AN INTEGRATED ACOUSTIC / MICROSEISMIC APPROACH TO MONITORING LOW FREQUENCY NOISE & VIBRATION

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ABSTRACT

Environmental low frequency noise and vibration is a growing cause of annoyance and a potential hazard to health for many people. The problem can be particularly acute in quiet rural or suburban settings, where background noise and vibration levels are low.

Studies in the published literature describing research into low frequency noise and vibration problems demonstrate that these cases are not easily solved. There are a number of complicating factors that have their origins both in the physics of propagation of low frequency waves, and in psychoacoustic phenomena.

This thesis describes the development of a new experimental system, drawing from two scientific disciplines, which provides comprehensive coverage of the sound and vibration levels within residences situated near to industrial sites. The versatility of the acquired data permits a wide range of useful analysis to be carried out.

Case studies are employed to illustrate the effectiveness of the integrated acoustic/microseismic approach.

It is demonstrated that the measurement system, which combines acoustic and microseismic transducers with microseismic data capture capabilities, is superior to what is currently available within either discipline alone.

A German national standard was utilised in the case studies to assess the measured levels of airborne low frequency noise. This proved to be a good predictor of annoyance.

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1 INTRODUCTION

1.1 BACKGROUND TO STUDY

Environmental low frequency noise and vibration is a growing cause of annoyance and a potential hazard to health for many people (Berglund et al., 1996).

A number of reported cases of low frequency noise are psychologically or physiologically self-generated, yet a significant number are caused by a low intensity, real acoustic stimulus (Vasudevan and Gordon, 1977). The number of industrial noise sources capable of creating low frequency noise and vibration is increasing, as plant and equipment sizes become larger.

Adverse effects of low frequency noise and vibration on humans may include permanent or temporary hearing loss, aural pain, loss of balance, effects on the respiratory system, annoyance, cardiovascular and endocrine effects, decreased performance and cognition, sleep disturbance, effects on communication and psychosocial and mental health effects (Berglund et al., 1996).

The primary effect due to low frequency noise appears to be annoyance (Broner, 1978). Annoyance levels are particularly high in cases where masking effects due to other sources of background noise such as traffic are low (Vasudevan and Leventhall, 1989). Complainants therefore often dwell in otherwise quiet rural or suburban areas.

The definition of low frequency noise in this thesis includes infrasound, which is considered by standard definition to be that 'inaudible' part of the noise spectrum below 20 Hz. This 20 Hz cut-off point is arbitrary and, in fact, sounds at frequencies below 20 Hz can be audible to humans at sufficiently high sound pressures (Berglund et al., 1996).

The upper limit of low frequency noise for the purpose of this thesis is taken to be 100 Hz. This is consistent with the upper limit set by others (e.g. Backteman et al., 1983).

The researcher into low frequency noise and vibration will encounter a wide range of difficulties. These have their origins both in the physics of propagation of low frequency waves, and in psychoacoustic phenomena.

As a result of the combined effects of these difficulties, low frequency noise and vibration problems can be extremely unpredictable, and this makes them difficult to resolve.

1.2 OBJECTIVES OF STUDY

The aim of this thesis is to develop an integrated microseismic and acoustic measurement system for assessment of low frequency noise/vibration problems.

Acoustic techniques utilise microphones to measure sound pressure fluctuations in air. This may provide characterisation of a sound field in both space and time domains, which may be compared with the subjective response of a complainant to identify the particular aspect of the sound that is giving rise to disturbance.

Standard acoustic methods often involve RMS time-averaging of a signal that is assumed to be steady. Standard acoustic procedures for indoor measurements also involve space-averaging i.e. they are based upon the assumption that the indoor sound field is of a diffuse nature.

However, averaging of sound pressure variations in time and space may not be valid for low frequency acoustic waves because of the modal behaviour of the sound waves in enclosures and because of the intermittent, unpredictable nature of low frequency noise.

Microseismology involves measuring three-dimensional ground vibrations in the time domain over lengthy periods, in order to study the waveforms generated by intermittent, highly unpredictable seismic events. High capacity, multi-channel data storage systems are utilised to maximise the prospects of successfully capturing events of interest.

The type of data acquisition systems used in microseismology may therefore be ideally suited for monitoring intermittent and unpredictable low frequency noise in the environment. Monitoring over long periods may allow the effects of changing environmental conditions such as wind to be distinguished from physical variations in source power.

Installation of pressure and velocity or acceleration transducers in a study may allow the characterisation of both the sound and three-dimensional vibration fields to be determined in time and frequency domains. This may be important if the primary cause of disturbance (low frequency noise and/or vibration) is not known at the outset.

The high storage capacity of microseismic monitoring equipment allows very fine frequency resolution to be achieved, which is advantageous when studying tonal low frequency noise that is highly tonal and therefore particularly annoying in nature.

Digital microseismic monitoring utilises a high dynamic range, so large variations in signal amplitude may be detected without the need to adjust the instrumentation to account for the noise floor or full-scale deflection of the instrument. Sampling may also take place in the frequency range below 20 Hz, where sound may be audible and annoying if it is of sufficiently high pressure amplitude.

Cross-channel analysis of the data acquired by a combined acoustic/microseismic system is possible, allowing a wider variety of interpretations than using the data from each channel individually. In particular, propagation paths of low frequency sound/vibration may be inferred by direct comparison of simultaneous recordings from the various channels.

Further information may be obtained by calculating transfer functions between two components of the data. By studying three mutually-orthogonal vibration components, directionality of motion may be determined which may facilitate the identification of source and/or propagation paths of the disturbance.

For the above reasons it is hypothesised that a measurement system which combines acoustic and microseismic transducers with microseismic data capture capabilities is potentially superior to what is currently available within either discipline alone. The objectives of the study are therefore to develop a combined measurement system suitable for analysis of low frequency noise/vibration problems and to test its efficacy in field trials.

1.3 THESIS PLAN

Chapter 2 covers background theory relating to sources of low frequency noise and vibration and how it propagates through the air, the ground and into building structures. A brief discussion follows of noise/vibration control measures and their effectiveness at low frequencies.

In developing the integrated acoustic/microseismic model, the author took account of the shortcomings involved in applying standard acoustic or microseismic techniques to low frequency noise/vibration problems. The development of the measurement strategy is described in Chapter 3.

Chapter 4 outlines a few aspects of subjective response to low frequency noise/vibration, and discusses the objective criteria against which recorded levels may be assessed.

In Chapter 5, the detailed methodology utilised in subsequent field trials is specified.

Chapters 6 and 7 describe two case studies in which low frequency noise and/or vibration were suspected of causing disturbance to residents of semi-rural locations situated close to industrial sites. The case studies served as field trials of the integrated acoustic/microseismic technique developed to tackle such problems. Levels of annoyance were assessed in these cases with reference to a German national standard.

The vast array of data acquired during the two field trials were subject to more rigorous analysis in Chapters 8 and 9.

In Chapter 8, Finite Element Method modelling was carried out to test two possible mechanisms by which low frequency sound energy might enter a room.

Chapter 9 reports on the application of a Singular Value Decomposition transform to seismic records in order to determine whether any trends could be established from the resultant polarisation data.

Chapter 10 summarises the advantages and shortcomings of the integrated acoustic/microseismic approach and draws together the main conclusions of the thesis, in particular whether or not the objectives have been met.

1.4 REFERENCES

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2 BACKGROUND THEORY

This chapter outlines the primary mechanisms by which low frequency waves are created and subsequently transmitted through the ground, the air and into building structures and rooms. The principles involved are illustrated by reference to case studies from published literature. A brief summary of the range of noise and vibration control techniques that may be utilised, either at the receiver position or at source, is then included.

2.1 SOURCES OF LOW FREQUENCY SOUND & VIBRATION

Environmental low frequency noise and vibration has a large number of potential sources of both natural and human origin. Natural causes include air turbulence (wind), thunder, ocean waves and tectonic activity (Berglund et al., 1996). Sources of human origin include industrial installations and machinery, road and rail traffic, aeroplanes, modern large-scale music systems, and indoor heating, ventilation and air-conditioning systems.

Low frequency noise caused by human activity appears to cause a greater degree of annoyance than that from natural phenomena because of its unusual nature (see Section 4.1.1).

Tempest (1989) carried out a survey of low frequency noise complaints received by U.K. local authorities, and found that there are approximately 500 complaints per annum in the

U.K. alone. The commonest sources were found to be factories (35%), music (13%), and traffic/vehicles (11%).

According to Vasudevan and Gordon (1977), certain types of industrial plant such as petrochemical plants and power stations produce substantial low frequency noise energy.

Brown (1989) discusses natural phenomena that may cause low frequency pressure waves indoors e.g. a wind gust on an aperture or flexible panel, electrical storms. Effects of civilisation are also discussed e.g. sonic booms from aircraft overflights, air pressure waves due to close passage of large vehicles, structural vibration due to road, rail or air traffic. Within dwellings the operation of heating/air conditioning fans may also contribute to low frequency noise levels.

Tandara (1993) describes the low frequency noise output from vehicles in detail. A stationary vehicle has only two sources of low frequency noise – the engine and cooling fans. For a moving vehicle, additional sources include transmission noise, tyres, air turbulence and vehicle vibration.

According to Tandara, the increase in output noise level (in dB) of an engine between idling conditions and maximum revs, is approximately linear as a function of frequency. Thus the noise spectrum from an idling engine is more dominated by low frequencies than the corresponding spectrum from the engine running at full output. The unbalanced spectrum from the former is more likely to give rise to annoyance in residential areas where background noise levels are low (see Section 4.1.1). A characteristically annoying noise is that caused by diesel engines 'idling' (Tandara, 1993).

2.2 PROPAGATION OF LOW FREQUENCY SOUND THROUGH THE AIR

The primary physical factors that affect the propagation and attenuation of sound through the atmosphere are spherical divergence, air and ground absorption, physical barriers and meteorological conditions such as wind speed, temperature gradient and humidity of the air.

If sound energy from a sound source is free to travel in all directions, then spherical divergence of the energy occurs. Sound levels will decrease in proportion to the square of the distance from the sound source ('inverse-square law'). This is equivalent to a 6dB drop for a doubling of distance, and is the method by which sound will dissipate geometrically from an omni-directional source in free space.

If a low frequency sound source is located above a hard reflecting ground surface (or water), then sound energy reflecting off the surface may interact with the directly transmitted component of sound, giving rise to a radial interference pattern of maxima and minima. The sound level at a receiver point will then vary depending on the wavelength of the sound and the source-receiver distance i.e. whether the direct and reflected components of sound are constructively or destructively interfering at the receiver.

As well as the attenuation caused by geometric spreading, sound energy is lost due to molecular absorption, both in the air and due to the ground cover between source and receiver.

Absorption loss in air (in terms of dB/m) follows an approximately linear increase with frequency (energy loss during propagation occurs as a function of the number of wavelengths travelled), but is dependent on a number of other factors including temperature, pressure and humidity. Figure 2.1 (from Kinsler et al., 2000) shows typical values for air absorption.

Ground absorption is a more complex function of the type of terrain over which the sound waves are propagating (smooth or hilly, with or without plant cover, built-up area, etc.), the source and receiver height, and the frequency of the sound. Unlike air absorption, it cannot be stated simply as excess attenuation per metre. Figures 2.2 and 2.3 (Dept. of Transport, 1988 and 1995) provide empirical data for a range of ground distances, based on road and railway traffic noise respectively. Note that these may only be applicable to sound sources of similar frequency content to road and railway traffic noise. They also give values in dB(A), and are therefore not useful when measuring and assessing unweighted sound spectra (see Section 4.2).

At the sound frequencies (1-100 Hz) under consideration in this thesis, it is likely that absorption losses will be insignificant compared with the much greater attenuation due to geometric spreading. However, higher frequencies will be selectively attenuated more with distance, and this leads to a low frequency-rich spectrum at positions distant from the source.

The prevailing wind direction may distort the spherical contours of equal loudness surrounding a sound source, with enhanced propagation downwind and a shadow zone (reduced levels) in the upwind direction (see Figure 2.4 from White, 1975). In addition, a sound source may have inherent directivity i.e. a tendency to propagate sound energy more strongly in some directions than others.

Variations in air temperature, pressure, humidity, etc. also cause slight variations in sound velocity. If an air column has variations in sound velocity with height, this can give rise to vertical refraction of sound waves. This phenomenon has an effect on propagation/attenuation models for sound.

For example, if the atmosphere has a normal daytime temperature gradient (i.e. temperature decreasing with altitude, see Figure 2.5 from White, 1975), the speed of sound also decreases with altitude and therefore sound waves are refracted upwards, giving rise to an acoustic shadow zone near the ground surface. Conversely at night, a temperature inversion may occur due to rapid ground cooling (Figure 2.5 from White, 1975) and this may cause sound to be channelled downwards leading to enhanced propagation (Vasudevan and Leventhall, 1989). For low frequency noise this effect may negate what little air absorption and ground attenuation occurs at such long wavelengths.

Thus, for a constant source power level, the amount of sound energy reaching a receiver point may vary greatly depending on a number of environmental factors.

Barriers may be erected between source and receiver positions, and these may provide additional attenuation of the sound waves. However, high frequencies will once again be attenuated to a greater extent than low frequencies. Long wavelength sound may diffract around barriers (especially when the wavelength is of the order of magnitude of the barrier dimensions or greater), whilst high frequencies are more easily blocked.

A large natural barrier such as a hill may cause significant attenuation, even for relatively low frequency sound waves. In a case study described by Vasudevan and Leventhall (1989), the position of a low frequency noise source on high ground aided the propagation of the low frequency noise, as did flat ground between source and the house where complaints arose. Measurement positions 'down in the valley below the house' did not reveal excessive low frequency noise levels.

An unusual barrier effect is described in Porges (1977). As well as absorbing part of the incident sound, the ground surface tends to reflect sound waves. At certain distances from the source and for certain low frequencies, the direct and reflected components may destructively interfere, causing further attenuation. The effect of barriers, which block high frequency noise but which low frequency sound waves can diffuse around, may actually be to prevent this destructive interference, and in extreme cases the sound intensity at the receiver may be higher with a barrier present than without.

Dibble (1997) discusses the various effects outlined above in the context of a case study into low frequency noise emanating from an all-night 'rave' event in rural Leicestershire. Despite the site of the event being 2.5 km away from the nearest settlement, and screened by landscape topography, the low frequency noise gave rise to complaints at distances of up to 15 km. However, an unexpected change in wind direction caused a major reduction in the level of complaints during the night.

All of the factors described in this section may combine to lead to an increasingly 'unbalanced' spectrum as the distance from a source of low frequency noise increases. In the absence of significant local noise sources at the receiver position, noise from an industrial site reaching residents a few miles from the site might be expected to be dominated by energy at frequencies below 100 Hz (Vasudevan and Gordon, 1977).

2.3 PROPAGATION OF VIBRATION THROUGH THE GROUND

A major difference between groundborne and airborne vibrations is that both longitudinal (compressional) and transverse (shear) waves may travel through the solid ground, whereas fluids such as air can only support compressional waves, and not shear waves. Ground waves may also be sub-divided into body waves and surface waves. Figure 2.6

(from Kearey and Brooks, 1991) illustrates elastic deformations and ground particle motions associated with the passage of an array of ground waves.

Body waves travel through the body of the earth. Variations in physical properties such as seismic velocity and density occur both laterally and with depth (tending to increase with depth) in the earth. This has an effect on the propagation path of body waves, which may undergo refraction and reflections as a result of gradual variations in these parameters or sharp changes at interfaces between different rock types or strata.

Compressional body waves in the earth are known as P-waves, and as seen in Figure 2.6 are characterised by a series of compressions and rarefactions of the host medium parallel to the direction of propagation. There is no rotation involved in the displacement caused by P-waves.

Shear body waves (Figure 2.6) are known as S-waves, and involve shearing and rotation of the host material as the wave passes through it but no volume change. The motion at any given point is perpendicular to the propagation direction of the wave.

Groundborne vibrations, like acoustic waves, are subject to absorption that is wavelength-dependent, with the effect that low frequency waves with significant amplitudes can travel longer distances through the ground than higher frequencies.

Surface ground waves are guided along the surface of the earth and the layers near the surface, without penetrating into the deep interior. They may be further sub-divided into Rayleigh waves and Love waves (Figure 2.6).

Rayleigh waves are characterised by particle motions in a vertical plane containing the direction of propagation. They can therefore be recorded in both horizontal and vertical components of a seismometer. The locus of displacement at a given point on the surface is a retrograde ellipse i.e. the direction of motion of the surface at the highest part of the elliptical cycle is opposite to the propagation direction of the wave (see Figure 2.6). For most surface structures, the orientation of the elliptical locus within the vertical plane is such that its major axis is horizontal i.e. the amplitude of horizontal displacement (along the azimuth of the Rayleigh wave) is greater than that of the vertical.

Love waves involve transverse horizontal motion, perpendicular to the propagation direction of the wave (Figure 2.6), so they may only be detected by horizontal seismometer components.

Surface waves tend to be larger in amplitude and longer in duration than body waves, when observed at distance from a common source. These features may be explained in terms of the properties of shallow strata in the earth.

Body waves propagate in three dimensions through the earth and are subject to geometric spreading attenuation according to spherical or hemispherical divergence, which results in a 6 dB decrease in amplitude per doubling of distance.

Surface waves are channelled along the upper layers of the earth, and so experience cylindrical divergence, resulting in a 3 dB reduction in amplitude per doubling of distance.

The amplitude of a surface wave decays exponentially with depth beneath the surface, dependent on the wavelength. A good rule of thumb (Fowler, 1990) is that surface waves 'sample' to a depth of their wavelength divided by three (i.e. amplitudes drop to levels approaching background noise at such depths). A vertical profile of seismic velocity near the surface usually shows an increase with depth. Thus, surface waves of longer wavelength tend to sample deeper rocks with higher seismic velocities and hence travel with a faster mean velocity. This gives rise to dispersion.

For a surface wave 'event' containing energy in a band of frequencies, the duration of the arrival will increase with distance, as low frequency components will arrive increasingly earlier than higher frequencies. This also gives a characteristic to a surface wave arrival at distance that seems to sweep upwards in frequency with time.

Typical P-wave velocities in solid media range from 500-6000 m/s (Kearey and Brooks, 1991). S-wave and surface wave velocities are slightly slower than these, but still significantly higher than acoustic wave velocities (~340 m/s).

According to Kostarev (1996), calculations of vibrational fields in soil are very complex, even for a homogeneous medium with a free surface. After taking inhomogeneities such as layering into account, computational methods of modelling wave fields become impracticable. As well as mathematical complexities, there are difficulties in obtaining geological, morphological and mechanical properties for realistic soil. Therefore most methods of modelling vibrational fields in soil are semi-empirical.

Krylov (1995[1-3]) has however published a number of theoretical papers based on mathematical modelling of ground vibrations from a number of man-made sources such as underground trains, heavy lorries and underground gas pipes. Whilst detailed discussion of this work is beyond the scope of this thesis, Krylov concluded that many of these sources may create groundborne vibrations at frequencies corresponding to the human low frequency acoustic range, with the potential to travel long distances with little attenuation. The amplitudes of vibration that would result from such ground waves would be sufficiently high to cause annoyance to sensitive individuals, either by the direct impact of vibrations or by radiation of low frequency acoustic waves from building structures.

2.4 TRANSMISSION OF LOW FREQUENCY SOUND INTO BUILDINGS

It was argued in Section 2.2 that the spectrum of sound reaching a dwelling in an otherwise quiet location from a distant low frequency noise source, is potentially unbalanced in the sense that it may contain a relatively high proportion of energy in the low frequency range. The effect of transmission of such a noise into buildings may be to enhance this imbalance still further (Vasudevan and Leventhall, 1989).

Figure 2.7 (Bies and Hansen, 1988) illustrates the sound transmission loss as a function of frequency, that is caused by placing a simple, isotropic panel between a noise source and receiver. The incident sound waves may set up flexural waves (see Section 2.5) in the panel, dependent on its physical properties and the frequency of the sound. The panel may then radiate sound into a room on the other side. Transmission loss represents the level difference of incident and transmitted sound power across the panel.

At low frequencies, the behaviour of the panel is stiffness-controlled – the panel is acting like a spring, and transmission loss decreases as the incident sound waves increase in frequency. Increased stiffness leads to increased transmission loss at a given frequency.

At higher frequencies, the partition exhibits mass-law behaviour. Transmission loss is controlled by the surface density of the panel, and increases with frequency at a rate of around 6 dB per octave (Hall, 1987). The higher the surface density of the panel (mass per unit area), the greater the transmission loss (6 dB per doubling of surface density for a fixed frequency (Hall, 1987)).

In the intermediate frequency range, the transmission loss curve passes through a minimum (Figure 2.7) due to the first flexural mode of resonance of the panel.

The modes of resonance or eigenfrequencies, $f_{ny,nz}$ (Hz) of a simply supported rectangular panel, of dimensions L_y and L_z (m), may be determined using the following equations (from Leissa, 1993 and Cremer et al., 1988):

$$f_{n_y,n_z} = \frac{\pi}{2}\left(\frac{B}{\rho_s}\right)^{1/2}\left[\left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2\right] \quad \text{[Formula 2.1]}$$

where n_y and n_z are integers, ρ_s is the surface density of the panel (kg/m^2) and B is the bending stiffness (N.m), given for an isotropic panel by:

$$B = \frac{Eh^3}{12(1-\nu^2)} \quad \text{[Formula 2.2]}$$

where h is the thickness of the panel (m), E is Young's Modulus (Pa) and ν is Poisson's ratio for the panel material.

For panel standing waves, $f_{ny,nz}$ is the eigenfrequency for which there are n_y and n_z half-wavelengths along the directions parallel to L_y and L_z respectively. Alternatively, there are (n_y+1) and (n_z+1) nodal lines of zero displacement perpendicular to L_y and L_z (including the edges which are nodal lines by definition).

A more realistic façade (wall) would be anisotropic and non-uniform and its bending stiffness, surface density, thickness and other physical properties may vary across the plate. Applying different edge conditions such as clamping may also affect the modes of resonance of the panel (Maluski and Gibbs, 2000).

Walls therefore display considerable variation in modal behaviour and transmission loss, which may be hard to predict exactly. Nevertheless, empirical data may be obtained for the low frequency transmission loss behaviour of different wall types. Maluski and Gibbs (1999) reported that lightweight walls (e.g. an internal plasterboard partition) are mass-controlled between 50 and 160 Hz, whilst a typical 200 mm thick heavyweight wall (such as an external domestic wall) is stiffness-controlled below 125 Hz.

The heavyweight wall may be described as having a lower modal density between 50-160 Hz than the lightweight wall. For this reason, resonant peaks will be relatively sharper for the heavyweight wall, leading to larger variations in transmission loss in this frequency range.

The sharpness of the structural modal peaks, and hence the increased transmission at a resonant frequency, is also affected by the degree of damping in the system (absorption coefficient). However, in practice, even high-mass cavity walls do not provide good sound insulation for long wavelengths at high energy levels (Dibble, 1997).

Window panes behave in a similar manner to walls. Vibrations in the glass pane are excited by the external pressure wave, and these are in turn passed on to the air inside the room as compressions and rarefactions.

However, for the case of a window set in an external heavyweight wall, the pane of glass has both a lower surface density and a lower bending stiffness than the surrounding wall structure, and will therefore act as a 'path of least resistance' to incident sound waves (Knudsen and Harris, 1978).

The transmission of sound into a room at low frequencies is further complicated by the modal characteristics of the room's sound field. Standing waves may be set up in a room if the frequency of an incoming sound wave is equal to an eigenfrequency of the room. The eigenfrequencies for a cuboid room may be determined using the following equation (Maluski, 1999):

$$f_{n_x,n_y,n_z} = \left(\frac{c}{2}\right)\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2}$$ [Formula 2.3]

where c is the velocity of sound in air ($\approx$ 340 m/s), L_x, L_y and L_z are the dimensions of the room (m), and n_x, n_y and n_z are integers.

For room standing waves, $f_{nx,ny,nz}$ represents the eigenmode for which there are n_x, n_y and n_z nodal planes of zero pressure perpendicular to L_x, L_y and L_z. The walls of the room are anti-nodal planes, where pressure is at a maximum.

At low frequencies, the eigenmodes of the room are widely spaced in frequency (Maluski, 1999). Because of the low modal density, the air mass in the room cannot be considered to be a diffuse, statistical sound field i.e. measured sound pressure levels can vary greatly depending on microphone position. Section 3.2 considers the implications of this for methods of measuring low frequency noise indoors.

The presence of damping in the room has the effect of reducing the amplitudes of the standing waves. If the boundaries of the room have high surface absorption coefficients, the resonant peaks will be broader and less sharp, and may shift down in frequency slightly (Bies and Hansen, 1988).

When a wall or window through which low frequency sound energy is passing has a structural resonance that is close in frequency to a modal frequency of the room within, then coupling may occur between the structural and acoustic modes, leading to enhanced transmission at that frequency (Maluski and Gibbs, 2000).

To summarise, a wall or façade of a dwelling may exhibit an overall trend of blocking high frequency sound more effectively than low frequencies. The room on the far side of the wall may respond favourably to excitation by low frequency sound, especially if a room mode is excited. The combined effect of these factors will be to enhance further the relative strength of low frequency component of sound passing from outside to inside a building.

2.5 TRANSMISSION OF VIBRATION THROUGH BUILDING STRUCTURES

Vibration in buildings due to incoming ground waves or an internal source may cause high levels of vibration and/or noise in parts of the house far removed from the source or point of entry (the basement slab for external ground waves). This is particularly likely if the frequency of the ground wave or internal source matches resonant frequencies of building structures.

There are several modes of propagation of vibrational energy through buildings. Longitudinal waves are analogous to P-waves in the earth (Section 2.3), and involve extensional/compressional strain parallel to the direction of propagation but no shear strain (Cremer et al., 1988). Thick beams may transmit longitudinal waves quite effectively.

Transverse waves may also occur, involving rotation of individual elements in planes perpendicular to the direction of propagation (shear strain) but no volume change. One example of transverse waves in buildings are torsional waves, which occur when a narrow beam is excited by a torque i.e. a moment whose axis coincides with the axis of the beam. In torsional waves, cross-sections of the beam rotate about its axis, with circumferential displacements increasing with distance from the beam axis. The wave then propagates along the length of the beam (Cremer et al., 1988).

The wave types discussed so far are not responsible for radiating large amounts of sound energy into the air. However, they may act as intermediate carriers of energy, which may be radiated elsewhere as a result of other wave types such as bending waves (Cremer et al., 1988).

Bending (or flexural) waves involve waves of flexure propagating parallel to the surface of the host structure, resulting in normal displacement of the surface.

In thin wall panels, bending waves are the primary means of transmission. The panels undergoing bending wave displacement may radiate significant quantities of sound energy into rooms.

Kudo et al. (1995) outlined a case study in which a water pump in the basement of a six-storey building caused disturbance in an office near the top of the building. It was determined that the noise was propagating through the building's structure.

Shear wave vibrations in the foundations, caused by the water pump, were generating longitudinal waves in vertical pillars supporting the upper floors of the building. Upon encountering joints in the vertical structures, such as floors and ceilings, the longitudinal waves were converted into bending waves. These bending waves in the ceiling of the office were found to be radiating sound waves that gave rise to the disturbing noise.

Jakobsen (1989) determined a set of typical transfer functions, based on vibrations from trains passing close by to buildings, for transmission of vibrations between a point on the ground and various positions inside the buildings. Different styles of building were considered, with various types of foundation and upper floor materials.

Figure 2.8, taken from Jakobsen (1989), displays the transfer function curve for a two-storey house with suspended wooden floors upstairs. The dB gain between a point on the basement floor and points near the centre of three rooms in the house, are plotted versus frequency.

This situation is similar to ones encountered by the author during the case studies described later in this thesis. The vibration amplifications observed by Jakobsen never exceeded much more than +20 dB i.e. a factor of 10. Therefore, if the measured vibration levels upstairs are greater than one order of magnitude higher than the basement levels, the likelihood is that the upstairs floorboard vibrations are caused by airborne excitation or an internal source, rather than groundborne waves in the basement slab emanating through the building structures.

According to Carman (1996), transfer function measurements on buildings yielded amplification factors in the range 3 to 6 and higher for wooden frame residences (wood floor supported by joists). This is consistent with Jakobsen's findings.

2.6 NOISE & VIBRATION CONTROL

The discussion so far has involved the mechanisms by which low frequency noise and vibration is created and how it is transmitted from its source into the rooms and/or structures of buildings. This section gives a brief outline of a range of noise/vibration control techniques and products that may be utilised either at the receiver (where complaints arise) or source positions. The purpose of this is to review, with reference to case studies from the literature, the effectiveness of the various methods in controlling low frequency noise and vibration in particular.

2.6.1 At Receiver

Conventional noise control measures utilise acoustic absorbers made of fibrous materials, but these are ineffective for low frequency noise unless very thick layers of material are used (Leventhall, 1997). This is not always practical in dwellings.

Benton and Leventhall (1982) point out that acoustic insulation that cuts out mid/high frequency noise can lead to a reduced overall sound level whilst actually increasing the sensation of loudness due to an increase in the proportion of sound energy in the low frequency range. Installation of double glazed windows may have this effect.

Vasudevan and Gordon (1977) suggest that noise control devices that act as mid/high frequency attenuators may even increase absolute levels of sound energy at low frequencies.

Cocchi et al. (1992) describe a case in which personnel in the control room of an industrial plant were disturbed by low frequency tonal noise emanating from a pump room, despite the fact that the control room was fitted with acoustic absorbers and mounted on vibration isolators. Workers in the pump room itself reported less annoyance, despite higher absolute levels of low frequency, as the noise levels at mid/high frequencies were also high in the pump room and this had a masking effect.

One subject in a case study by Vasudevan and Gordon (1977) installed a small fan in their bedroom to increase the sound levels in the mid/high frequency range in attempt to mask the low frequency noise. This alleviated the problem for the individual concerned, but is clearly not a viable long-term solution.

In a case study described by Vercammen (1992), a single frequency source was 'tuned' to shift the frequency away from a particular room mode. This achieved the desired effect of reducing the level of disturbance in the room, but such an approach may simply shift the problem to a different room/house where resonance may take place at the new source frequency.

All of the above examples serve to illustrate the fact that it is far better to eliminate or control low frequency noise/vibration emissions at their source. (Of course, this also illustrates the need for an experimental method capable of pinpointing precisely the source).

2.6.2 At Source

Possibilities for control of sound at source are many and varied and a detailed discussion is beyond the scope of this thesis. Among many possible references, *Woods Practical Guide to Noise Control* (Sharland, 1998) gives detailed descriptions of a wide array of noise/vibration control measures. Possibilities include the use of insulating partitions (single or double leaf), resonant absorbers, lining of ductwork with absorbent materials, installing splitter attenuators in ducts and mounting machinery on vibration isolation mounts.

For tonal problems, resonant absorbers may be utilised that are designed to absorb sound at a specific frequency (Leventhall, 1997).

Sondergaard (1997) notes that low frequency noise/vibration problems are better (and more cheaply) solved in the planning phase. However, it is not always possible to identify the characteristic frequencies responsible for structural or room mode resonances prior to the construction of an item of plant. In such instances, counter-measures can only be implemented 'post hoc' (Kudo, 1995).

Active noise control (ANC) is a relatively recent development in noise control, which uses a digital system to generate an opposite (180° phase-shifted) replica of the noise. The noise and 'anti-noise' then cancel each other out by destructive interference (Leventhall, 1997).

Active noise control is actually technically easier for low frequency noise than for higher frequencies, because sound waveforms become more difficult to reproduce as their wavelength decreases and the waves become less spatially stable. The anti-noise source must be placed close to the noise source (i.e. within about a tenth of a wavelength) for the ANC process to be effective. For noise at 100 Hz, this means that the distance between the two opposing sources must be ~30 cm, which is feasible, whereas for 400 Hz noise the separation must be only a few centimetres, which may not be feasible. In addition, an error of a few centimetres in positioning the anti-noise source is less important for low frequency (long wavelength) waves, but can be critical for high frequency (short wavelength) sound, and may even cause constructive rather than destructive interference to occur.

Active noise control techniques could become more commonplace in the future as the technique is developed further.

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Fig. 2.1 (after Kinsler et al, 2000) - typical values for air absorption.

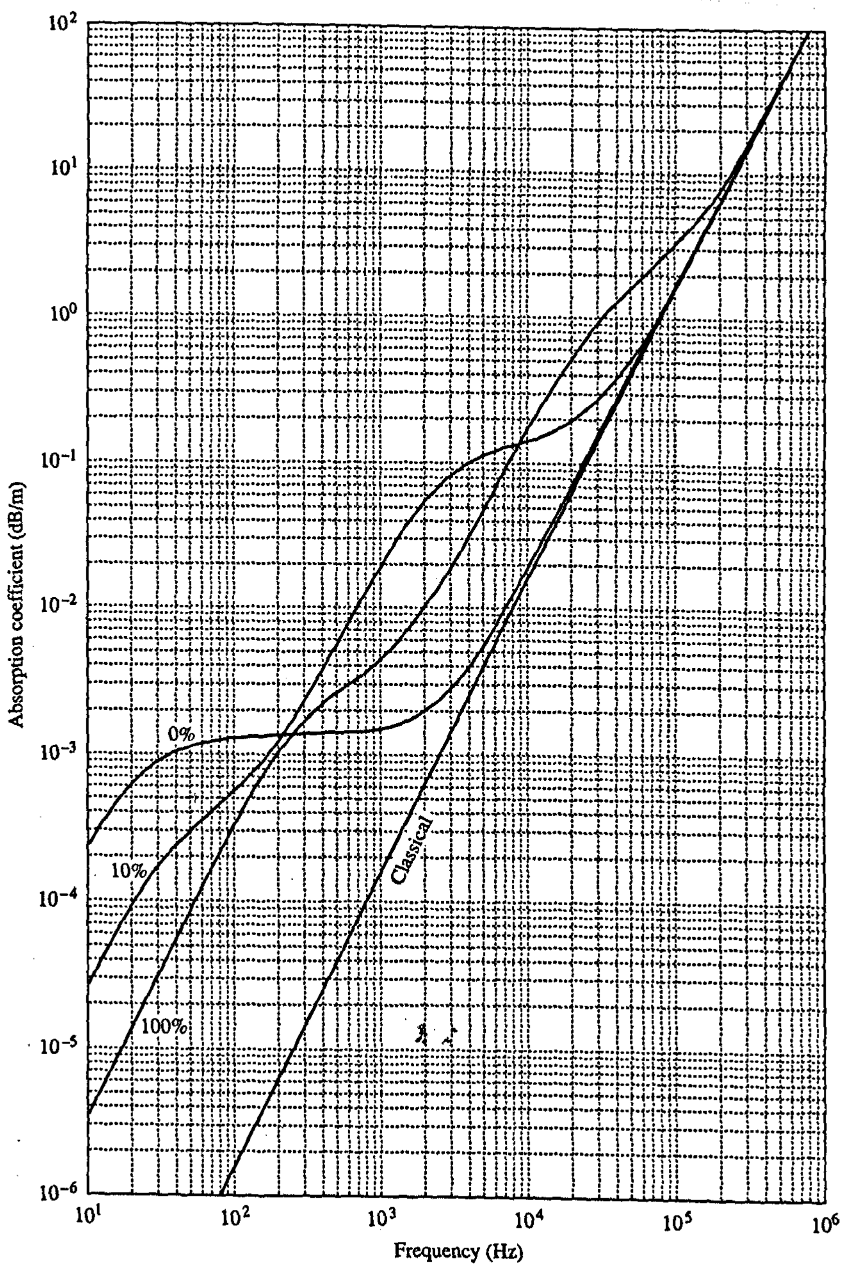
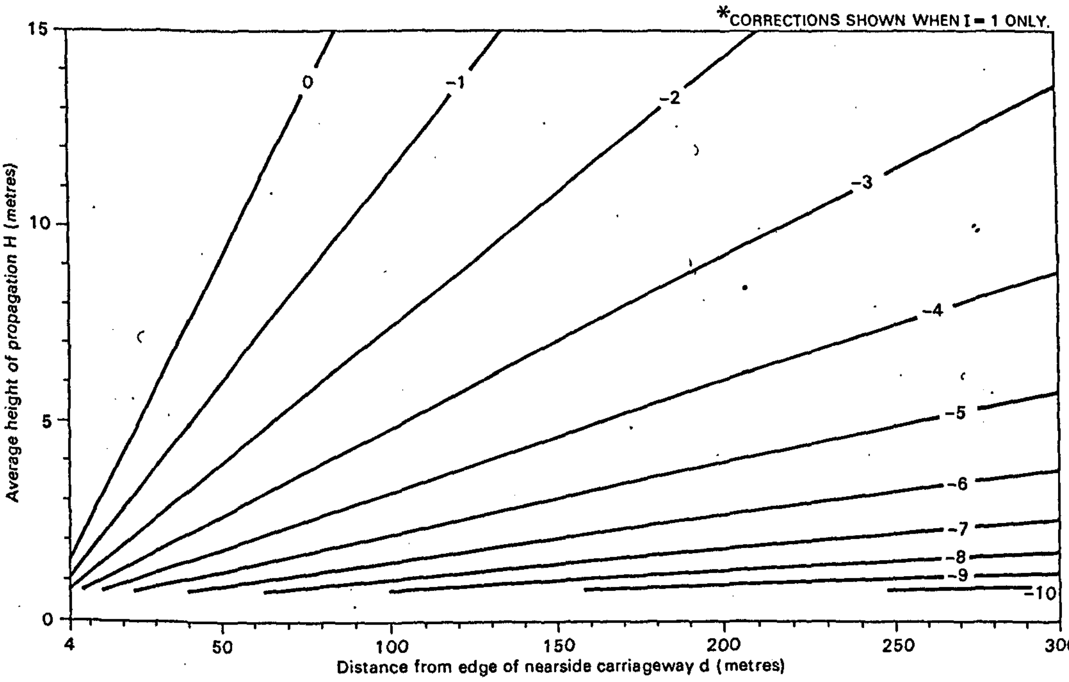


Figure 8.6.2 Absorption of sound in air at 20°C and 1 atm for various relative humidities. (After Bass et al., *op. cit.*)

Fig. 2.2 – ground absorption as a function of distance, based on road traffic noise (Dept. of Transport, 1988)



For $0.75 \leqslant H < \frac{d+5}{6}$; CORRECTION = $5.2\,I\ \mathrm{LOG}_{10}\left(\frac{6H-1.5}{d+3.5}\right)$ dB (A)

For $H < 0.75$ CORRECTION = $5.2\,I\ \mathrm{LOG}_{10}\left(\frac{3}{d+3.5}\right)$ dB (A)

For $H \geqslant \frac{d+5}{6}$ CORRECTION = 0

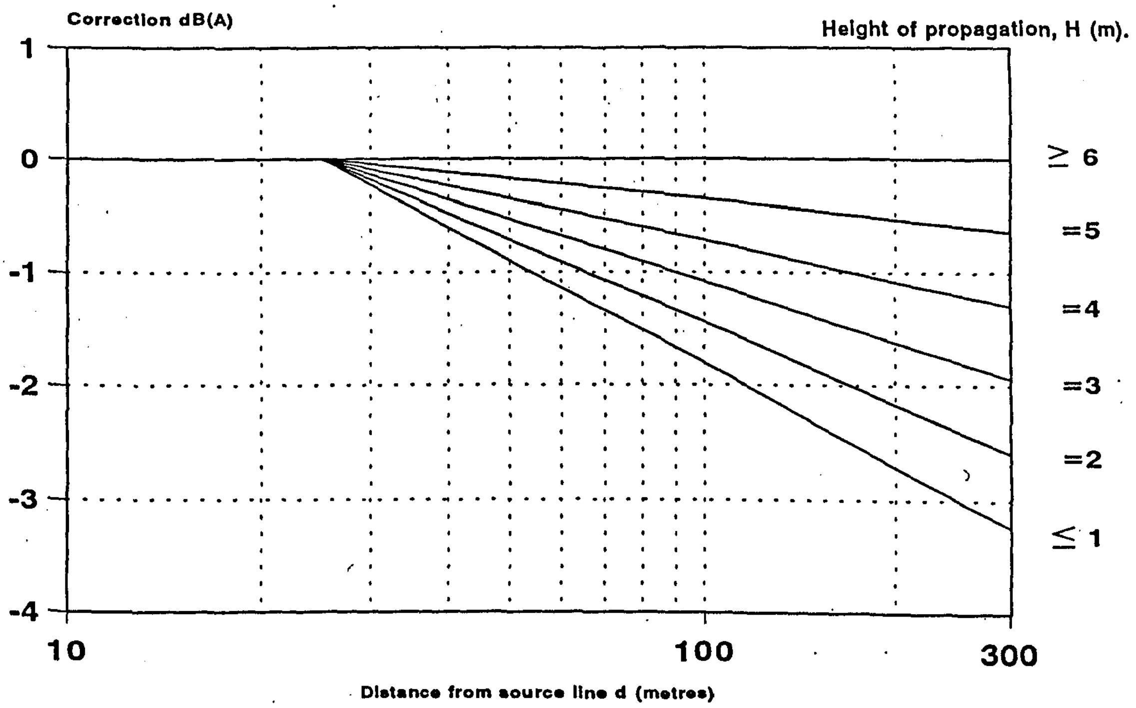
Valid for $d \geqslant 4$ metres

Fig. 2.3 – ground absorption as a function of distance, based on railway noise (Dept. of Transport, 1995)

GROUND CORRECTION AS A FUNCTION OF THE HORIZONTAL DISTANCE, d, MEAN HEIGHT OF PROPAGATION, H, AND THE PROPORTION OF ABSORBING GROUND, I .

The chart shows the correction when I = 1

The formulae below the chart give the correction for $0 < I < 1$



For $10 \leq d \leq 25$m Correction = 0 dB(A)

For d > 25m:

- For $1.0 < H < 6.0$m Correction $= -0.6 I (6 - H) \log_{10}(d/25)$ dB(A)
- For $H \leq 1.0$m Correction $= -3 I \log_{10}(d/25)$ dB(A)
- For $H \geq 6.0$m Correction = 0 dB(A)

Fig. 2.4 (after White, 1975) – effect of wind gradient on sound propagation

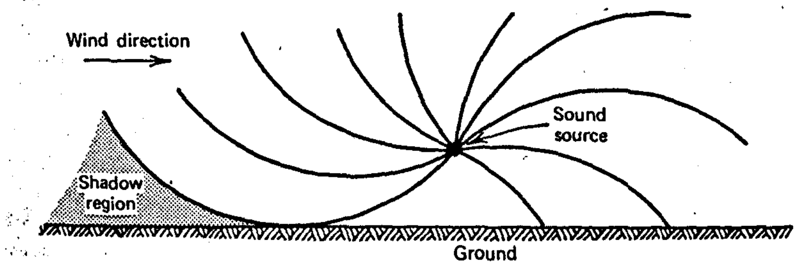


Fig. 2.5 (after White, 1975) – effect of normal and inverse temperature gradients on sound propagation

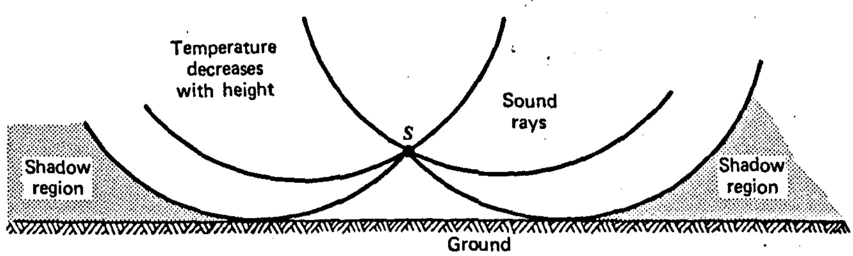


Figure 9*a* Upward bending of sound rays with normal temperature gradient.

