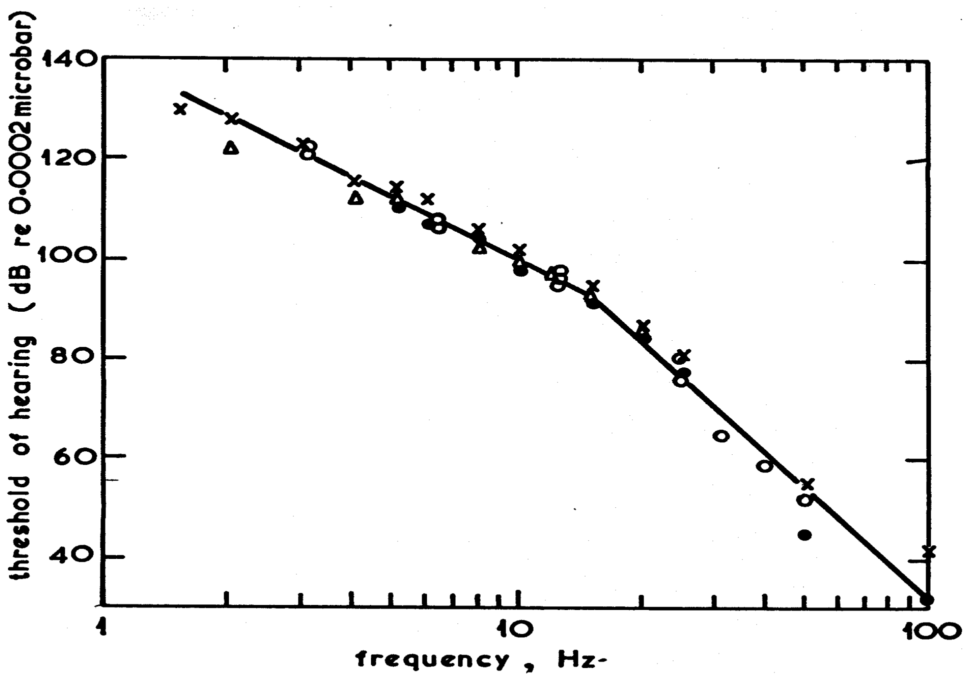

Fig 2. LF hearing thresholds

Secondly, low frequencies have little air absorption - about 0.1dB/km at 63Hz and less at lower frequencies, so that they travel long distance with level reductions mainly due to geometrical spreading.

4 SUBJECTIVE EFFECTS OF LOW FREQUENCY NOISE

There is a question of whether there are any significant subjective effects of low frequency noise and whether differences arise between the effects of low frequency noise and audio frequency noise. There are, of cause, different degrees of effect. The American interest in relation to the space programme was to determine the maximum exposure which could be endured by astronauts. At a lower sound level, there are questions of task performance and annoyance, rather than direct physiological effects, whilst at even lower levels the annoyance effects persist, but assume a different and rather elusive character, with pronounced individual differences.

The World Health Organisation's "Guidelines for Community Noise" (5) makes a number of references to low frequency noise including:

> ***Special attention should be given to sources with low frequency components***
>
> ***If the noise includes a large proportion of low frequency components, still lower values than the guideline values …….will be needed***
>
> ***Disturbance may occur even though the sound pressure level during exposure is below 30dBA***
>
> ***Health effects due to low frequency components in noise are estimated to be more severe than for community noises in general***
>
> ***The evidence on low frequency noise is sufficiently strong to warrant immediate concern.***

It is unlikely that there are direct physiological effects at low levels, but effects occur as a result of stress. Stress is certainly a factor in responses to low frequency noise, in that long-term exposure to even low levels in an unresolved complaint, leads to a condition of chronic stress.

A good review of low frequency noise, containing about 200 citations, is in reference (6).