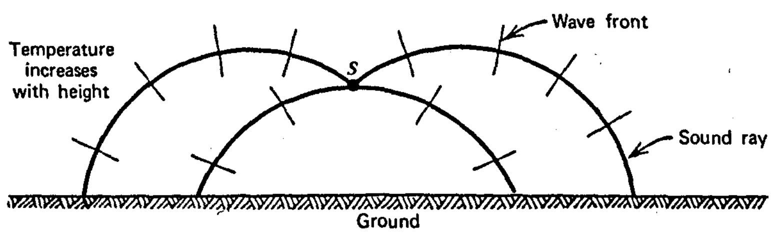
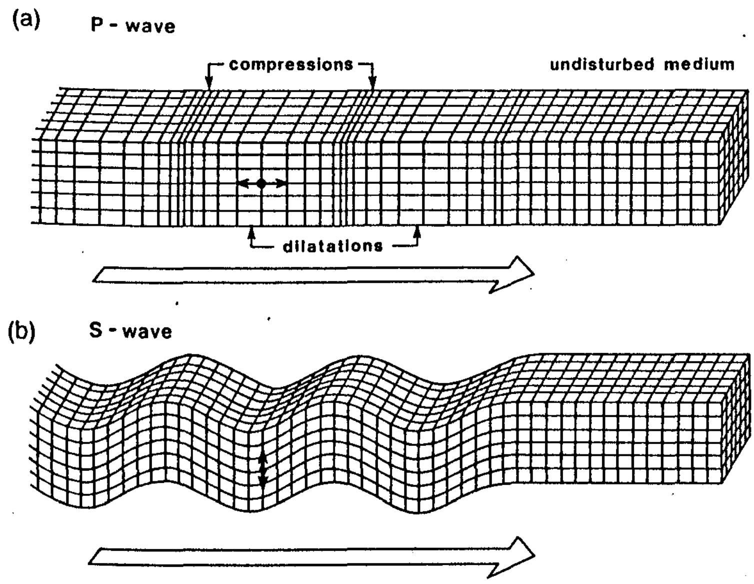
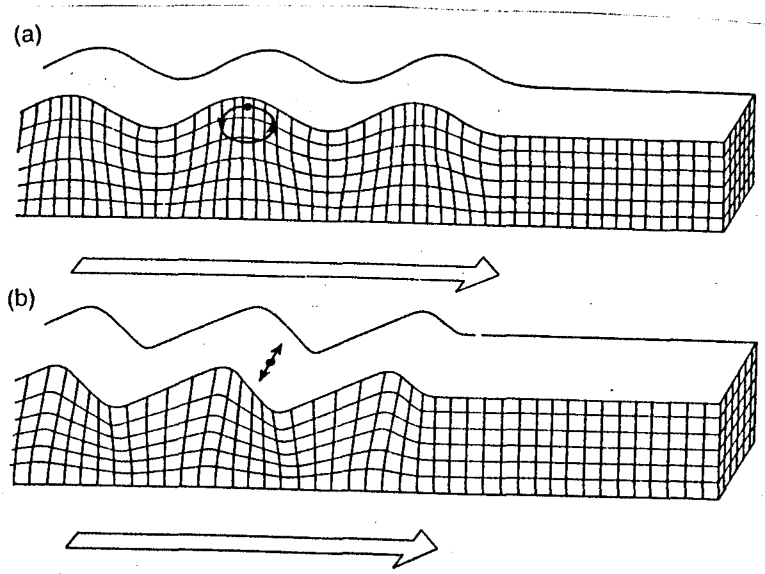


Figure 9*b* Downward bending of sound rays because of a temperature inversion.

Fig. 2.6 (after Kearey and Brooks, 1991) - elastic deformations and ground particle motions associated with the passage of body waves and surface waves through the earth



Elastic deformations and ground particle motions associated with the passage of body waves. (a) A *P*-wave. (b) An *S*-wave. (From Bolt 1982.)



Elastic deformations and ground particle motions associated with the passage of surface waves. (a) A Rayleigh wave. (b) A Love wave. (From Bolt 1982.)

Fig. 2.7 (after Bies and Hansen, 1988) - sound transmission loss across an isotropic panel as a function of frequency

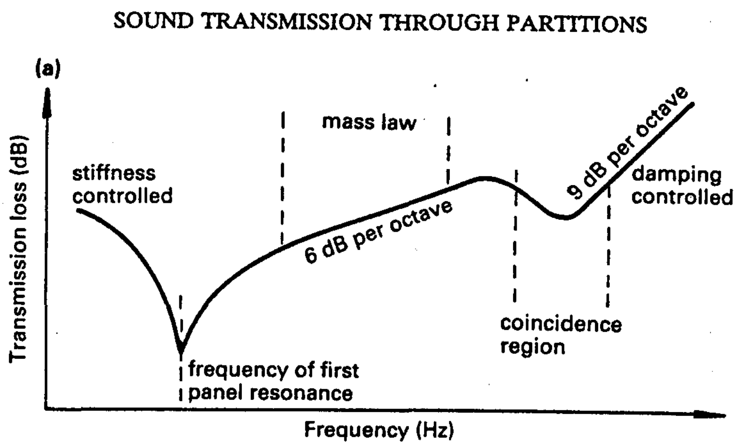
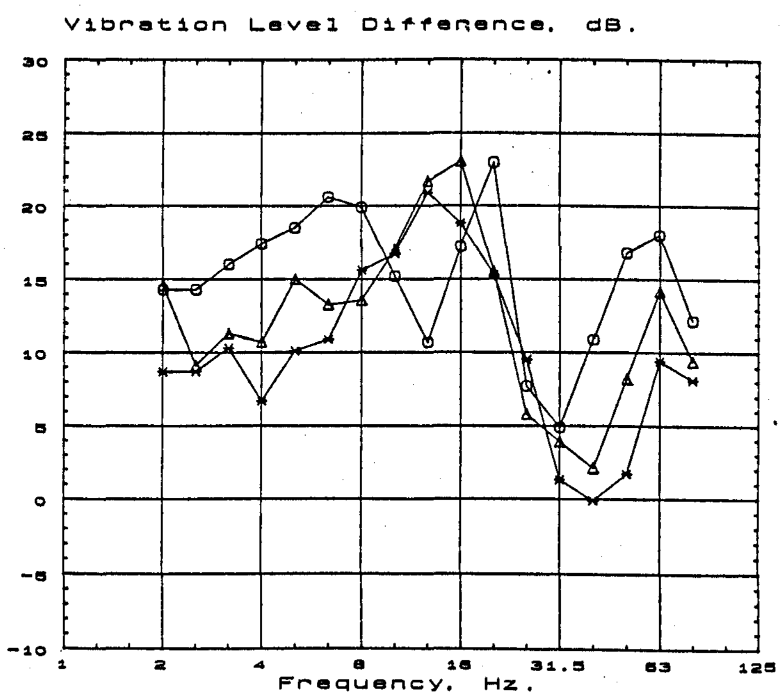


Fig. 2.8 (after Jakobsen, 1989) - transfer functions for vibrations propagating from the ground floor to the suspended wooden floor of a two-storey house



Transmission functions between a point on the basement floor and points near the midpoints of the floors of three rooms in a bungalow.

3 DEVELOPMENT OF THE MEASUREMENT STRATEGY

Measurement of low frequency noise and vibration is fraught with difficulties of a physical origin that do not affect measurement of noise at mid/high frequencies. This is reflected in the relatively small number of successful case studies into low frequency noise reported in the literature.

In developing the integrated acoustic/microseismic technique, the author took account of the shortcomings involved in applying standard acoustic techniques to low frequency noise/vibration problems.

This chapter describes the development of the measurement strategy with reference to ways in which it is favourable over standard techniques. Published case studies are used to illustrate some of the principles involved.

3.1 OUTDOORS VERSUS INDOORS ACOUSTIC MEASUREMENTS

The British Standard BS 4142 (1990) – "Rating industrial noise affecting mixed residential and industrial areas" – states that noise recordings must be made outdoors, 3.5 metres from any reflecting structure. However, room resonances (Section 2.4) have a strong effect at low frequencies, and such effects are completely excluded from measurements taken outside. Consequently, BS 4142 does not provide an accurate estimate of the actual sound levels in buildings, especially at low frequencies.

According to Vercammen (1992), if tones in the external noise spectrum coincide with peaks in the transmission loss function (see Section 2.4), then the outside measurements will underestimate true sound levels inside the building. Conversely, outside measurement will overestimate the indoor sound levels if no such coincidence occurs.

The methodology developed in this thesis was based on indoor measurements for these reasons.

It is possible to employ a three-element microphone array to determine the unknown source of a low frequency noise by application of sound intensity techniques (Vasudevan and Leventhall, 1989; Pawlaczyk-Luszczynska, 1996). However, these must be conducted in free-field conditions i.e. outside, with all the practical considerations that entails.

It is hoped that the proposed method will allow determination of source without the need for outdoor measurements. Chapter 9 examines whether direction to source may be determined on the basis of indoor measurements using polarisation information extracted from three-component seismometer data.

3.2 EFFECT OF ROOM POSITION ON ACOUSTIC MEASUREMENTS

When taking conventional sound level measurements indoors, standard procedures involve placing microphones at positions at least 1.2 metres from all room boundaries (Maluski, 1999). This requirement is based on the assumption, for mid/high frequency sound, that the sound field within the room approximates to a diffuse field.

In a diffuse (statistical) sound field, sound pressure levels are in theory equal at all points. In reality, a pressure build-up occurs at the walls due to the boundary conditions. Therefore microphone positions for measuring mid/high frequency sound levels are chosen to be away from the walls.

This does not apply to indoor low frequency noise, for which wavelengths are of the same order of magnitude as the room dimensions. Standing waves may be set up and the sound field is resonant and non-statistical. A microphone placed at one position may be at a nodal point, where the measured sound levels will be low relative to other positions in the room. Thus, applying standard measurement methods will underestimate the effects of low frequency noise on the sound field in rooms.

Simmons (1997) proposes a new method for the measurement of low frequency sound indoors. Sound levels are measured at three positions: two positions being chosen as the most representative positions with respect to use of the room (as pointed out by the occupants), the third position being close to one of the corners. (The loudest C-weighted corner may be determined by a quick survey of all possible corner positions using a hand-held sound level meter). The energetic average of these three positions is then calculated.

Simmons applied this procedure to a limited number of rooms and laboratories and found that it gave a reproducibility of about 6 dB in third-octave bands (with 95% confidence).

The procedure has three major advantages over other methods considered by Simmons (1997):

(1) High reproducibility;

(2) The results are representative to habitants or users of the room;

(3) The method is quick and easy to perform.

When developing the integrated acoustic/microseismic technique the method of utilising three microphone channels and taking the energetic average as described above was considered. However, the data storage system available at the time could record data in parallel from a maximum of six channels. Four of the channels were connected to transducers other than microphones, and so it was not possible to do this.

The reported measurements outlined in this thesis made use of a single microphone, at a chosen position representative of the use of the room. This does not preclude the possibility of utilising Simmons' technique alongside microseismic data collection using a more modern data acquisition system that may now be available i.e. the potential may now exist to employ the three-microphone method proposed by Simmons in parallel with microseismic monitoring.

3.3 VIBRATION MEASUREMENTS

It may not be known at the outset whether the disturbance giving rise to annoyance is due to low frequency noise or vibration. Ideally, vibration measurement should be carried out in parallel with measurement of sound levels, via a multi-channel data-logging device. In this way, direct comparison of airborne sound and groundborne vibration levels may be carried out, which may allow the determination of propagation path(s) of the disturbance.

The methodology developed in this thesis utilised multi-channel data acquisition, taking signals from a range of pressure and vibration transducers.

Even for evidently airborne problems, it is useful to measure ground vibration levels, as being able to rule out structural damage to the property under scrutiny is often of reassurance to complainants.

3.4 LONG-TERM UNMANNED MONITORING

Low frequency noise/vibration problems are often intermittent and unpredictable in nature. Meteorological and other environmental factors may greatly influence the levels of low frequency sound and vibration recorded within dwellings. In addition, the source itself may not output constant levels of sound power or vibration.

In a case study by Vasudevan and Leventhall (1989), low frequency noise was inaudible on certain nights at the complainant's house despite the source being known to be active at that time. This was explained by the prevailing wind conditions. When the source was downwind from the receiver, the noise levels were reduced compared with levels during still conditions (see Section 2.2).

This type of environmental change is not predictable in advance and has the potential to affect the outcome of investigations into low frequency noise. Such experiments must therefore coincide with both an active source and favourable environmental conditions. This is an elusive combination that necessitates long periods of monitoring in order to diagnose the cause of low frequency noise/vibration problems.

Furthermore, taking measurements over long periods allows narrow frequency resolution to be achieved. Vasudevan and Leventhall (1989) state that "when dealing with an unknown, low level, low frequency noise problem, it is vital to obtain narrowband spectral analysis of the noise at times when it is clearly audible to the complainant."

In order to distinguish and characterise low frequency noise/vibration due to a problematic source, it is helpful to take measurements during periods of low background noise, such as late at night or early in the morning. Experience of low frequency noise problems shows that this is also the time when complainants' subjective annoyance levels are highest (see Section 4.1.1). Correlating measured sound levels with periods of relatively high subjective annoyance is an important aspect of the analysis (Vasudevan and Gordon, 1977).

An unmanned monitoring system, employed during periods of low background noise, would be useful for tackling these types of problems. A further advantage of unmanned monitoring is that the instruments do not detect movement on the part of the experimenter(s).

Therefore, to maximise the prospects of successfully resolving low frequency noise/vibration problems, the technique developed by the author employed periods of unmanned monitoring over long periods when background noise levels were low.

(Note that although unmanned monitoring was the primary method of data acquisition, the system was sufficiently flexible and portable to allow manned measurements on-site; this proved to be useful in some instances in the field.)

3.5 TIME & FREQUENCY DOMAIN ANALYSES

Low frequency noise/vibration problems are best approached by studying the recorded data in both time and frequency domains.

Frequency domain analysis is particularly important if the noise/vibration contains characteristic spectral components, for example due to rotating machinery. Matching of tones in the measured frequency spectra, with speeds of rotation of specific items of plant, may provide a way of linking cause and effect.

A case study by Ellison (1991) successfully investigated a low frequency noise/vibration problem caused by low speed rotating machinery close to residential properties. Frequency analysis and tone-matching was a crucial part of the study.

Motylewski et al. (1994) also report a case in which analysis of infrasonic noise spectra and their spatial distribution, allowed the detection of two dominant sources within an industrial zone and the determination of the ranges of influence of these sources in a nearby residential area. A set of cooling towers proved to have the widest range of influence in this case.

Recording time histories allows time-variant aspects of the sound/vibration field to be studied that would not be observed by recording frequency spectra alone. This is because it is not possible to reconstruct a time series from a magnitude-frequency spectrum without the corresponding phase spectrum.

The methodology developed by the author involved collection of data in the form of time histories. Throughout the case studies detailed in the thesis, a variety of useful signal processing analyses were conducted in both time and frequency domains, which were only possible because of this approach.

3.6 MICROSEISMIC DATA ACQUISITION

Standard (macro)seismology involves measuring the earth's vibration levels over lengthy periods, using seismometers which contain three mutually orthogonal geophones. The results are captured on multi-channel recording systems capable of storing vast amounts of data utilising a high dynamic range. This is necessary in order to study the three-dimensional waveforms generated by earthquakes, which are intermittent, highly unpredictable impulsive events with high signal-to-noise ratios.

The high sensitivity of modern geophones allows minute ground vibrations, including those with a human origin, to be detected and distinguished above the internal background noise of the measurement chain. This is the basis of microseismology, which has a wide range of applications. One such application, carried out by Prof. Peter Styles at the University of Liverpool, is the monitoring of underground stress fields in regions with high levels of mining-induced seismicity (Styles et al., 1997).

3.7 A NEW METHOD FOR MONITORING LOW FREQUENCY NOISE & VIBRATION

This thesis is based on the application of microseismic techniques and principles to the detection of environmental low frequency noise and vibration.

The combination of long-term unmanned monitoring, simultaneous multi-channel time history recordings, wide dynamic range and versatile signal processing tools available using this approach, would appear to be ideally suited to tackling such unpredictable, intermittent and complex problems.

The methodology is described in detail in Chapter 5.

The following quote from Lundin and Ahman (1998), illustrates the need for improved instrumentation for attempting to solve low frequency noise problems:

"From a technical point of view we conclude that finding the sources to this kind of noise requires considerable resources, including the use of measuring instruments often not available to the local health protection authorities."

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4 ASSESSMENT OF LOW FREQUENCY NOISE & VIBRATION

Although the primary objective of this thesis was to develop a new measurement technique, this could not be conducted in isolation from the problem of psychoacoustic interpretation. Firstly, the measured data must be compatible with a suitable assessment method. Secondly, in order to bring meaning to the recorded data, one must have some idea as to whether what has been measured is significant or not.

There are two issues in interpretation of recorded levels:

- Comparison with subjective response (psychoacoustics);
- Assessment with respect to objective criteria.

This chapter outlines a few aspects of subjective response to low frequency noise/vibration, and discusses the objective criteria against which recorded levels may be assessed.

The two issues are linked, as the assessment criteria were originally devised on the basis of subjective responses (although how well they match is a subject of debate). In effect, the criteria are an attempt to quantify in objective terms the subjective response of those exposed.

4.1 SUBJECTIVE RESPONSE - PSYCHOACOUSTICS

The physical complexities involved in measuring low frequency noise levels are compounded by other problems of a psychological nature.

Assessing low frequency noise on the basis of subjective responses is clearly going to be an inexact science.

Berglund et al. (1996) describe several 'methodological issues' affecting field studies where inferences are drawn from cross-sectional studies of subjective response to low frequency noise. Variations in response between subjects may owe more to variations in individual sensitivity, than to actual variations in source output.

The reliability of such assessments may be improved by comparing the subjective responses of each individual over relatively long periods. This is consistent with the need (discussed in Section 3.4) for long-term monitoring of physical data.

Loudness response measurement (drawing up contours of equal loudness) is a complex field of psychoacoustics, detailed analysis of which is outside the scope of this thesis.

However, the subject cannot be overlooked completely, as the standard A-weighting techniques used for assessing sound pressure levels (Section 4.2) are based on equal loudness contours set out in ISO R226 (1961), and shown in Figure 4.1.

A few aspects of psychoacoustics that have a bearing on low frequency noise problems are now outlined and illustrated by reference to published case studies.

4.1.1 <u>Effect of Character of Low Frequency Noise on Level of Annoyance</u>

For low frequency noise, annoyance reactions depend upon the character of the noise as much as, or more than, the absolute sound pressure level (Piorr and Wietlake, 1990). Low frequency noise that is tonal, fluctuating or unbalanced (with a relatively high proportion of energy in the low frequency range) tends to be more annoying.

Annoyance levels are particularly high in cases where masking effects due to background noise in the mid-high frequency range are low (Vasudevan and Leventhall, 1989).

Mirowska (1998) found that residents in several case studies found tonal low frequency noise annoying at levels comparable with the threshold of perception, but tolerated broadband traffic noise at considerably higher levels.

Lundin and Ahman (1998) state that exposure to time-varying low frequency noise leads to stronger effects than constant level noise.

According to Ellison (1991), time-variability of a low frequency signal, particularly 'beating', produces very attention-demanding effects.

In a case study by Vasudevan and Leventhall (1989), the occurrence of two low frequency tones separated by only 2 Hz gave rise to beating – and a most unpleasant throbbing sensation.

The additional annoyance caused by noise in the low frequency range, over and above that of more 'normal' sounds, may relate to the fact that in nature, low frequency noise (e.g. thunder) tends to be associated with danger (Vercammen, 1992).

4.1.2 Tightness of Loudness Contours for Low Frequency Sound

The bunching together of the loudness contours at low frequencies (Figure 4.1) means that for an individual, a slight increase in level can cause a big increase in loudness level (Persson, 1997; Landstrom and Pelmear, 1993).

The loudness contours apply to the average human. An individual will have their own set of appropriate loudness contours. At high frequencies, the mean contours are widely spaced and flat, so individual variations in sensitivity will have little effect on the subjective perception of a particular noise. At low frequencies, however, the equal loudness contours are steep and tight (Figure 4.1). Inter-individual sensitivity variations may be such that low frequency noise at a particular level may be inaudible for one person, but relatively loud for the next.

In a case study by Vasudevan and Leventhall (1989), no other person in the complainant's family was affected by the low frequency throbbing noise that was causing great distress to the complainant.

This large difference in individual susceptibility may contribute to feelings of helplessness and isolation. Vasudevan and Gordon (1977) mention cases in which lack of sympathy on the part of the investigators caused additional frustration for complainants.

4.1.3 Poor Directionality Capability of the Human Ear for Low Frequency Sound

Humans cannot determine the direction of origin of low frequency sounds in the way that they can for higher frequencies (Kinsler and Frey, 1950). This may be exacerbated in rooms where standing wave patterns mean that the direction of the sound source is not clear. Because the direction of the source cannot be determined, the human brain cannot habituate (grow accustomed on a subconscious level) to low frequency noises. This contributes to feelings of helplessness.

Benton and Leventhall (1994) state that coping mechanisms break down as the brain can neither locate the low frequency noise by increasing sensitivity, nor habituate by decreasing sensitivity. Essentially, low frequency noises are difficult to 'ignore'.

Perceived stimulus control for general mid/high frequency noise can help to reduce stress levels; there is a lack of perceived stimulus control for low frequency noise (Benton and Leventhall, 1994).

4.1.4 Build-up of Sensitivity to Low Frequency Noise with Time

Sensitivity to low frequency noise appears in some individuals to build up over time, until in some extreme cases an individual may claim to still be able to hear a low frequency noise when it is known by an independent observer to have been switched off.

Nagai et al. (1989) reported that residents near a newly built superhighway first complained about rattling of windows, then started to experience sleep disturbance. Insomnia and weariness built up steadily, and many of the residents ended up being highly sensitive to infrasound. Thus, infrasound which formerly had no adverse effects on certain individuals, built up to become a stressor.

In a case study by Lundin and Ahman (1998), a fridge that was found by means of a switch-off test to be responsible for a 49 Hz tonal noise in a bedroom, was replaced with a quieter model. The complainant's subjective annoyance/loss of sleep persisted, but symptoms were reduced when the resident slept elsewhere. The resident in this case now automatically associates the onset of disorders to her presence in the flat.

Motylewski et al. (1994) state that the duration of infrasonic exposure seems to be an important factor for the evaluation of acceptability.

4.2 ASSESSMENT OF LOW FREQUENCY NOISE MEASUREMENTS

Neither British nor International Standards dealing specifically with low frequency noise problems exist as of yet.

Conventional methods of assessing environmental noise are largely based on A-weighted sound levels. The A-weighting filter largely de-emphasises low and high frequencies in an attempt to account for the varying sensitivity of the human ear with frequency. A single value may then be used to represent the entire spectrum, in units of dB(A).

The A-weighting curve is based on an inversion of the 40 phons equal loudness contour, and is shown in Figure 4.2.

However, most researchers into low frequency noise now agree that dB(A) values are poor indicators of annoyance in cases where there is a high amount of energy in the low frequency range (Persson, 1997; Piorr and Wietlake, 1990; Broner and Leventhall, 1983; Mirowska, 1998; Cocchi et al., 1992).

According to Mirowska (1998), until a new index is developed, that better responds to low frequency tones, assessment of the whole noise spectrum is necessary for cases involving low frequency noise.

Several authors have proposed alternative low frequency noise assessment techniques (e.g. Vercammen, 1989; Mirowska, 1995; Persson, 1997), but to date the only one that has been incorporated into a national standard is that put forward by the German researchers Piorr and Wietlake (1990).

Piorr and Wietlake (1990) give limiting values for third-octave band levels in the range 10-100 Hz. The night-time limits correspond to the 50% audibility threshold, and only apply for low frequency noise of an 'unusual' character, that is:

- Low frequency noise with significant tonal components;
- Low frequency noise of a strongly fluctuating nature;
- Low frequency noise in an area that otherwise has very low background noise levels (i.e. an unbalanced spectrum dominated by low frequency noise).

The limits given in Piorr and Wietlake (1990) formed the basis of the German national standard DIN 45680 (1997).

The present author used the recommended limits in DIN 45680 to assess the low frequency noise problems described in this thesis. The current legal status of this approach in the U.K. is unclear.

Piorr and Wietlake also give a useful rule-of-thumb for making a preliminary assessment of the potential impact of low frequency noise in a particular case: if the difference between the C-weighted and A-weighted sound pressure levels (see Figure 4.2), as measured by a standard sound level meter, is greater than 20 decibels, then it is recommended that a more detailed frequency analysis be carried out; if the difference is less than 20 dB, the possibility of low frequency noise having a major contribution may be discounted.

4.3 ASSESSMENT OF VIBRATION MEASUREMENTS

The British national standard BS 6472 (1992) provides general guidance on human exposure to building vibration in the frequency range 1 Hz to 80 Hz, including limiting vibration levels that may give rise to adverse comment in various situations. The lowest of these levels supposedly correspond to the human threshold of feeling, and the curves giving threshold values as a function of frequency are known as base curves (there are separate base curves for horizontal and vertical vibration).

BS 6472 is widely regarded as having a number of shortcomings, and is currently undergoing revision by a BSI Committee (private correspondence, D. Trevor-Jones, 2000). One of the main problems with the standard is that it is not specific enough on how the base curves were determined and how the recorded data should be compared with them.

Base curves for root-mean-square velocity or acceleration (vertical and horizontal) are laid out in BS 6472, in the form of a table of vibration limits at third-octave band centre frequencies between 1 and 80 Hz (1 Hz, 1.25 Hz, 1.6 Hz, 2Hz, ... 40 Hz, 50 Hz, 63 Hz, 80 Hz). The standard recommends that unfiltered time histories be recorded, "from which any desired value can later be determined".

However, the standard does not make clear whether the recorded time histories should be converted into narrow band frequency spectra in order to directly compare measured vibrations with the recommended limits; or whether third-octave band vibration levels should be calculated.

A calculated third-octave band level will sum together all the energy within that frequency band, leading to a curve of recorded vibration levels that is more likely to exceed the BS 6472 limiting curve, than a narrow band frequency spectrum derived from the same time history. This is especially true for broadband vibrations or tonal vibrations with low signal/noise ratios.

However, the BS 6472 limits were used in the case studies outlined in this thesis, due to the apparent lack of an alternative.

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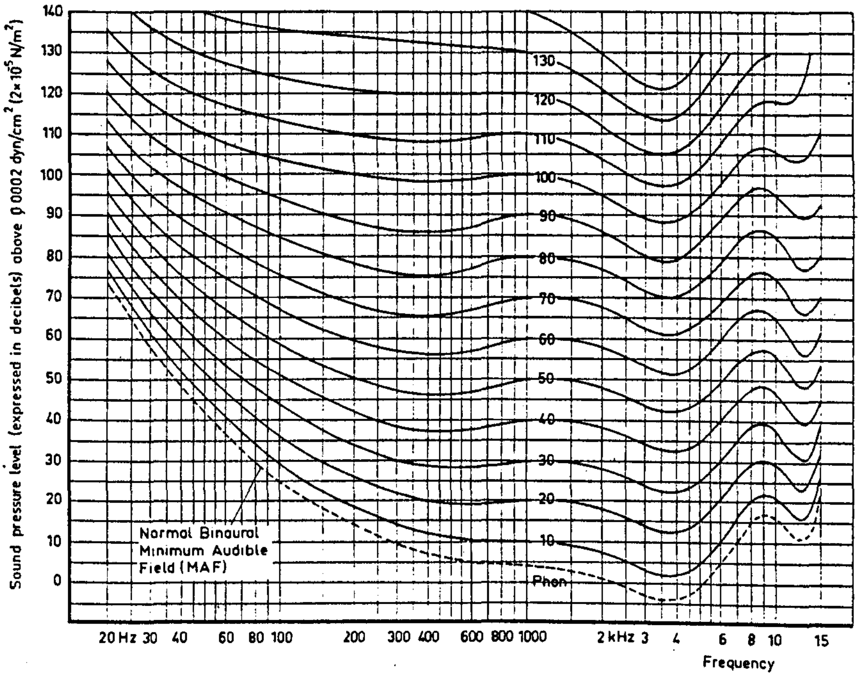
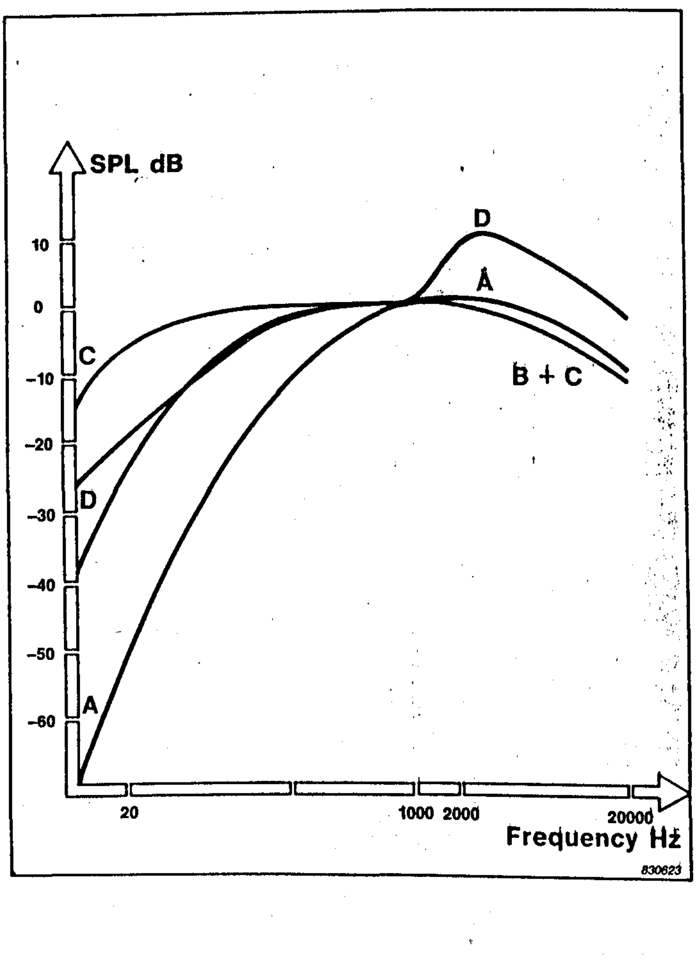
Fig. 4.1 – equal-loudness contours for pure tones of the average human aged 18-25 in the free-field (ISO R226)



Equal-loudness contours for pure tones and normal threshold of hearing for persons aged 18–25 years. using free-field listening. (ISO Recommendation R226.)

Fig. 4.2 – A-weighting curve, based on an inversion of the 40 phons equal-loudness contour



5 METHODOLOGY

5.1 INSTRUMENTATION

A number of case studies were investigated in which low frequency noise and/or vibration was causing complaints at one or more locations in residential areas. In each case, early interviews with residents suggested that the noise was intermittent and unpredictable. Therefore, a strategy of long-term unmanned monitoring was adopted, as opposed to shorter periods of manned monitoring.

Noise and vibration monitoring equipment was set up within the dwellings of complainants. In each case, a large array of equipment was utilised in order to achieve comprehensive coverage of the low frequency sound and vibration fields within the house.

The dimensions and orientation of the rooms in which monitoring took place were noted, along with any other salient features of the properties such as window positions and dimensions.

5.1.1 Vibrosound System

The bulk of the data were recorded in upstairs bedrooms. This is where annoyance due to low frequency noise and vibration tends to be most acute, as sleep disturbance is one of the major symptoms in such cases.

Data were logged on a six channel 24-bit A/D recording system with a maximum bandwidth of 0-500 Hz. The datalogger utilised is known as a Vibrosound SP1 and is made by MAGUS Electronics of Sandbach, Cheshire, to the specification of Professor Peter Styles.

The a.c. outputs from a highly sensitive three-component seismometer, a microphone and accelerometer were all fed into the Vibrosound.

The seismometer (a Lennartz LE-3D/1s), which contains three mutually orthogonal geophones (one vertical) each with a flat frequency response from 1-100 Hz, was mounted on the bedroom floorboards. It was aligned to point north with the use of a compass, and to sit horizontally by using adjustable legs and a small spirit level bubble set into the seismometer mounting. Power was provided by a simple 9-volt laboratory power supply.

The microphone used was a B&K type 4165, which has a flat frequency response from ~1-2 Hz to ~1000 Hz. It was powered by a B&K type 2807 power supply along with a B&K type 2619 emitter-follower amplifier.

The microphone was mounted on a tripod, preferably at the room position where low frequency sound levels are loudest (see Section 3.2). The 'loudest position' can be indicated subjectively by the noise complainant or determined objectively by a quick scan of the room using a hand-held sound level meter with third-octave band filter set attached.

The accelerometer used was a B&K type 4371, with a flat frequency response from d.c. to 10 kHz. This was mounted on a windowpane using beeswax (the choice of position is discussed in Chapter 8), and powered by a charge amplifier (Environmental Equipment type 2022). The charge amplifier's frequency response is flat within 10% between 1.5 Hz and 20 kHz.

The Vibrosound datalogger was set to record the inputs from the sound and vibration transducers at a sampling rate of 250 Hz. This gives a Nyquist (maximum measurable) frequency of 125 Hz; in reality, an inbuilt low-pass anti-aliasing filter gave an upper frequency limit of around 100 Hz.

The dynamic range of the Vibrosound is > 118 dB, which allows velocities as small as ~1 nm/s and as large as ~100 mm/s to be measured. Unlike sound pressure level meters, there is no need to shift the dB range of the Vibrosound recording system between the measurement of very loud (e.g. pistonphone calibrator) and very quiet sounds.

The data were recorded on 20 Mbyte PCMCIA flash cards in the form of individual time series 'events', each of which ordinarily had a duration of ten seconds. This is the maximum possible event length, though shorter recordings are possible using the Vibrosound.

The event recordings could be triggered manually, or an inbuilt timer could be set to record at regular intervals (multiples of 1 minute). The shortest possible interval between recordings using the Vibrosound is 1 minute; thus the maximum possible temporal coverage is 1/6th (ten seconds in every minute).

Huge numbers of data events could be collected by this system. Each 20 Mbyte flash card could record almost 400 ten-second events, and two flash cards were usually available. Once set up, the system was simple enough that the residents could swap flash cards themselves, once one card had filled up (as notified by an inbuilt screen prompt). Thus, almost 800 event recordings of ten seconds in length could be recorded by the unmanned system, without the need for the author to return to the site.

The system could also be switched off and back on and would resume recording automatically without system reset, allowing the residents discretion as to when they thought recordings would be most useful e.g. periods when the disturbance was subjectively loud, or at night when traffic levels and movement within the house were reduced.

The Vibrosound recorded the date and time of the start of each event in a log file, which was used during subsequent analysis in conjunction with the individual event files.

5.1.2 DV-1 System

Vibrations were also measured in the ground floor slab using a Geosense DV-1 three-component seismometer with direct PC interface. The frequency response of the DV-1 is flat in the range 1-135 Hz. The DV-1 seismometer was mounted downstairs on a suitable solid surface with direct connection to the foundations of the house.

A computer program called *triseisa* and supplied by Geosense was set to continuously record the output from the DV-1 seismometer whenever the PC was switched on. The residents could therefore choose the times when recording occurred (usually night and/or periods when the disturbance was relatively loud).

The program *triseisa* saved the constant stream of data as event files consisting of time series of 64 seconds duration. The events could subsequently be displayed on the PC as time series or frequency spectra. Amplitudes in the output files represented velocity and were automatically converted by *triseisa* into units of m/s.

The time and date of the start of each DV-1 event was recorded; the PC and the Vibrosound's internal clock were synchronised so that simultaneous events recorded in the bedroom and on the ground floor slab could be compared during subsequent analysis.

5.1.3 Figure of Equipment Set-up

Figure 5.1 shows the full equipment set-up in schematic form.

5.1.4 On-Site Measurements

In some instances, when a particular industrial site had been established as a source of low frequency noise/vibration, a site visit was carried out in an attempt to pinpoint the precise source. The Vibrosound system is sufficiently portable that it was used to take on-site measurements.

An accelerometer was mounted (using beeswax) on various items of plant within the industrial site, and the output fed into the Vibrosound datalogger. Ten-second events were recorded, similar to those taken at the nearby households where complaints arose. The Vibrosound was triggered manually in such instances.

The data thus collected (and analysed as outlined below) could then be compared with the data from the complainants' houses to try to identify common features and establish cause and effect.

5.1.5 Calibration

Microphone calibration was achieved on site by manually triggering an event recording on the Vibrosound whilst a B&K pistonphone (type 4228) was positioned over the microphone head. This emits a pure tone of 250 Hz, at a root-mean-square sound pressure level of 124 dB(Lin).

It was necessary to adjust the sampling rate of the Vibrosound for this purpose to its maximum setting of 1000 Hz, as the frequency of the pistonphone signal lay outside the frequency range usually used during monitoring (0-100 Hz).

A 'calibration event' was obtained, in the form of a vector of the digitised signal from the appropriate Vibrosound channel. The root-mean-square value of this calibration event was calculated using the mathematical software package *Matlab*, and this value (whose units at this stage were Volts) was converted to decibels re: $20*10^{-6}$ Pascals. The result was compared with 124 dB, the sound pressure level of the calibration signal.

The calibration event vector was then divided by an arbitrary scale factor in *Matlab*, and the RMS value in dB was recalculated and compared with 124 dB. The scale factor was altered iteratively to bring the RMS value of the calibration event to within 0.1 dB of 124 dB re: $20*10^{-6}$ Pa. A typical value for the scale factor required for the calibration process was $8.5*10^{5}$ V.Pa^{-1}.

Subsequent data from the microphone channel of the Vibrosound event recordings were divided by this scale factor. The resulting vectors corresponded to digitised records of sound pressure in Pascals.

For any given period of unmanned monitoring, a calibration as described above was usually undertaken beforehand (during setting up of the Vibrosound system), and again at the end of the monitoring period, immediately prior to removal of the equipment. This allowed drift to be accounted for, by comparing the scale factors required for calibration for the initial and final calibration events. In practice, such drift variations were minimal (< 1%).

In cases where more than one microphone was input into more than one of the Vibrosound channels, it was necessary to utilise the pistonphone on each microphone and independently calibrate each microphone channel as described above. The scaling factors thus derived were of the same order of magnitude, but differed slightly for each channel.

The pistonphone tone (250 Hz) was about two octaves above the frequency range of interest, and the sampling rate had to adjusted accordingly (as mentioned above).

Therefore, as an additional precaution, further calibrations were sometimes carried out using a multi-frequency, pink noise calibrator (B&K type 3541).

The calibration chart for the pink noise calibrator (Figure 5.2) shows RMS sound levels for each third-octave band, extending down to the 31.5 Hz band.

Figure 5.3 shows a typical pink noise calibration event (recorded by the Vibrosound with the pink noise calibrator positioned over the microphone head), analysed and plotted by *Matlab* in terms of third-octave band levels (see Section 5.2.2). The scale factor used to calibrate the microphone with a pistonphone in an event recorded at around the same time, was used to scale the pink noise data (again giving pressure in units of Pa).

This scale factor gave rise to third-octave band levels (Figure 5.3) that closely matched the pink noise calibrator chart band levels (Figure 5.2). This confirms that it is valid to apply the scaling factors derived using the pistonphone, to the low frequency signals recorded during monitoring. It also validates the method of constructing third-octave band levels from raw time series data, as described in Section 5.2.2.

The accelerometer used for measuring windowpane vibrations was also calibrated on site by mounting it on a B&K type 4294 calibrator, which emits a tone at 159 Hz with a root-mean-square amplitude of 10 $m.s^{-2}$. The accelerometer channel of a Vibrosound 'calibration event' went through a similar iterative process as described above for pistonphone calibration. The resulting scaling factor, with units of $V.(m/s^2)^{-1}$, was used to scale all subsequent accelerometer channel data so that acceleration levels were output in units of m/s^2.

Seismometer calibration was automatically achieved via a calibration signal internal to the instruments. An additional calibration was performed using a validated calibration table at MAGUS Electronics.

Data from the seismometer channels of the Vibrosound recordings were converted to velocity (in units of m/s) by simply dividing the corresponding vectors by the gain of the Lennartz, which is equal to 400 $V.(m/s)^{-1}$ for all three channels.

5.2 *MATLAB* ANALYSIS

Because of the way the data were gathered (raw time histories known as event records, or simply 'events'), it was possible to perform a wide range of useful analyses at a later date. Such extensive analysis, as outlined below, is not possible with the type of data available by using for example a sound level meter with filter set attachment.

The multi-channel Vibrosound events, recorded in upstairs bedrooms, were downloaded from the PCMCIA flash card into the PCMCIA slot of a VIGLEN Dossier notebook computer and the binary data converted to ascii using bespoke software written by the research group. Ground floor vibration data recorded by the DV-1 seismometer could also be downloaded to ascii files by the program *triseisa*.

The mathematical software *Matlab* was used to analyse the data. *Matlab* is a versatile package, which allows a wide variety of signal processing and graphics outputs using in-built procedures. A detailed description of some of these now follows.

5.2.1 Time Series & Frequency Spectra

The Vibrosound events were recorded as six-column matrices. Each column of an event matrix is a vector representing the digitised signal from the corresponding channel. These vectors can be analysed individually, but because they were recorded simultaneously, comparisons between the signals from each channel of a given event may also be made, and this provides further useful information.

Individual time series events were analysed in both the time domain and, by Fast Fourier Transform, in the frequency domain. The length of the events analysed (ten seconds) gave a resolution for the frequency spectra of 0.1 Hz.

Matlab routines were written and used to create plots showing both time series and frequency spectra for a given event (the input argument to the routine being the name of the event file). This was carried out for each channel of the data, to display the outputs of the microphone, window-mounted accelerometer and each component of the Lennartz seismometer.

Figure 5.4 shows an example of how the microphone component of a typical event is plotted in the time and frequency domains. In the magnitude-frequency spectrum, amplitudes are given in dB re: 20 μPa.

Figure 5.4 includes the phase-frequency spectrum (unwrapped) for the event, which is created alongside the magnitude-frequency spectrum by Fast Fourier Transform of the time series.

The magnitude and phase spectra for a given event are both essential for recreating the time series from frequency domain information (by Inverse Fourier Transform). This was not a part of the analysis outlined in this thesis. All events are kept on file in the form of time histories.

Therefore it was not usually necessary to display phase spectra for events plotted in the following chapters describing case studies. Accordingly, phase information has been omitted in most cases for reasons of brevity and only magnitude spectra shown.

Note that because of the non-stationary nature of the signals under consideration in cases involving intermittent low frequency noise/vibration, each individual event was treated as a 'snapshot' and no attempt was made to average the events in either time or frequency domains. This accounts for the 'fuzzy' nature of the background noise portions of the plotted frequency spectra (see Figure 5.4).