5 SOURCES OF LOW FREQUENCY NOISE

There are many sources. Any system which has a reciprocating motion, such as pumps, compressors, diesel engines etc is a potential low frequency source. Combustion and turbulence are other sources. The roar of combustion is well known, but there may also be low frequency combustion resonances in the combustion chamber/flue system. Fans, in building services or for industrial applications eg. for material handling, are often a source of low frequency tonal noise. A fan which is not operating efficiently may also produce unstable low frequency noise. Structure borne noise, normally originating as vibration, is at low frequencies – the frequencies of vibration of the source. All forms of transport, particularly those based on diesel or gas turbine engines, produce low frequency noise.

The noise from the other side of a party wall usually comes through as low frequency, as does environmental noise heard indoors.

6 ACOUSTICALLY INDUCED BODY VIBRATIONS

An area of low frequency noise in which there are some misconceptions is that of direct effects on the body. It is often claimed that the effects are similar to those of mechanical vibration i.e. vibration

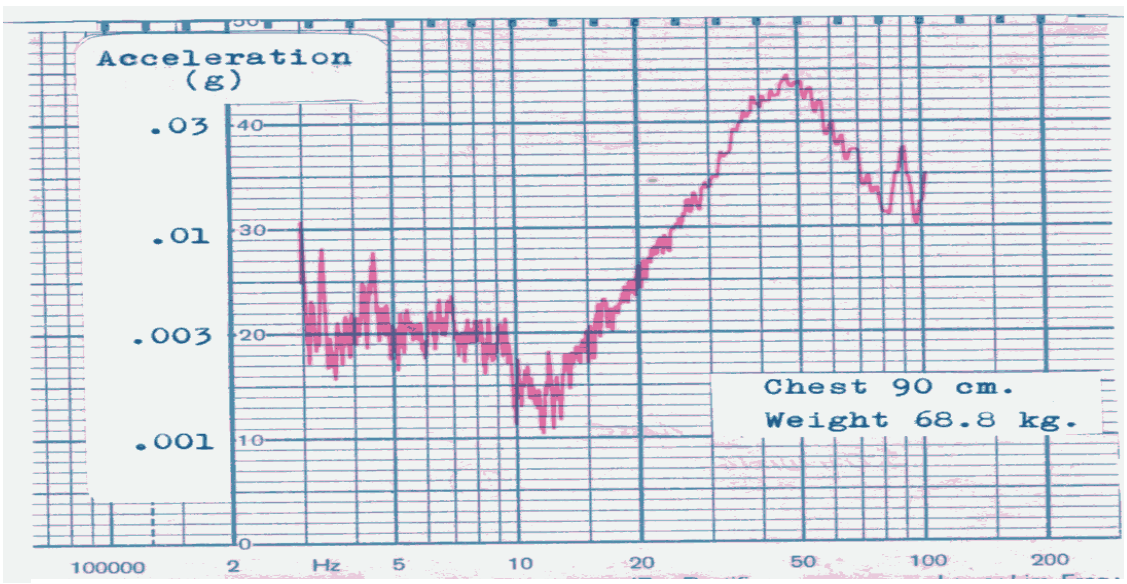

Fig 3 Acoustically induced chest resonance. Frequency sweep at 107dB

through the feet or seat. However, in mechanical vibration excitation, extensional moduli of parts of the body are involved, whilst for acoustic excitation at low frequencies a compressional effect takes place results, involving bulk moduli. This produces a different set of resonant frequencies.

The most pronounced effect is a chest resonance in the range 30 Hz to 70 Hz depending on stature. Fig. 3 shows a typical resonant response, taken at the sternum, to a pure tone frequency sweep at 107dB. Repetition with subjects breathing a 90% Helium-10% Oxygen mixture did not change the resonance, indicating that it is due to a structural effect rather than involving air cavities. If a simple model of a cylindrical chest is assumed, it is possible to estimate both the body mass associated with the resonance and the stiffness of the system. The mass is in general about 15% of the body weight, agreeing with anatomical data, and the stiffness is about 10^6 Nm^{-1}. (7,8)

7 THE HUM

For some years press and radio have carried stories of a mysterious "hum" which seems to have developed mainly since the late 1960's. A common description of the noise is that it is like an idling diesel lorry in the distance. Complainants have described the noise on a subjective scale from Quiet to Violent, the latter condition being associated with pains in the ear, neck etc. Sometimes the head seems to be "bursting". People of all ages are affected, although many are mature women. Often only one person in a household hears the noise and this adds to their distress by making them feel very isolated.