5.2.2 Constructing Third-Octave Bands for Comparison with Published Criteria

In order to ascertain whether an airborne low frequency noise is of a level that is likely to give rise to annoyance, it is necessary to compare the recorded levels with some sort of published criterion (see Section 4.2). The German national standard DIN 45680 (1997) outlines recommended limits for low frequency noise in terms of third-octave band levels. To assess the data recorded by the microphone channel of the Vibrosound against this criterion, it was important to display the data in a comparable way.

Part of the analysis of the data therefore involved constructing third-octave bands, by applying a root-mean-square method to the narrowband sound pressure-frequency spectra. A *Matlab* routine was written for this purpose. The routine plotted the calculated RMS third-octave band levels for a given event record against the DIN-recommended night-time limits, in dB(Lin).

Figure 7.3 gives an example of a third-octave band level plot, including the DIN curve.

The method of calculating third-octave band levels is an approximation, but can be justified on the basis that the pink noise calibration signal analysed and displayed in this way earlier (Figure 5.3), matched the pink noise calibration curve (Figure 5.2).

5.2.3 Comparing Measured Vibration Levels with Published Criteria

Similarly, measured levels of vibration should be compared with published criteria in order to assess whether the levels are acceptable. The measured vibration levels were assessed against the limits recommended by the British Standard BS 6472 (1992).

Using *Matlab* routines, plots were created showing narrowband frequency spectra for the various components of the seismometer recordings, compared with the BS 6472 recommended limits for night-time residential areas.

Figure 7.6 gives an example of such a plot.

5.2.4 Transfer Functions

On some occasions the a.c. outputs of two microphones were fed into separate channels of the Vibrosound; one microphone being situated outside the house under investigation, the other placed in the usual position in the upstairs bedroom. Because the individual event records were collected in the form of raw time histories, it was possible from such events to calculate a Transfer Function Estimate for acoustic waves travelling from outside to inside the upstairs bedroom.

This was performed by the *Matlab* signal processing function *tfe* (Little and Shure, 1992). For an input x (signal outside the house) and output y (signal recorded in the bedroom), *tfe* estimates the transfer function Txy between x and y, in dB as a function of frequency. Txy is the quotient of Pxy and Pxx, where

Pxy is the Cross Spectral Density of signals x and y, and

Pxx is the Power Spectral Density of signal x.

The resultant Transfer Function Estimate was displayed along with the frequency spectra recorded outside (x) and inside (y) the bedroom, for comparison.

Figure 7.11 gives an example of a transfer function estimate.

5.2.5 Time Domain Filtering

It is sometimes helpful to filter the recorded data in order to emphasise certain aspects of the time series or frequency spectra. For instance, in events where two sharp peaks were seen in close proximity in the spectrum, applying a digital filter in the time domain could reveal 'beating' in the time series. 'Beating' observed in data recorded by the microphone channel would be perceived as fluctuations in the sound level of a tone at a frequency equal to the mean value of the two peak frequencies, with the rate of 'beating' being equal to the difference in frequency between the peaks.

Figure 5.4 shows an event that contains two such peaks close to 50 Hz, raising the possibility that beating would occur. There follows a demonstration of the application of a digital band-pass filter to this event in the time domain, to emphasise the beating.

The choice of filter type is important and each has its merits and drawbacks. The ideal band-pass filter would have rapid roll-offs above and below the upper and lower cut-off frequencies respectively, whilst having as flat a response as possible across the bandwidth.

In practice, some filters have a flat response across the bandwidth whilst only rolling off slowly outside the cut-off frequencies; others display rapid roll-off behaviour but their response is not flat between the cut-offs.

A compromise must be reached; the optimum type and order of filter to use is best determined by trial and error. In this case, a 10^{th}-order Butterworth band-pass filter seemed to display a reasonably flat central response without rolling off too slowly outside the band.

Another aspect of the filter that needs careful consideration is the bandwidth i.e. the difference in frequency between the upper and lower cut-off frequencies.

It is important that the bandwidth is sufficiently narrow to allow the filter to be successful in the task for which it is applied - drawing out salient features from the time series, which were not apparent in the unfiltered data. However, if the filter bandwidth is too narrow, other problems arise.

Filtering at a bandwidth narrower than the frequency resolution of the average human ear, will not yield results that can realistically be matched to subjective responses in case studies such as those described in this thesis.

Furthermore, the Bandwidth Theorem (Newland, 1984) states that the narrower the bandwidth of a filter, the greater the inherent error on the root-mean-square value of the filtered signal.

According to the Bandwidth Theorem, the relationship between the fractional error e (standard deviation divided by the mean) on the RMS signal (assuming a stationary signal), and the frequency bandwidth is given by

$$e = 1/[2*\sqrt{(BT)}] \qquad \text{[Formula 5.1]}$$

where B is the bandwidth in Hertz and T is the length of the filtered event in seconds.

Thus the narrower the bandwidth, the longer the recording time must be in order to minimise the error in estimated amplitudes due to the Bandwidth Theorem.

The bandwidth chosen for filtering the event shown in Figure 5.4 has lower and upper cut-off frequencies of 48.6 Hz and 51.5 Hz respectively. This is equivalent to a twelfth-octave (semitone) centred on 50 Hz.

The frequency response of this filter is shown in Figure 5.5, in terms of magnitude and unwrapped phase spectra.

To give an idea of the size of the Bandwidth errors involved, the application of this filter of bandwidth 2.9 Hz to a 10-second time series leads to an error on the estimated RMS value of 0.09 or 9%, according to Formula 5.1. This is equivalent to less than 1 dB, and serves to establish reasonable confidence in the results.

In any case, the data filtered in this way in the case studies described later were used mainly for qualitative, rather than quantitative comparisons.

The *Matlab* function *filtfilt* (Little and Shure, 1992) was used to apply the 50 Hz semitone band Butterworth filter (Figure 5.5) to the event shown in Figure 5.4.

The function *filtfilt* filters the input event in the forward direction, then reverses the filtered sequence and runs it back through the filter. The time reverse of the output of the second filtering operation is the final filtered time series, shown in Figure 5.6.

The result has precisely zero phase distortion and a magnitude modified by the square of the filter's magnitude response. Thus at frequencies within the bandwidth of the filter (where the magnitude response is approximately equal to 1), the output of the filter is virtually unchanged in amplitude or phase. Frequencies outside the bandwidth are filtered out rather effectively.

Filtfilt minimises start-up and ending transients by matching initial conditions, so that the lengths of the unfiltered and filtered time series are the same, with ringing kept to a minimum.

After band-pass filtering at around 50 Hz, the event shown in Figure 5.6 displays very clear beating in the time series. The beat frequency expected (by taking the difference in frequency between the peaks) matches the number of beat cycles per second observed in the filtered time series.

Note that it is important to discount the possibility that the beating observed is an artefact of the filtering process due to 'Envelope Fluctuation' effects, as discussed in Robson (1963).

According to Robson, even if a white noise signal is passed through a narrowband filter, the output will display amplitude fluctuations whose carrier frequency is the central frequency of the filter, and which fluctuate with a mean frequency dependent on the properties of the filter.

Rice (1944, 1945) showed that, as a result of this phenomenon, the maximum amplitudes of the signal occur with a mean frequency of $0.641\Delta f$, where Δf is the filter bandwidth.

Thus for a twelfth-octave bandpass filter centred on 50 Hz (as in Figure 5.5), $\Delta f = 2.9$ Hz and amplitude fluctuations at a rate of 1.9 cycles per second (or 19 cycles over a ten-second Vibrosound event) would be expected. In contrast, the filtered time series in Figure 5.6 displays strong beating at 16 cycles per second.

This type of analysis was carried out in all cases where time-series beating was examined in the case studies to follow, to verify that the beating was a real acoustic phenomenon and not an artificial construct due to the filtering process.

5.2.6 Polarisation Analysis Using a Singular Value Decomposition Method

Jackson et al. (1991) describe a method of obtaining the polarisation direction of a seismic arrival recorded by a three-component seismometer. This is achieved by treating a time window of the seismic recording as a three-column matrix and carrying out a Singular Value Decomposition (SVD). The SVD analysis produces an eigenanalysis of the cross-energy matrix and rotates the data onto the principal directions given by the eigenanalysis.

The application of SVD as outlined by Jackson et al. (1991) makes three requirements of the chosen time window of seismic data: first, the window should contain only one arrival; second, the window should be chosen to maximise the signal to noise ratio; and third, the window should be as long as possible to allow discrimination of noise from signal. Without prior knowledge of what is noise and what is signal, it is necessary to define noise as the component of variation that is uncorrelated between the three triaxial channels. Mutually orthogonal variations may be identified, if the time window is sufficiently long.

The seismic data components $\mathbf{x}_x$, $\mathbf{x}_y$ and $\mathbf{x}_z$ of length l samples form the columns of the data matrix $\underline{\mathbf{X}}$, which is therefore of dimension l x 3. The 3 x 3 cross-energy matrix $\underline{\mathbf{M}}$ is obtained as

$$\underline{\mathbf{M}} = \underline{\mathbf{X}}^t . \underline{\mathbf{X}} \qquad \text{[Formula 5.2]}$$

where $\underline{\mathbf{X}}^t$ is the transpose of $\underline{\mathbf{X}}$.

The energy expectation in a triaxial trace can always be decomposed into three components corresponding to orthogonal (in time) variations along mutually perpendicular axes (Jackson et al., 1991). Thus eigenanalysis of the cross-energy matrix $\underline{\mathbf{M}}$ produces a principal components analysis of the energy in the time window. The eigenvalues λ_1, λ_2 and λ_3 of $\underline{\mathbf{M}}$ give the magnitude of the energy components along the corresponding eigenvectors $\mathbf{v}_1$, $\mathbf{v}_2$ and $\mathbf{v}_3$.

Singular value decomposition allows the data matrix $\underline{\mathbf{X}}$ to be expressed as the product of three matrices:

$$\underline{\mathbf{X}} = \underline{\mathbf{U}}.\underline{\mathbf{W}}.\underline{\mathbf{V}}^t \qquad \text{[Formula 5.3]}$$

where

$\underline{\mathbf{U}}$ is an l x 3 matrix whose columns are the eigenvectors of $\underline{\mathbf{X}}.\underline{\mathbf{X}}^t$;

$\underline{\mathbf{W}}$ is a diagonal matrix (3 x 3) whose diagonal elements σ_1, σ_2 and σ_3 are the 'singular values', equal to the positive square roots of the eigenvalues λ_1, λ_2 and λ_3 of $\underline{\mathbf{M}}$;

$\underline{\mathbf{V}}$ is a 3 x 3 matrix whose columns are the eigenvectors of $\underline{\mathbf{M}}$; $\underline{\mathbf{V}}^t$ is the transpose of $\underline{\mathbf{V}}$.

Finally, polarisation analysis may be completed by rotating the data $\underline{\mathbf{X}}$ into the eigenvector frame. The rotated data matrix $\underline{\mathbf{K}}$ (l x 3) is obtained by:

$$\underline{\mathbf{K}} = \underline{\mathbf{X}}.\underline{\mathbf{V}} \qquad \text{[Formula 5.4]}$$

Jackson et al. (1991) then go on to estimate the signal/noise ratio of the data, based on (a) an elliptically polarised arrival (for example a surface Rayleigh wave) and (b) a rectilinearly polarised arrival (such as a body P-wave). The signal/noise ratio should reflect, and quantify, the 'degree of polarisation' of the seismic arrival in the time window.

(a) An elliptically polarised signal is confined to a plane defined by the axes of the polarisation ellipse. The vectors $\mathbf{v}_1$ and $\mathbf{v}_2$ provide least-squares best estimates of the major and minor axes of the signal polarisation ellipse, respectively. Vibration parallel to $\mathbf{v}_3$ is assumed to be pure noise (of energy σ_3^2), and there is considered to be an equal component of noise (σ_3^2) along $\mathbf{v}_1$ and $\mathbf{v}_2$. The energy signal/noise ratio for elliptical polarisation is then given by:

$$\text{signal/noise} = \frac{\sigma_1^2 + \sigma_2^2 - 2\sigma_3^2}{3\sigma_3^2} \qquad \text{[Formula 5.5]}$$

(b) The rectilinear signal is confined to the primary axis of polarisation, $\mathbf{v}_1$. Vibrations parallel to $\mathbf{v}_2$ and $\mathbf{v}_3$ are purely due to noise, of energy σ_2^2 and σ_3^2 respectively. The estimate of noise energy along $\mathbf{v}_1$ may be taken as $(\sigma_2^2 + \sigma_3^2)/2$. The energy signal/noise ratio for rectilinear polarisation is then given by

$$\text{signal/noise} = \frac{\sigma_1^2 - (\sigma_2^2 + \sigma_3^2)/2}{\sigma_2^2 + \sigma_3^2 + (\sigma_2^2 + \sigma_3^2)/2} \qquad \text{[Formula 5.6]}$$

The *Matlab* function *svd* (Little and Shure, 1992) may be used to perform a singular value decomposition on an input triaxial seismic recording matrix. Figures 5.7a-c (Styles and Toon, 2000) show an application of *svd* to a standard seismic arrival. A window of data containing the first arrival (a P-wave; see Section 2.3) is selected (Figure 5.7a).

In Figure 5.7b, the particle motion (shown in red) is plotted in three dimensions, illustrating the rectilinear motion pointing directly away from the earthquake hypocentre. A line of best fit is calculated by Singular Value Decomposition, shown by the straight blue line.

Finally, the data may be rotated onto the principal axes (Figure 5.7c). In the new co-ordinate frame the x-axis is parallel to the direction of propagation of the P-wave (shown in the upper component of Figure 5.7c).

5.3 DISTINGUISHING PROPAGATION PATHS AND EXTERNAL / INTERNAL SOURCES

This section provides a quick summary of a series of 'rules-of-thumb' by which airborne/groundborne and external/internal sources of sound and vibration may be distinguished. Whilst this is based on an intuitive approach and is introduced to inform the reader prior to the case studies in Chapters 6 and 7, a more rigorous analysis of this aspect of the methodology was carried out and this will be detailed in Chapter 8.

Figure 5.8 illustrates the principles involved in schematic form. Comparison of contemporaneous data from all Vibrosound channels (each column vector of a single event record matrix), and from the DV-1 seismometer mounted on the foundation slab, allowed the following distinctions to be made.

5.3.1 Groundborne Vibration

Groundborne vibration gives rise to a strong signal in the ground floor seismometer, and a weak signal in the microphone.

The seismometer in the bedroom and the window-mounted accelerometer would probably display signals of comparable amplitude to the ground floor seismometer, though some amplification of the ground floor vibration by the building structures may occur. As discussed in Section 2.5, if the vibration levels in the upstairs seismometer are more than an order of magnitude greater than the levels measured in the foundation slab, then the vibration upstairs is unlikely to be an amplified groundborne signal.

5.3.2 Airborne Sound, External Source

External airborne vibration gives rise to a strong signal in the window-mounted accelerometer and the microphone. The seismometer in the bedroom would probably display a relatively weak signal.

The ground floor seismometer mounted on the foundation slab would not pick up any significant signal from external airborne sound.

5.3.3 Structure-Borne Sound, Internal Source

The seismometer located on the suspended wooden upper floor may detect a relatively strong signal due to an internal sound source, if building structures are set into resonance.

Structure-borne sound from a source internal to the house may give rise to a relatively strong microphone signal, but a comparatively weak signal in the window-mounted accelerometer.

Levels of vibration in the foundation slab due to an internal source would be expected to be weak.

5.4 CONCLUDING REMARKS

The Vibrosound datalogger allows large numbers of multi-channel time series events to be recorded during long periods of unmanned monitoring, in dwellings where the occupants are being disturbed by an unidentified source(s) of low frequency noise and/or vibration. By employing a broad array of transducers in conjunction with the Vibrosound, comprehensive coverage of the low frequency sound and vibration fields within the house may be acquired.

Matlab software provides a variety of signal processing analysis that may subsequently be applied to the multi-channel data. Far more information can be gleaned by this method than is possible with, say, a few sound level meter readings.

The presence of characteristic features in the time and/or frequency domains, coupled with records of subjective loudness levels, may in some cases allow a specific source and mode of propagation to be attributed to the subjectively disturbing phenomenon. Following this, a course of remedial action may be recommended that will mitigate the low frequency noise/vibration giving rise to complaints.

Subsequent chapters of this thesis will utilise case studies carried out by the author to illustrate the flexibility and effectiveness of the methodology described in tackling low frequency noise/vibration problems, and to demonstrate the application of the wide range of *Matlab* analyses detailed above.

5.5 REFERENCES

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Fig. 5.1 – equipment set-up

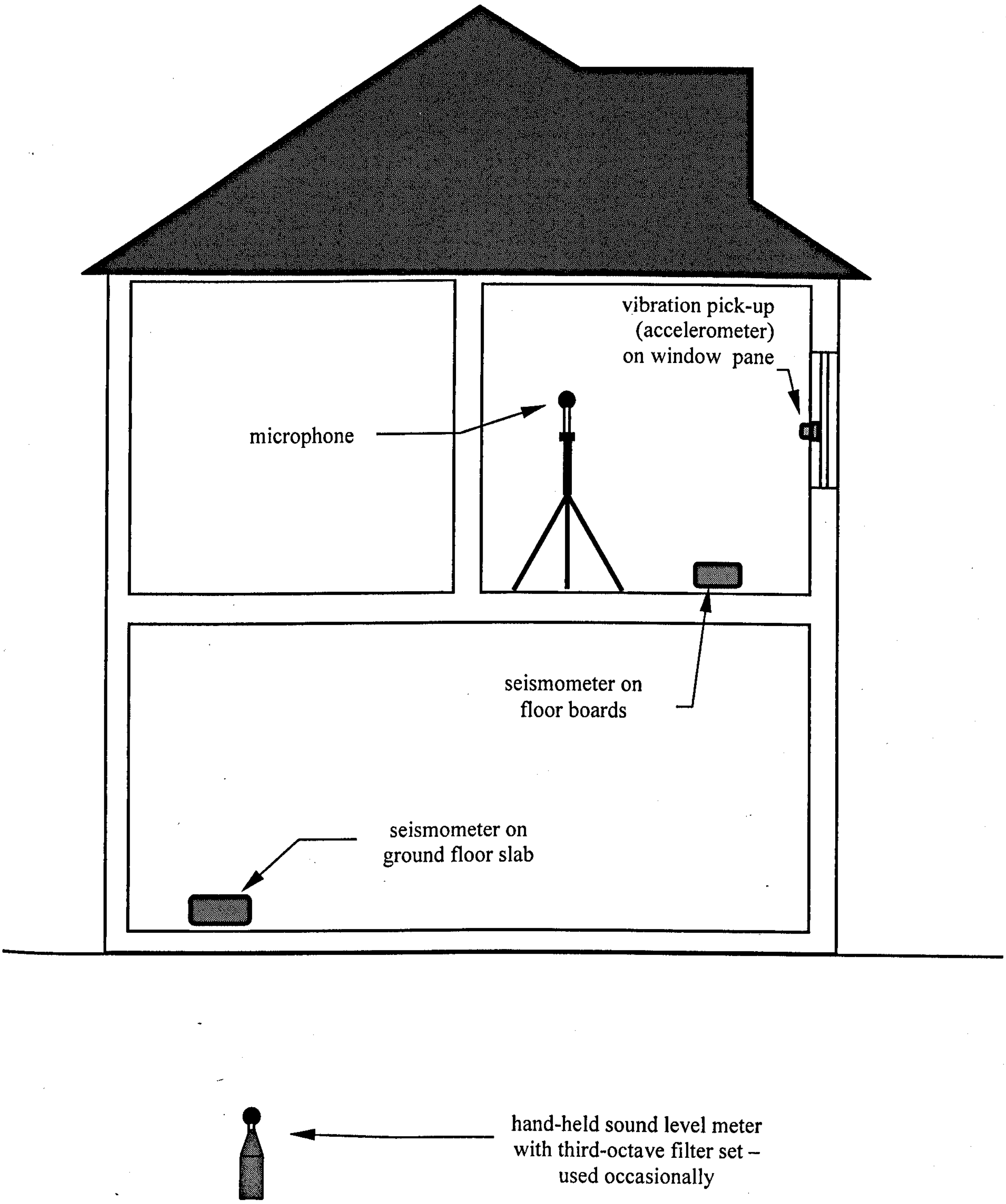


Fig. 5.2 – calibration chart for a pink-noise calibrator, showing RMS sound levels for third-octave bands down to 31.5 Hz

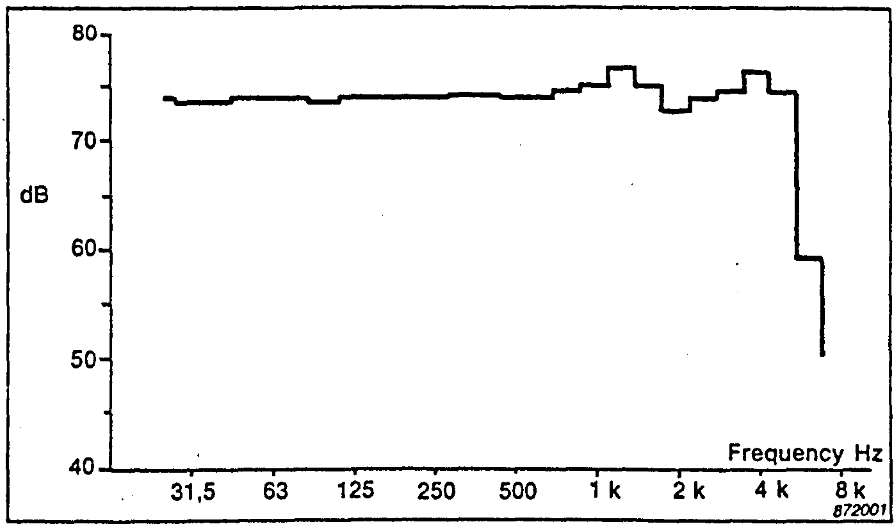


Fig. 5.3 - a pink noise calibration event, in third-octave band levels

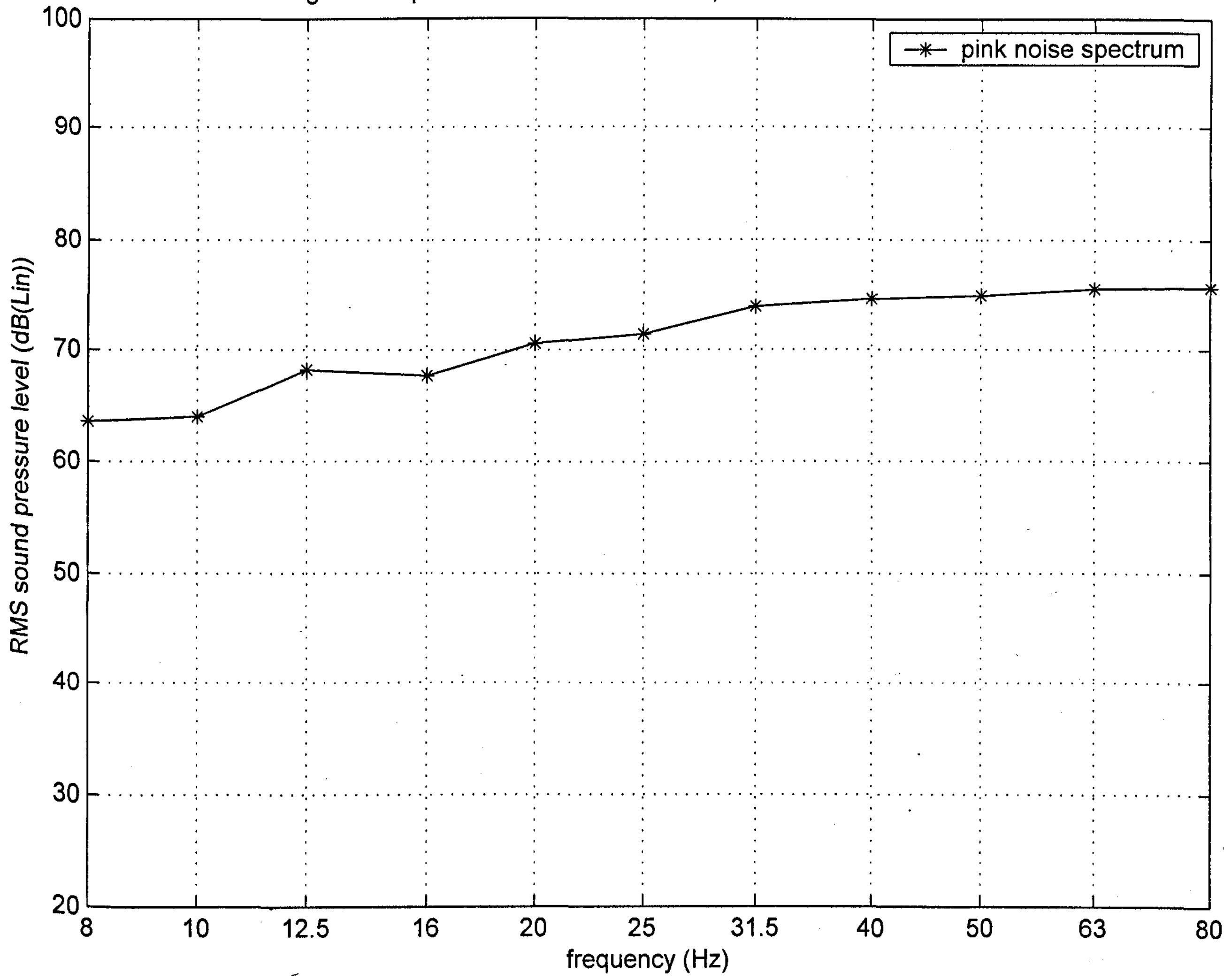


Fig. 5.4 - a typical Vibrosound event plotted using a Matlab routine; time series and magnitude & phase spectra are all shown

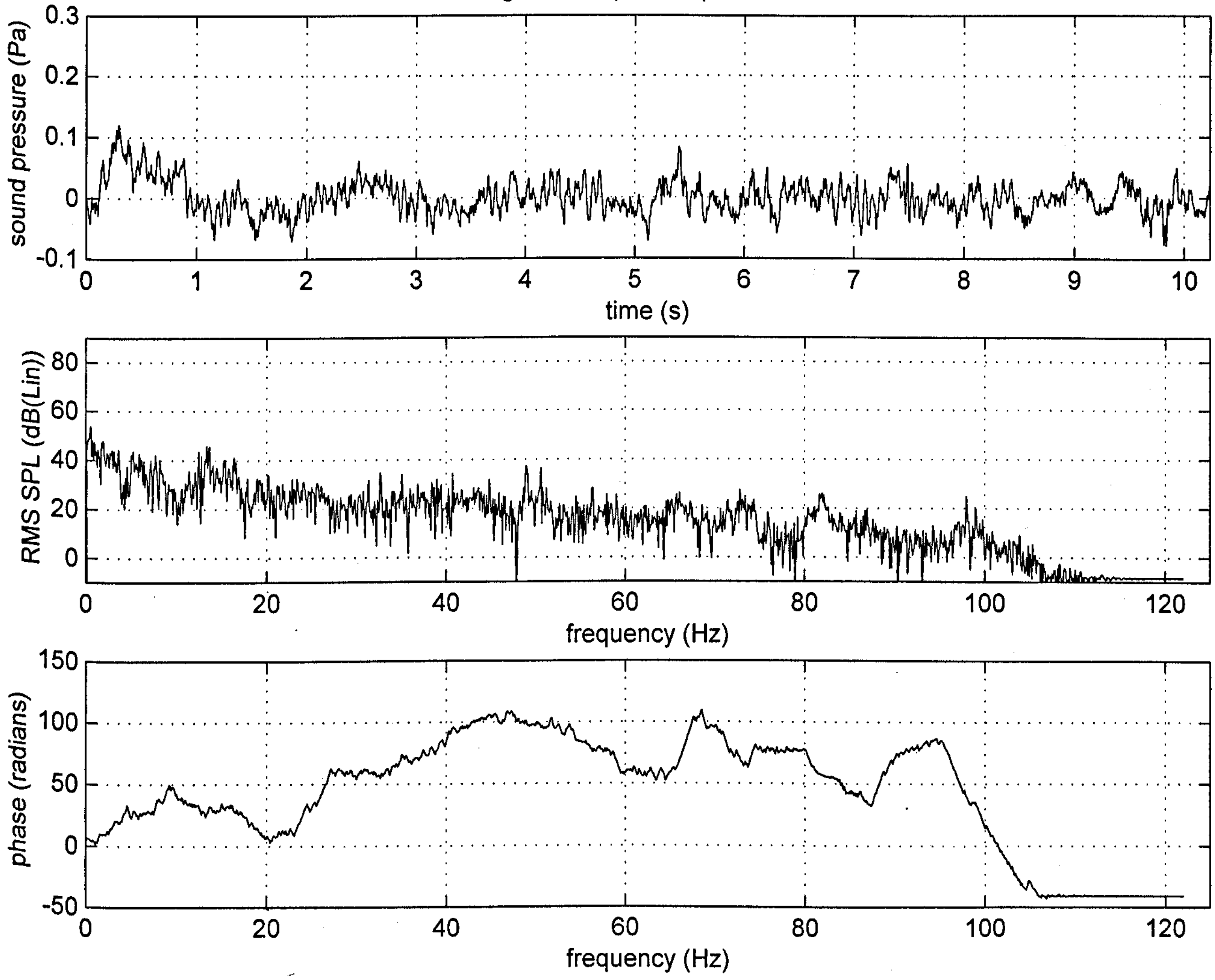


Fig. 5.5 - frequency response of a twelfth-octave digital Butterworth bandpass filter centred on 50 Hz

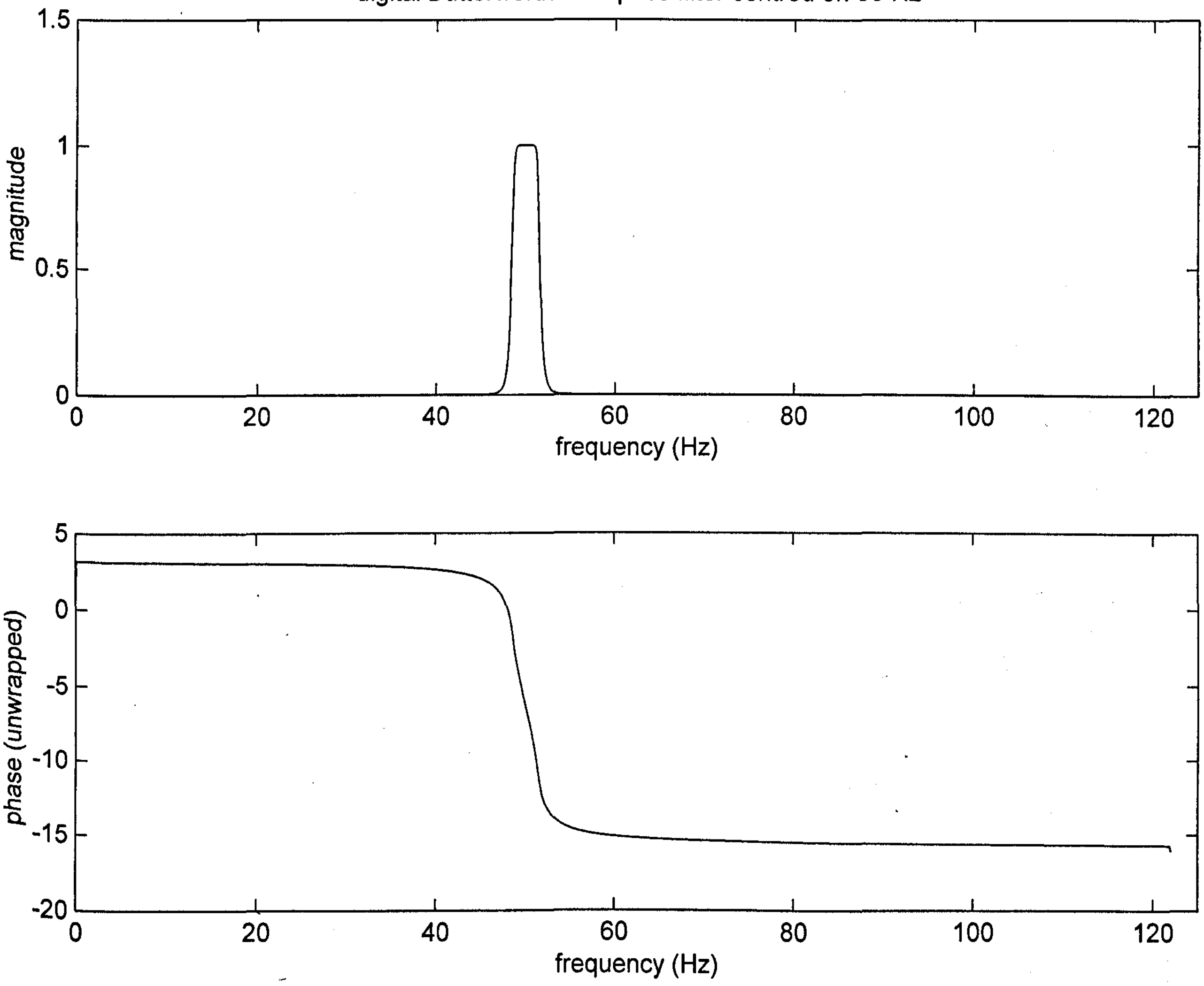


Fig. 5.6 - the Vibrosound event from Fig. 5.4,
after the application of the bandpass filter shown in Fig. 5.5

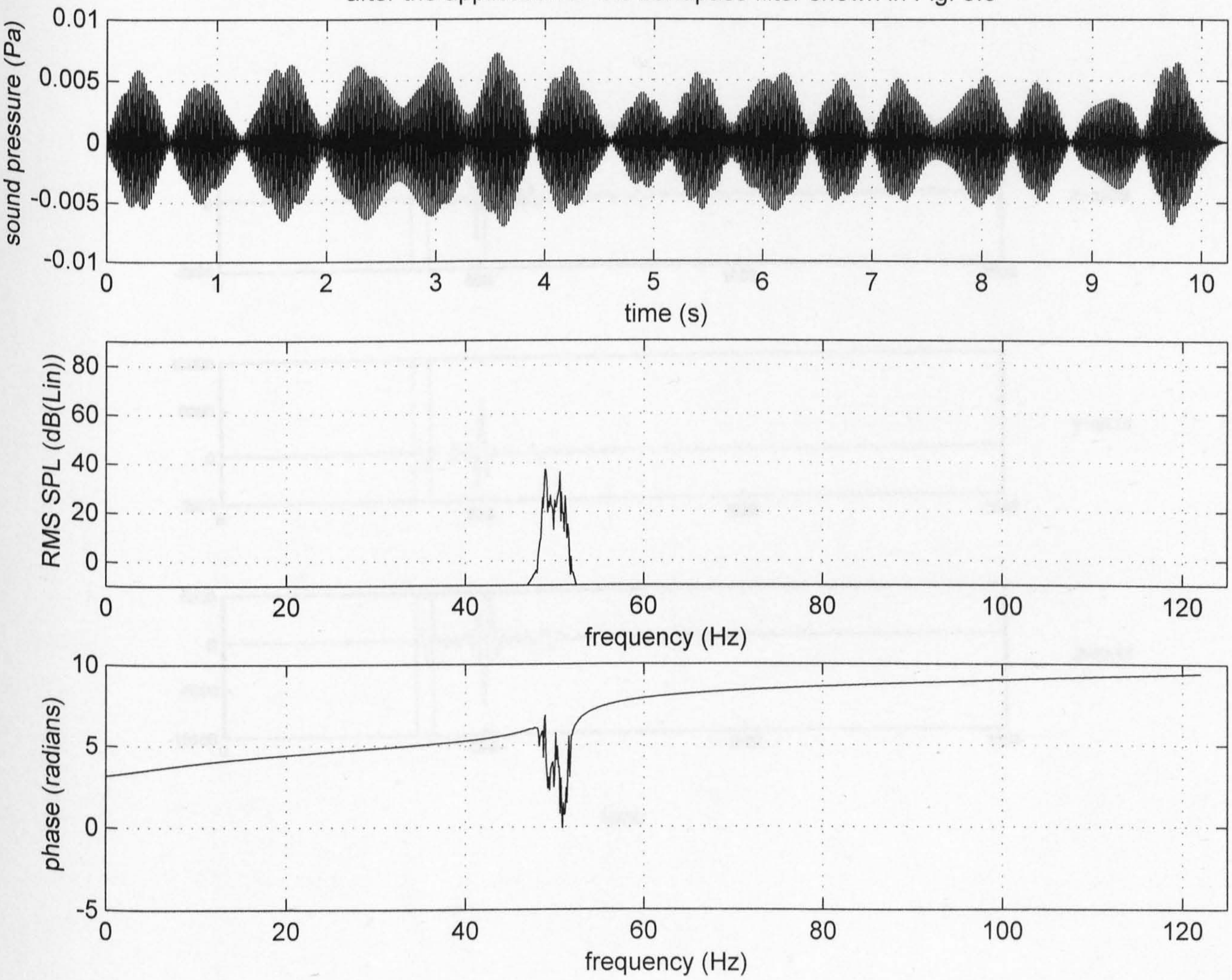


Fig. 5.7a – a typical seismic arrival. The P-wave phase, shown between the two blue lines, is selected for analysis by Singular Value Decomposition. (Taken from http://www.esci.keele.ac.uk/geophysics/html/event_location.html)

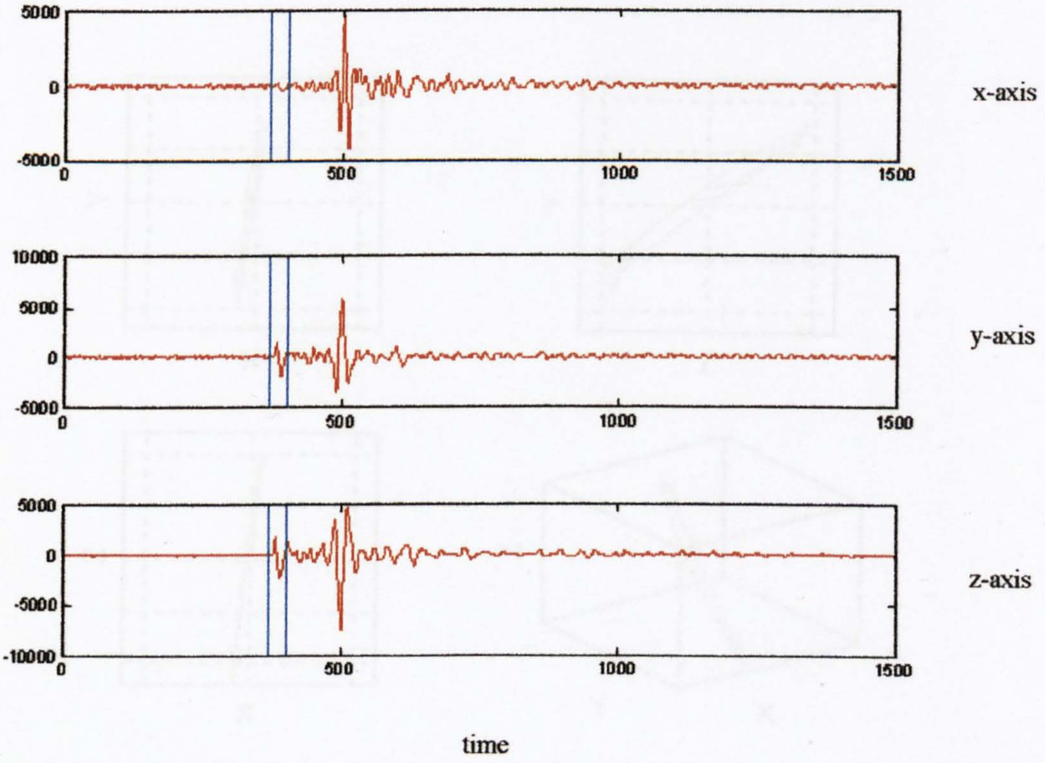


Fig. 5.7b – three-dimensional particle motion for the seismic arrival selected in Fig. 5.7a, shown in red. The straight blue lines represent lines of best fit for the motion, calculated by Singular Value Decomposition. (Taken from http://www.esci.keele.ac.uk/geophysics/html/event_location.html)

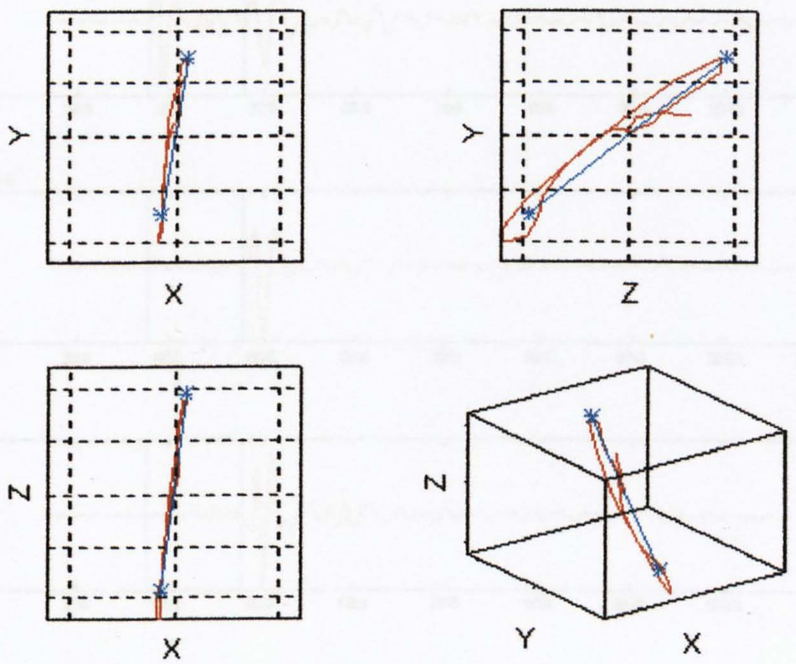


Fig. 5.7c – the seismic arrival from Fig. 5.7a, after rotation onto its principal axes. The x-axis of the new co-ordinate frame (upper component) is parallel to the direction of propagation of the P-wave. (The second blue line here indicates a later arriving phase.) (Taken from http://www.esci.keele.ac.uk/geophysics/html/event_location.html)

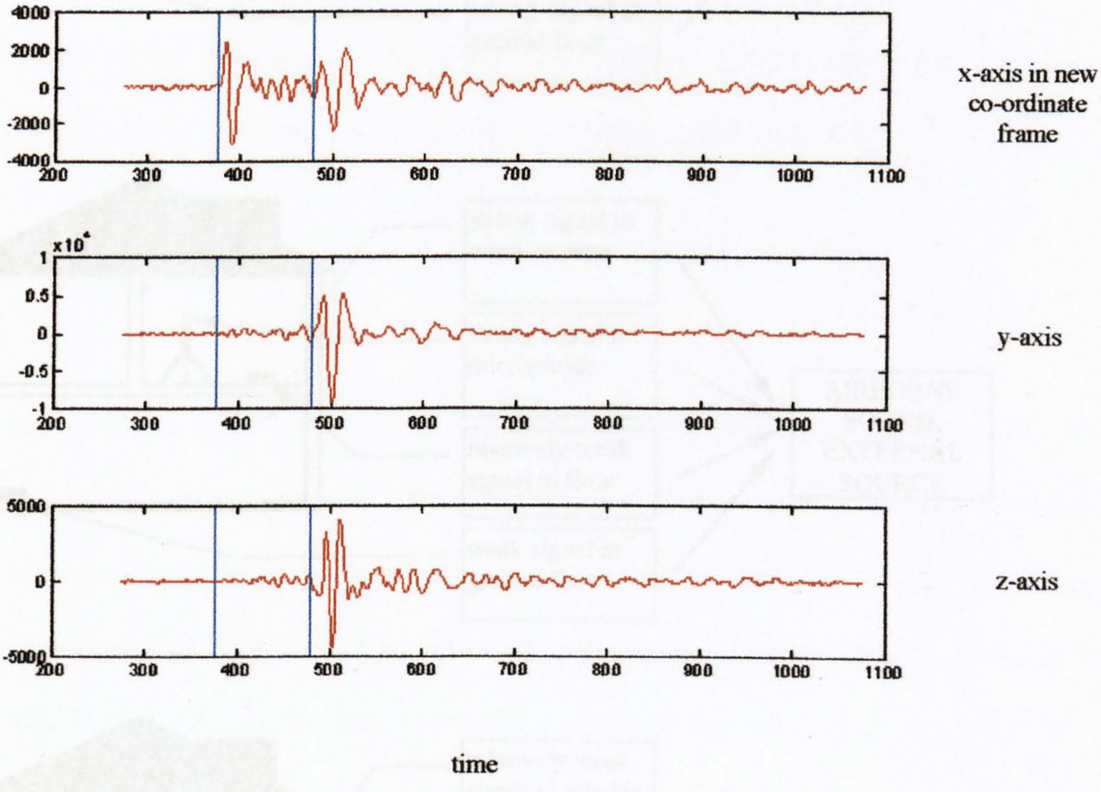
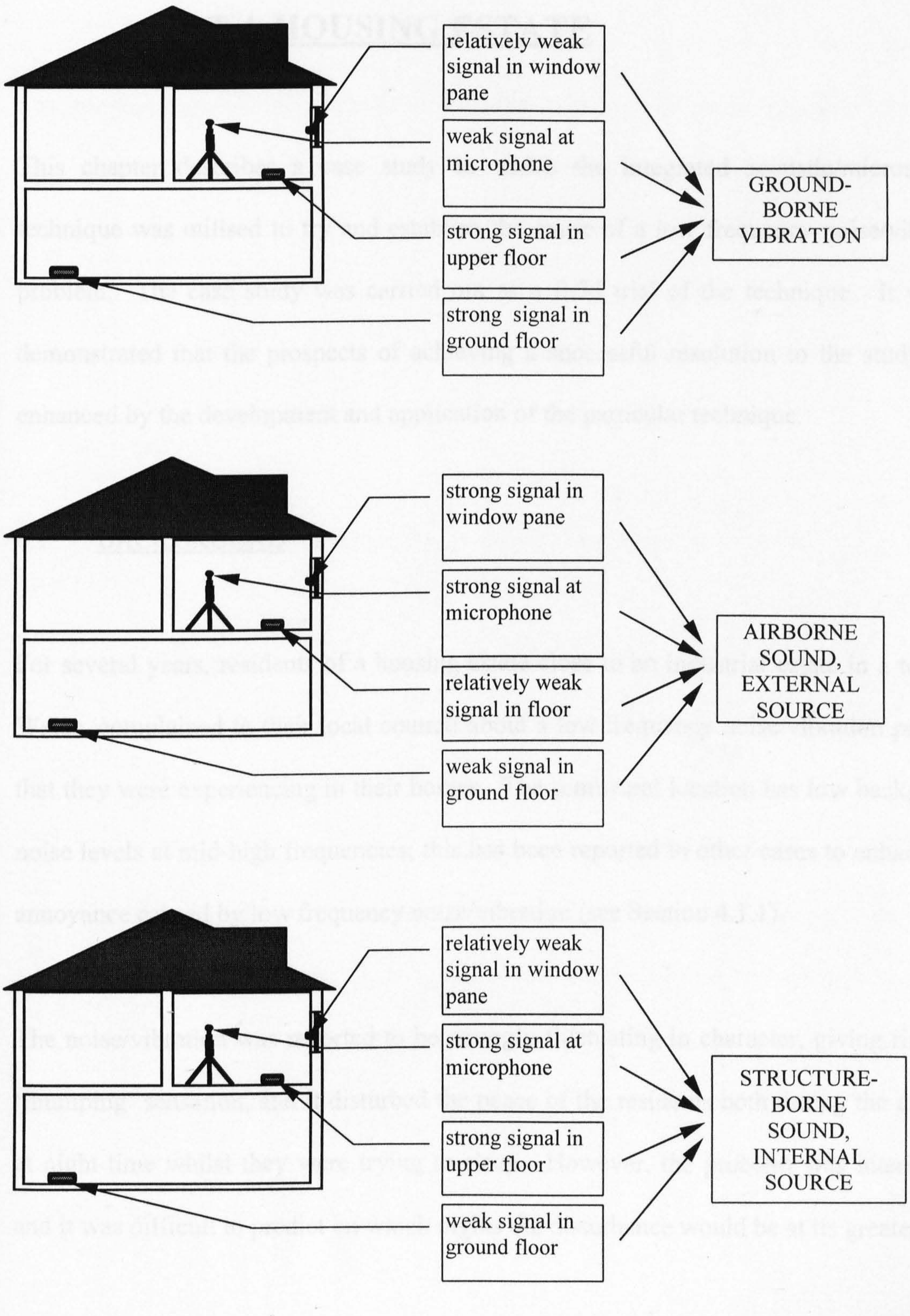


Fig. 5.8 - identification of transmission paths and external/internal sources of low frequency noise/vibration



6 CASE STUDY A – INVESTIGATION OF A LOW FREQUENCY NOISE / VIBRATION PROBLEM AT A HOUSING ESTATE

This chapter describes a case study in which the integrated acoustic/microseismic technique was utilised to try and establish the cause of a low frequency noise/vibration problem. The case study was carried out as a field trial of the technique. It will be demonstrated that the prospects of achieving a successful resolution to the study were enhanced by the development and application of the particular technique.