The "hum" has a continuous presence for some people, but may disappear when they are in another part of the country. In addition to individuals, there is periodic publicity of larger scale effects, involving numbers of people. A few years ago it was the Taos hum in New Mexico. At present, the Kokomo hum in Indiana is attracting attention. In the UK, the Bristol hum was current in the 1980's and was never satisfactorily resolved, although industrial and similar fans were suggested as the source. The Taos hum is said to have a frequency between 30Hz and 80Hz, whilst the Kokomo hum is claimed to be lower, at 10 to 30Hz, but there is no hard evidence for these frequencies. Sources of the hum have been suggested as the high pressure gas mains, pulsed radio transmissions, power lines, defence installations etc. in addition to the more prosaic fans and industry.

People who hear low frequency noises, which the majority of people cannot hear, raise a number of problems.

- Are the noises self generated e.g., tinnitus or body sounds? This is the easy explanation.
- Do the complainants have exceptionally acute hearing?
- Do the complainants have some quirk in their hearing contours, which makes them preferentially sensitive to low frequency noise?

There is, of course, a spread of sensitivity about the standardised average threshold values and the complainants may represent the extreme of the distribution. It is also possible that loss of audio frequency sensitivity, whilst maintaining normal low frequency hearing, could weight a perceived spectrum towards the lower frequencies.

The hearing threshold is usually shown as a continuous curve, obtained by the average of many measurements. However, the threshold of an individual has a 'microstructure' with sensitivity peaks(9,10) Fig 4 shows the thresholds of two subjects measured at 5Hz intervals. There are irregularities in each threshold. The lower one has a sensitivity peak at 34Hz, such that a tone at this frequency could be clearly audible to subject A, but inaudible to subject B.

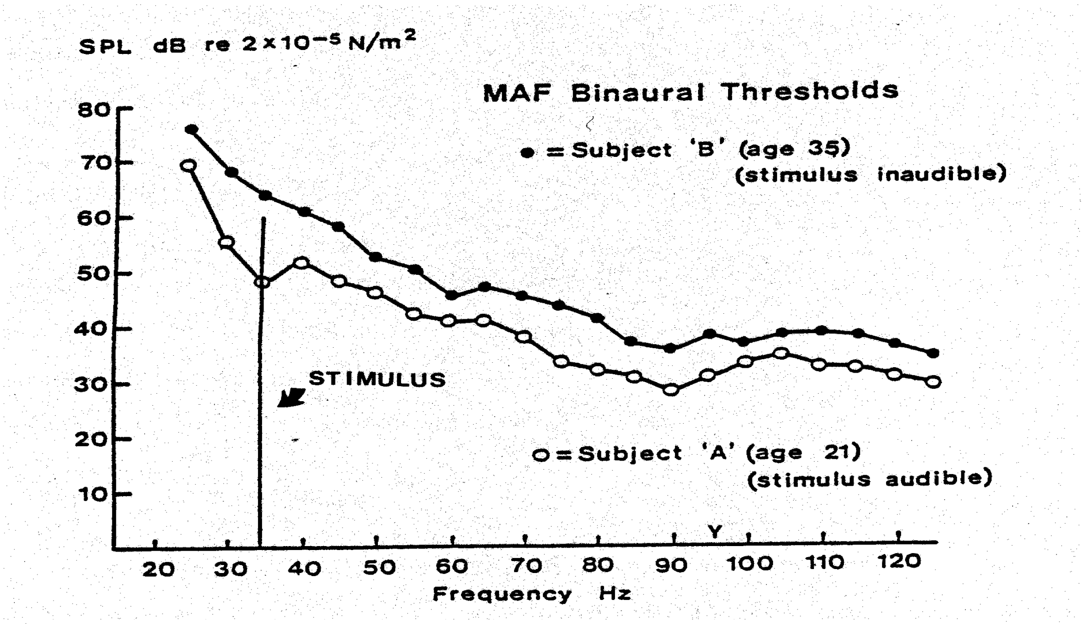

Fig *4 Microstructure of threshold

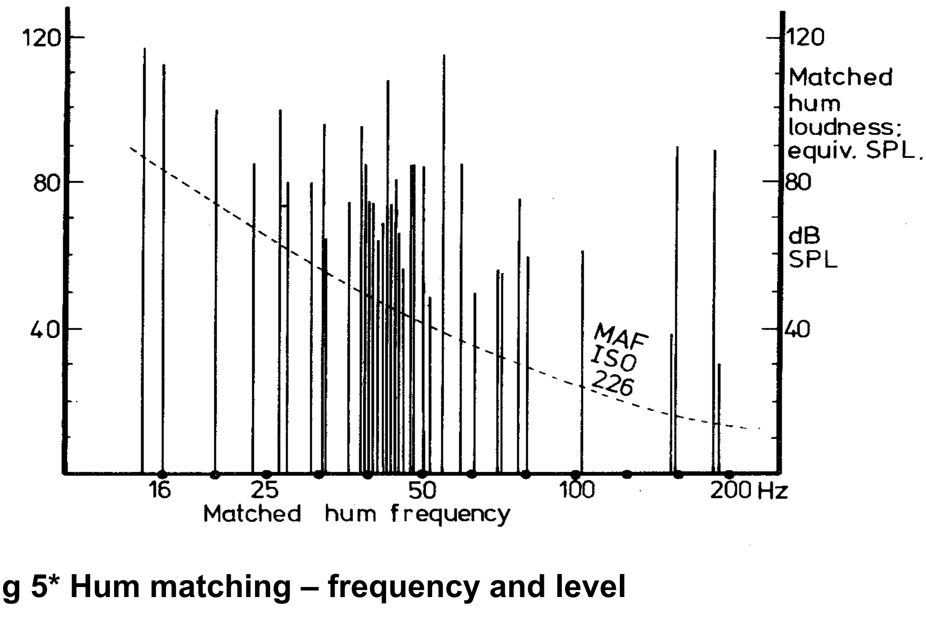

Fig 5* Hum matching – frequency and level

Hum matching by complainants has indicated 40Hz as a common frequency. In Fig 5, each vertical line represents the matched frequency and its level (10). There is a cluster of frequency matchings around 40Hz, but the matching of levels, obtained by the sufferers' memory of what they had heard in their homes, gives very high results, such that these should have been clearly audible to investigators who visited the sufferers, although, in fact, they were not audible to the investigators.

Experiments exposing complainants to bands of noise 10Hz wide, showed a peak of unacceptability at around 40Hz, as in Fig 6. The bands were presented at three levels, 55dB, 65dB and 75dB, whilst the subjects judged their 'unacceptability'. There is a peak of unacceptability, for all the sound levels, at 40-50Hz. Non-sensitives showed a similar peak in unacceptability, but did not reach a level of 100% (12.) Work by Inukai (13) on development of a weighting network for low frequency sound level meters included a penalty in the region of 40Hz. The results of Fig.3 led to Low Frequency Noise Rating Curves, which are similar to NR at higher frequencies, but reduce the level permitted at the low frequencies (12). These curves check the spectrum balance in order to assess low frequency problems.