6.1 BACKGROUND

For several years, residents of a housing estate close to an industrial estate in a town in Wales, complained to their local council about a low frequency noise/vibration problem that they were experiencing in their homes. The semi-rural location has low background noise levels at mid-high frequencies; this has been reported in other cases to enhance the annoyance caused by low frequency noise/vibration (see Section 4.1.1).

The noise/vibration was reported to be strongly fluctuating in character, giving rise to a 'thumping' sensation, and it disturbed the peace of the residents both during the day and at night-time whilst they were trying to sleep. However, the problem was intermittent and it was difficult to predict on which nights the disturbance would be at its greatest.

Previous attempts by others to establish the cause of the complaints using conventional acoustic techniques had proved unsuccessful, probably because of the intermittent nature of the disturbance. The author decided that application of the combined acoustic/microseismic technique to the problem may enhance the prospects of success, as this allowed for long periods of unmanned monitoring over several nights, when background noise due to traffic and other sources was lowest. The technique involves measurement of both sound and vibration levels within a property; this was thought to be particularly important in this case as it was not known from the outset whether the disturbance was caused by noise or vibration, or both (or neither).

The various stages of the investigation are detailed in chronological order.

6.2 LOCATION

The area under investigation is shown in the sketch map in Figure 6.1.

The industrial estate contains several factories that were considered to be possible sources of the disturbance. The most likely cause of the disturbance was thought to be a factory that is situated closest to the housing estate. This will be known in this thesis for confidentiality reasons, as Factory F.

The households where the disturbance led to complaints are shown in Figure 6.1, as are Factory F and other relevant features in the vicinity.

6.3 INITIAL INVESTIGATION

The noise and vibration levels were initially monitored at three properties in the area over the period 2/11/97-29/12/97. All three locations were the households of residents who had experienced disturbance in relation to the low frequency noise/vibration under investigation. To protect the identity of the residents, the houses have been designated Locations A1, A2 and A3. The relative positions of these locations and Factory F can be seen on the sketch map (Figure 6.1).

At each location, the Vibrosound recording system was set up in an upstairs bedroom, with inputs from a microphone, window-mounted accelerometer and the Lennartz three-component seismometer which was placed on the suspended wooden floorboards of the room. All windows were closed during the monitoring periods. The DV-1 three-component seismometer with PC link was placed downstairs on the ground floor slab.

This set-up is described in more detail in Section 5.1 (see Figure 5.1).

Each occupant was asked to note down descriptions of their perception of the disturbance during each night of the monitoring period, whether or not the equipment was installed at their property on a particular night. Night-time monitoring ensured that traffic noise/vibration were kept to a minimum in the recordings. One Sunday afternoon was also selected for monitoring as the residents indicated that this was a time when disturbance often occurred. The investigators also made subjective evaluations during the evenings in which the equipment was installed and dismantled.

Residents also made diaries of other environmental factors and variations such as weather conditions, where appropriate.

The monitoring period included the Christmas period, during which much local industry including Factory F was shut down; this gave an indication of background levels of low frequency noise and vibration in the area.

6.3.1 Initial Results – Subjective Assessments

6.3.1.1 Location A1:

The residents at Location A1 did not remain there during the period (27/11/97 to 2/12/97) for which recordings were taken there. However, they returned to occupy their home whilst measurements were being taken at Locations A2 and A3, and during the Christmas period when local industry had shut down and background readings were taken.

During the installation and removal of equipment at the start and end of the monitoring period at Location A1, a low frequency throbbing sound could be perceived by the author at a level near to the threshold of audibility. The throbbing had an almost regular beating character. Mid-frequency tones and other industrial noise (including on-site vehicular noise) were heard emanating from Factory F in rooms that face the factory.

On a later visit to Location A1 (on 21/12/97), a low frequency throbbing sound was clearly audible, with slightly irregular fluctuations that could be counted repeatably at 84 beats per minute. The perceived level varied throughout the house; this is to be expected for low frequency noise (see Section 2.4). Subjective levels were highest on this occasion in the upstairs bathroom and in the living room, by the fireplace. Residents of Location A1 were present at this time, and significantly they stated that the noise present at that time was the one that they found disturbing; this was an "average night" in terms of disturbance.

The residents of Location A1 all reported that their house was very quiet throughout the Christmas period, with no external sounds perceptible except occasional traffic.

6.3.1.2 Location A2:

One resident occupied Location A2 during the entire monitoring period (2/11/97-29/12/97), including the period when equipment was installed there from 16/12/97 to 20/12/97.

No low frequency noise or vibration was perceptible by the author during installation or removal of the equipment at Location A2. Dr Andy Moorhouse of the University of Liverpool's Acoustics Research Unit also stayed overnight on 21/12/97 to establish the effects of long-term exposure to the sound field on the housing estate. Dr Moorhouse did not notice any sleep disturbance, nor perceive any low frequency sounds during the overnight stay. A mid-frequency whine could be heard throughout the house, but this was outside the frequency range under investigation.

The resident of Location A2 reported hearing a thumping sound in most rooms of the house, and feeling a vibration through the floor, during the entire monitoring period including the Christmas 'background noise' period when local industry had largely shut down.

6.3.1.3 Location A3:

Residents occupied Location A3 during the entire period of the investigation. The monitoring equipment was installed at their home from 21/12/97 to 27/12/97; this included the Christmas period when local industry had shut down for the holidays.

No low frequency sounds or vibration were perceived by the author at Location A3 during installation or removal of the equipment. A mid-frequency whine was audible in the bedrooms of the house, but as at Location A2 this lay outside the frequency range of interest and was not further investigated.

Residents concurred that the monitoring period at Location A3 was a relatively quiet period; the noise levels would be considered acceptable "if it was like this all the time". Windy weather was noted over this monitoring period, with storms on 24th December.

6.3.2 Initial Results – Analysis of Recorded Data

Having analysed the thousands of recorded events in both time and frequency domains, from each channel of the Vibrosound (microphone, accelerometer and three-component seismometer), as well as the ground floor slab vibration data, several recurring features were distinguished. As well as being considered as likely candidates for causing disturbance to the residents, consistent features of the data were very useful for developing a range of analytical techniques that could test out the effectiveness and versatility of the integrated acoustic/microseismic technique.

Part of the analysis necessarily involved assessing the levels of the tonal noise and vibration with regard to published standards (DIN 45680 (1997), BS 6472 (1992)). A frequency-by-frequency analysis of the salient features now follows, highlighting where appropriate the significance of the measured levels with regard to human perception of them.

6.3.2.1 Tone(s) Close to 38 Hz:

At least one sharp tone of frequency ~38 Hz was commonly present in the microphone, accelerometer and upstairs seismometer spectra at all three locations where measurements were taken. Figures 6.2-6.4 show examples, taken from Locations A1, A2 and A3 respectively, of microphone recordings in which the ~38 Hz peak stands proud of the surrounding spectrum by up to 20 dB.

On some occasions, a second, distinct tonal peak could be observed at ~36 Hz of lesser amplitude than the first (~10 dB lower). The exact frequency of the tone(s) also varied slightly (by 1-2 Hz) over the monitoring period of several weeks.

No peaks in the range 36-40 Hz were observed (at any of the properties) in the frequency spectra recorded by the seismometer mounted on the ground floor slab.

The only time when the 38 Hz tone did not appear in the microphone, accelerometer and upstairs seismometer spectra was during the Christmas period, when local industry had shut down and 'background' readings were taken. Figure 6.5 shows a typical background microphone recording, taken at Location A3. The sharp peak at 50 Hz is assumed to be internal electrical noise at mains frequency.

At Location A1, the levels recorded by the microphone channel of the Vibrosound were often slightly (1-2 dB) above the limit recommended in DIN 45680 (1997) for the 40 Hz third-octave band (48 dB), at the chosen microphone position (see Figure 6.6). The DIN 45680 limits for low frequency noise, which have been shown in other case studies to be a reasonably good predictor of annoyance (Piorr and Wietlake, 1990), are based on the '50% audibility threshold' for humans (see Section 4.2).

This suggests that the 38 Hz tone at Location A1 was present at a level close to the average human's threshold of perception, at times exceeding that threshold. Furthermore, the noise being highly tonal is of an 'unusual' nature and would therefore be judged to be potentially annoying according to DIN 45680.

The chosen microphone position at Location A1 was situated in a spare bedroom, to minimise inconvenience to the residents. A quick 'scan' around the property using a hand-held sound level meter (with filter set) on the occasion when the monitoring equipment was being removed from Location A1, showed that other positions in the house were objectively louder than the chosen position. This was borne out subjectively by the author's experience and the residents' comments.

It is therefore possible that the DIN 45680 limit in the 40 Hz band may have been exceeded to a greater extent at other positions throughout the house, though this cannot be confirmed objectively from the data collected using the Vibrosound machine. Nevertheless, the data do show that noise exceeding the DIN 45680 curve, and of a tonal and therefore potentially annoying nature, was present at Location A1 at ~38 Hz.

The levels of the 38 Hz tonal noise recorded at Locations A2 and A3 were below the DIN 45680 recommended limit (see Figures 6.7-6.8).

Typically the 40 Hz third-octave band level at Location A2 was ~20 dB below the DIN recommended limit, whilst at Location A3 it was ~10-15 dB below. On the basis of the recorded levels taken at these two locations over the measurement period, it would not be expected that noise in the 40 Hz third-octave band would cause any considerable disturbance.

The existence of the 38 Hz tone at all three houses suggests an external, rather than internal source. This postulate is confirmed by the absence of any likely internal source at Location A1, where domestic items such as refrigerators were purposely switched off during the measurement period at that property. Also, the 'disappearance' of the tone over the Christmas period (Figure 6.5) suggests a local industrial source for the tone.

The presence of the 38 Hz tone in the windowpanes and its absence from the ground floor slab spectra, suggest an airborne propagation path. This hypothesis is analysed more rigorously in Chapter 8, by use of a Finite Element Modelling method.

The slight variations in frequency of the tone observed over time are consistent with the source possibly being a rotating item of machinery, whose rotational frequency varies slightly from a nominal running speed due to variable loading. The existence of two distinct peaks on some occasions may suggest two distinct sources with rotational speeds close to 38 Hz. These features were rather subtle and it was only possible to identify them because of the combination of narrow frequency resolution, obtained over long monitoring periods by the Vibrosound datalogger.

The 38 Hz tone exhibited both temporal and spatial variations in amplitude within all three houses. Spatial intra-house variations were distinguished both subjectively and objectively; quick scans with a hand-held sound level meter and filter set gave variations of ~10 dB in all frequency bands from 20 to 125 Hz throughout each property. This is to be expected for low frequency sound (see Section 2.4).

However, a general trend could be determined throughout the housing estate, namely that the recorded levels of the tone were 15-20 dB higher in Location A1 than in Locations A2 and A3. This is outside the typical spatial variations in level of low frequency noise found within each property, and therefore cannot be explained by them.

Reference to the sketch map of the area (Figure 6.1) shows that Location A1 is situated to the northeast of Locations A2/A3, and closer to Factory F. Thus the higher sound levels at 38 Hz at Location A1 are consistent with a source for the tone located to the northeast of the housing estate, possibly at Factory F. (This assumes that the sound power of the source was constant over the entire monitoring period; notes made by the residents suggest that no major changes in wind speed and direction occurred which could account for the variations in amplitude.)

Location A2 is in fact slightly closer to Location A1/Factory F than is Location A3, yet levels of the 38 Hz tone were on average ~5 dB higher at Location A3 than at Location A2. This is not inconsistent with a source to the northeast of the estate, as 5 dB is within the typical spatial variations in level of low frequency noise found within each property. Also, the bedroom at Location A2 in which monitoring took place faces away from Factory F, whereas the measurement rooms in Locations A3 (and A1) face towards it.

The general drop in level of the 38 Hz tone between Location A1 and Location A3 was analysed to see if it indicated an approximate distance to the source of the tone, and whether this could confirm Factory F as the likely source. In theory, a doubling of distance in a free-field leads to a 6 dB drop in sound level (inverse square law – see Section 2.2).

A large drop in sound level of 15-20dB in a free-field would therefore suggest an increase in distance of at least a factor of 4. In fact, according to the sketch map (Figure 6.1), the distance between Location A3 and Factory F is approximately 3 times the distance between Location A1 and Factory F.

The environment around the housing estate is not a free-field environment. The presence of houses, the ground surface, etc. all lead to reflections and the row of houses nearest to Factory F (which includes Location A1) serves to shield the rest of the estate from sound emanating from sources to the northeast. This latter effect could partially explain the large drop in sound level in the measurement locations at the southwest end of the estate.

The findings are broadly consistent with Factory F being the most likely source of the 38 Hz tonal noise recorded and perceived in the housing estate, although it should be appreciated that precise analysis of low frequency sound propagation is not possible in such situations.

6.3.2.2 Fluctuations and Broad Peak at 12.5 Hz:

Some of the recorded time histories contained short fluctuations of high peak pressure amplitude and 1-2 seconds duration, accompanied by a fairly broad (~1 Hz wide) peak in the corresponding frequency spectra at a frequency of ~12.5 Hz. These features were only observed occasionally in the Vibrosound 'events', for around 1 event in 5 or less. Note that they may not have been observed at all by standard acoustic measurement methods, which often filter out any pressure fluctuations of frequency < 20 Hz.

These 'pulses' were detected by the microphone and by the vertical component of the upstairs seismometer at all three locations where measurements were taken. Examples of the feature, as recorded by the microphone channel, can be seen in Figures 6.2-6.4. The pulsing appeared to be absent from the data recorded by the window-mounted accelerometer, and from the ground floor slab vibration data.

A distinct, sharper peak at 13.9 Hz of similar amplitude was sometimes seen as well (see Figure 6.4). In other events, the 13.9 Hz peak was the only peak present in the 12.5 Hz third-octave band of the spectra. However, all the events that showed the strong fluctuations in the time domain, had frequency spectra containing the 12.5 Hz peak.

The 12.5 Hz pulsing/peak was not recorded during the Christmas period when local industry was shut down (Figure 6.5), nor was the 13.9 Hz peak.

At Location A1, the instantaneous peak pressure amplitude of the 12.5 Hz fluctuations reached as high as ~0.3 Pascal. This is equivalent to a RMS sound pressure level of ~80 dB.

Figure 6.9(a) gives an example of an event in the time domain containing very strong fluctuations at 12.5 Hz. Figure 6.9(b) shows the result of applying an FFT to the full ten-second event. The RMS sound pressure level of the corresponding peak at 12.5 Hz on the frequency spectrum is lower than would be expected on the basis of the instantaneous peak pressure amplitude, due to averaging across the entire 10-second event.

Figure 6.9(c) shows the result of applying an FFT to a one-second portion of the same event (from 2.8 seconds to 3.8 seconds) that contains the strongest 'pulsing' at 12.5 Hz. The magnitude of the 12.5 Hz peak in the spectrum is now closer to the maximum instantaneous peak pressure amplitude reached in the time series. However, the frequency resolution in the latter plot has become less narrow, and this reduces the potential for distinguishing between the 12.5 and 13.9 Hz peaks.

It should be pointed out that a standard sound level meter, with a dynamic range of ~72 dB, would probably have 'clipped' the 12.5 Hz, 0.3 Pascal fluctuation if it had been set to record RMS sound pressure levels, unmanned, over otherwise quiet periods. The chosen instrumentation in this case had a very high dynamic range (~144 dB), and was thus able to record both the very low sound pressure levels seen in some parts of the frequency spectra, and the high amplitude 'pulse' as described above.

The DIN 45680 (1997) recommended limit for the 12.5 Hz third-octave band is 86.5 dB. Thus the instantaneous peak pressure amplitude of the 12.5 Hz fluctuations recorded at Location A1 were lower than the DIN limit, but only by ~6 dB on occasion.

The fluctuating character in the time domain matched the residents' subjective descriptions of the problem that they experience. It was considered possible that these fluctuations may exceed the DIN limit at the loudest part of their cycle, at other positions within Location A1. The fluctuations at positions other than the microphone position were indeed subjectively louder. The 'scan' conducted at this property using a hand-held sound level meter with third-octave band filter set, did not extend down as far as 12.5 Hz (again this illustrates the limitations of standard equipment for low frequency problems), although it indicated that variations in sound level of around 10 dB occurred throughout the property in the frequency range 20-125 Hz.

The character of the sound at 12.5 Hz was both pulsing and tonal i.e. 'unusual' according to the DIN 45680 definition of a potentially disturbing low frequency noise. It may be speculated that in certain 'hot spots' within Location A1, the 12.5 Hz fluctuations reached sufficiently high sound levels at their peak pressure variations to exceed the DIN recommended level. However, on the basis of the sound levels recorded at the chosen microphone position within Location A1, it is not possible to establish that the 12.5 Hz fluctuations did violate the DIN recommended level. Therefore although it may be suspected that the 12.5 Hz pulsing is a cause of the disturbance at Location A1, it is not possible to prove this on the basis of the available data.

The instantaneous peak pressure amplitudes of the 12.5 Hz fluctuations reached values of 0.2 Pa and 0.1 Pa at Locations A3 and A2 respectively, equivalent to RMS sound pressure levels of 77 dB and 71 dB. Again, it is not possible to establish the fluctuations as the cause of disturbance at A2 or A3 on the basis of DIN 45680.

The existence of the 12.5 Hz fluctuations at all three houses suggests an external, rather than internal source, as does the absence of any likely internal source at Location A1 (no domestic electrical items were left on during the measurement period). Also, the 'disappearance' of the pulsing over the Christmas period suggests a local industrial source of the fluctuations.

The pulsing was not observed in the ground floor seismometer recordings, either in the time or the frequency domain. This seems to suggest that the 12.5 Hz fluctuations arrived at the three locations via an airborne propagation path. However, the 'absence' of the feature from the time series and frequency spectra recorded by the window-mounted accelerometer seems to contradict this.

(It is possible that a 12.5 Hz peak is present in the window vibration spectra, but masked by background noise. An attempt is made to resolve this in Chapter 8, by application of FEM.)

There is no definitive conclusion at this stage, then, as to whether the 12.5 Hz pulsing was propagated via airborne or groundborne waves. Without this information, a precise source determination for the 12.5 Hz noise is difficult. However, it is likely to be caused by a local industrial source because it disappeared over the Christmas 'shutdown' period. Also, the relatively high levels of the 12.5 Hz fluctuations observed at Location A1 compared with the levels at Locations A2 and A3, may suggest a source to the northeast of the housing estate. (Although the intermittent nature of the pulsing combined with the non-simultaneous collection of the data from the three houses, means that this could not be determined beyond doubt.)

6.3.2.3 Peak at 4 Hz:

The data recorded by the seismometer mounted on the ground floor slab displayed a sharp peak at ~4 Hz consistently throughout the measurement period, at all three properties and in all three triaxial components. The strongest amplitudes were observed in the two horizontal components, which gave approximately equal amplitudes. The only time when this feature was not observed was during the Christmas 'shut-down' period.

The seismometer mounted on the suspended first floor also recorded a 4 Hz signal, in all components at all the houses. Again, levels were higher in the horizontal components upstairs. There was generally a factor of 2-3 increase in amplitude from ground floor to bedroom floor. This is consistent with transfer functions reported in published literature (see Section 2.5).

The 4 Hz signal was observed in the window-mounted accelerometer data, but could not be distinguished in the microphone channel above background noise.

Figures 6.10-6.11 show vertical and east-west horizontal vibration spectra from an event recorded in the ground floor at Location A1, plotted against the respective BS 6472 (1992) base curves. It can be seen that the recorded vibration levels lie at least two orders of magnitude below the BS 6472 limits, and are therefore imperceptible to humans.

The shortcomings and ambiguities of BS 6472 (1992) were discussed in Section 4.3; however it should be pointed out that the signal under consideration is highly tonal and therefore summing the energy in the narrowband spectra to construct third-octave band levels would not have much effect on the conclusion that the recorded ground vibrations are imperceptible.

Since the 4 Hz signal was recorded at all three measurement locations, it is likely to have an external source. The signal is clearly groundborne in its propagation.

Ground slab vibrations at 4 Hz were strongest at Location A1, where the measured amplitudes were greater by a factor of 2-10 than those recorded at Locations A2/A3.

A crude determination of direction based on relative amplitudes across the estate suggests that the 4 Hz groundborne vibrations may be emanating from the northeast, possibly from Factory F.

The strongest 4 Hz signal in the ground floor slab is displayed by the horizontal components, but it is also present in the vertical, therefore it is likely to be a Rayleigh rather than a Love wave (see Section 2.3). If so, there should be a horizontal 'null' direction, perpendicular to the direction of propagation.

This was not immediately apparent because of the particular configuration of the locality. If the groundborne signal is assumed to be propagating from Factory F, located to the northeast of the housing estate, then a southwest-travelling Rayleigh-type wave would be resolved into equal components in the north-south and east-west aligned geophones built into the seismometer.

It is possible, however, to rotate the three-component seismometer data into another frame of reference where the primary axis (horizontal direction of maximum vibration amplitude) lies parallel to the direction of motion of the Rayleigh wave. This type of polarisation analysis is explored in Chapter 9.

The 4 Hz vibrations do not appear to be a cause of the disturbance in this case study, due to their negligible amplitudes. Note, however, that they may not have been detected at all using standard acoustic techniques alone.

6.3.2.4 Other Features:

Some recorded events displayed sound levels in some third-octave bands in excess of the DIN 45680 recommended limit, but the sound spectrum in those third-octave bands was broadband and did not have 'unusual' characteristics i.e. were not fluctuating or tonal (e.g. see Figures 6.12-6.13, especially the 50 Hz and 63 Hz third-octave bands). In such instances the sound in those frequency bands was not considered to be potentially disturbing according to DIN 45680.

Sharp peaks were occasionally present at 17 Hz and 32 Hz in the microphone, window-accelerometer and vertical upstairs seismometer channels at all three houses. An intermittent 26 Hz airborne peak was also observed at Location A3 only.

All these features of the frequency spectra had amplitudes that were well below the recommended limits for noise and vibration, and therefore were not considered likely causes of the disturbance. They were also more highly intermittent than the other features described above, and were therefore considered of less interest with regard to the current objectives of utilising the data from the case study to illustrate the advantages of the combined acoustic/microseismic technique. Therefore, they were not analysed in detail.

6.3.3 Summary of Initial Findings

Analysis of the output from the microphone channel revealed significant peaks in the frequency spectrum, at frequencies close to 38 Hz and 12.5 Hz. The limits recommended by the German national standard DIN 45680 (1997) were exceeded on occasion, particularly at Location A1. The character and propagation behaviour of these features of the sound spectrum, were determined in greater detail using the integrated acoustic/microseismic techniques than would have been possible using conventional methods.

Ground vibration levels, as measured by the ground floor seismometer, were found at all three dwellings to be significantly below the maximum levels permitted by BS 6472 (1992). There also appeared to be no danger of structural damage to buildings, which was an initial concern of the residents. This reassurance illustrates one of the benefits of measuring vibration levels alongside sound pressure, even when a case turns out to involve disturbance of a purely airborne nature.

Most of the residents' subjective observations throughout the housing estate tied in with fluctuations in the 40 Hz third-octave band level and the 12.5 Hz third-octave band level.

Disturbance was recorded at Location A1 where the DIN recommended limit was exceeded at 40 Hz. On some occasions, it may be speculated although not proven that the DIN limit for the 12.5 Hz third-octave band was exceeded at some positions within the house. The residents of Location A1 reported that the Christmas 'shut-down' period was very quiet; the objective results confirm that absolute levels of noise and vibration were much reduced over Christmas and the 'unusual' features described above were not detected.

The residents of Location A3 reported the entire monitoring period to be quiet; the DIN limits for the 40 Hz and 12.5 Hz third-octave bands were not exceeded at Location A3.

The only exception to the rule that subjective loudness variations matched 40 Hz and 12.5 Hz third-octave band levels, was at Location A2, where the resident reported being disturbed throughout the measurement period. This included the Christmas 'shut-down' period. It is considered likely that the resident of Location A2 has a medical hearing condition such as tinnitus, and this is the cause of their distress.

A possible cause of the disturbance was starting to emerge at this stage of the investigation, namely low frequency, tonal airborne sound, probably emanating from Factory F, in the 40 Hz third-octave band (at sound levels in excess of the DIN standard).

Also of note were intermittent fluctuations at 12.5 Hz, lasting 1-2 seconds, probably airborne, consistent with subjectively observed fluctuations although the recorded sound levels at that frequency were below the DIN 45680 limit.

An experiment was suggested involving a more comprehensive shutdown of Factory F. This would take the form of a 'blind test' involving the local residents making subjective comments, at the same time as the combined acoustic/microseismic technique was utilised to take objective measurements.

The purpose of the experiment would be to confirm low frequency noise from Factory F as the cause of the disturbance to the residents of the housing estate, as well as to try to pinpoint more precisely the source of the airborne 38 Hz tone and the 12.5 Hz fluctuations. This experiment, which is described in the next section, also served to further test the capabilities of the integrated acoustic/microseismic approach.

6.4 SHUTDOWN EXPERIMENT

6.4.1 Test Procedure

A sequential shutdown experiment was conducted on 19/3/98 with the co-operation of the proprietors of Factory F, the local council and the residents of the housing estate. Monitoring of sound and vibration levels was undertaken once again at Location A1, where the greatest sound pressure levels corresponding to the suspected problematic sound features had been observed during the earlier monitoring period. The various transducers were placed in the same positions as before, to allow direct comparison with earlier results.

The procedure for the test was agreed in advance between the team from University of Liverpool and staff at Factory F. All plant was run up to full power, followed by a rapid shutdown of as much plant as possible, followed by a controlled run up of all plant. A detailed timetable of the on and off times of plant was logged.

Recordings were taken simultaneously in the upstairs bedroom of Location A1 using the Vibrosound datalogger, set to record a single 10-second event every minute. This was the maximum coverage possible using the equipment available at the time. Ideally, complete time coverage would have been possible; however, the length of time between running up individual items of plant was ten minutes on average, so it is hoped that all major 'occurrences' were sufficiently covered by the recordings.

At the same time, residents of the housing estate were asked to complete a log sheet within their own homes, indicating what they could hear and whether they were disturbed against time to the nearest minute. These log sheets were later compared with the measured results.

Continual contact was maintained between Factory F and the measurement site during the test by two-way radio. Each item of plant was given a code name so that the residents of

Location A1 would not be influenced by knowledge of what was operational at any particular time. The measurements should not have been affected by the radio noise as that noise lay above the frequency range of interest.

6.4.2 Results from Shutdown Experiment

6.4.2.1 Measured Noise and Vibration:

The noise and vibration spectra obtained during the shutdown experiment were confirmed as being broadly similar to those recorded during the earlier period of measurement at Location A1 in November 1997.

Sharp peaks at ~38 Hz were once again observed in the microphone and window vibration spectra during the period when the plant was running at full power, but they were not detected after the works had been shut down. Figures 6.14 and 6.15 show the microphone spectra recorded immediately before and immediately after the shutdown. Vibrations at 38 Hz were not detected in the ground floor slab. These observations confirm that the 38 Hz tones emanate from Factory F and are transmitted into the house via an airborne propagation path. Figures 6.16 and 6.17 demonstrate that the DIN 45680 recommended limit for the 40 Hz third-octave band was exceeded at A1 immediately prior to the shutdown, but not afterwards.

On this occasion there were observed to be three distinct peaks during times of full output at frequencies close to 38 Hz, namely 36.4 Hz, 37.5 Hz and 38.4 Hz. The frequency range 36-39 Hz was studied for each successive event recorded during the run-up part of the experiment, to try and ascertain which was the most important peak in terms of contributing to the 40 Hz third-octave band level, and which item of plant was responsible for causing each tone.

The 12.5 Hz fluctuations in the time series were also observed intermittently once again during the full output period, along with a peak in the frequency spectrum at 12.5 Hz. There was a second peak in this region of the spectrum at 13.8 Hz. These features, which ceased immediately after shutdown (confirming they emanate from a source within Factory F), were also kept under scrutiny for each successive event from the run-up period. Again, these features were not detected in the window accelerometer channel or in the ground floor slab, and their exact propagation path from Factory F to Location A1 remains unclear.

Figures 6.18-6.20 show various microphone channel recordings taken during the sequential run-up at Factory F. It was also possible to construct a plot of 40 Hz third-octave band variations throughout the shutdown experiment, using a *Matlab* routine. This plot is shown in Figure 6.21, which also details the points at which each item of plant was switched on. The DIN 45680 limit (night) for the 40 Hz band is shown for comparison. Since the Vibrosound had been set to record one event per minute, the x-axis (event number) also represents the time in minutes that had elapsed since the start of the shutdown experiment.

The plot in Figure 6.21 proved very useful in ascertaining which plant contributed most to the disturbance, and it is another example of the versatility of the combined acoustic/microseismic method.

Firstly, it can be seen from Figure 6.21 that background levels in the 40 Hz band were ~13 dB below the DIN limit during the period when all plant was shut down.

In Figure 6.18, there is a single peak close to 38 Hz that is 10 dB above the surrounding background noise. The exact frequency of the peak is 38.4 Hz, and it first 'appeared' when an item of machinery called "Caster 2 Cooling Tower" was switched on. The overall 40 Hz third-octave band level for this event fell short of the DIN limit by around 2 dB.

Figure 6.19 shows an event recorded soon afterwards in which a second peak has 'emerged' at 36.5 Hz, of similar amplitude to the 38.4 Hz peak. The plant known as "Bag Plant 2" (BP2) had just been switched on. A sharp peak at 13.7 Hz has also 'appeared', and the overall 40 Hz third-octave band level has increased to ~1 dB above the DIN limit.

Bag Plant 2 therefore seems to be the source of sharp tones at 36.5 Hz and 13.7 Hz, and has increased the 40 Hz band level above the DIN limit for the first time since the shutdown took place. (The nominal running speed of BP2 was 2175 rpm, equivalent to 36.25 Hz.)

Figure 6.20 shows the first 're-emergence' of the 37.5 Hz peak, at a sound pressure level greater than either of the other two nearby peaks, and of the large peak pressure amplitude fluctuations in the time series, lasting 1-2 seconds and coupled with a distinct peak at 12.3 Hz (at higher amplitude than the 13.7 Hz peak). This event was recorded immediately after "Bag Plant 1" (BP1) had been switched on. The overall 40 Hz third-octave band level had increased to 2-3 dB above the DIN limit, where it remained on average for the duration of the rest of the experiment.

Bag Plant 1 was therefore established as the source of a 37.5 Hz peak (which is suspected to be the same tone as recorded earlier at ~38 Hz, shifted slightly in frequency), and of the large time series fluctuations at ~12.5 Hz. (The nominal running speed of BP1 was 2295 rpm, equivalent to 38.25 Hz.) BP1 also seems to provide the greatest contribution to the 40 Hz third-octave band level.

It may be noted at this point that the subtle differences between the peaks involved were only picked out because of the narrow frequency resolution (0.1 Hz) of the technique. A less narrow bandwidth, even twelfth-octave bands, may not have made the distinction between the peaks, and so the major 38 Hz tone may have been attributed to another item of plant, for example the Caster 2 Cooling Tower that gave rise to a lesser 38.4 Hz tone.

6.4.2.2 Subjective Evaluations:

It was important to corroborate the results with reference to the subjective comments made by the residents of the estate and by the experimenters.

Several residents detected a "fluctuating sound" or "feeling of pressure on the ears" when BP1 was switched on. This correlation mainly occurred for the subjective comments of those residents located at the northeastern end of the housing estate i.e. nearest to Factory F. Residents at the 'far' (southwestern) end of the estate logged comments that correlated less well and a clear link could not be established between perceived disturbance at these more distant properties and operations at Factory F.

In particular, the sole resident of Location A2, who had taken part in the earlier monitoring, produced a log in which she claimed to hear 'her noise' at times when all plant was shut off; she also claimed that the period of full output towards the end of the run-up was 'much quieter'. This seems to confirm the earlier conclusion that the 'disturbance' as perceived by that particular individual, is due to a hearing disorder.

The residents at the closest property to Factory F, Location A1 (where monitoring was taking place) were logging subjective comments sitting in the kitchen downstairs, which they considered to be the loudest part of the house. They heard "rotating (slow)" when BP2 switched on, whilst they perceived the sound to be "rotating faster, louder" immediately after the switch on of BP1. The author's personal judgement from a listening position upstairs, outside the bedroom where the monitoring equipment was installed, was that fluctuations were audible when BP1 was on, but were inaudible when it was off.

Thus Bag Plant 1 was established as the cause of most of the disturbance perceived by the residents of the nearest properties to Factory F, with Bag Plant 2 possibly making a minor contribution. In fact, it transpired that these two items of plant shared a common stack and were therefore linked. It was recommended that the factory owners apply noise control treatment to both BP1 and BP2.

6.4.3 Summary of Findings from Shutdown Experiment

Several tones at around 38 Hz and fluctuations at 12.5 Hz were confirmed to be emanating from Factory F. The ~38 Hz tones were confirmed as being airborne, but the propagation path of the 12.5 Hz 'pulsing' remained unsolved. Vibration levels in the ground floor slab were again shown to be several orders of magnitude below perceptible levels.

The precise sources of three tones around 38 Hz were established by sequential shutdown of various items of plant at the factory. These could be distinguished more easily because of the narrow-band nature of the data collection methodology.

The sources of tones at 12.5 Hz and 13.8 Hz were also identified. Many acoustic measurement procedures and systems do not sample frequencies below 20 Hz.

The cause of the disturbance perceived by many of the residents was linked to the items of plant that had been pinpointed, by reference to changes in subjective responses and measured variations in the 40 Hz third-octave band levels.

The times when residents at the 'near' end of the estate made complaints or comments referring to perception of a fluctuating sound, corresponded to times when the 40 Hz third-octave band levels at Location A1 exceeded the DIN 45680 limit for that band. Comments from the far end of the estate did not correlate, but in the previous monitoring period it was shown that the 40 Hz (and other) third-octave band levels in this part of the estate were 10-20 dB below those observed at Location A1. This case study therefore confirmed the usefulness of DIN 45680 (1997) as a reasonably good predictor of annoyance.

Note that the methodology used cannot entirely replace the use of subjective observations in establishing the cause of a subjective disturbance, but it may complement them.

Finally, remedial work for the suspect item(s) of plant was recommended. The owners of the Factory F brought in consultants who applied noise control treatment to Bag Plant 1. Following this treatment, the level of complaints received by the local council about low frequency noise and/or vibration problems in the housing estate, dropped considerably.

6.5 CONCLUDING REMARKS

The case study outlined above demonstrates the usefulness and versatility of the combined acoustic/microseismic approach when tackling complex low frequency noise/vibration problems.

Long-term monitoring was shown to be valuable for solving this case, as the reported disturbance was intermittent, unpredictable and initially little was known about it.

Subtle changes in frequency of certain tones were observed over several nights, which helped to illuminate their source (rotating machinery at a nearby factory). This was enhanced by the narrow frequency resolution of the recordings.

The simultaneous recording of sound pressure, window vibration and first-floor seismometer data in parallel allowed direct comparisons of the levels in each channel to be made. From this analysis, propagation paths (groundborne vs. airborne, internal vs. external source) could be determined (although this didn't work in all cases). The recording of ground vibration levels allowed the author to rule out any potential damaging effects (either to humans or to building structures) as a result of groundborne vibration.

The recordings extended in frequency down to d.c., which allowed important features of the sound spectra to be observed at 12-13 Hz. Many acoustic instruments use high-pass filters that roll off below 20 Hz.

The wide dynamic range (24-bit, 144 dB) of the Vibrosound datalogger was also crucial in this particular case study. Large peak pressure displacements were recorded at 12.5 Hz (one event was recorded with a peak pressure displacement of 0.3 Pascal, equivalent to 81 dB RMS sound pressure level), whilst background levels during quiet events were below 20 dB in some frequency regions. These features would probably have exceeded the range of a standard analogue or 12-bit (72 dB) digital sound level meter. Either the peak pressure would have exceeded the full-scale deflection of the meter, leading to a clipped signal (overload), or the background levels would have fallen below the noise floor of the instrument.

The technique involved collection of raw time histories, from which a wide range of useful analyses could be carried out. It is not possible to reconstruct time histories from sound level meter readings, and many of the features detailed in this case study (such as the 12.5 Hz fluctuations in the time series) could not have been observed in such detail using standard acoustic instrumentation.

The German national standard DIN 45680 (1997) was demonstrated to be a reasonably good predictor of annoyance, based on third-octave band levels constructed from the recorded time histories and on subjective assessments provided by the residents of the housing estate and the author. This also validates the method used to derive third-octave band levels, even though it is a non-standard procedure.

Finally, one important finding that may have gone unnoticed had a standard acoustic technique been used, was that the tone at ~38 Hz and fluctuations at ~12.5 Hz were shown to emanate from a common source. In a way this compensated for the fact that the propagation mechanism of the 12.5 Hz fluctuations had not been fully explained, as it meant that the two could be resolved together by noise control investigation. It was also rather fortunate, for the following reason.

At the chosen microphone position in Location A1 it was only the 38 Hz peak, and not 12.5 Hz, that exceeded the DIN 45680 recommended limits. Thus action could only be recommended on the basis that the 40 Hz third-octave band levels were in excess of the standard.