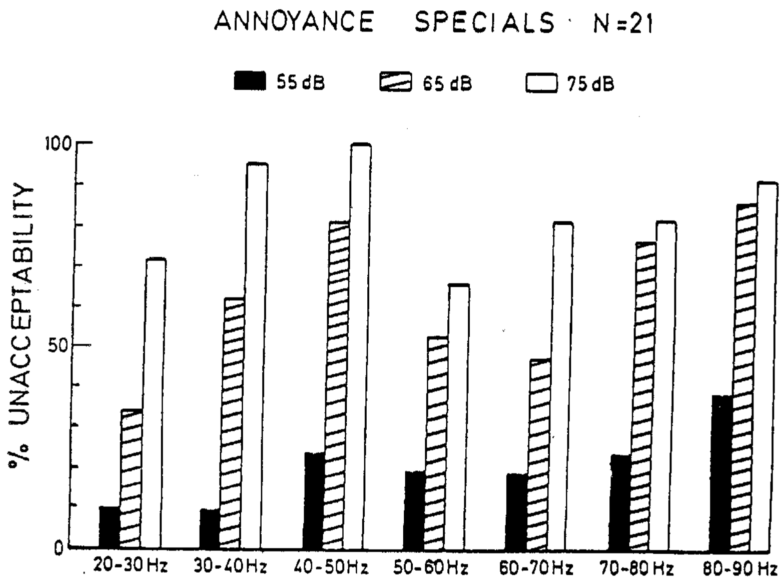

Fig *6 Unacceptability for 10Hz wide bands

Tests on perception of low frequency noise are carried out in special test chambers. Early ones were small, just big enough for one person, and acted as pressure chambers, driven by, say, four loudspeakers . The latest chamber in Aalborg University, Denmark is about 2.7m square and 2.4m high. It is driven by a bank of 20 loudspeakers in one wall, whilst a similar array in the opposite wall acts as an active absorber, so giving simulated free field conditions up to at least 250Hz, which is well into the modal region for this room(14).

Some of the annoying qualities of low frequency noise are known to be:

a. Spectrum shape. A rapid fall in level from low to high frequencies leads to an unbalanced spectrum. Work in air conditioned offices has shown that a fall of 5dB per octave gives a neutral sound without annoying characteristics (15). However, higher rates of fall gradually become more annoying and a fall of, say, 9dB/octave is unpleasant.

b. The presence of tones adds to unpleasantness. A low frequency tone has an annoyance penalty, depending on frequency, in relation to its A-weighted level. It is also possible for the annoyance of tonal noise to increase even though the loudness decreases. (16)

c. Fluctuations add to annoyance (17). Fluctuations may occur from a beat between two tones of similar frequency or from inherent variations in level, which are more likely to occur at low frequencies.

Propagation over long distances leads to both a more rapid fall off into the high frequencies and greater fluctuations in level, so emphasising the annoying characteristics, though the overall level reduces.

8. MEASUREMENT OF LOW FREQUENCY NOISE

There are problems with using L_{Aeq} for assessing low frequency noise, as indeed there are for its use with all noises. The extracts of the views of the WHO, in Section 4 above, show WHO's belief that, in comparison with noise at higher frequencies, there is "something different" about low frequency noise and its effects. This difference is probably related to the "quality" of the noise, but an L_{Aeq} measurement of low frequency noise has the following limitations:

a. It discriminates against the main components in the noise through A-weighting
b. It suppresses all fluctuations through averaging.

A frequency analysis gives equal weight to all components but, as averaging still occurs, this does not solve the whole problem.

Vehicle and appliance manufacturers are interested in how their products sound and have a number of quality indices which, in some applications, combine to an "annoyance index". The quality indices include loudness, sharpness, fluctuation strength, impulsiveness, roughness, periodicity, etc. Determination of these quantities requires access to the noise waveform and follow-up computations, which is possible in laboratory determinations on a commercial end-product. But it is time that similar ideas were applied to measurement and assessment of low frequency environmental noise.

9.0 A RECENT LOW FREQUENCY NOISE PROBLEM

A CHP plant had been installed in a converted boiler house. The plant had two 18 cylinder gas engines, each producing about 4.5MW of electricity with hot water from heat recovery of the exhaust. Engine speed was 1000rpm, giving 16.667 rps. As each cylinder fires once every two revolutions, the firing rate of the engines was 8.33Hz. Low frequency noise problems occurred when the engines were operated and gradual solution of the problems left an apparent very low frequency noise, consisting of an insistent beat, which appeared to be at 5 to 10 per second (18) Many measurements had been made down to 31.5Hz and 25Hz third octave bands. Follow-on measurements down to 12.5Hz did not show high levels at low frequencies. Fig 7 , which is the spectrum taken on the roof of