However, it is suspected that the 12.5 Hz fluctuations, whose nature closely matched the subjective descriptions of the disturbance as a "pulsation", "feeling of pressure on the ears", were the primary cause of the disturbance.

Placement of the microphone at another position in the house might well have yielded instantaneous peak pressure amplitudes at 12.5 Hz in excess of DIN 45680. This highlights the fact that ideally, the microphone should be placed in the worst case position, although there will often be practical reasons why this is not possible for long-term monitoring in a dwelling.

6.6 REFERENCES

British Standard BS 6472 (1992): *'Evaluation of human exposure to and measurement of vibration in buildings'*, British Standards Institute, London.

German Standard DIN 45680 (1997): *'Messung und Bewertung tieffrequenter Geräuschimmissionen in der Nachbarschaft'*, Deutsches Institut für Normung e.V., Berlin.

Piorr, D. and Wietlake, K., (1990): *'Assessment of Low Frequency Noise in the Vicinity of Industrial Noise Sources'*, Journal of Low Frequency Noise and Vibration, Volume 9(3:116-119).

Fig. 6.1 – sketch map of the area under investigation in Case Study A
(houses not to scale)

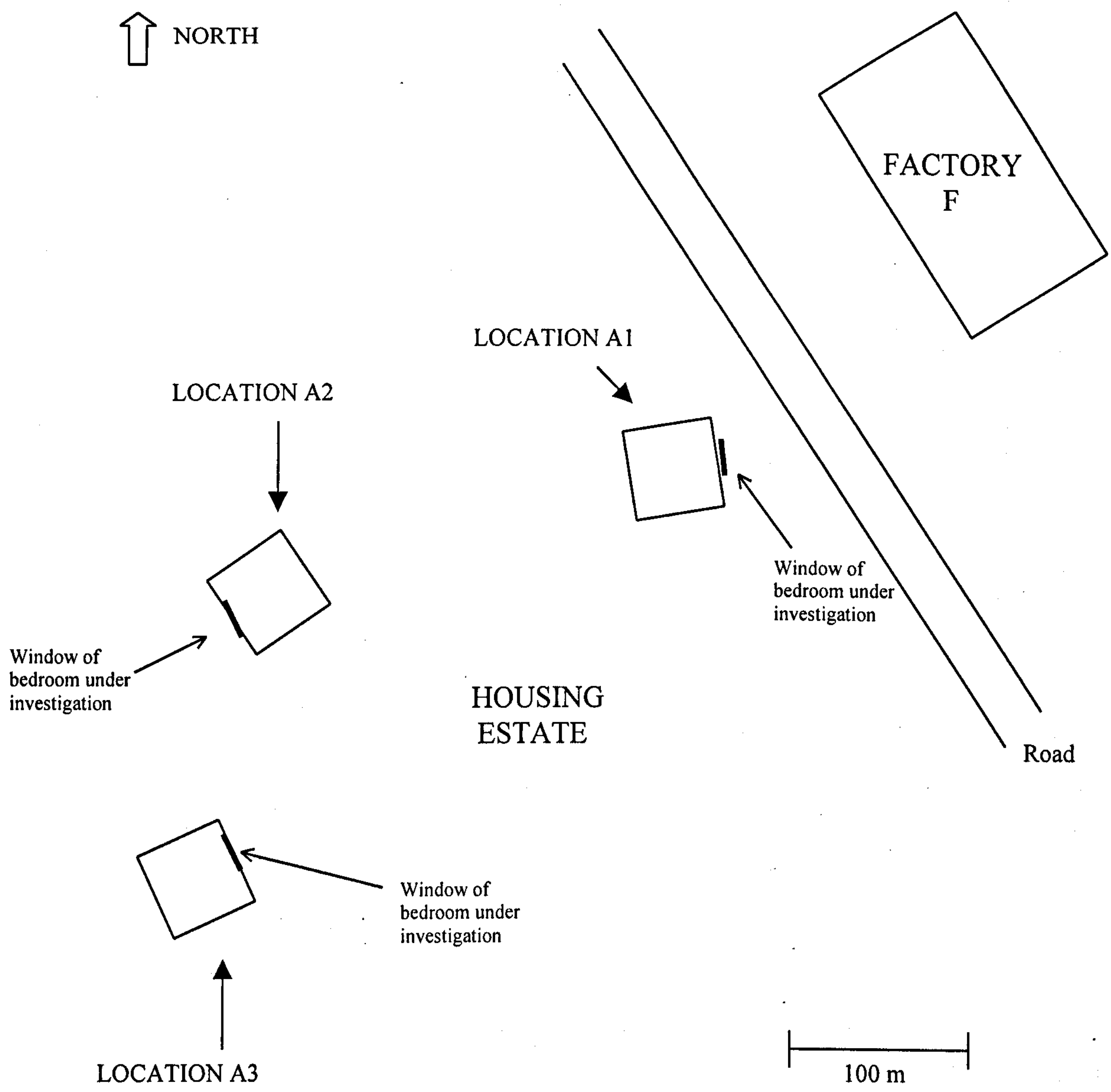


Fig. 6.2 - a typical microphone channel recording from Location A1

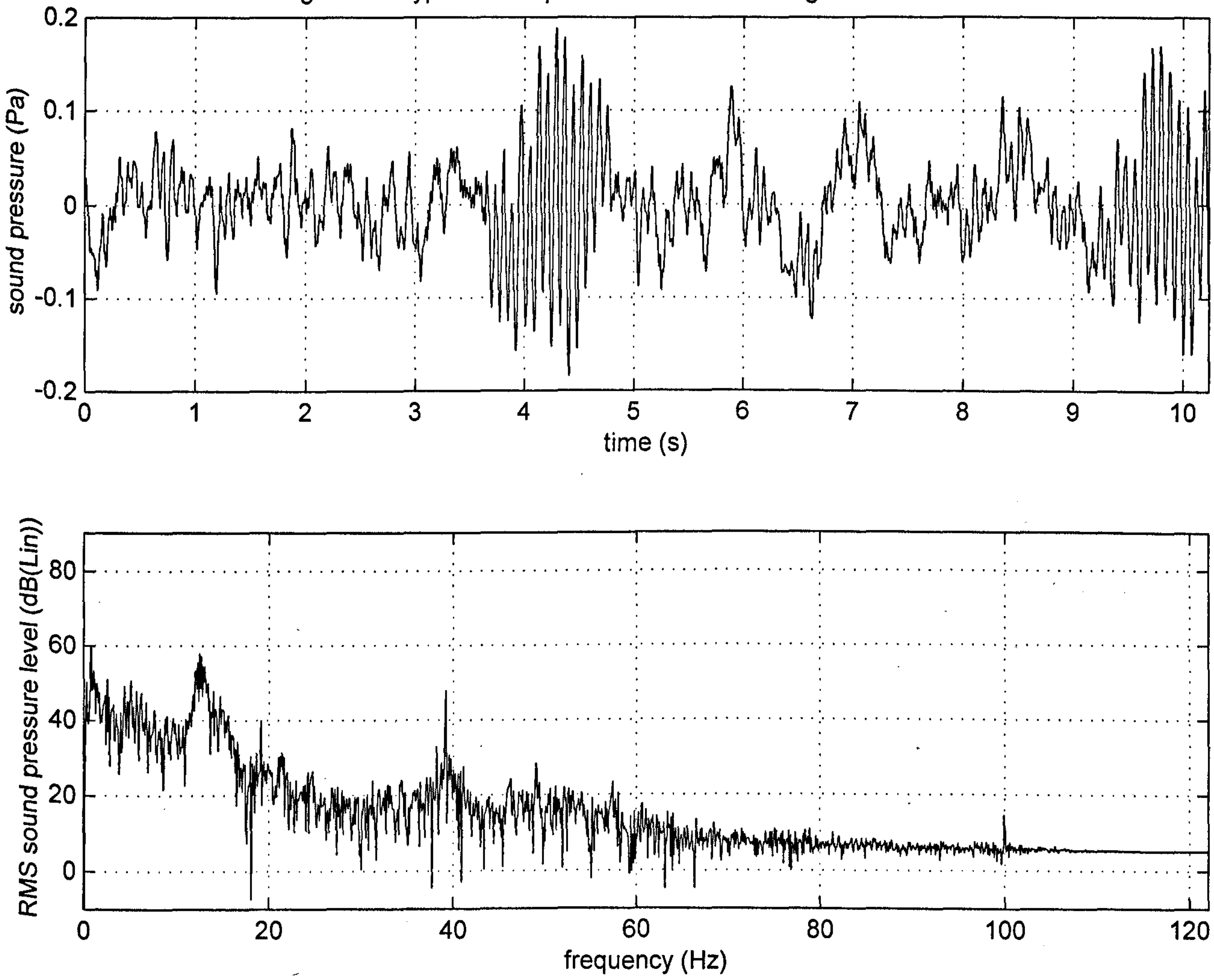


Fig. 6.3 - a typical microphone channel recording from Location A2

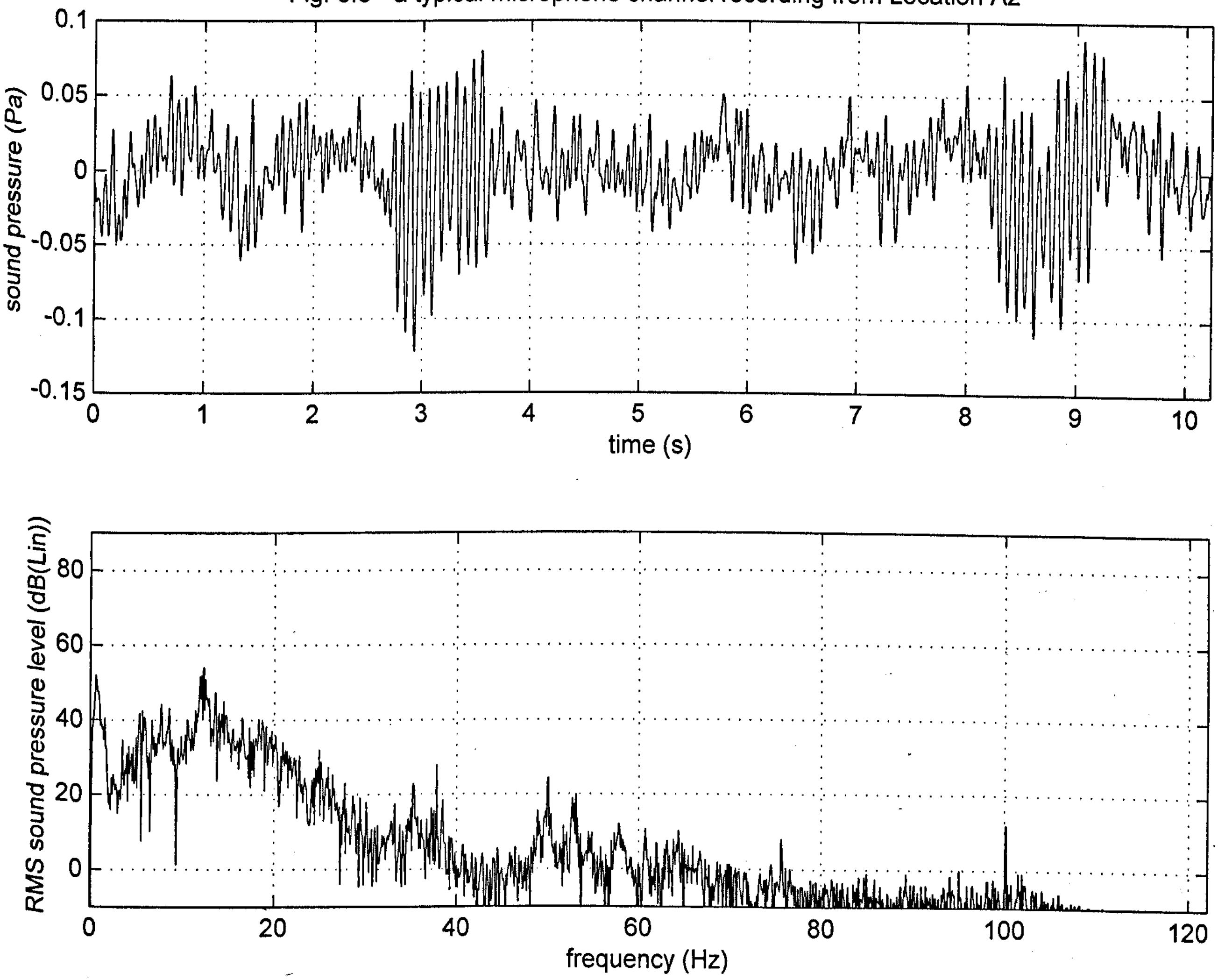


Fig. 6.4 - a typical microphone channel recording from Location A3

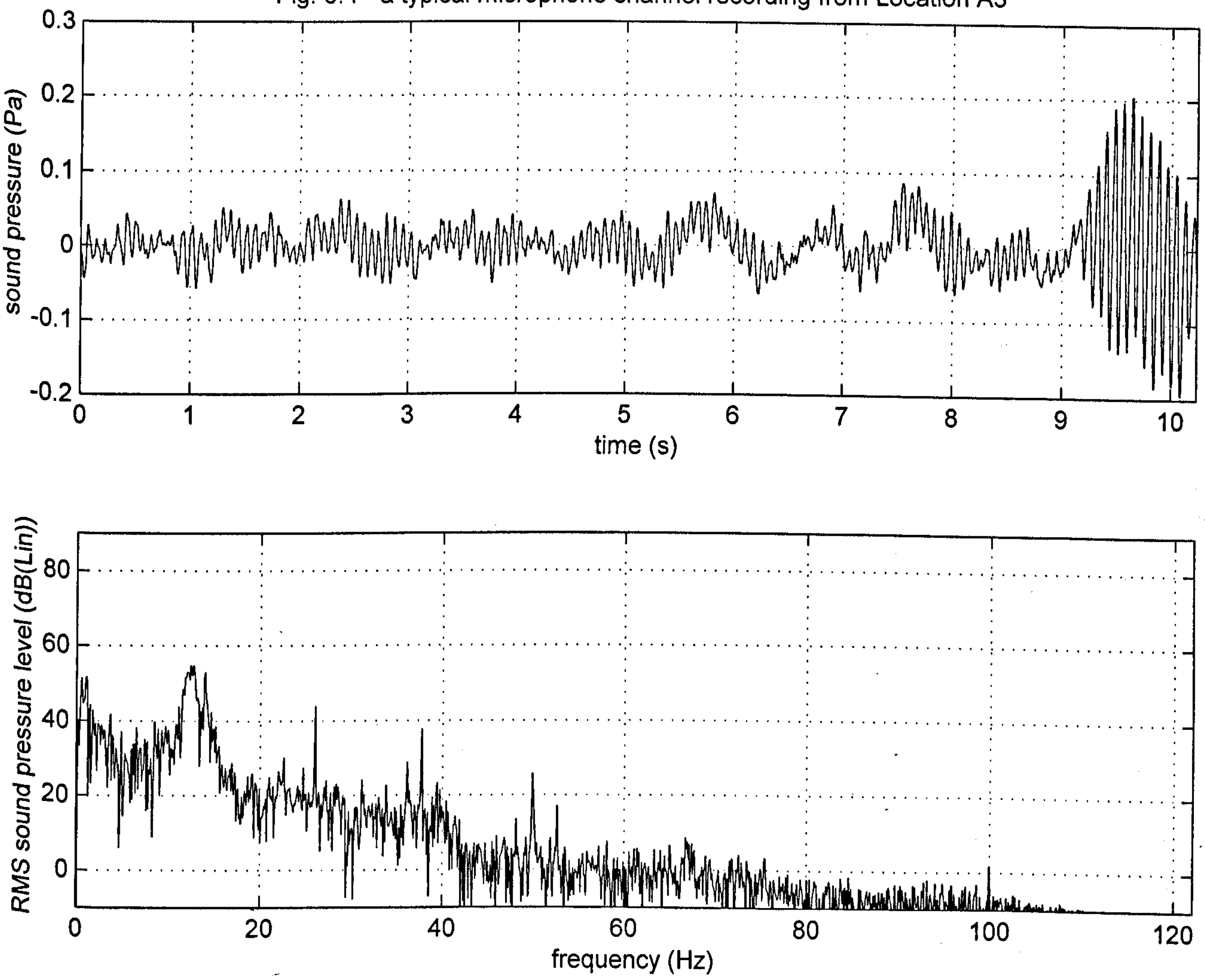


Fig. 6.5 - a background noise recording from Location A3

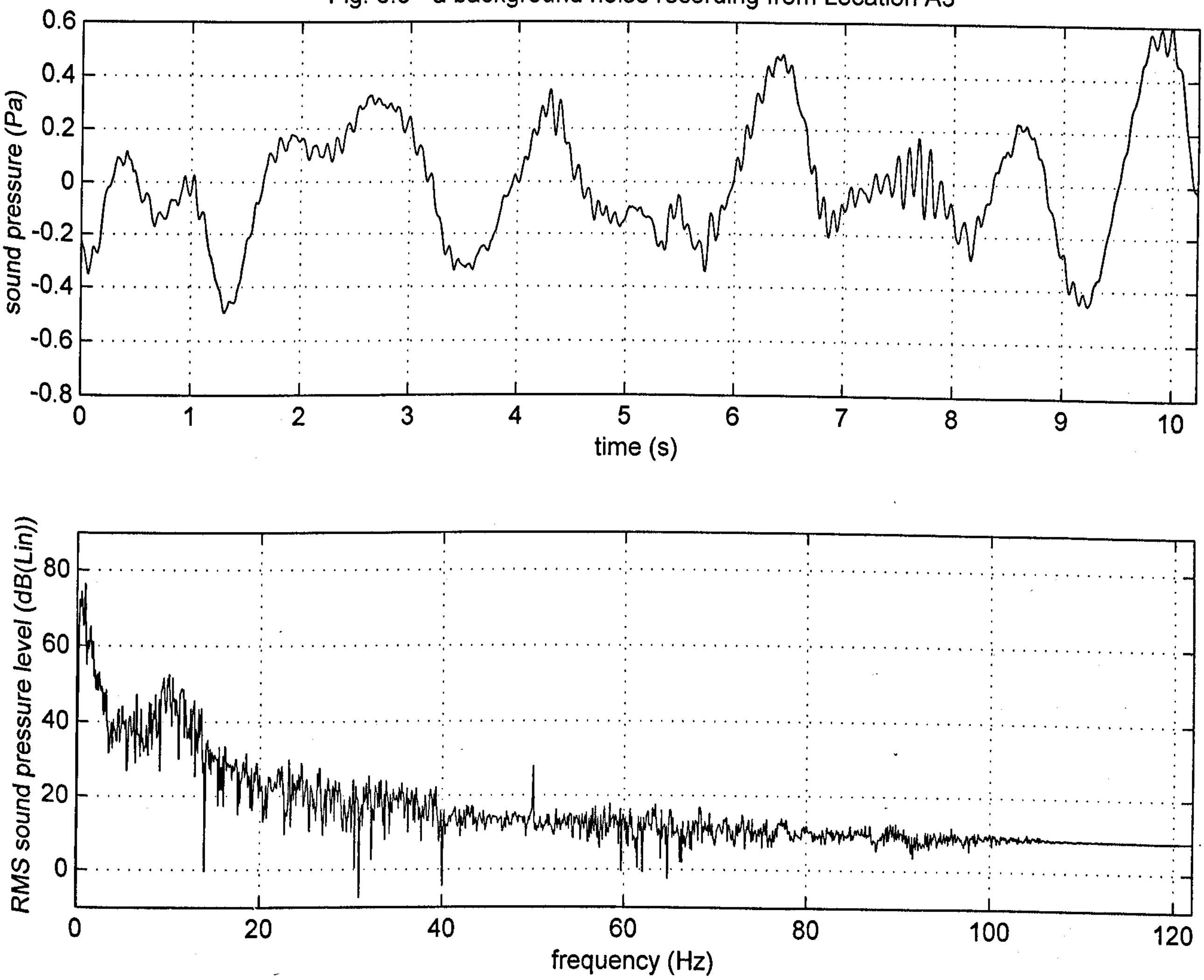


Fig. 6.6 - typical third-octave band levels from Location A1, compared with DIN 45680 limits

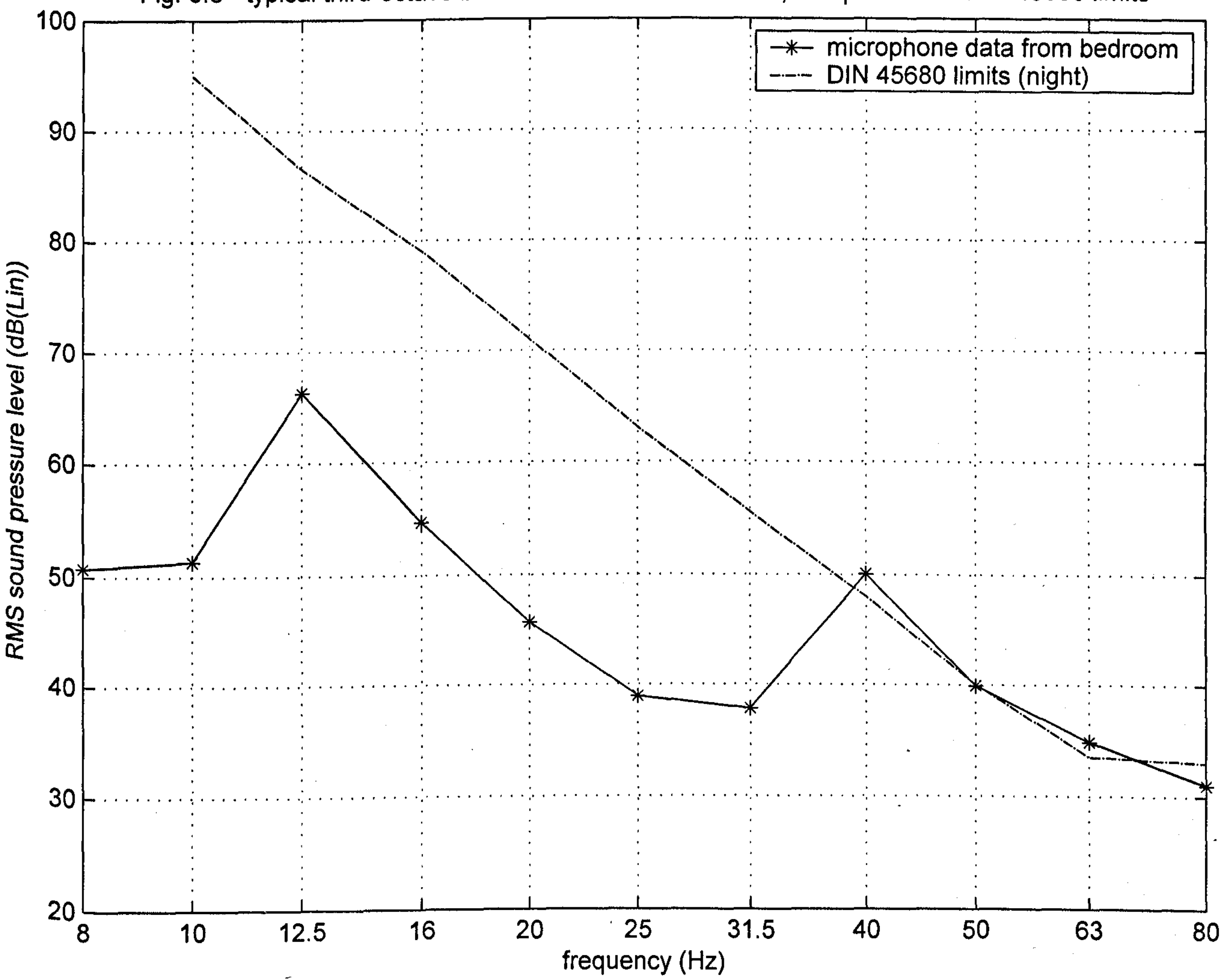


Fig. 6.7 - typical third-octave band levels from Location A2, compared with DIN 45680 limits

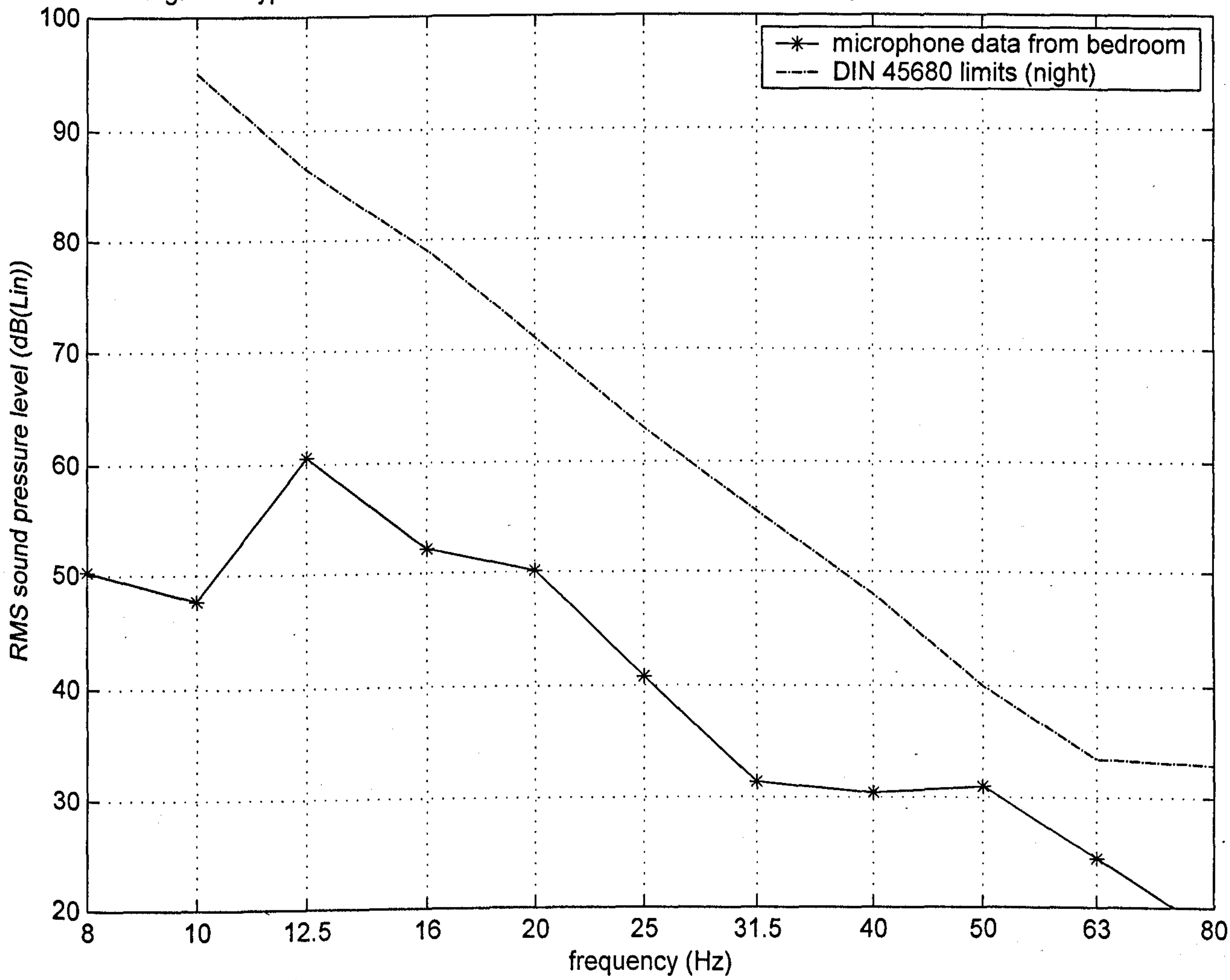


Fig. 6.8 - typical third-octave band levels from Location A3, compared with DIN 45680 limits

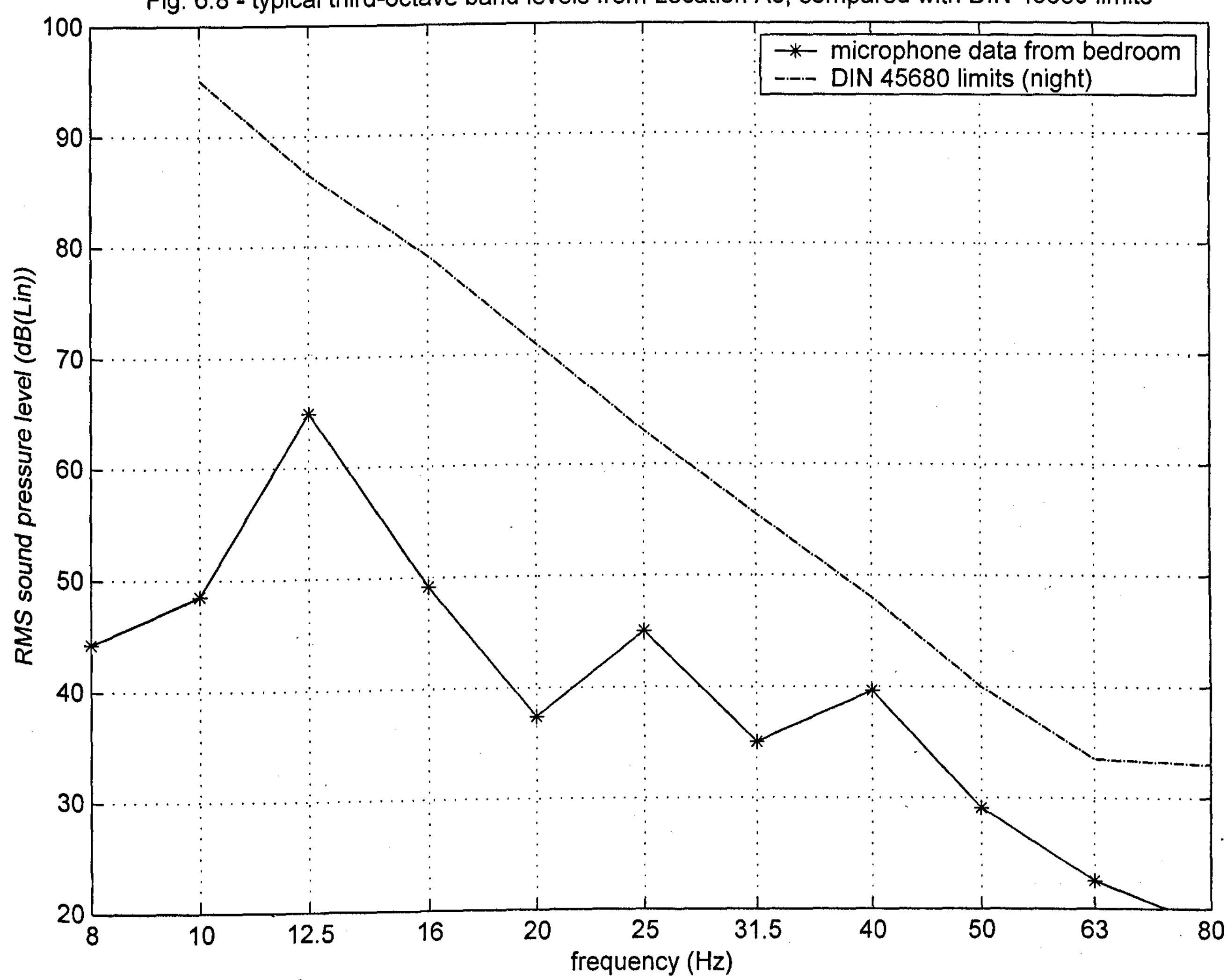


Fig. 6.9 - (a) time series showing strong 12.5 Hz fluctuations recorded in the air at Location A1;
(b) shows the result of applying an FFT to the full ten-second event in (a);
(c) shows the result of applying an FFT to one-second portion of the time series between the vertical lines in (a)

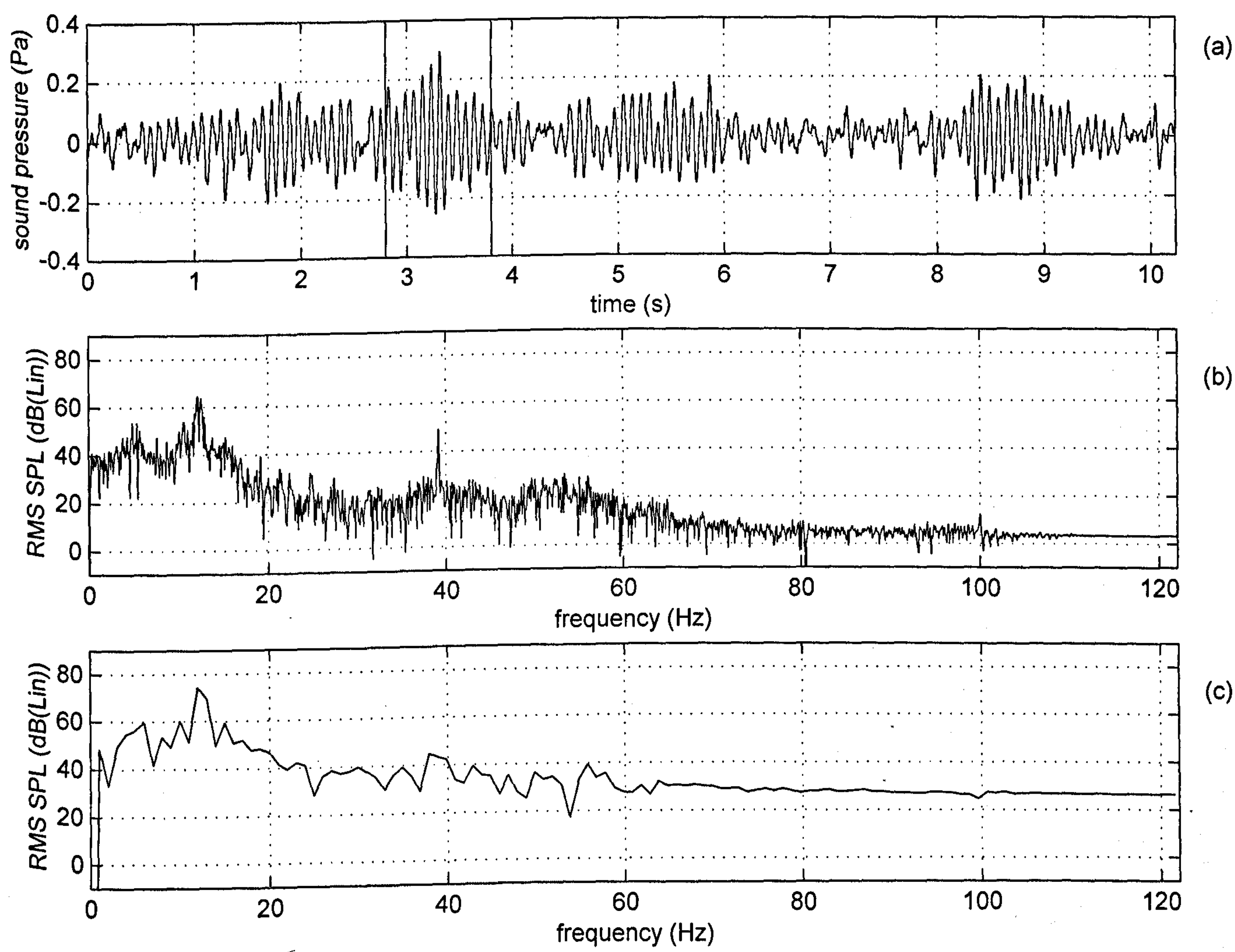


Fig. 6.10 - vertical vibration levels in the ground slab at Location A1, compared with BS 6472 limits

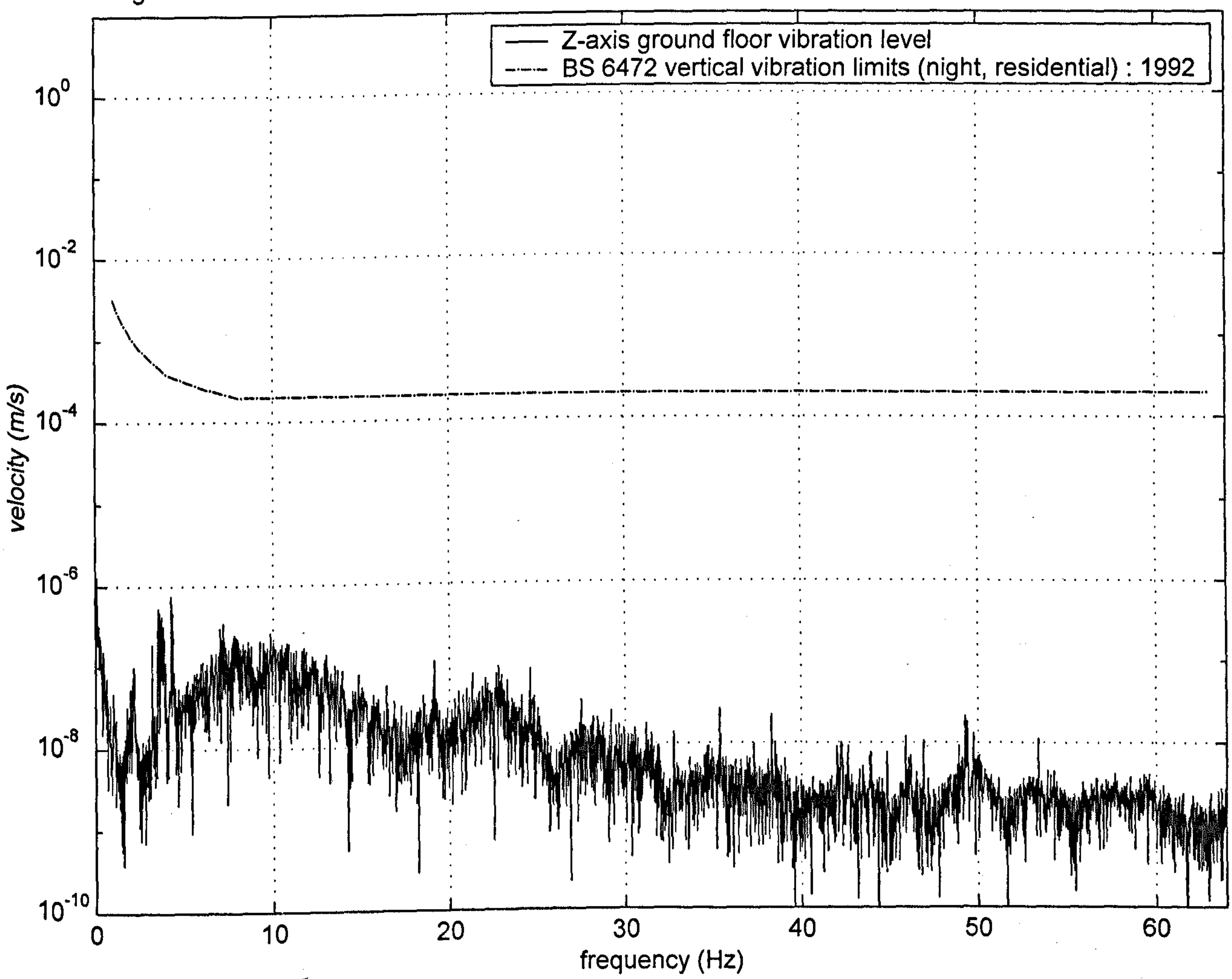


Fig. 6.11 - horizontal vibration levels in the ground slab at Location A1, compared with BS 6472 limits

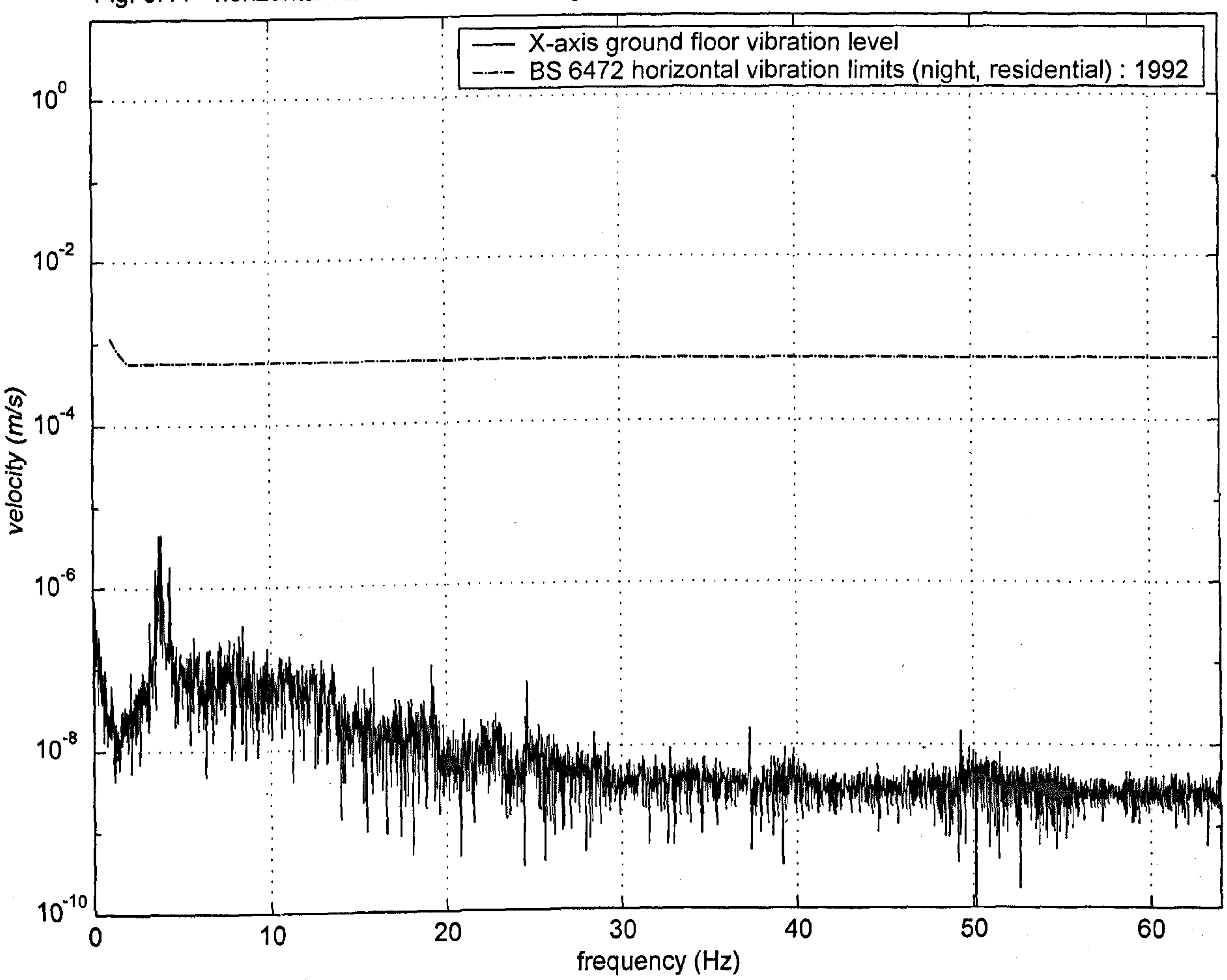
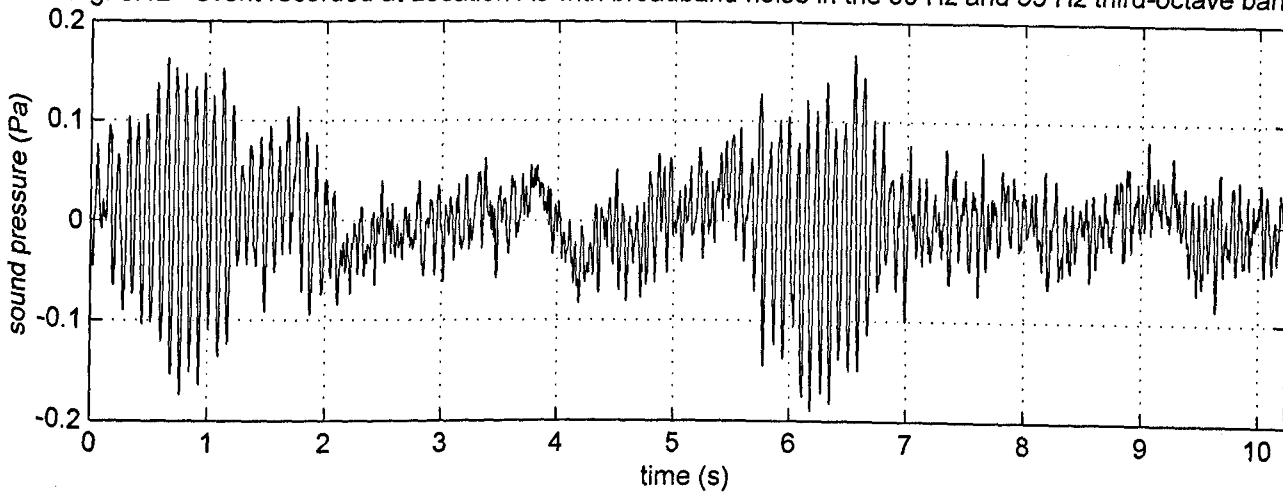


Fig. 6.12 - event recorded at Location A3 with broadband noise in the 50 Hz and 63 Hz third-octave bands



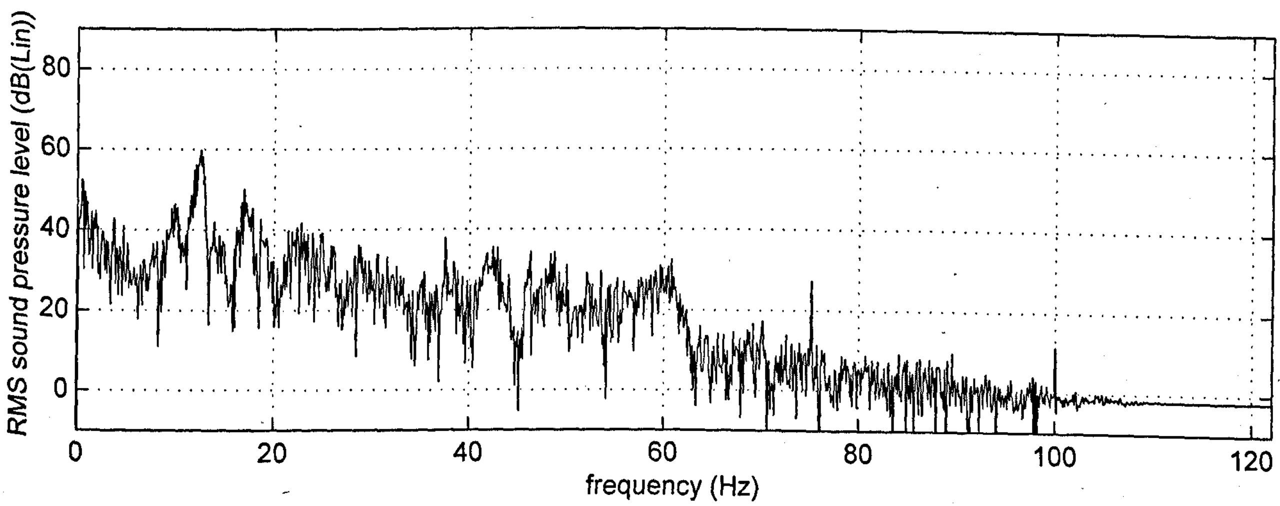


Fig. 6.13 - event recorded at Location A3 with broadband noise in the 50 Hz and 63 Hz third-octave bands

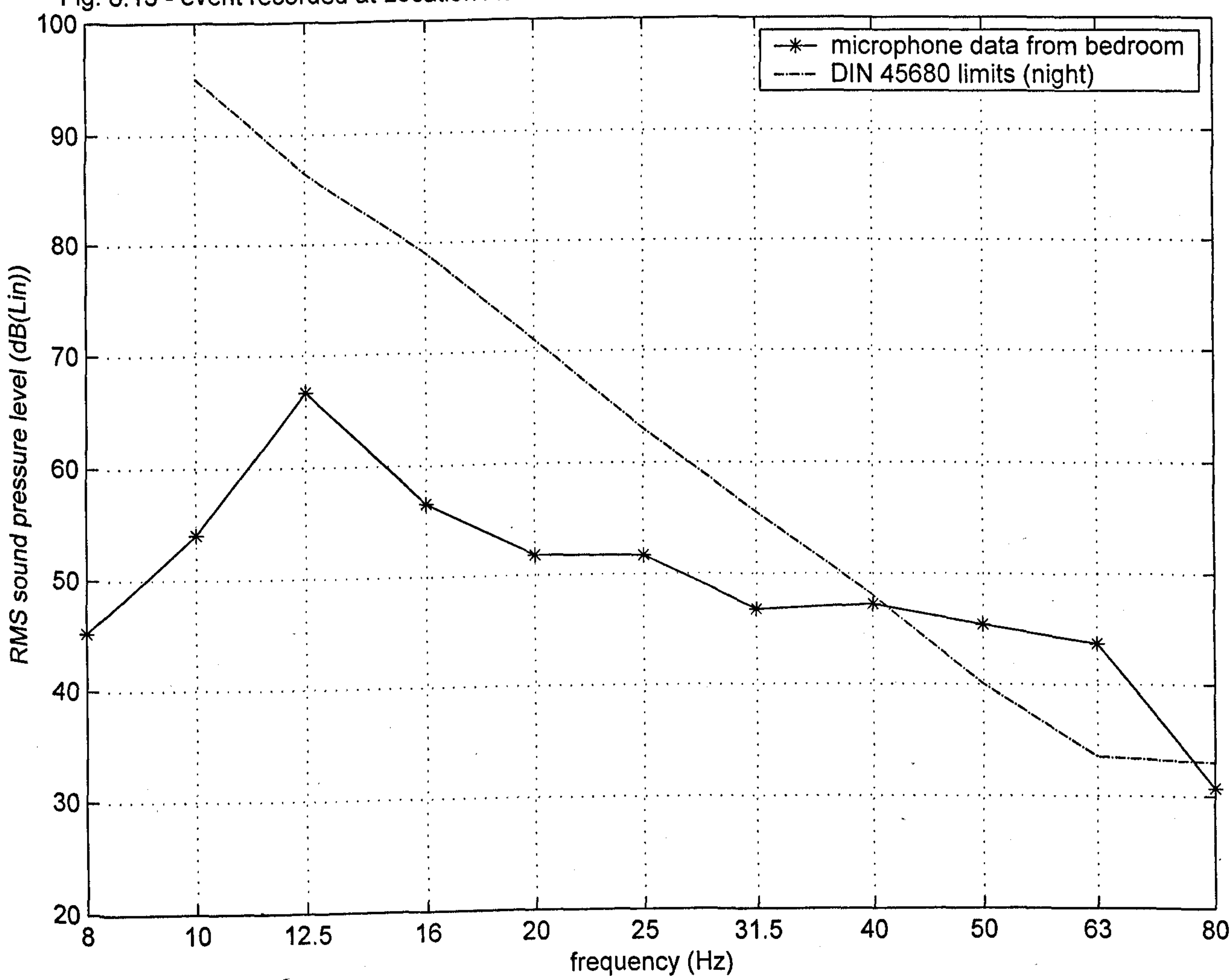


Fig. 6.14 - event recorded at A1 immediately prior to shutdown of Factory F

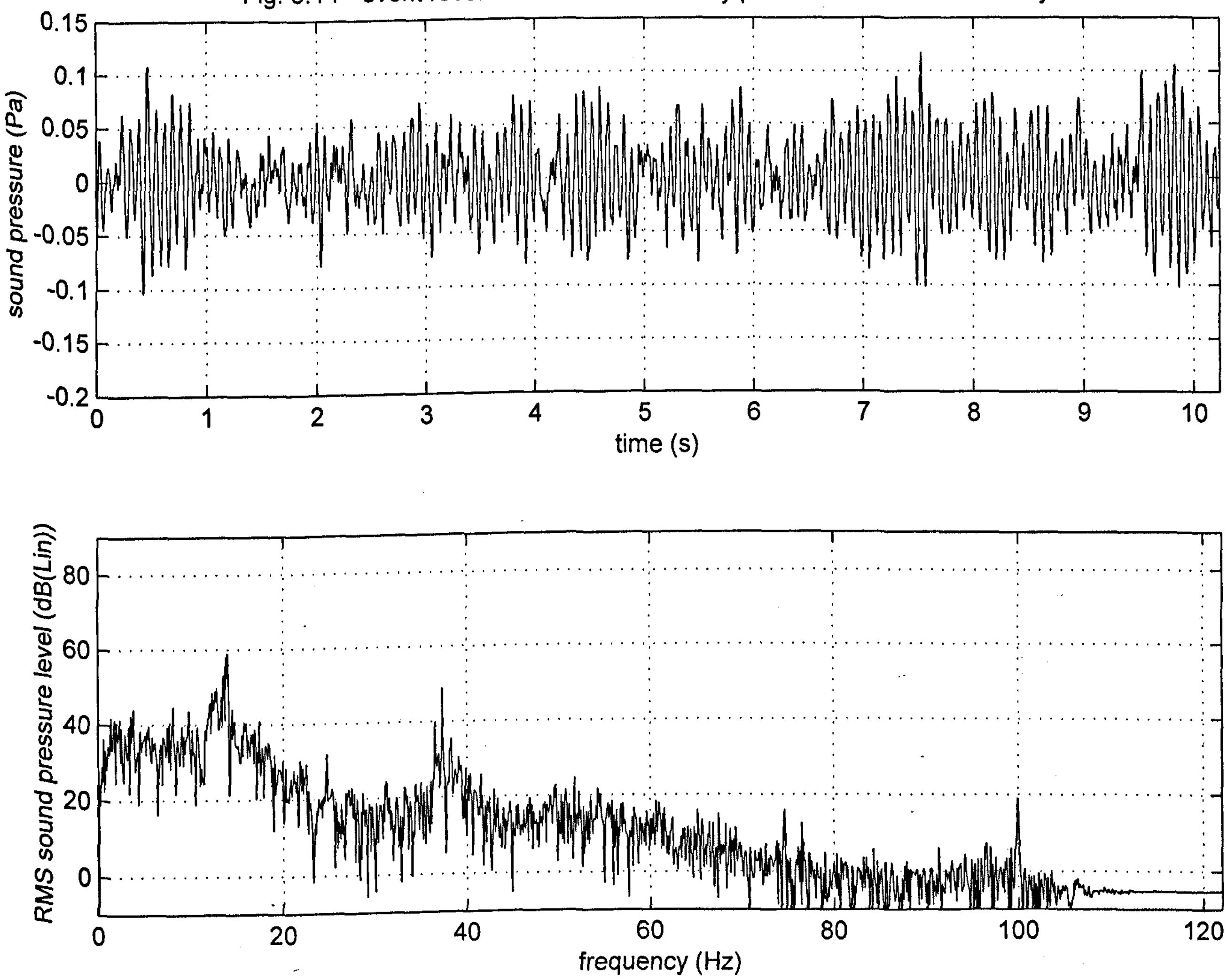


Fig. 6.15 - event recorded at A1 immediately after shutdown of Factory F

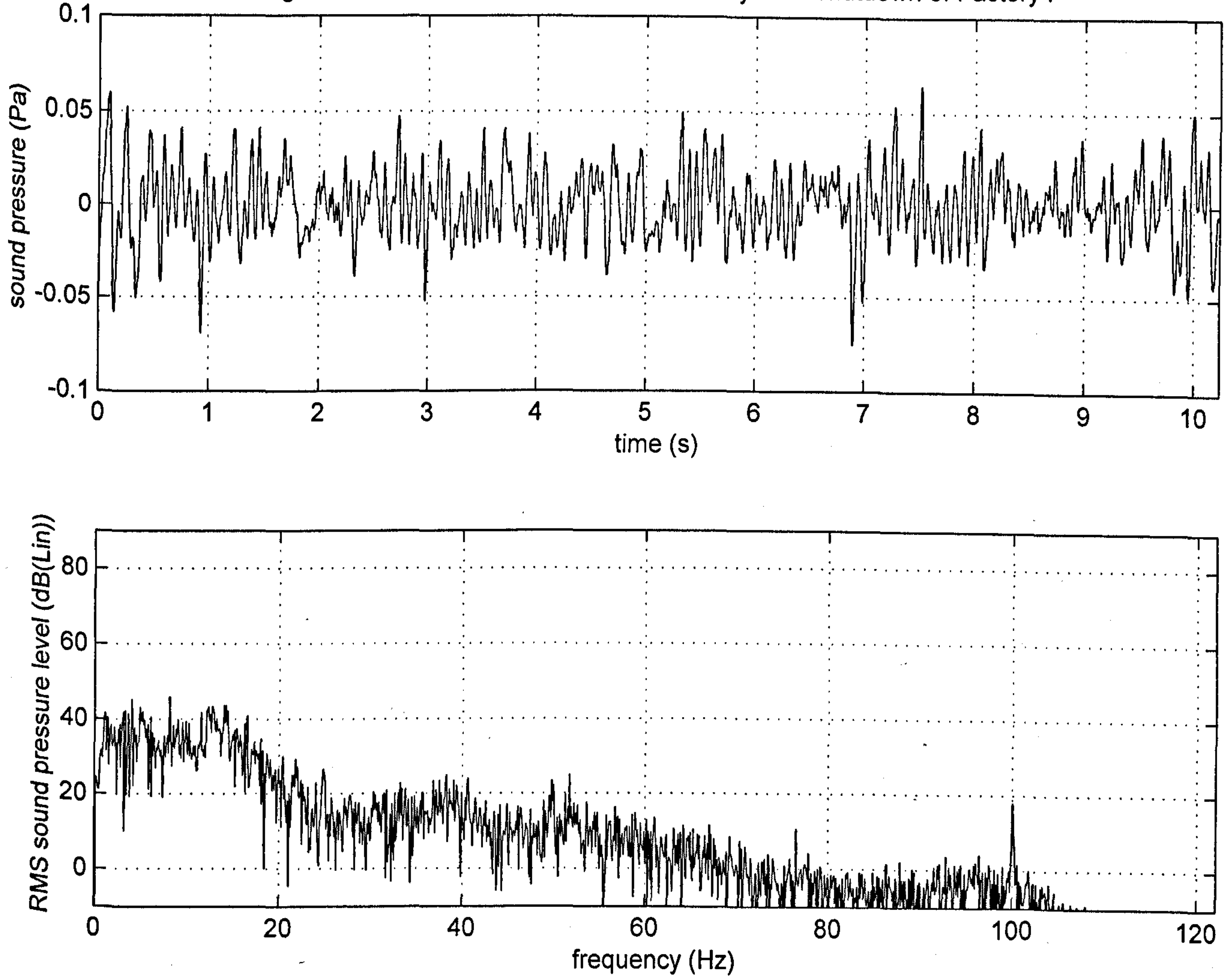


Fig. 6.16 - event recorded at A1 immediately prior to shutdown

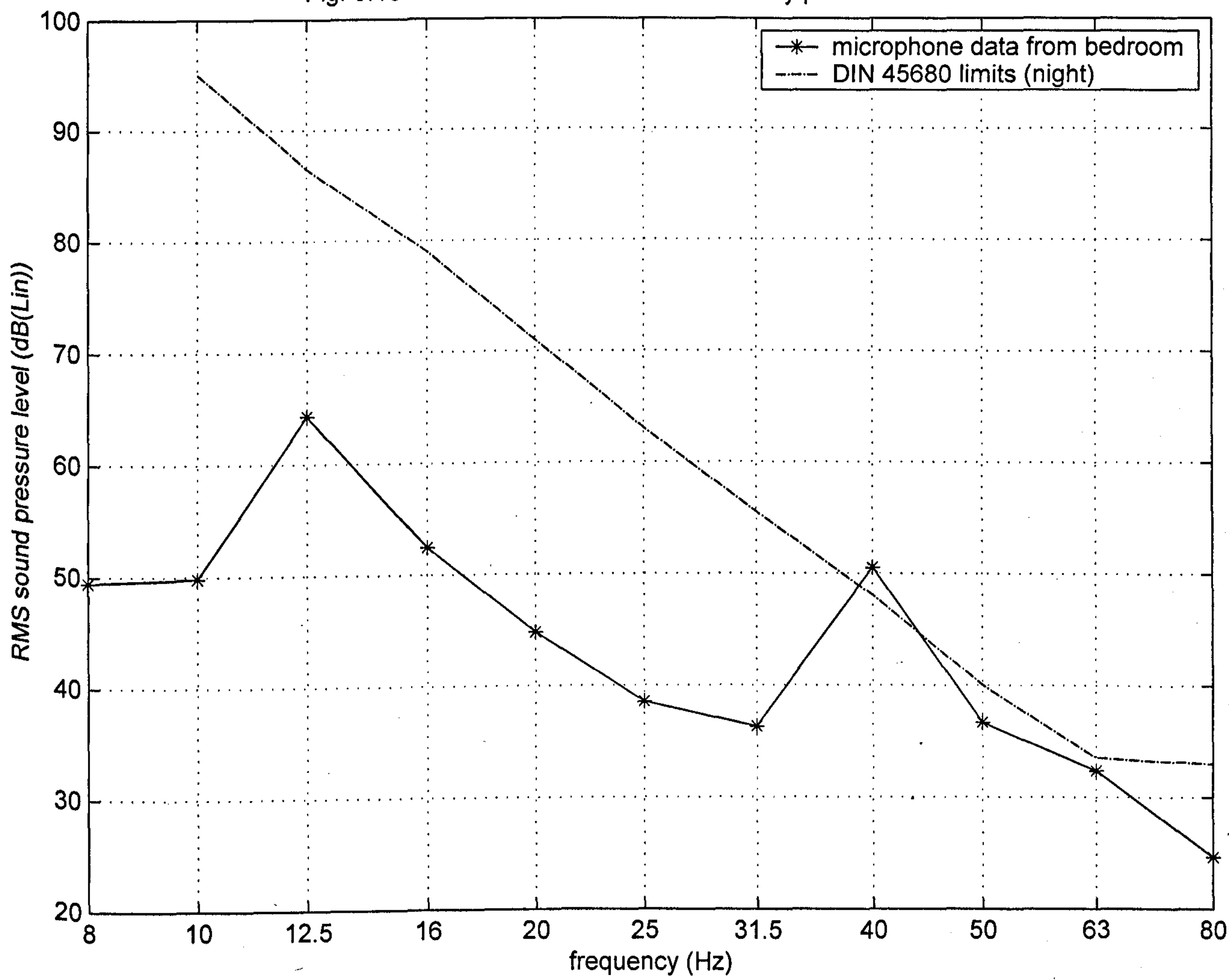


Fig. 6.17 - event recorded at A1 immediately after the shutdown

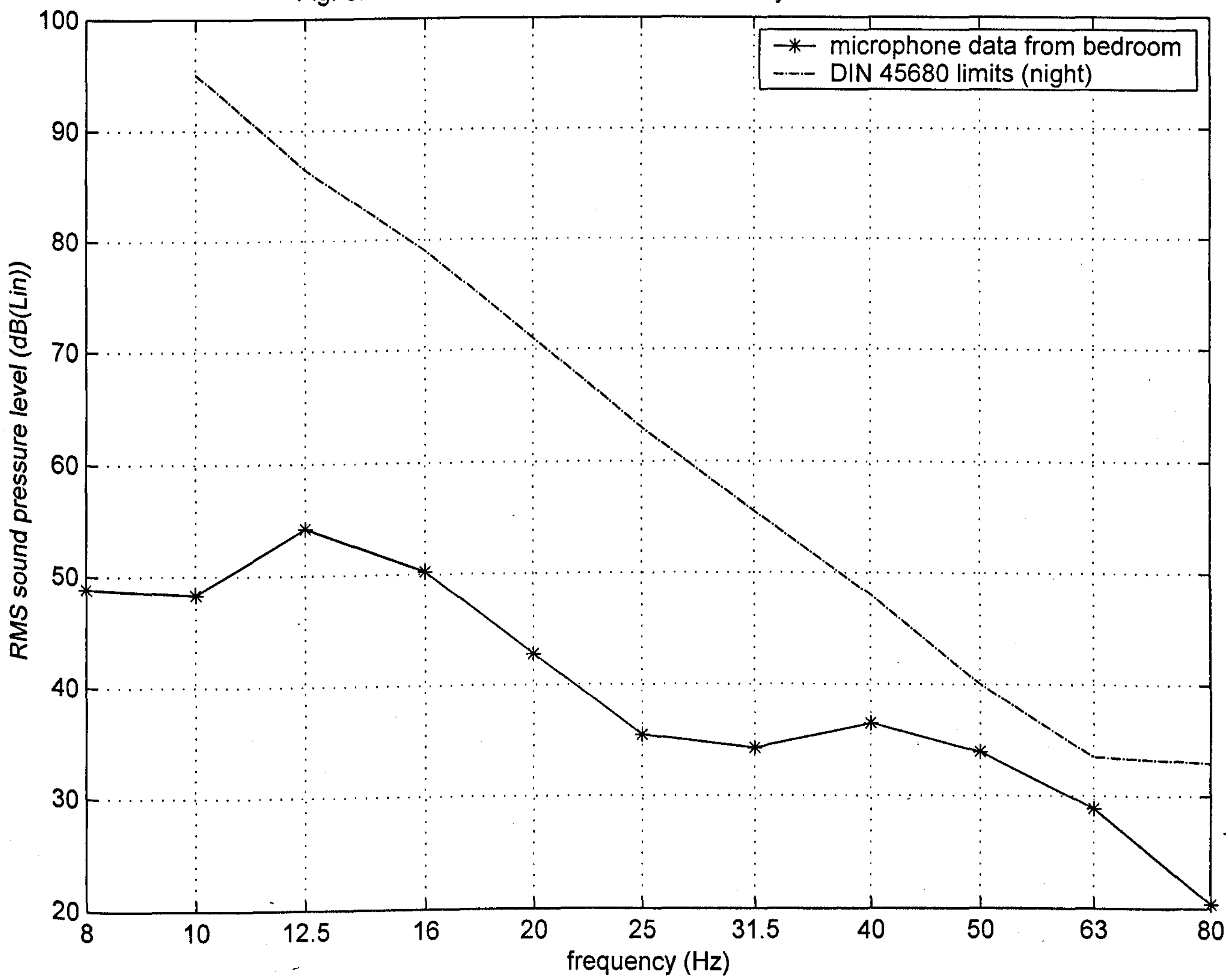


Fig. 6.18 - event recorded at A1 shortly before Bag Plant 2 switched on

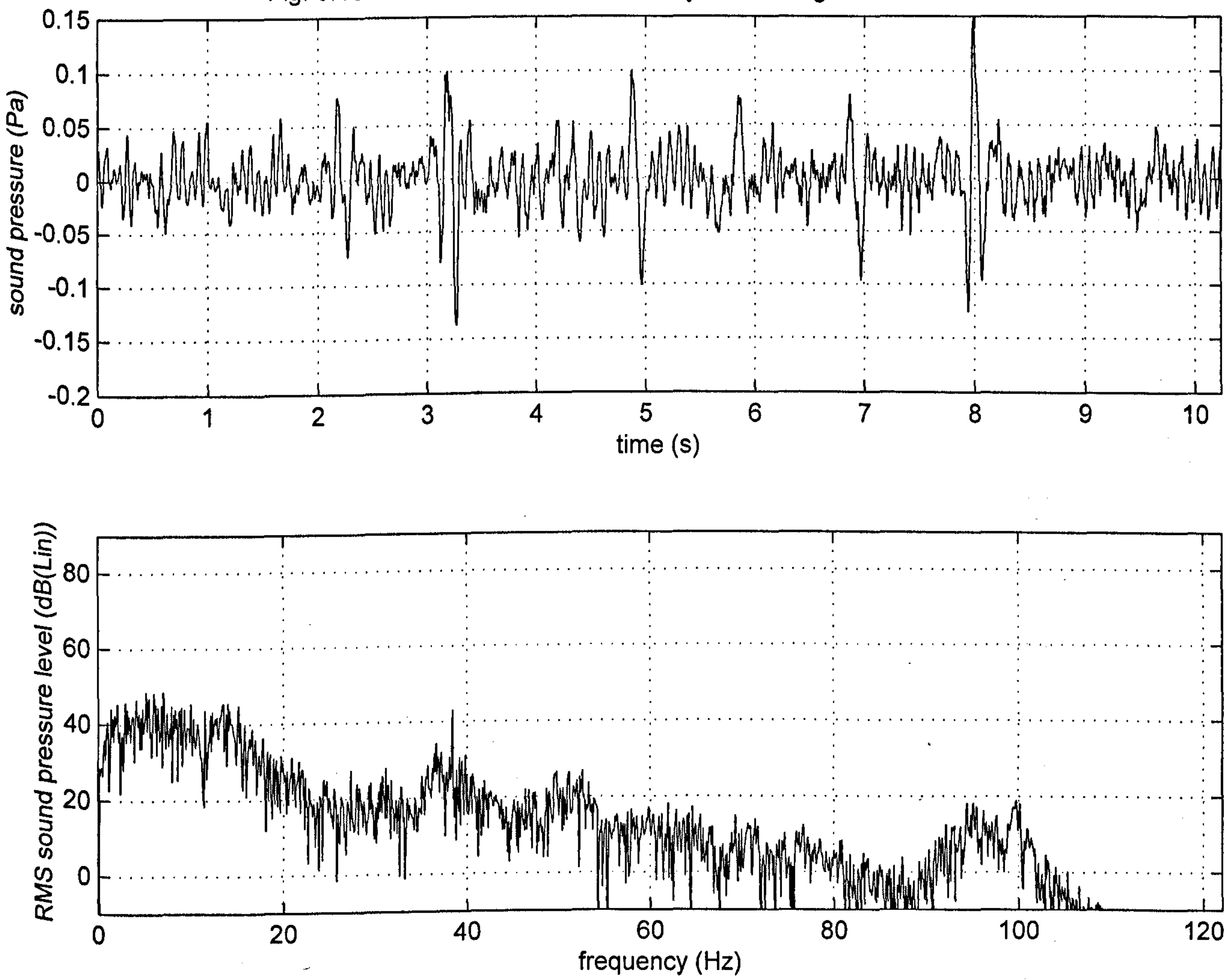


Fig. 6.19 - event recorded at A1 shortly after Bag Plant 2 switched on

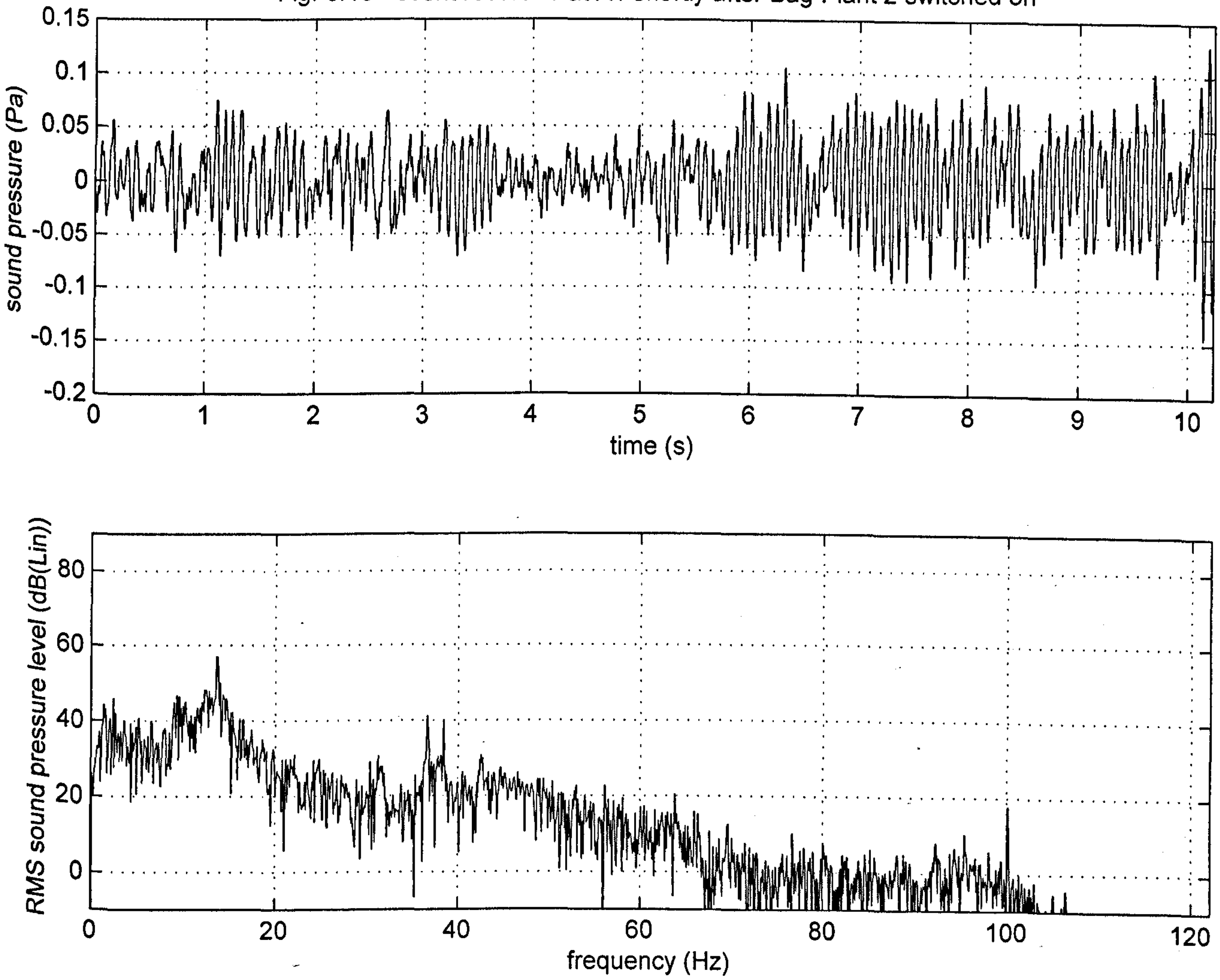


Fig. 6.20 - event recorded at A1 shortly after Bag Plant 1 switched on

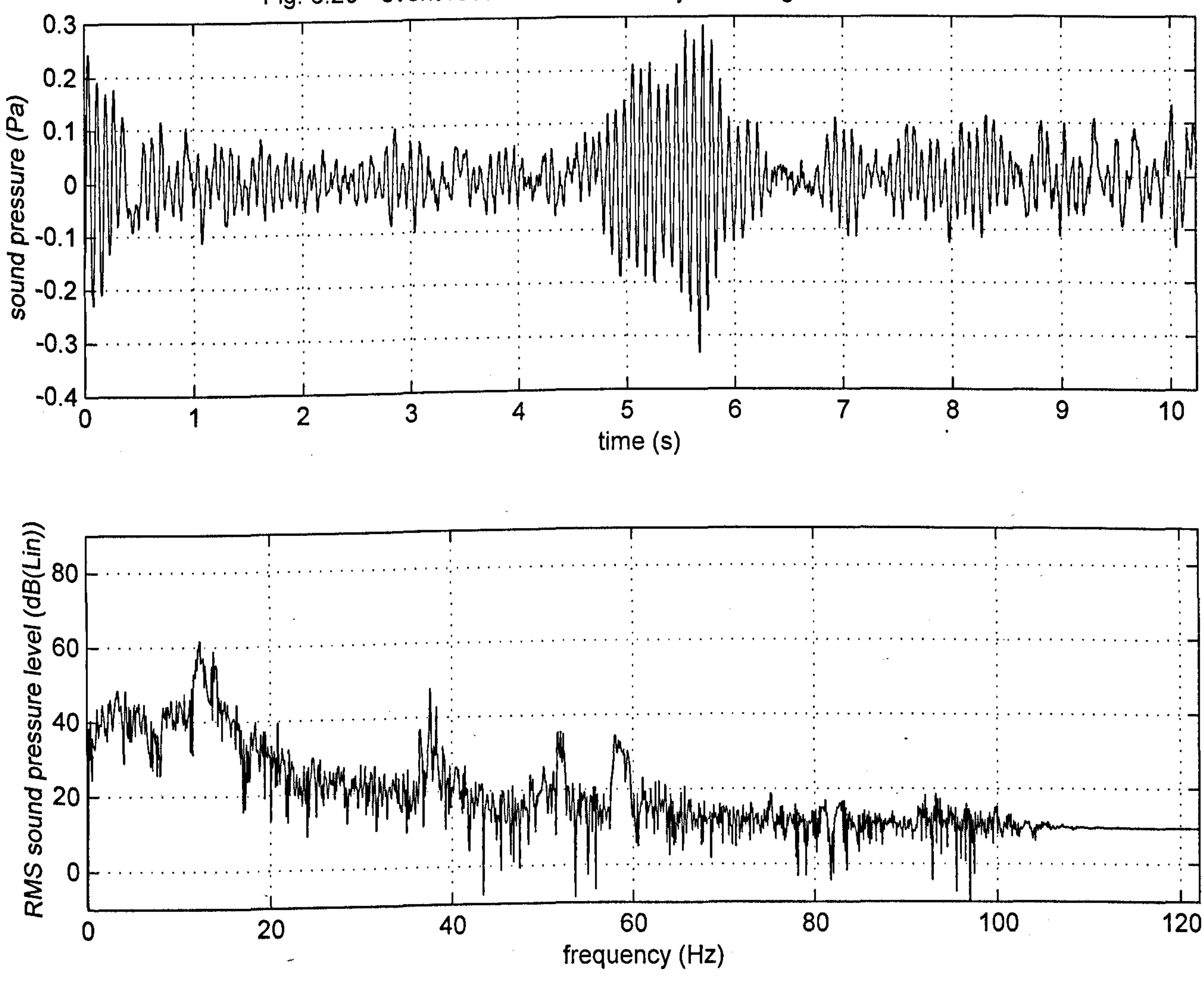
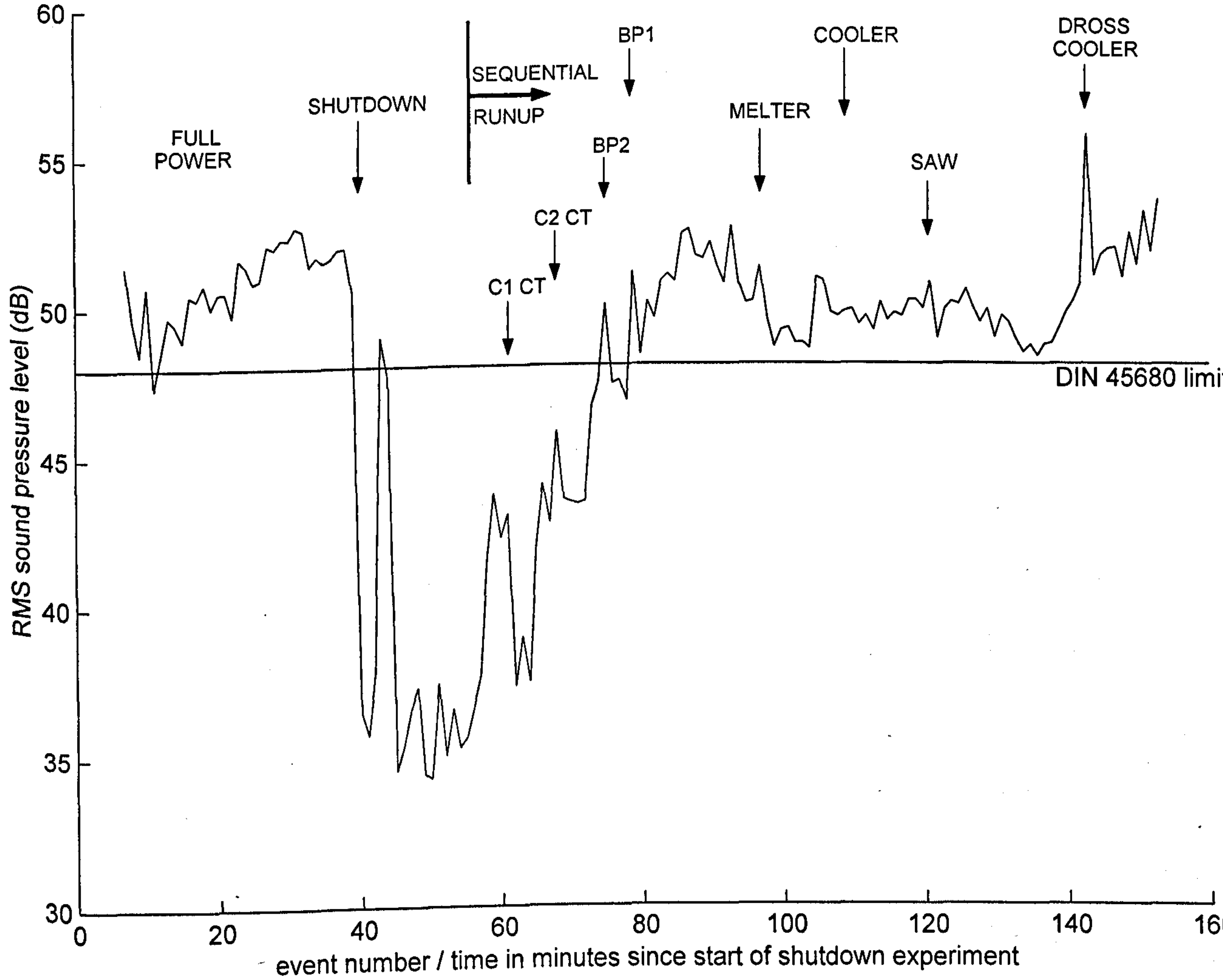


Fig. 6.21 - variations in 40 Hz third-octave band level throughout the shutdown experiment, with details of plant activity (C1 CT = Caster 1 Cooling Tower; C2 CT = Caster 2 Cooling Tower; BP1 = Bag Plant 1; BP2 = Bag Plant 2)



7 CASE STUDY B – INVESTIGATION INTO LOW FREQUENCY NOISE EMISSIONS FROM A FACTORY

This chapter details a second case study in which the integrated acoustic/microseismic technique was utilised to try to establish the cause of a low frequency noise/vibration problem. The case study was carried out as a further field trial of the technique. It will be demonstrated that the integrated acoustic/microseismic technique was crucial to the prospects of achieving a successful resolution to the study.

7.1 BACKGROUND

In early 1998, residents of a village in northern England complained to their local council about a low frequency noise problem that they were experiencing in their homes. The noise was reported to be strongly fluctuating in character, giving rise to a 'thumping' sensation, and disturbing the peace of the residents both during the day and at night-time whilst they were trying to sleep.

The village is set in a rural location near to an industrial estate where several factories comprise possible sources of the disturbance. In such an environment, low levels of background noise at higher frequencies may enhance the disturbing qualities of low frequency noise (see Section 4.1.1).

Previous attempts by local council employees to establish the cause of the complaints using conventional acoustic techniques had proved unsuccessful, probably because of the intermittent nature of the disturbance. The author, based on the experience of the previous case study (Chapter 6), decided that application of the integrated acoustic/microseismic technique to the problem would enhance the prospects of resolving it satisfactorily. Long periods of unmanned monitoring were carried out over several nights, when background noise levels due to traffic and other sources were lowest. The technique involves measurement of both sound and vibration levels within a property; this allowed groundborne vibration to be measured or ruled out as a cause of the disturbance.

The case study demonstrates the usefulness and versatility of the combined acoustic/microseismic approach when tackling complex low frequency noise/vibration problems.

The various stages of the investigation are detailed in chronological order. Although some of the work turned out to be a 'distraction' in retrospect (not relevant to solving the problem), it is included as an illustration of the nature of low frequency noise problems, namely that the identification of the 'problematic' tone(s), or other aspect of the sound and vibration field responsible for causing disturbance, is not easy. One does not know at the outset what one is 'looking for'.

7.2 LOCATION

The area under investigation is shown in the sketch map (Figure 7.1).

The most likely cause of the disturbance was thought to be a factory known in this thesis for confidentiality reasons, as Factory X. New plant had recently been installed at this site.

The households where the disturbance led to complaints are shown, as are Factory X and other factories in the vicinity.

It can be seen that an A-road and an underground railway line run through the area. These were other potential sources to be considered and/or eliminated.

7.3 INITIAL INVESTIGATION

The noise and vibration levels were initially monitored at two locations in the area over the period 16-22/2/98. Both locations were the households of residents who had experienced disturbance in relation to the low frequency noise/vibration under investigation. To protect the identity of the residents, the houses have been designated Location B1 and Location B2. The relative positions of these locations and Factory X can be seen on the sketch map (Figure 7.1).

The Vibrosound recording system was set up in an upstairs bedroom, with inputs from a microphone, window-mounted accelerometer and the Lennartz three-component seismometer which was placed on the suspended wooden floorboards of the room. Windows were normally kept closed during monitoring. The DV-1 three-component seismometer with PC link was placed downstairs on the ground floor slab.

This set-up is described in more detail in Section 5.1 (see Figure 5.1).

Occupants were asked to note down descriptions of their perception of the disturbance during the monitoring periods, which spanned three consecutive nights at each property. Night-time monitoring ensured that traffic and train noise/vibration were kept to a minimum in the recordings. The investigators also made subjective evaluations during the evenings in which the equipment was installed and dismantled.

Production records from Factory X were available showing times and dates of operation of various items of plant, for the duration of the monitoring periods.

7.3.1 Initial Results –Location B1

Data were collected at Location B1 between 16-19/2/98.

7.3.1.1 Frequency Characteristics:

Ground vibration levels, as measured by the seismometer mounted on the ground floor slab, were found throughout the monitoring period at Location B1 to be at least two orders of magnitude below the maximum levels permitted by BS 6472 (1992). This appears to rule out groundborne vibration as a cause of any disturbance perceived at Location B1, and was a reassurance to the occupants.

Extensive study of all the events recorded by the Vibrosound datalogger was carried out. Analysis of the output from the microphone channel at Location B1 revealed significant peaks in the frequency spectrum. The limits set by the German national standard DIN 45680 (1997) were exceeded on occasion.

Figure 7.2 shows a typical event, as recorded by the microphone channel of the Vibrosound, in the time and frequency domains. Figure 7.3 shows the same data analysed in terms of third-octave band levels (see Section 5.2.2), compared with the maximum levels for night-time low frequency noise recommended by the German national standard DIN 45680. It can be seen that the DIN curve is exceeded in the 40, 50 and 63 Hz third-octave bands by at least 10 dB.

In the third-octave bands that exceed the DIN limits, there are sharp peaks at 48.5 and 49.3 Hz (both ~10-15 dB above background levels), and a broad 'hump' in the spectrum across the frequency range 36-41 Hz. The 'hump' stands proud of background levels by over 20 dB, reaching its peak at ~37.5 Hz and it may be due to some type of resonance.