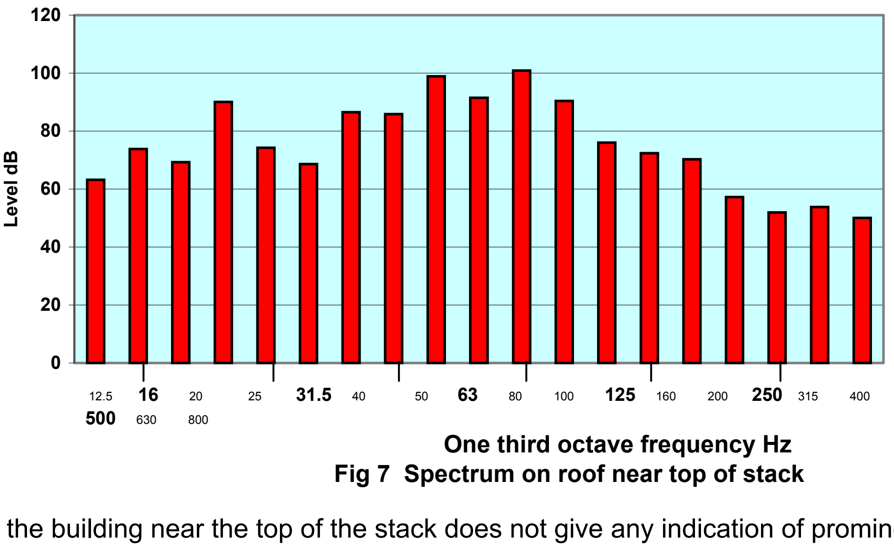

Fig 7 Spectrum on roof near top of stack

the building near the top of the stack does not give any indication of prominent very low frequencies.

A narrow band analysis of the waveform resulted in Fig 8. There is a harmonic spectrum based on 8.33Hz, but the main components are around 75Hz and 125 Hz. Both Figs 7 and 8 are averages over time, and suppress important characteristics of the noise, so that they fail to show the source of the problem. Inspection of the waveform, as in Fig 9 , immediately revealed the source. From the time scale of the trace, it follows that the main frequency is actually at 125Hz, but with an 8.33Hz modulation. Thus, noise control should be aimed at 125Hz not 8.33Hz. The modulation occurs from the interaction of 125Hz and its adjacent "sidebands" of (125 + 8.33)Hz and (125 - 8.33)Hz. A reactive silencer, designed to give good attenuation at 125Hz, reduced the noise to below complaint level. The averaging inherent in frequency analyses had stalled the resolution of the problem, which was instantly revealed by inspection of the waveform. Note that this problem is not generic to all