The peak at 1 Hz is probably caused by very low frequency atmospheric pressure variations and gives rise to the oscillations of period ~1 second seen in the time series.

Figure 7.4 shows the same event as recorded simultaneously by the window-mounted accelerometer. The very low frequency data (< 1 Hz) can be ignored; it relates to atmospheric (wind) pressure variations.

There are sharp peaks of interest in the spectrum at 37.5, 44.6 and 49.3 Hz. This gives an indication that the sound pressure signal at these frequencies may be airborne and derived from a source external to the house, rather than an internal source. Transmission into the house is via the windowpane radiating sound pressure into the room. The amplitudes of window vibration are consistent with the measured sound pressure levels in the bedroom at these frequencies, assuming this model. (This analysis will be dealt with more vigorously in Chapter 8, by Finite Element Method modelling.)

One of the major peaks in the microphone spectrum (48.5 Hz) was not observed in any of the window vibration spectra recorded at Location B1. This may suggest that the 48.5 Hz tone is not entering the room through the window. (The peak observed in the window spectrum at 44 Hz in Figure 7.4 may be present in the microphone spectrum, Figure 7.2, but masked by the tail of the broad 'hump' between 36-41 Hz.)

Figure 7.5 displays the same event using the signal from the vertical component of the seismometer mounted on the bedroom floorboards. There is a very strong, sharp peak at 48.5 Hz with an amplitude of ~15000 nm/s. Note that other tones which were observed in the microphone and window-vibration spectra, and attributed to an airborne source external to the house (such as 49.3 Hz), are absent from the floor-vibration spectra.

The ground slab vibration spectra did not display any vibration at 48.5 Hz. This appears to rule out a groundborne transmission path for the 48.5 Hz tonal vibration.

The 48.5 Hz peak was not observed in all microphone and floor vibration spectra recorded at Location B1 during the monitoring period. It was present in about 50% of the events, but no clear pattern was discerned at this stage of the investigation. However, at any particular time the presence or absence of the peak was a common feature of both the vertical floor-vibration and the microphone spectra.

Comparison of the recorded vibration levels in the suspended floor with BS 6472 (1992) recommended limits (Figure 7.6) suggests that these 48.5 Hz vibrations are imperceptible. Direct disturbance to the residents of Location B1 due to vibration of the floorboards would not be expected in the bedroom.

However, it is possible that pressure variations detected by the microphone at 48.5 Hz, and potentially audible to humans, are resulting from the vertical motion of the bedroom floor at this frequency. The observed floor vibrations may possibly be excited in turn by some unknown internal source. (This is also explored in Chapter 8 by Finite Element Modelling.)

It should be noted that the subtle distinction between two peaks in the microphone spectra, differing in frequency by < 1 Hz, one evidently due to an external source and one apparently not; was only possible because of the fine frequency resolution of the methodology that was applied to this case.

It is also notable that the proximity of both 48.5 Hz and 49.3 Hz peaks to mains frequency (50 Hz), may give rise to the possibility that one of them is caused by the internal electrical 'noise' of the instrumentation. To rule this out, the output from an unused channel of the Vibrosound was analysed in the frequency domain, and was shown to have a spectrum dominated by a sharp peak at precisely 49.97 Hz. Thus, the use of multi-channel instrumentation in this case allowed mains 'hum' to be ruled out as a possible cause of two tones detected at frequencies close to 50 Hz.

7.3.1.2 Third-Octave Band Level Analysis:

The DIN 45680 (1997) limits for low frequency noise had been shown in the previous case study (Chapter 6) to be a reasonably good predictor of annoyance. In order to evaluate which of the recorded events might be expected to have caused annoyance in this case study, the DIN 45680 limits were utilised in the construction of a series of charts.

For each of the third-octave bands in which significant spectral peaks were found during the analysis, the band level was plotted as a function of event number i.e. time. Hiatuses along the 'event #' axis correspond to calibration events and/or gaps between successive nights of monitoring. The DIN-recommended night-time limit for the particular third-octave band under consideration, was shown on the same plot for comparison.

The 40 Hz, 50 Hz and 63 Hz third-octave band levels consistently exceeded the DIN limits. Of these, only the 40 Hz and 50 Hz bands contained 'unusual' i.e. tonal features that were potentially annoying (Piorr and Wietlake, 1990). (Broadband noise in the 63 Hz band may have been due to traffic, etc.) Therefore, only the 40 Hz and 50 Hz third-octave band variations were analysed in detail.

The variations in third-octave band level were compared with subjective comments regarding the perceived level of disturbance logged by the residents of Location B1 throughout the monitoring period. Comparisons were also made with production records from Factory X.

40 Hz Third-Octave Band Level:

The broad 'hump' around 38 Hz was clearly the most dominant feature of the frequency spectra recorded at Location B1. The 40 Hz third-octave band levels (Figure 7.7) exceeded the DIN 45680 limit by ~10 dB or higher, which is greater than was observed for any other band level.

The 40 Hz third-octave band was therefore initially considered the band most likely to contain the sound feature that was causing the disturbance at Location B1.

One item of recently installed plant at Factory X was a set of cyclone fans. These had operational frequencies for full output at around 38 Hz, coinciding with the broad 'hump' in the recorded frequency spectra. Figure 7.7 also shows periods when the cyclone fan system was operating at full output, and other times when it was running at reduced speeds (idling).

Some, but not all, increases in the 40 Hz band level coincided with periods when the cyclone fans at Factory X were being run-up from an idling speed to full output. The fans were therefore demonstrated to be at least contributing to the 40 Hz third-octave band levels in the monitoring room at B1.

However, it was not possible to demonstrate a direct correlation between most of the cyclone fan run-up periods associated with increased 40 Hz band levels, and the variations in subjective loudness reported by the residents. This is important, as subjective observations provide the best indicator of what is essentially a subjective disturbance.

On one occasion there was a correlation between an increase in cyclone fan activity/40 Hz band level, and a subjective increase in loudness as perceived by the residents. However, this also coincided with the 'appearance' of the (presumed internal) 48.5 Hz tone, between two consecutive recorded events (Figures 7.8 and 7.9). It was therefore considered possible that the onset of the 48.5 Hz tone led to the increased subjective loudness.

The consecutive events were recorded five minutes apart, which made it harder to determine precisely which physical phenomenon (if any) gave rise to the increased subjective disturbance. The data storage capacity of the equipment available at the time, necessitated a trade-off between the lengths of the monitoring period (number of nights) covered, and the hiatus between recorded events. Ideally, continuous coverage of the sound/vibration data in the house would have been gathered; this may now be possible with current data collection apparatus.

Note that the sound in the 40 Hz band was not as highly tonal as, for instance, the sound in the 40 Hz third-octave band recorded in the previous case study (see Chapter 6), or the 50 Hz noise in this case study. It may therefore be considered less 'unusual' and less likely to cause annoyance according to DIN 45680 (1997).

50 Hz Third-Octave Band Level:

Apart from on one occasion (described above), no clear trend was distinguished at this stage of the investigation between the 50 Hz third-octave band level and the subjective observations of the residents and/or activity at Factory X.

However, the 50 Hz band levels (Figure 7.10) were shown to exceed the DIN 45680 limit by ~5 dB throughout the monitoring period. The sound in this band was also observed to be highly tonal in the fine-resolution frequency spectra, and therefore it was potentially annoying according to DIN 45680.

7.3.1.3 Transfer Function:

The data collected on the afternoon of 19/2/98 also made use of a second microphone fed into the spare channel of the Vibrosound. This microphone was located outside the house, in the front garden that faces towards the factory under scrutiny. Because data were logged for the two microphone channels simultaneously in time series format, it was possible to construct transfer function estimates for acoustic waves travelling from outside to inside the upstairs front bedroom of the house.

The precise method of doing this is described in Section 5.2.4. This analysis illustrates one of the advantages of carrying out multi-channel data acquisition, and the versatility of the data collected using the integrated acoustic/microseismic technique.

Figure 7.11 shows one such transfer function estimate. Included in the figure are:

(a) the noise spectrum outside;
(b) the noise spectrum in the bedroom;
(c) transmission loss from outside to inside, in dB.

It is worth noting the presence of a broad 'hump' in the transmission loss spectrum at around 38 Hz. This, together with the absence of such a feature in the flat spectrum recorded outside, suggests that the 38 Hz hump that is commonplace in the bedroom microphone spectra, is due to the specific resonant properties of the house and not caused by an external airborne signal at that frequency.

The broad 38 Hz peak may be due to acoustic modes of the bedroom in which monitoring took place, resonances in the building façade (wall or window), or a combination of both. The fundamental acoustic mode of resonance of the bedroom, calculated using Formula 2.3 by equating half a wavelength to the room's largest dimension (4.2 metres), is around 40.5 Hz. Surface damping in the room may shift the modal peak down in frequency slightly (see Section 2.4), but is unlikely to explain a discrepancy of > 2 Hz.

It would appear unlikely that a standing wave in the room could account by itself for the excess sound pressure at 38 Hz.

A window pane structural resonance may explain the drop in the façade's sound insulation performance around 38 Hz. Applying Formulas 2.1 and 2.2 to a 1m^2 pane of glass of thickness h = 8mm, Young's Modulus $E = 6.2*10^{10}$ Pascals, Poisson's ratio ν = 0.24 and surface density ρ_s = 20 kg/m^2 gives a fundamental mode of resonance of ~37 Hz for the window structure. This is a reasonably good match with the observed peak considering the uncertainties on variables such as the window thickness.

Assuming the above estimates for room and window resonant frequencies are correct, it is possible that the proximity of the two frequencies would give rise to coupling between the acoustic and structural modes (see Section 2.4). This may lead to enhanced transmission across the window and may explain the broadness of the 38 Hz 'hump' recorded at Location B1.

It is also worth noting that the amplitude of the 38 Hz 'hump' in the indoor spectrum, is less than the amplitudes of that feature obtained from the previous three nights' data. Recording the sound levels outside and inside simultaneously necessitated opening the bedroom window slightly, in order to feed the second microphone and its lead out to the garden. This slight opening of the window may have affected the sound insulation performance of the façade, leading to transmission loss curves with less prominent 38 Hz peaks than had been observed with the window shut.

The frequency spectra recorded outside the house (Figure 7.11a) displayed a sharp peak at 49.3 Hz, confirming that this tone is an external airborne sound. There was no 48.5 Hz tone detected outside, whilst in the bedroom both 48.5 Hz and 49.3 Hz tones were recorded (Figure 7.11b). This is consistent with the 48.5 Hz tone recorded in the bedroom having a source somewhere within Location B1. Again, these observations demonstrate the benefits of the multi-channel technique.

7.3.1.4 Preliminary Findings from Location B1:

The primary feature of the sound recorded at Location B1 was a broad 'hump' across the frequency spectrum from 36-40 Hz, with a maximum at 38 Hz. Transfer function estimates from outside to inside the bedroom, suggest that this may be an artefact of the building, caused by an acoustic mode of the chosen monitoring room and/or a minimum in the transmission loss curve of the building façade.

Two sharp peaks were observed in the sound spectra close to 50 Hz, namely 48.5 and 49.3 Hz. These could be distinguished because of the fine frequency resolution provided by the methodology. Electrical noise at mains frequency was ruled out as the origin of the two tones by use of a 'spare' Vibrosound channel.

The 49.3 Hz peak was observed in the window vibration spectra and was inferred to be airborne, emanating from an external source. In contrast, the 48.5 Hz peak was not detected in the window but was observed in the vibration spectra measured by a seismometer on the suspended wooden floor. The latter was thought to be a structure-borne tone emanating from a source somewhere inside the house. Sound spectra recorded outside the house, in parallel with indoor measurements, were consistent with these findings.

Sound levels in both 40 Hz and 50 Hz third-octave bands were above the recommended limits in DIN 45680 (1997). The 50 Hz band in particular contained sound of a highly tonal, therefore 'unusual' and potentially annoying character.

Some activity at nearby Factory X, particularly rapid increases in output of several cyclone fans, correlated with short-term increases in the recorded sound levels in the 40 Hz third-octave band at Location B1.

However, subjective perception of annoyance logged by the residents of Location B1 did not clearly correlate with third-octave band level variations or Factory X output.

It was not possible to conclude with certainty at this stage that the recently-installed cyclone fans were a direct cause of annoying low frequency noise at Location B1.

7.3.2 Location B2

Data were collected at Location B2 from 19-22/2/98.

7.3.2.1 Results from Location B2:

Ground floor vibration levels were found throughout the monitoring period at Location B2 to be at least two orders of magnitude below the maximum levels permitted by BS 6472 (1992). This appears to rule out groundborne vibration as a cause of any disturbance perceived at Location B2, and was a reassurance to the occupants.

Extensive study of all the events recorded by the Vibrosound datalogger was carried out. Figure 7.12 shows a typical event, as recorded by the Vibrosound's microphone channel, in the time and frequency domains. Figure 7.13 shows the same spectrum, analysed in terms of third-octave band levels, with the DIN 45680 (1997) curve (night-time limits) shown for comparison. It can be seen that the third-octave band levels are well below the DIN curve at all frequencies except at 50 Hz where the level is just at the DIN limit. This was a typical finding for all the events recorded at Location B2.

The only significant spectral peak in a frequency band that has sound levels close to the DIN limiting values, is a sharp tone at 49.3 Hz (in the 50 Hz band). Data from the other channels of the Vibrosound suggest that the 49.3 Hz tone is from an external source and airborne.

The 49.3 Hz tone was also recorded at Location B1. Note that the 48.5 Hz peak observed at Location B1 was not detected at Location B2, nor was the prominent broad 'hump' in the spectrum around 38 Hz. This suggests that these sound features are specific to Location B1.

Figure 7.14 plots the variations in 50 Hz third-octave band level at Location B2 against event # (i.e. time), along with the DIN 45680 recommended limit for that band. The 50 Hz band level was generally close to the DIN limit during three nights of monitoring.

The last few events (events # 245-259) were recorded during the day on 22/2/98. Some of these events displayed 50 Hz third-octave band levels that exceeded the DIN night-time recommended level by more than 10 dB. This part of the monitoring period will be discussed in Section 7.3.2.2. Note that the night-time level was used in this case for consistency, even though the data were recorded during the day. Since daytime limits are 5 dB above night limits according to DIN 45680, the daytime limits were still exceeded at 50 Hz by over 5 dB at times.

Similar plots for the 31.5 Hz and 40 Hz third-octave bands showed levels that were generally more than 10 dB below the DIN limits, whilst 63 Hz band levels only occasionally exceeded DIN 45680 and the sound within that band was not particularly 'unusual' i.e. tonal. Therefore, these plots have been omitted.

Comparison of Figures 7.10 and 7.14 shows that overall, the recorded sound pressure levels were significantly greater at Location B1 than at Location B2. This amplitude drop off with distance from Factory X (see Figure 7.1) is consistent with Factory X being the source of the sharp tone at 49.3 Hz.

(This assumes that the sound power level of the source of the 49.3 Hz tone did not alter significantly between the two periods of observation; this is likely to be the case as Factory X production records show that output was similar before and after the equipment was moved from Location B1 to Location B2.)

The residents' log of subjective disturbance during the monitoring period at Location B2 was much more scant than that recorded at Location B1. Consequently, there were not as many opportunities to attempt to correlate subjective increases in the noise level with variations in Factory X operational status and/or sound levels as measured by the Vibrosound system.

The reduced subjective annoyance level may indicate that the problem was less severe over the period for which the equipment was in place at Location B2, or that the residents of Location B2 are less sensitive to low frequency noise than the residents of Location B1. Alternatively, it may indicate that the disturbance in general is not as severe at this location, which is consistent with Factory X being the source of the disturbance as B2 is further than B1 from Factory X.

7.3.2.2 Start-up Transient:

The residents' subjective log of their perception of the noise contained only one point of major significance. On 22/2/98, between 13:00 and 14:30, they noted, "Noise increased" and switched the equipment on to begin recording the noise and vibration levels. This coincides with the large increase in the 50 Hz third-octave band level shown in Figure 7.14, and with lesser increases in level for other third-octave bands.

Although higher traffic noise and general background noise would be expected in comparison with the earlier (night) monitoring times, production records from the cyclone fans at the factory showed an interesting variation correlating with the subjective and objective noise increase at location B2. One of the cyclone fans was running at a higher power output than usual between 13:10 and 14:01. After 14:01, all three cyclone fans were run down to 250 rpm (very low, lower than regular idling speed) and fan output dropped accordingly.

The Vibrosound captured events between 13:14 and 14:24 at five-minute intervals, corresponding to events # 245-259. Thus, recordings were made before and after the 'switch off', and comparison of these events may prove useful in assessing the detailed characteristics of the disturbance.

Figure 7.15 shows an event recorded at 13:24 (event # 247 on Figure 7.14), during the time of 'high output'. Figure 7.16 was recorded at 14:14 (event # 257 on Figure 7.14), after the 'switch off' had occurred.

From these, it can be seen that the subjective rise in noise level and the large increase in cyclone fan activity on 22/2/98, coincided with a 10 dB increase in sound pressure level at the 49.3 Hz tone. The 50 Hz third-octave band levels during the time of 'high output' were ~10 dB above the DIN limit. It may also be observed that the absolute sound levels, as well as subjective levels of disturbance, dropped back down as the fans slowed down.

The large, short-term increase in level was probably due to a start-up transient.

These observations established a direct correlation between the level of cyclone fan activity at Factory X, the measured sound pressure level of the 49.3 Hz tone and the subjective perception of the loudness of low frequency noise at Location B2. Thus the cyclone fans at Factory X were confirmed as contributing to the low frequency noise problem in the area, although not through tonal peaks equivalent to the rotational speeds of the fans (~38 Hz), as was earlier suspected.

The correlation between periods of subjective disturbance and times when the DIN 45680 recommended limits for RMS sound pressure level were exceeded in the 50 Hz band, confirms the validity of applying the German standard DIN 45680 (1997) to these types of low frequency noise problems.

7.3.2.3 Summary of Findings from Location B2:

A sharp 49.3 Hz tone was recorded at Location B2 and was shown to be airborne and from an external source.

Calculated 50 Hz third-octave band levels at Location B2 were on most occasions around the level recommended by DIN 45680 (1997) as a maximum limit for tonal low frequency noise. Subjective responses from the residents suggested that the level of low frequency noise was acceptable to them during three nights of monitoring.

The 40 Hz third-octave band levels at B2 were below the DIN limit throughout, unlike at Location B1. This confirms that the broad peak at 38 Hz was specific to Location B1. The sharp 48.5 Hz tone observed at B1 was not detected at B2, which is consistent with the theory that it emanated from a source internal to B1.

The overall sound pressure levels recorded at Location B2 were significantly lower than those recorded at Location B1. The decrease in 50 Hz third-octave band level with distance from Factory X provides corroborative evidence that the source of the low frequency noise recorded in the 50 Hz band is at Factory X.

During one short period, the 50 Hz band level at Location B2 exceeded DIN 45680 by ~10 dB, and the residents perceived a disturbing level of low frequency noise. This coincided with unusually high levels of cyclone fan activity at Factory X, and an increase in the amplitude of the 49.3 Hz tone.

Tones emanating from the cyclone fans at the running speeds of the fans themselves do not seem to be a direct cause of the disturbance at Location B2. Other fans with different running speeds may have been run-up in tandem with the cyclone fans, giving rise to peaks at other frequencies such as 49.3 Hz. These may be more directly responsible for the annoyance.

The data recorded at Location B2 confirmed the German standard DIN 45680 (1997) as a good predictor of annoyance due to low frequency noise.

7.4 SHUTDOWN EXPERIMENT

7.4.1 Introduction

The opportunity arose to conduct another experiment in a further attempt to pinpoint the source of the disturbance. Factory X was undergoing a partial shutdown (including switching off the cyclone fan system) for routine maintenance from 28/7/98 to 9/8/98. This provided an opportunity to take unmanned measurements of background levels during the shutdown, at Location B1 (the nearest property to the factory), in the hope that this would yield further information as to the potential source(s) of the disturbance.

The owners of the factory also co-operated in a sequential run-up experiment, in which each of several items of plant was switched on in turn whilst monitoring took place at Location B1 using the Vibrosound system at its maximum possible coverage setting (one ten-second event per minute). At the same time, the residents of Location B1 and the author made notes regarding their subjective perception of how the low frequency noise and vibration levels varied throughout the test.

The equipment, including the various transducers, was installed in the same position as in the earlier Location B1 monitoring, to enable comparisons to be made. Production records from Factory X were subsequently made available to the author for comparison with measured levels and logs of subjective comments.

Again, the run-up experiment enabled the author to test out the integrated acoustic/microseismic method, and to further develop the range of signal processing techniques that may be applied to the accumulated data.

7.4.2 Background Levels during Shutdown

Figure 7.17 shows a microphone record from the period when the partial shutdown had taken place at Factory X. The same event, analysed in terms of third-octave band levels and plotted against DIN 45680 (1997) limits is shown in Figure 7.18.

A sharp tone was detected at 48.5 Hz, at pressure levels ~40 dB. The 50 Hz third-octave band level was 2-3 dB above the DIN limit during this event. This tone was observed in the earlier measurements from Location B1, and was thought to emanate from an internal source because it was not picked up in the bedroom window vibration spectra. This was confirmed to be the case during the current period of monitoring.

The 48.5 Hz tone also exhibited the same attribute as before, of only being present in about 50% of the event records. Figure 7.19 shows an event in which the 48.5 Hz was not detected, whilst Figure 7.20 shows that the 50 Hz band level for that event was close to the DIN limit at that frequency.

Comparison of Figures 7.17 and 7.19 with Figure 7.2 from the earlier monitoring period shows that the broad 'hump' recorded in the earlier spectra at ~38 Hz is still present, but is not as prominent. An airborne 'external' 49.3 Hz peak is still detected but at reduced amplitude (~5 dB above background levels). Since the cyclone fans had been shut down at this point, this confirms the result inferred from data recorded at Location B2 that the cyclone fans were not directly responsible for the 49.3 Hz tone.

It is evident also that the source of the 49.3 Hz tonal noise is not any of the other items of machinery that were shut down during this period. However, the unknown source of the tone may be connected in some way to the cyclone fans or other plant, as the measured sound level of the tone is much reduced during this period of low output from Factory X.

The variation of 50 Hz third-octave band levels over the course of one of the nights of 'background monitoring', is plotted in Figure 7.21. With much of the contribution from Factory X to the 50 Hz band level at Location B1 removed, a clear pattern emerged in the plot of 50 Hz third-octave band level against event # (time).

The plot displays a clear periodicity. The levels alternated between a relatively high RMS sound pressure (~3 dB above the DIN limit) for 1-2 events, followed by a lower RMS pressure (at around the DIN limit of 40 dB) for 1-2 events. The time spacing of the recorded events was 5 minutes, so this is equivalent to five to ten minutes at the higher level alternating with five to ten minutes at the lower one. The source of this periodic variation in 50 Hz band level was determined during the course of the next phase of the experiment, as described in Section 7.4.3.

Figure 7.21, showing periodic behaviour in the fluctuations in 50 Hz band levels at Location B1, demonstrates another way in which useful information about a case study may be obtained by plotting data obtained over long periods of unmanned monitoring.

7.4.3 Sequential Run-up of Plant

On the afternoon of 6/8/98, various items of plant at Factory X, including the cyclone fans, were switched on and off whilst monitoring of noise and vibration levels took place at Location B1. The Vibrosound datalogger sampled ten seconds of data every minute.

Throughout the experiment, the residents of Location B1 noted down their subjective perception of how the noise varied and at what times.

The author was located downstairs in the kitchen throughout the experiment making a detailed log against time of personal perception of the disturbance, and of traffic flow along the A-road which runs between the house and the factory. The purpose of this was to eliminate other sources of low frequency noise/vibration, such as lorries driving by, during the relatively busy time of the day when the test took place.

It was at this point that the author made an important discovery. A refrigerator was present in the kitchen and it periodically emitted a low frequency humming noise, probably because of an in-built thermostatic regulator. The cycle of noise output from the refrigerator was recurring and a pattern was logged consisting of approximately 12 minutes of low frequency humming interspersed by approximately 8 minutes of quiet.

This behaviour matched the observed variations of the 50 Hz third-octave band level during the earlier 'background level' part of the experiment (Section 7.4.2).

Careful analysis of the individual events (recorded one per minute) in the frequency domain in conjunction with the author's detailed log of fridge behaviour, showed that the emergence and disappearance of the 48.5 Hz tone matched the logged periods of fridge hum/no hum very closely i.e. ~12 events were recorded that displayed the peak followed by ~8 that did not, and so on throughout ~130 events. Thus, the fridge in the kitchen was established firmly as the source of the internal 48.5 Hz tone detected by the microphone and the bedroom floor-mounted seismometer.

Note that the kitchen at Location B1 is situated directly below the bedroom where monitoring took place, and it was thought that either sound or vibration emanating from the fridge was exciting the kitchen ceiling (and hence the suspended bedroom floor) into motion at 48.5 Hz. The flexural distortion of the floor at this frequency was in turn transmitted into the air volume of the bedroom. However, the precise structural path of the vibration from the fridge to the first floor bedroom was unclear.

One event in particular seemed to have captured the precise moment when a period of high fridge noise output started. This was only possible to observe by narrow-band filtering the event in the time series, using *Matlab* software as detailed in Section 5.2.5. Figure 7.22 shows the result of filtering the east-west component of the bedroom floor-mounted seismometer recordings using a digital Butterworth bandpass filter that is equivalent to a twelfth-octave (semitone) band centred on 49 Hz.

All three seismometer components exhibited similar behaviour during the event. After four seconds, there was a sharp increase in vibration level in the floorboards. Frequency analysis of the first four seconds of this event showed that the sharp 48.5 Hz peak observed in Figure 7.22, was not present until the sudden increase in vibration level. The ability to select a short portion of a recorded event for analysis further illustrates the flexibility of the technique.

Figure 7.23 shows the same event as recorded by the microphone channel. The time history does not display any apparent change after 4 seconds. However, this may be due to broadband noise across the frequency range 0-100 Hz.

Figure 7.24 displays the microphone time history after applying the same filter as was used on the seismometer data. The first four seconds of the event displays no notable features. The portion of the time history after four seconds elapsed was characterised by very clear beating, with a ratio of maximum:minimum sound pressure level of ~20 dB and four beat cycles occurring over six seconds. This is equivalent to a beat frequency of ~0.7 cycles/sec; the tones that are beating together are seen in the frequency spectrum to be 48.5 Hz and 49.2 Hz (with a difference in frequency of 0.7 Hz).

The latter peak appears to be the 49.3 Hz peak observed earlier, shifted down slightly in frequency. It may be speculated that the (unknown) source of the 49.3 Hz tone was operating at a slightly lower frequency at this point, possibly as a result of increased loading by a connected item of plant that was being run up during the test.

The sharp increase in vibration levels in the bedroom floor and the onset of beating in the sound pressure, as a result of increased noise output from the fridge, were only observed because of the use of a filtering process. This was possible because of the flexible nature of the methodology, collecting large numbers of time histories for subsequent analysis by advanced signal processing software.

The 50 Hz third-octave band variations in the bedroom during the run-up experiment did not display the same cyclicity as in the earlier background period (Figure 7.21). The sound pressure level of the 49.3 Hz peak varied as items of plant at the factory were switched on and off, and this affected the overall 50 Hz band level.

The variations in sound level at 49.3 Hz were not correlated directly with any specific item(s) of plant, but in any case it had earlier been established that the item responsible for the 49.3 Hz tone had remained operational throughout the experiment. The variation in levels observed did suggest some connection between the source of 49.3 Hz and other plant i.e. the source is located within Factory X, and start-up of other plant may be affecting its noise output.

The subjective comments of the residents of Location B1 did not show correlation with any particular item of plant being switched on or off. Comments about a noise "throbbing at about 1 beat per second" were noted during times when the author had simultaneously observed that the fridge was 'humming'. The residents' subjective observation resembled the beating at a rate of 0.7 cycles/sec that was objectively demonstrated to occur at a frequency close to 50 Hz in the air during times of high fridge noise output.

The disturbance perceived by the residents at Location B1 appeared to result from a complex interaction between internal (structure-borne) noise at 48.5 Hz from the fridge, and an external airborne tone at 49.3 Hz propagating into the house from somewhere within Factory X. This interaction produced an audible beating phenomenon that may have given the low frequency noise a particularly annoying character (see Section 4.1.1).

7.4.4 Findings from Shutdown Experiment

It was demonstrated that distinct tones of frequency 48.5 Hz and 49.3 Hz, detected in the air at recorded at Location B1, were caused respectively by structure-borne vibration from an internal source (refrigerator) and airborne sound emanating from an external source somewhere within Factory X.

Note that although domestic appliances such as refrigerators would normally be switched off during monitoring of low frequency sound levels in dwellings, in this case such action would have obscured part of the problem. Furthermore, in some situations such as an investigation within a block of flats, the current method may enable noise from an 'internal' source that is not directly accessible to the experimenter, to be distinguished.

Beating between the 48.5 Hz and 49.3 Hz tones was both subjectively perceived and objectively observed in the data by the use of band-pass filtering. This appeared to contribute to disturbing the residents of Location B1.

The precise source of the 49.3 Hz tone at Factory X remained undetermined at this stage.

The use of a multi-channel system to simultaneously record sound and vibration spectra was crucial in allowing the distinction between internal and external tones to be made in this case study. Acoustic or microseismic measurements alone would not have been sufficient to reach the conclusions drawn. This clearly demonstrates the advantages of employing an integrated acoustic/microseismic approach.

7.5 FURTHER INVESTIGATION: LOCATION B3

7.5.1 Introduction

Several months after the shutdown and maintenance at Factory X, complaints about low frequency noise from the factory persisted in the surrounding area. Particularly strong complaints arose from the occupant of a property that had not yet been the subject of acoustic/microseismic monitoring by the author. For reasons of confidentiality this property has been designated Location B3. The position of Location B3 can be seen in Figure 7.1.

A further survey of low frequency noise and vibration levels at this property was carried out using the integrated approach, to determine whether yet further applications of the technique could be developed, and whether they could help to resolve the low frequency noise problem in the area.

The methodology used was similar to the surveys at Locations B1 and B2 i.e.:

- The Vibrosound recording system was installed in an upstairs bedroom with microphone, window-mounted accelerometer and three-component seismometer input transducers;
- A three-component seismometer was installed on the basement slab;
- Logs of subjective disturbance levels (and changes in environmental conditions), were recorded by the occupant of B3 throughout night-time monitoring periods;
- Factory production records were made available for subsequent analysis.

Measurement took place during four consecutive nights over the period 18-22/12/98.

7.5.2 Results from Location B3

Again, ground floor vibrations were found to be negligible at Location B3.

A typical microphone-channel Vibrosound event from Location B3 is shown in Figure 7.25. The most important features of the spectrum are two strong, sharp peaks at 48 Hz (37 dB) and 49.3 Hz (27 dB). Both these features were also observed in the window-mounted accelerometer spectra, which suggests they were airborne with external source(s). A 49.3 Hz tone detected at Locations B1 and B2 was earlier identified as emanating from Factory X. External airborne noise at 48 Hz had not previously been picked up.

The event shown in Figure 7.25 was recorded in the early hours of one morning, around the same time as the resident made a note in the subjective log that read: "Got up 1:50 am. Vibratory, full orchestra & deep throb/pulse, noise outside unbelievable!"

It is likely that the "throb/pulse" described by the resident, was caused by beating between the two airborne tones close to 49 Hz. A semitone-bandpass digital filter was applied to the event shown in Figure 7.25, resulting in Figure 7.26 which displays beating very clearly in the filtered time history.

The only third-octave band containing tonal elements with sound pressure levels at or above the limit recommended by DIN 45680 (1997), was the 50 Hz band.

The employment of unmanned monitoring over several nights, along with the level of detail in the resident's comments, allowed the author to establish certain trends. The variation of the 50 Hz third-octave band level throughout the four nights of monitoring at Location B3 is shown in Figure 7.27, along with the DIN 45680 night-time limit for this band.

The subjective log from the resident suggested that the disturbance was greater on the third and fourth nights of monitoring. The detail in the log was such that nights 1 and 4 were described as moderately windy nights, with nights 2 and 3 relatively calm.

The portions of Figure 7.27 corresponding to the latter part of nights 1 and 4, are characterised by rapid fluctuations in the 50 Hz band level. These short-term fluctuations are probably due to 'windy' events; such an event is shown in Figure 7.28 and it has a broadband, high amplitude response across the whole frequency range.

If these 'windy' periods are discounted and only the 'smooth' parts of Figure 7.27 considered, there is a good correlation between 50 Hz third-octave band levels, and levels of disturbance as perceived by the resident. Indeed, those times when the 50 Hz band level exceeded the DIN limit by 2-3 dB, coincided with "noisy nights" (nights 3 and 4). Conversely, the 50 Hz band levels fell short of the DIN limit by 2-3 dB during relatively "quiet nights" (night 2 and the early, non-windy part of night 1).

The low frequency noise limits suggested by the German standard DIN 45680 (1997), were again confirmed as being a good predictor of annoyance for tonal low frequency noise.

An indication of wind direction was also given in the resident's subjective log, based on an observation of the direction of a plume of smoke emanating from a chimney at Factory X each evening:

"Night 1 – NE plume

Night 2 – vertical

Night 3 – vertical

Night 4 – E plume"

Location B3 lies east-south-east of the presumed source of the 50 Hz tones at Factory X (see Figure 7.1).

The resident felt that the disturbing noise, "tends to be better with the wind blowing away [from the factory]." This is compatible with a source for the disturbance at Factory X, bearing in mind theory on noise propagation through the atmosphere (see Section 2.2, Figure 2.4).

Measured sound levels in the 50 Hz third-octave band were relatively high on night 4, when the wind was approximately blowing from Factory X towards Location B3. However, they were also relatively high on night 3, which was not a windy night. Night 2 was equally still, yet the levels recorded in the 50 Hz third-octave band were markedly different (by ~5 dB) between nights 2 and 3.

Measured differences in sound level may therefore relate directly to increased noise output from the source, rather than wind strength or direction, although other environmental factors such as temperature gradients may have had an effect (see Section 2.2, Figure 2.5).

The 50 Hz third-octave band levels recorded at Location B3 were comparable with those found at Location B2, and ~5 dB less than those at Location B1. Other third-octave bands showed a similar pattern, which is again consistent with the source being situated at Factory X.

Despite the fact that Location B3 is the most distant of the three dwellings from Factory X, the resident of Location B3 seemed overall to be the worst affected by the low frequency noise disturbance. It is likely that this resident has a high individual sensitivity to low frequency noise.

<u>Variations in Beat Frequency</u>:

The 'beat' characteristic of the sound field at Location B3 was studied in detail.

Comparisons were made of all the microphone recordings after narrow-band digital filters had been applied around 49 Hz. A subtle trend could be detected in the data recorded over several nights.

The beating observed in the filtered time histories appeared to be slightly faster during nights 3 and 4, which were both objectively and subjectively louder than nights 1 and 2.

Figure 7.26 displays beating that is representative of night 4 (the loudest night). It is possible to count ~13 beats over 10 seconds, corresponding to a separation between the two sharp tones in the frequency spectrum of 1.3 Hz.

A filtered recording from night 1 is shown in Figure 7.29. The beating is demonstrably slower (~10 cycles over 10 seconds), which reflects the fact that the two strong tones close to 49 Hz are slightly closer in frequency (1 Hz separation).

It may be hypothesised that faster beating will tend to be more annoying (it 'draws attention to itself more') than slower beating. Thus, the increased levels of annoyance on nights 3 and 4 may partly be due to increased beat frequency, as well as increased amplitudes of the recorded tones.

7.5.3 Experimenter's Subjective Perception at Location B3

Dr. Andy Moorhouse of the University of Liverpool re-visited Location B3 in January 1999 and made a rather interesting observation whilst taking noise level readings in the bedroom, using a hand-held sound level meter with a third-octave band filter set attached. The beating measured earlier could be continually heard in certain, objectively louder positions in the bedroom.

At other positions in the room, where sound levels were slightly below the DIN 45680 (1997) limits, low frequency sound could be heard intermittently during the 'loud' part of the beating cycle but not during the 'quiet' part. Levels in these parts of the room must therefore have been around Dr. Moorhouse's personal threshold of hearing.

Dr. Moorhouse's judgement was that such low frequency throbbing sounds have the potential to cause great annoyance if one is subjected to them over long exposure times, despite their only being slightly above the threshold of perception.

This incident illustrates the effect of microphone position on recorded sound levels at low frequencies (see Section 3.2).

It was also noted during this visit to the site that the beat frequency was slightly slower (around 10 cycles over 20 seconds) than it was during the previous measurements. This suggests that the two beating tones had moved closer together in frequency in the intervening period, and is consistent with the variations in beat frequency extracted from the data gathered during the unmanned monitoring period.

7.5.4 Summary of Findings at Location B3

A throbbing sound at around 49 Hz was giving rise to annoyance at Location B3. The throbbing sensation was caused by two external airborne tones beating together. Only one of the tones had been previously detected at Locations B1 and B2.

The beating varied in magnitude, and was considered by the resident to be more annoying during periods when measurements showed that it exceeded the limiting levels recommended by DIN 45680 (1997). Thus, DIN 45680 was again confirmed as a good predictor of annoyance due to low frequency noise.

The frequency of beating was also observed to vary over time, due to slight variations in frequency of the tones.

Some of the recorded events were obscured by wind noise, but the length of the monitoring period maximised the prospect of obtaining suitable data during favourable conditions.

The sound levels at Location B3 were lower than the levels at Location B1. This is consistent with Factory X being the source of the noise. Despite the reduced levels, the resident of Location B3 was extremely disturbed by the noise and it is suggested that this individual is highly sensitive to low frequency noise.

The variations in beat characteristic observed over the monitoring period were rather subtle. It was only possible to observe them because of a combination of long-term monitoring over several nights, acquisition of data with fine frequency resolution, and subsequent analysis of large quantities of gathered time histories using advanced signal processing tools.

7.6 VISIT TO FACTORY X

Shortly after the measurement period at Location B3, Dr. Andy Moorhouse was taken on a guided tour around Factory X. During this tour, Dr. Moorhouse noticed an item of plant that was radiating high levels of throbbing, low frequency noise. This item of plant, known as a forehearth-cooling fan, was not previously considered as a potential source of annoyance and had not been switched off as part of the earlier shutdown experiment. The factory management were alerted to this potential source.

The author made a subsequent visit to Factory X to make vibration measurements using the Vibrosound recording system and an accelerometer mounted on the forehearth-cooling fan. This illustrates the robustness and portability of the datalogging hardware.

The accelerometer was attached by beeswax to various positions on the fan casing and ten-second time histories were recorded by the Vibrosound in the usual manner. The nominal running speed of the fan was 34.9 Hz.

Figure 7.30 shows a typical event recorded using the accelerometer mounted on the fan casing.

The spectrum does not contain a peak corresponding to the running speed of the fan itself (34.9 Hz). However, there is a very strong peak at 49.3 Hz with an RMS level of ~4 m/s^2. The 49.3 Hz peak possibly reflects the operational speed of the motor that drives the fan via a pulley. Motors often have a nominal running speed of 50 Hz (mains frequency), but run at slightly below this because of the effect of loading. Narrowband frequency analysis of the output from the other, unused Vibrosound channels allowed the instrumentation's internal electrical 'noise' to be distinguished from the 49.3 Hz 'signal'.

The 49.3 Hz tone in the fan vibration spectrum was at the same frequency as tones detected at all three dwellings in the area where the author had monitored sound and vibration levels using the combined acoustic/microseismic technique. The 49.3 Hz tonal noise had previously been demonstrated to propagate via an airborne path from somewhere within Factory X, but the precise source had not been established up to this point.

As a result of the site visit with the microseismic monitoring equipment and a small accelerometer, it was demonstrated that the forehearth-cooling fan was vibrating at very high levels at a frequency of 49.3 Hz. This seemed to be the most likely source of the airborne tonal noise in the 50 Hz third-octave band, as measured at the nearby households and correlated with levels of disturbance.

7.7 FINAL OUTCOME OF CASE STUDY B

Noise control measures were implemented on the forehearth-cooling fan identified at Factory X as being the source of annoying tonal noise at 49.3 Hz in nearby dwellings. The measures were carried out as a direct result of recommendations made by the research team from the University of Liverpool. These recommendations were based on the results obtained by the author using the integrated acoustic/microseismic technique.

Following the implementation of noise control measures on the forehearth-cooling fan, the low frequency noise problem in the environment around Factory X subsided to a large extent. Residents close to the factory were content that low frequency noise levels in the area had been reduced to an acceptable level.

The source of an external airborne tone at ~48 Hz, that was only detected at Location B3, was not identified. However, the attenuation of the 49.3 Hz tone at Location B3 probably reduced both the magnitude of beating (in terms of ratio of maximum:minimum sound pressure) and the absolute 50 Hz third-octave band levels to an acceptable level.

7.8 CONCLUDING REMARKS

The case study described in this chapter investigated a very complex, intermittent low frequency noise problem in a rural environment where background noise levels were very low. Finding a solution to the problem was rather difficult and time-consuming. There were many complicating environmental, physical and psychological factors. Earlier assumptions were subject to constant revision throughout the study.

It was confirmed that a low frequency tone was emanating from Factory X, via an airborne transmission path. The tone, which was assessed by reference to residents' logs of subjective loudness and the German national standard DIN 45680 (1997), contributed to high levels of annoyance at nearby dwellings. The precise source of the tone was eventually identified. Noise control measures implemented by the management of Factory X reduced the local levels of low frequency noise to an acceptable level.

Corroborative results from three different dwellings validated the noise limits set out in the German national standard DIN 45680 (1997) as a good predictor of annoyance due to low frequency noise.

The experimental method of recording large numbers of time histories of the sound and vibration levels in several locations over long periods, allowed detailed analysis to take place in both time and frequency domains. A wide array of useful signal processing could be carried out on the recordings. This versatility was an essential factor in allowing a solution to the problem to be determined.

The simultaneous recording of sound pressure, window vibration and first-floor seismometer data in parallel allowed direct comparisons of the levels in each channel to be made. From this analysis, propagation paths (groundborne vs. airborne, internal vs. external source) could be determined.

At one house, two tones that were very close in frequency were distinguished as deriving from two completely different sources. One was shown to emanate from Factory X, the other from an internal source (refrigerator). Note that in some situations, such as a block of flats, it may not be possible to determine 'internal' sources by other means, which illustrates another advantage of the current methodology.

Simultaneous recording using two microphone channels was possible using the Vibrosound datalogger. This allowed a transfer function for sound transmission from outside to inside a house to be calculated. The transfer function yielded useful information about the specific resonance properties of one bedroom where monitoring took place, which allowed the author to rule out, as the cause of the annoyance, relatively high sound levels measured within that room in the frequency range 36-41 Hz.

Narrow-band filtering of the time histories showed that beating was occurring in some dwellings between two tones close to 49 Hz. The subtle differences in frequency of the tones, and variations of the rate of beating between them over several nights, could only be observed because of the narrow frequency resolution of the recordings, and the long-term monitoring period which allowed variations in source output to be distinguished from environmental (wind) variations.