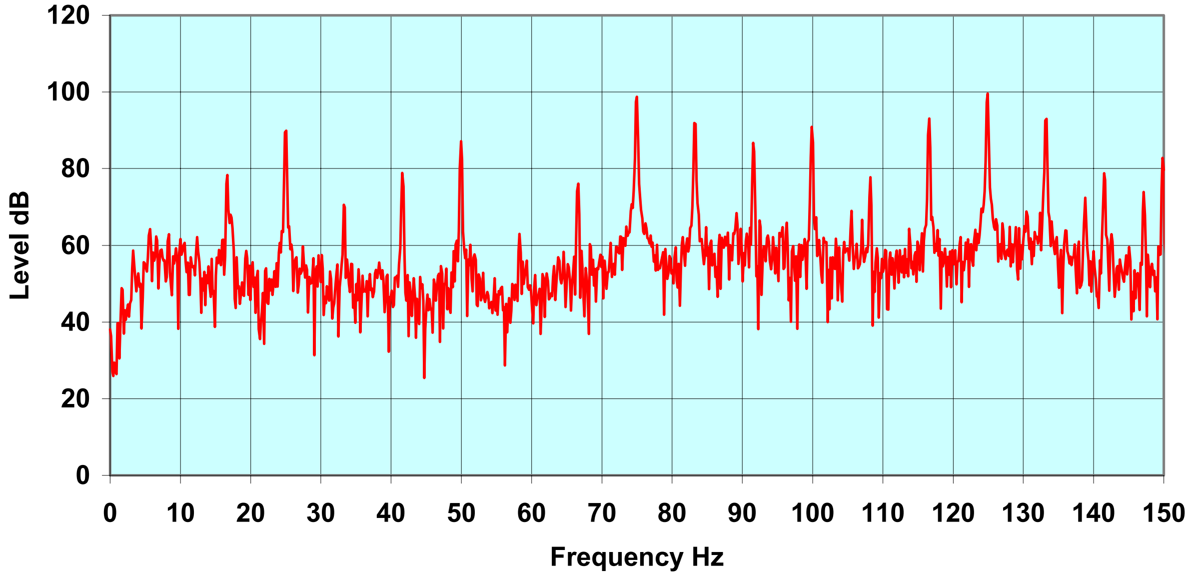

Fig 8 Narrow band analysis corresponding to Fig 7

installations using the same engine, but arose from a particular configuration of the engine and its very long exhaust system – about 100m long including the stack – resulting in a particular relation between harmonics in the region of 125Hz, which led to the beating effect.

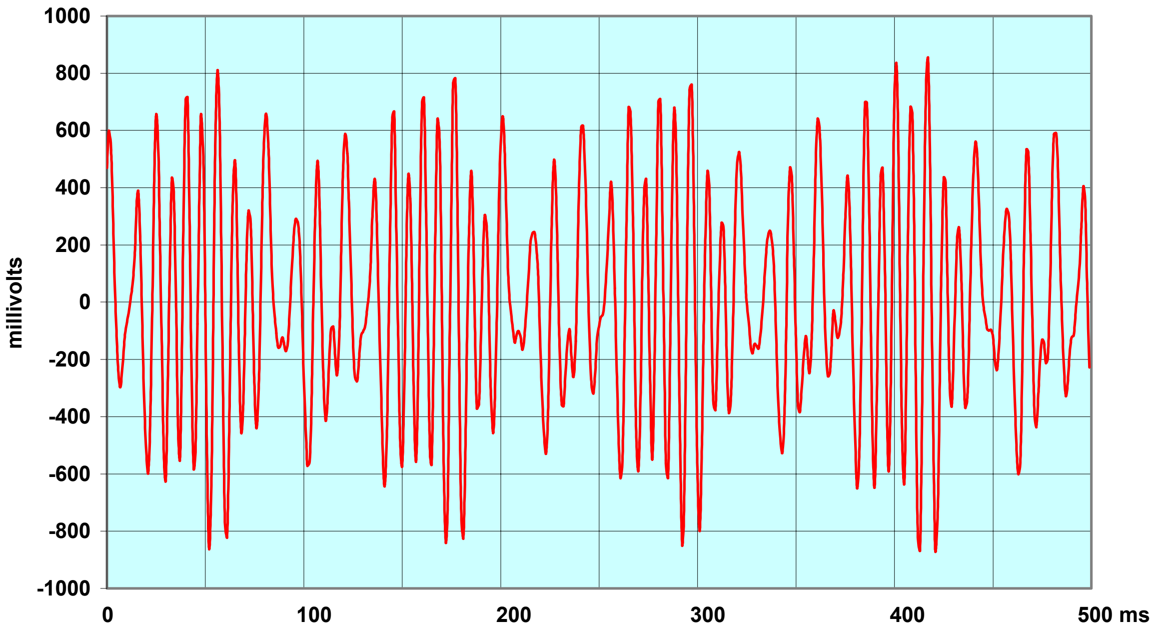

Fig 9 Waveform corresponding to Figs 7 and 8

10 Control of Low Frequency Noise

The requirements for the control of low frequency noise may be summarised as Mass, Thickness and Size. Mass for an enclosure or dividing wall, thickness for an absorbing material and size for attenuators, either passive or reactive. These requirements add to the difficulties of controlling low frequency noise in its transmission path. Additionally, the resonances of a wall are often in the low frequency region.

Under certain circumstances, active noise control can be a good solution to the control of low frequency noise.(19) Active ear defenders have been commercial for some years, as have duct attenuators for HVAC and similar applications. Recent development include an attenuator for ducts with flow, which does not use a loudspeaker as cancelling source (20), whilst studies on open air active attenuation have progressed for both stationary and moving sources (21, 22).

11 Limits for LF Noise

Some countries, but not yet the UK, have introduced limits for environmental low frequency noise in order to protect people in their homes. Fig 10 shows limits for Sweden, Poland and Germany together with an Dutch proposal (Vercammen) (23,24). The limits for Sweden, Germany and Poland are below threshold at frequencies lower than 50Hz. The Swedish limit goes down to only 31.5Hz, whilst the others are down to 10Hz. The top frequency in the German limit (DIN 45680) is 100Hz.

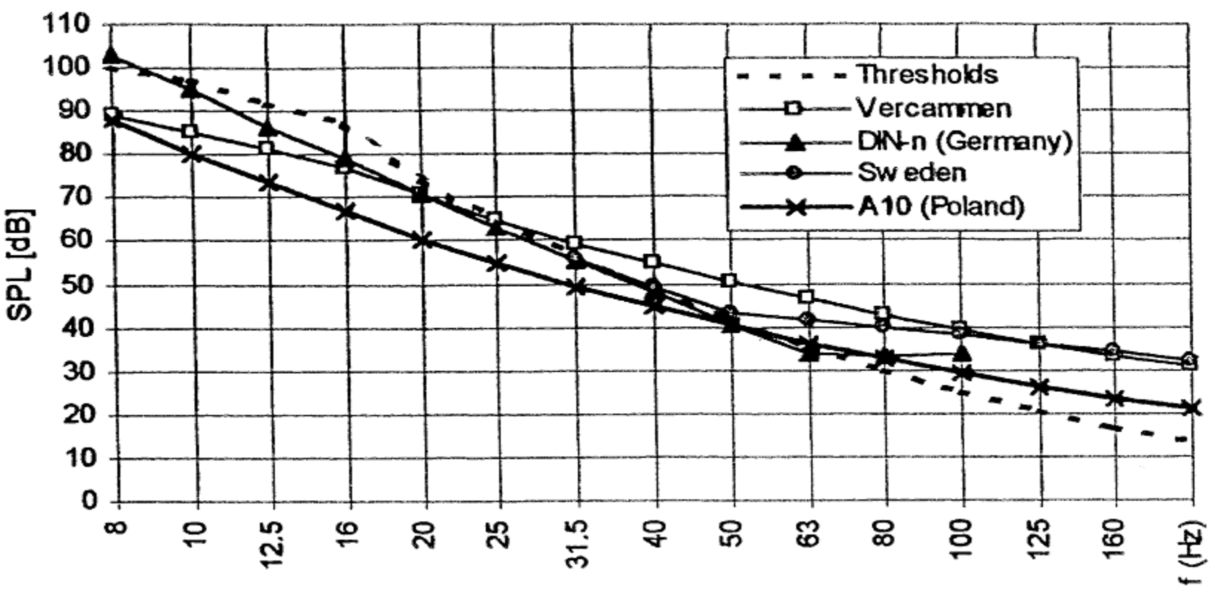

Fig 10 Limits for low frequency noise in dwellings

Denmark has a different approach, based on an approximation to the loudness of he low frequencies. The third octave frequency bands between 10Hz and 160Hz are A-weighted and summed to give a single figure, the $L_{pA,LF}$. Limits are placed on this, for example:

Housing	$L_{pA,LF}$	< 20dB	18.00 to 07.00 and
		<25dB	07.00 to 18.00
Classrooms, offices	$L_{pA,LF}$	< 30dB	

In addition, there is a 5dB penalty for impulsive character of the noise. Recent laboratory comparisons in Denmark suggested that the Danish method gave greatest correlation with subjective effects. (23)

12 CONCLUDING REMARKS

It is thought that, in the UK, there are about 500 complaints a year of disturbance from low frequency noise, which is small in comparison with the total number of noise problems(25). Most of the complaints are resolved, but there remains a core of unsolved problems, bringing great distress to the sufferers, who have formed their own pressure group – the Low Frequency Noise Sufferers Association. Complaints require careful and sympathetic understanding to avoid heightening of tensions and stress. (25,26). It is both technically inadequate and unfair to the complainant to take an A-weighted reading and make an assessment based on those criteria which are normally used for higher frequencies.

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