The problematic tones were close in frequency to 50 Hz i.e. mains frequency, but the latter was ruled out as a possible cause by analysing the output from an unused channel of the datalogger, which showed a peak due to mains 'hum' at precisely 50 Hz. This illustrates another advantage of using the multi-channel technique; when a tone at a frequency close to 50 Hz is detected using single-channel instrumentation, it may not be possible to discount electrical noise with certainty.

The monitoring equipment was employed on site at Factory X to measure the vibration spectrum of the particular item of plant that was ultimately identified as the source of the annoying tone. This illustrates the portability and robustness of the equipment.

To summarise, this case study demonstrates the usefulness and versatility of the combined acoustic/microseismic approach when tackling complex low frequency noise/vibration problems. It is doubtful whether the problem in the case study could have been solved using standard acoustic or microseismic techniques alone.

7.9 REFERENCES

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German Standard DIN 45680 (1997): *'Messung und Bewertung tieffrequenter Geräuschimmissionen in der Nachbarschaft'*, Deutsches Institut für Normung e.V., Berlin.

Piorr, D. and Wietlake, K., (1990): *'Assessment of Low Frequency Noise in the Vicinity of Industrial Noise Sources'*, Journal of Low Frequency Noise and Vibration, Volume 9(3:116-119).

Fig. 7.1 – sketch map of the area under investigation in Case Study B (houses not to scale)

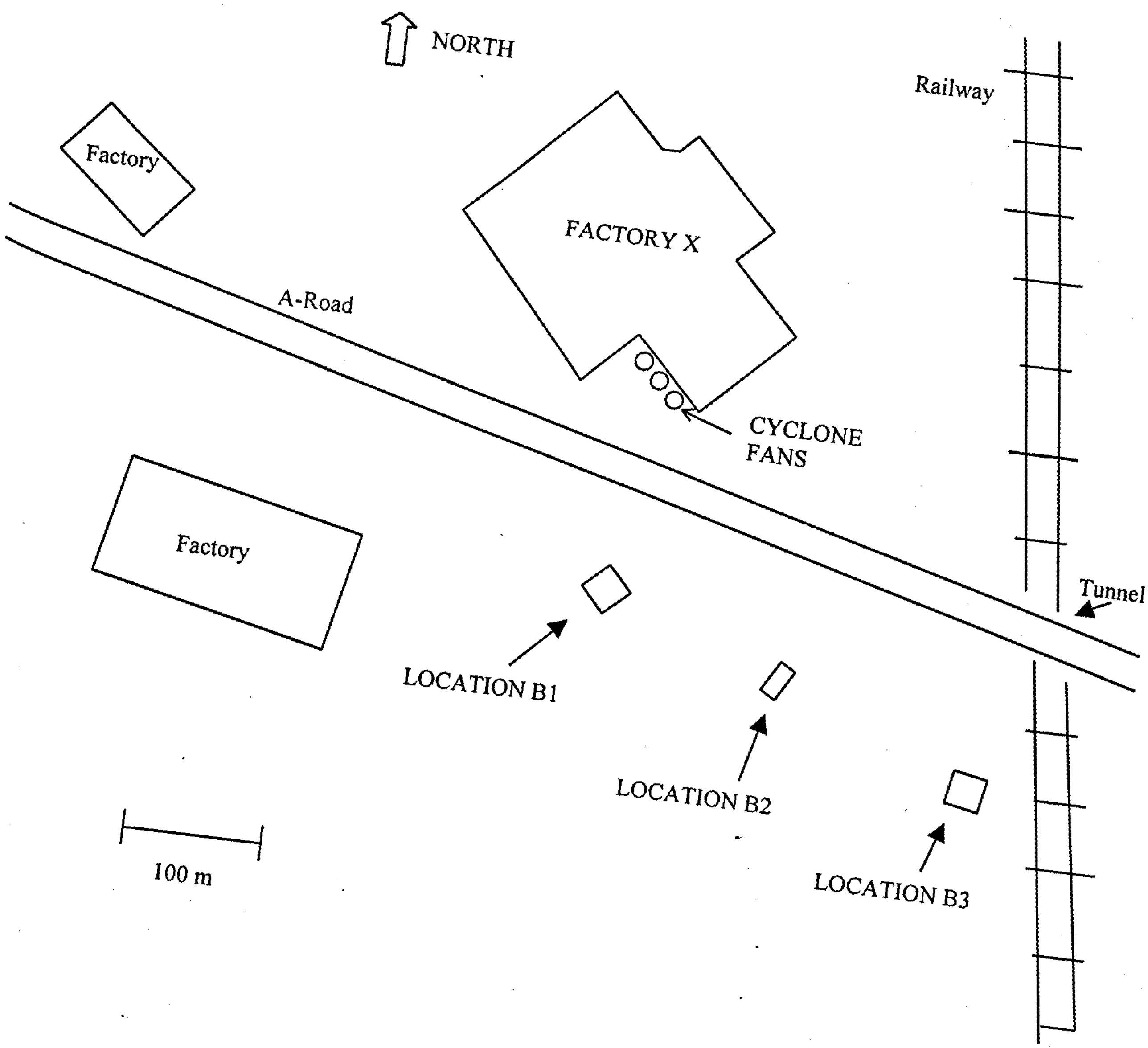


Fig. 7.2 - a typical microphone channel recording from Location B1

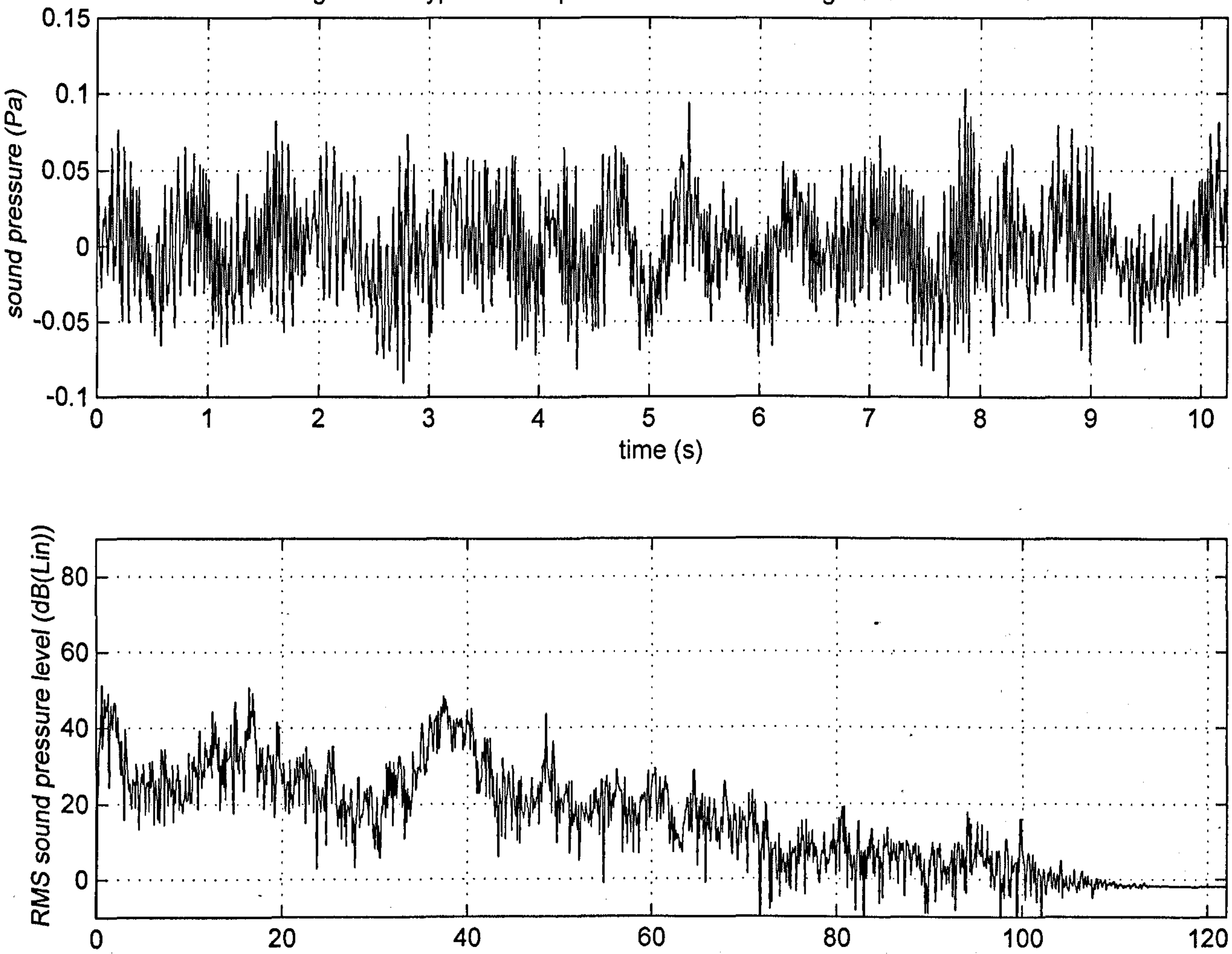


Fig. 7.3 - typical third-octave band levels from Location B1, compared with DIN 45680 limits

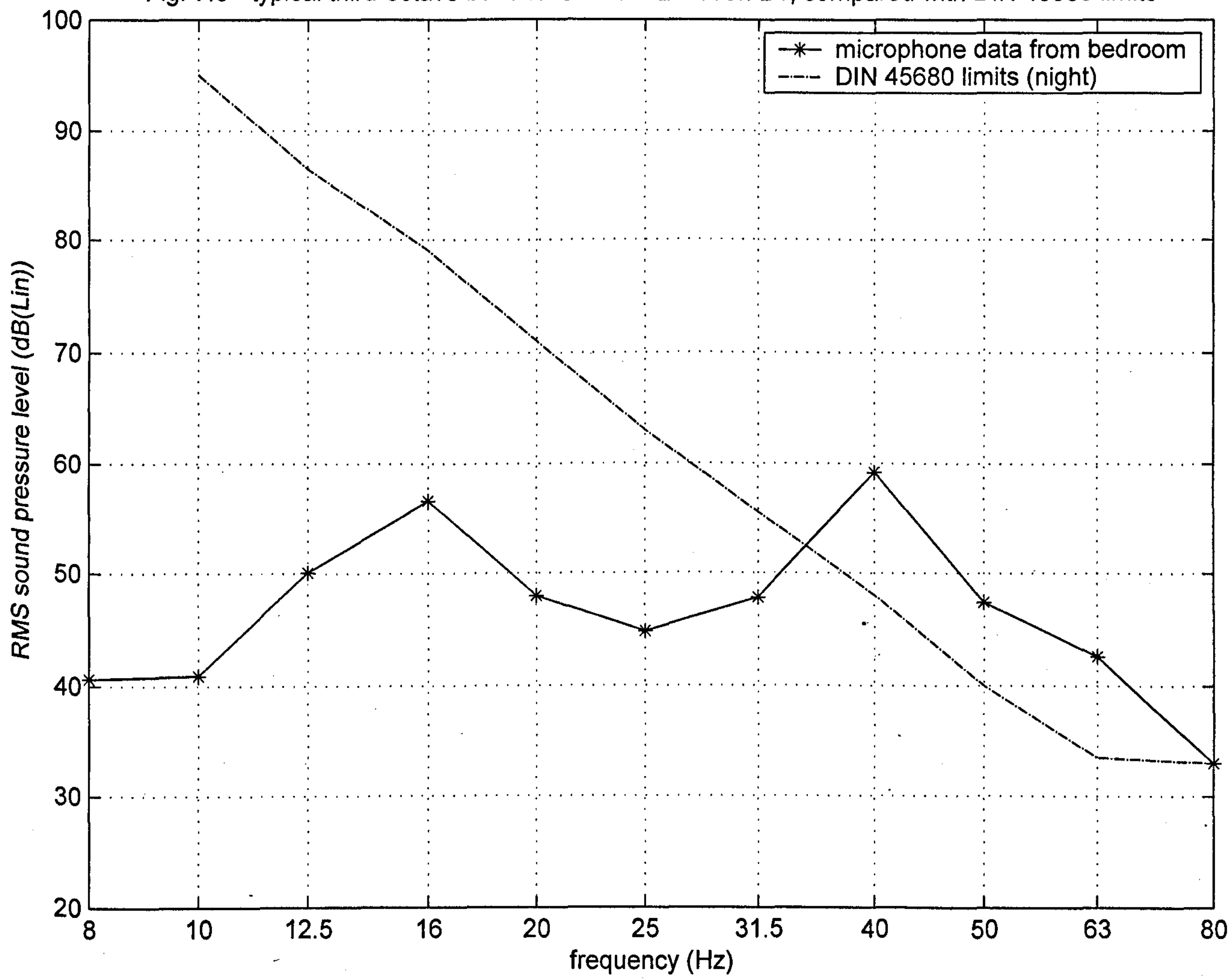


Fig. 7.4 - a typical window vibration recording from Location B1

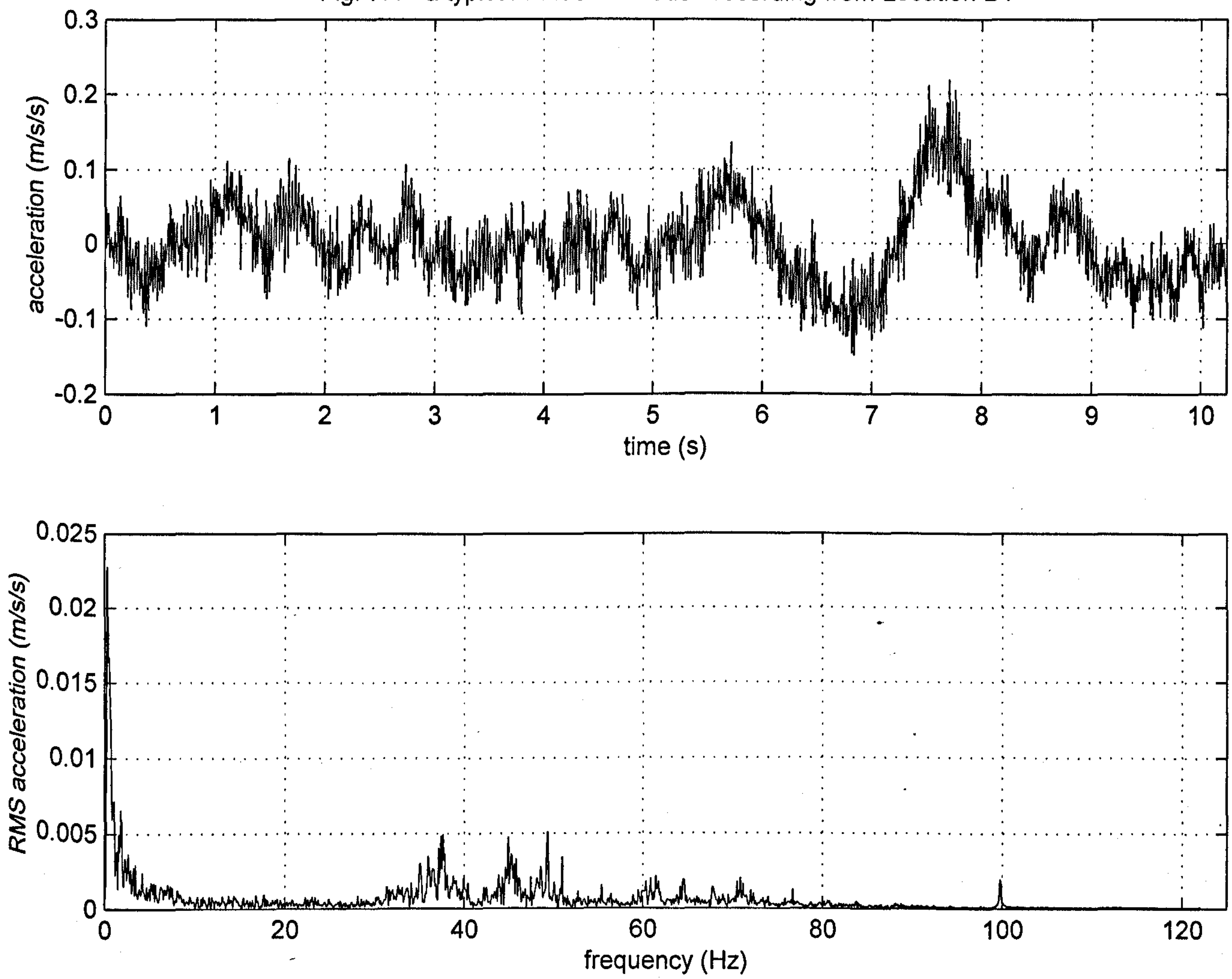


Fig. 7.5 - a typical vertical bedroom floor vibration recording from Location B1

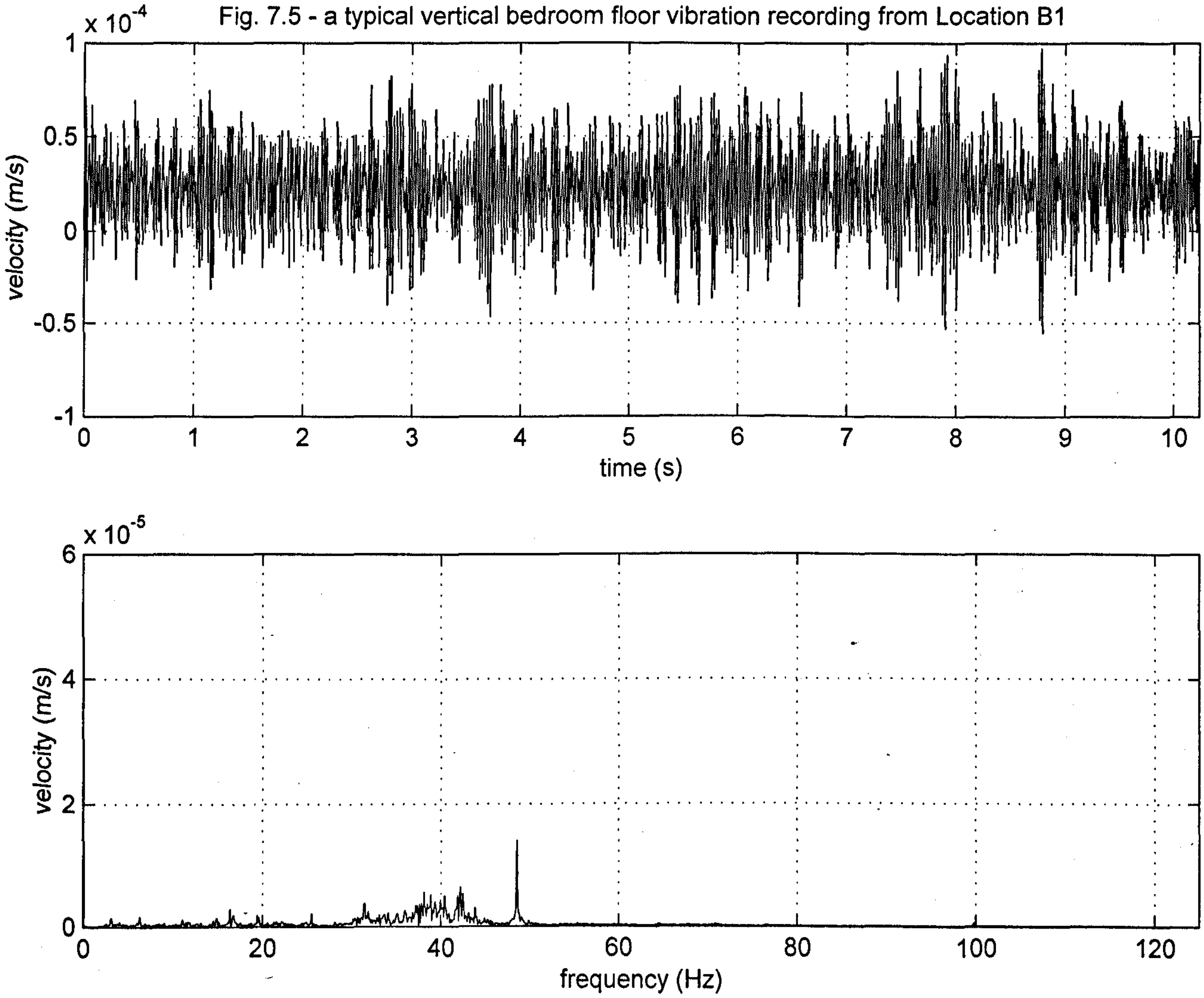


Fig. 7.6 - vertical vibration levels in the bedroom floor at Location B1, compared with BS 6472 limits

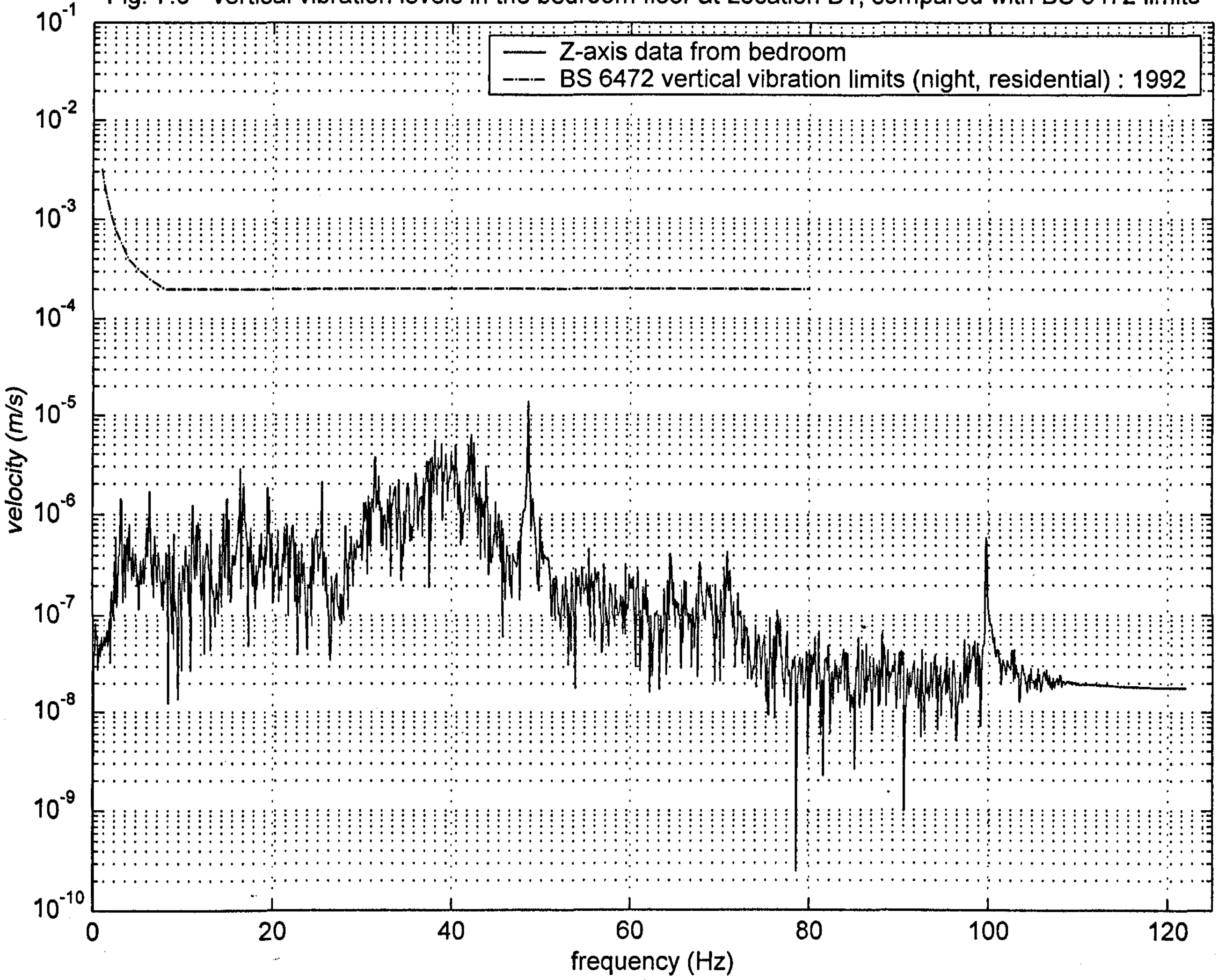


Fig. 7.7 - variations in 40 Hz third-octave band level during three nights of monitoring at Location B1; cyclone fan activity at Factory X is shown at the bottom of the figure

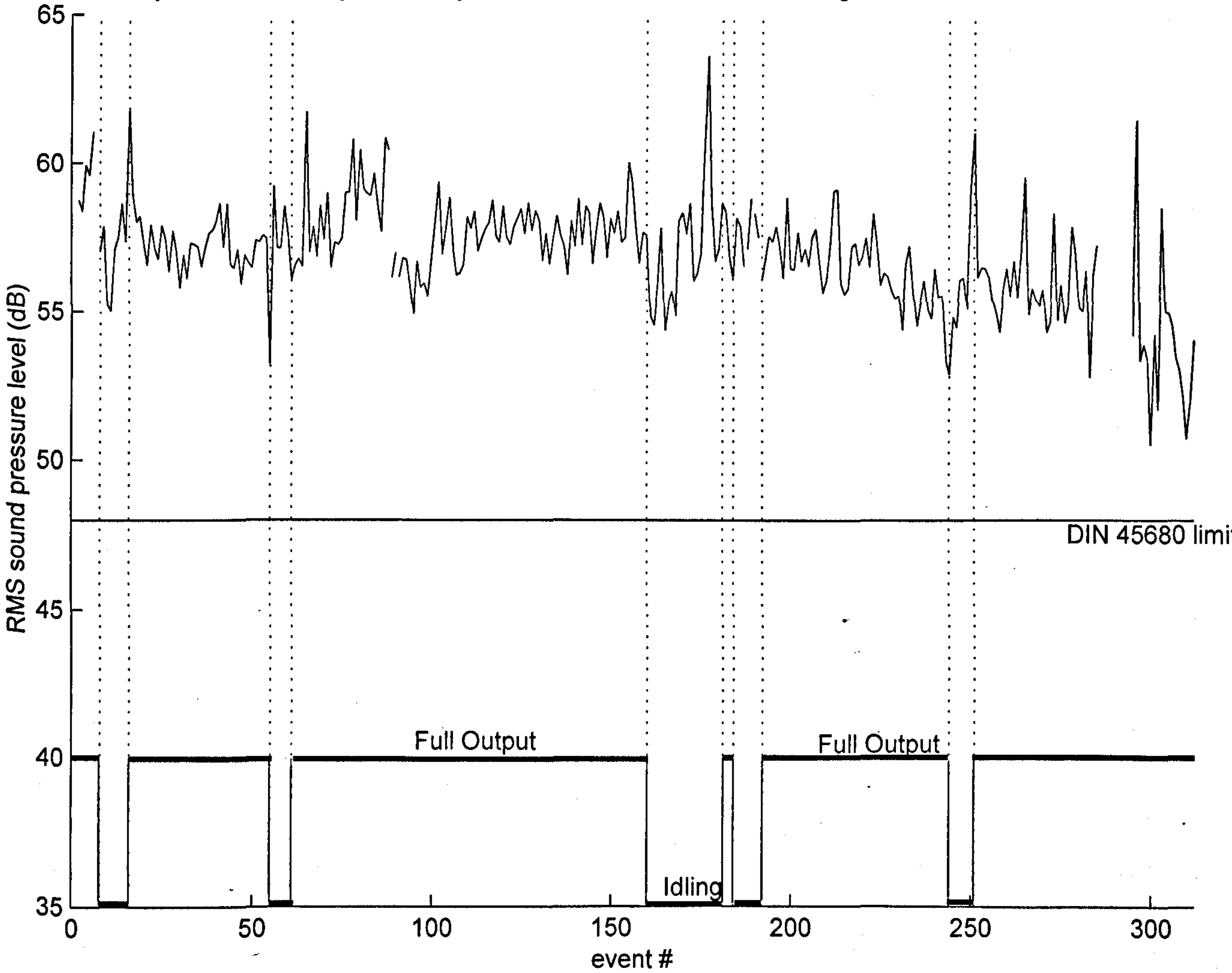


Fig. 7.8 - event recorded at Location B1 shortly before emergence of 48.5 Hz peak

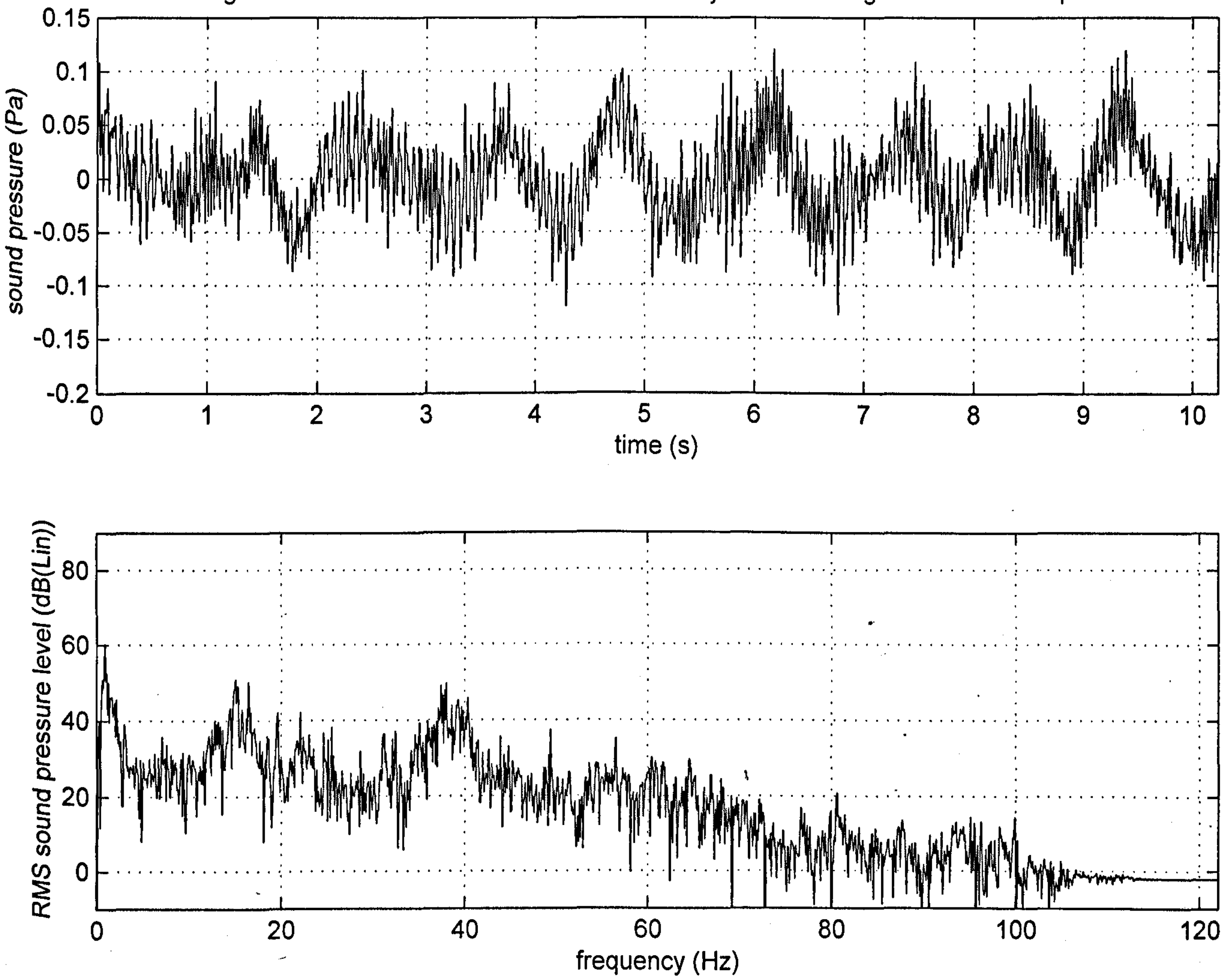


Fig. 7.9 - event recorded at Location B1 shortly after emergence of 48.5 Hz peak

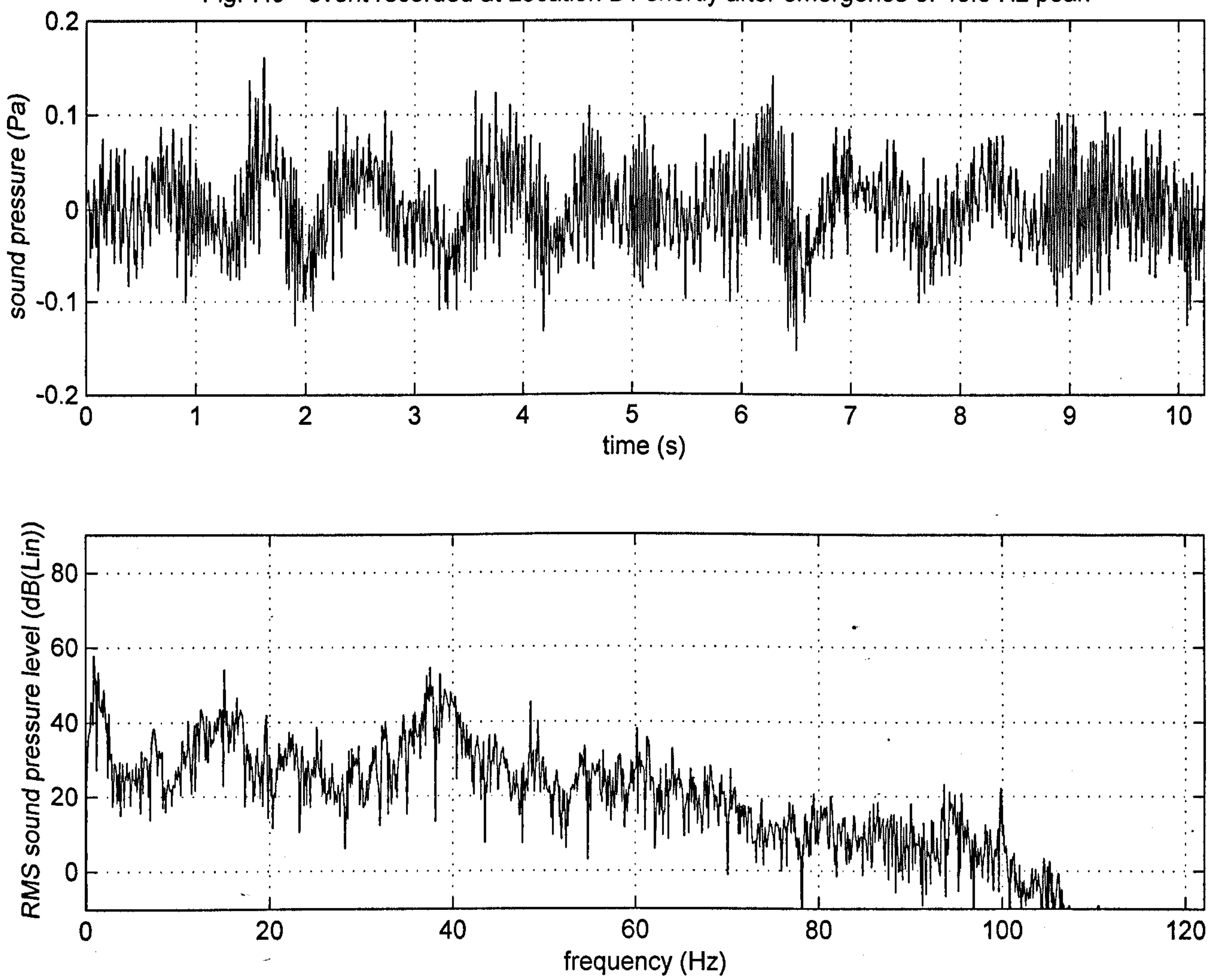


Fig. 7.10 - variations in 50 Hz third-octave band level during three nights of monitoring at Location B1; cyclone fan activity at Factory X is shown at the bottom of the figure

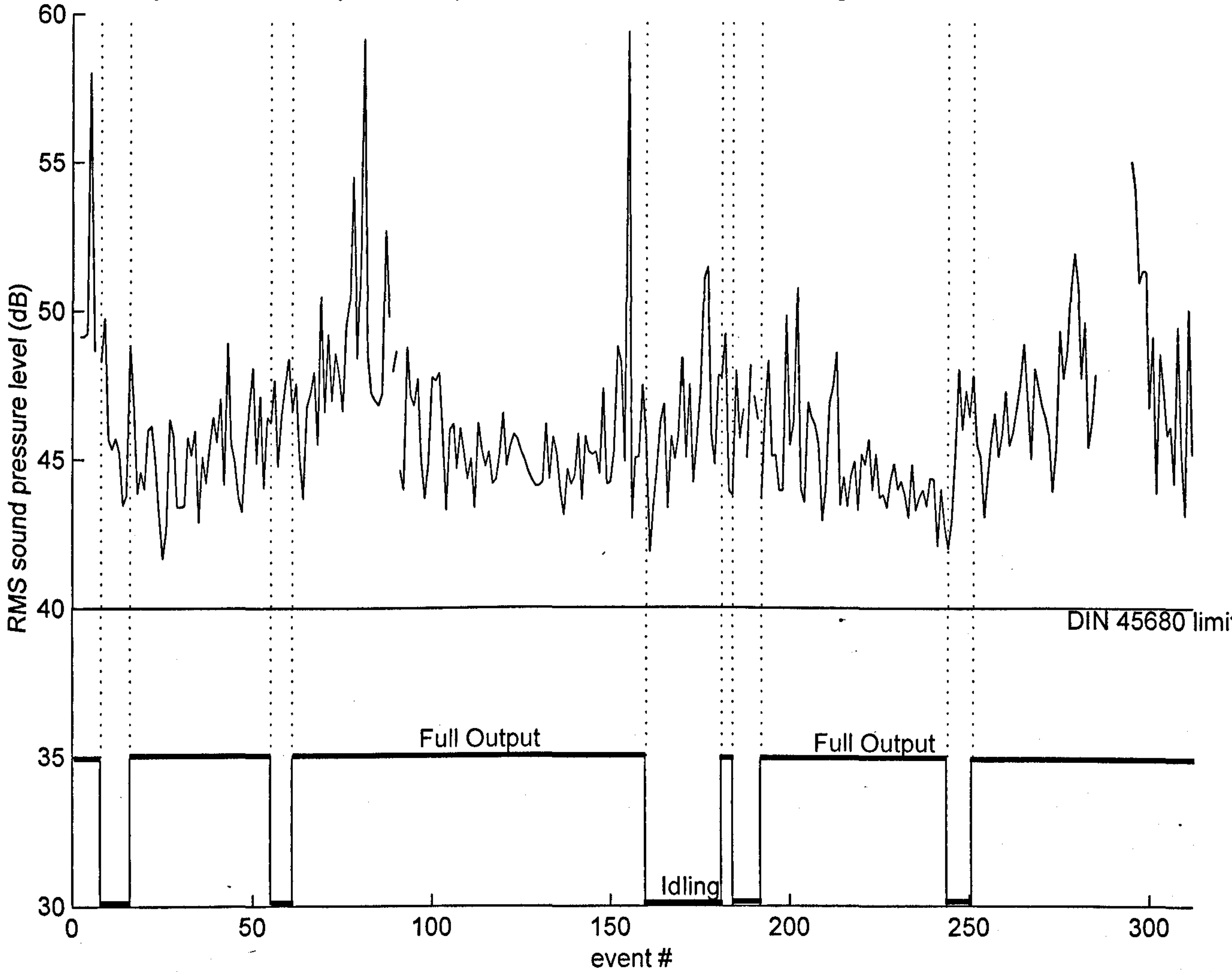


Fig. 7.11 - transfer function (c) for sound measurements at Location B1 from (a) outside to (b) inside

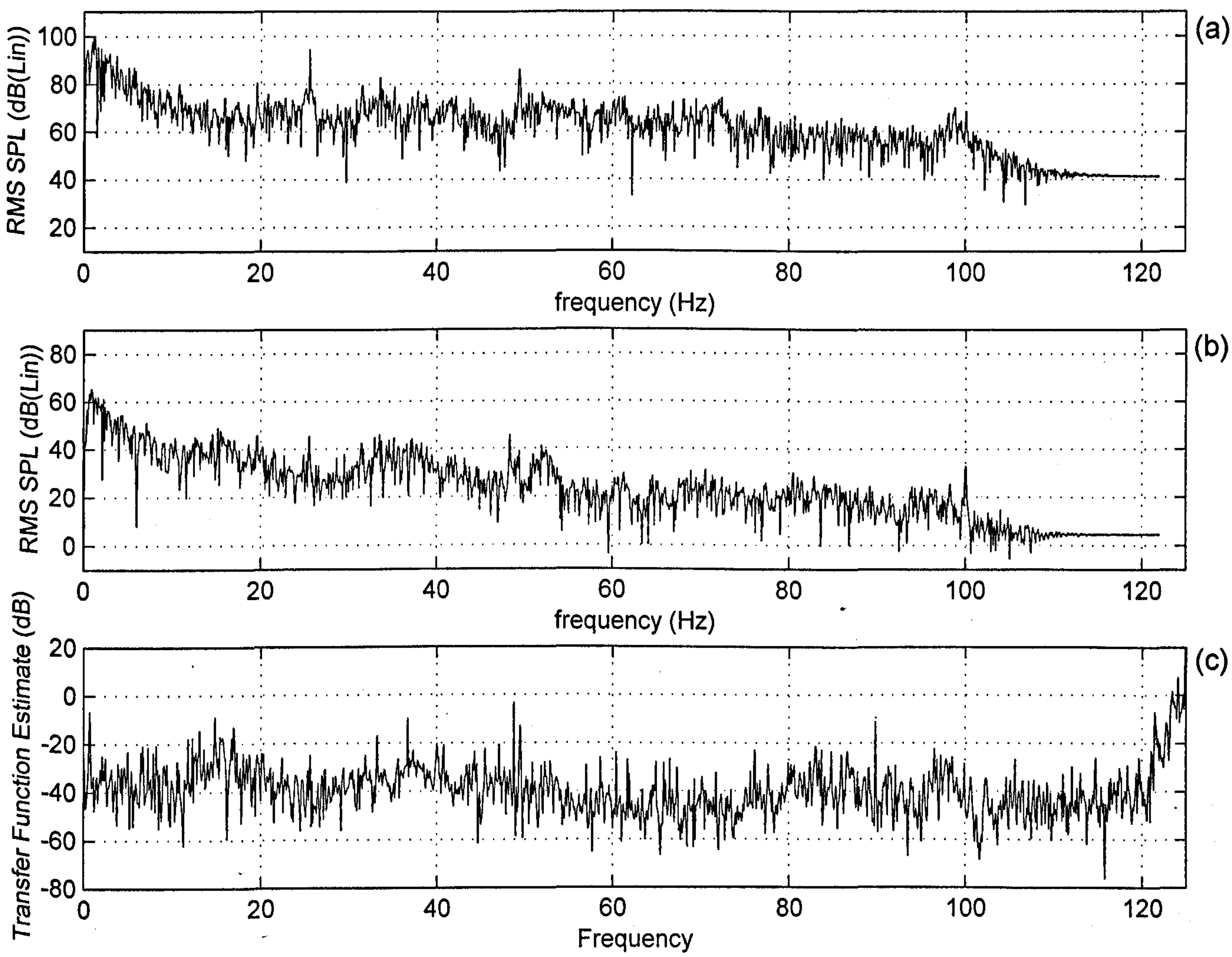
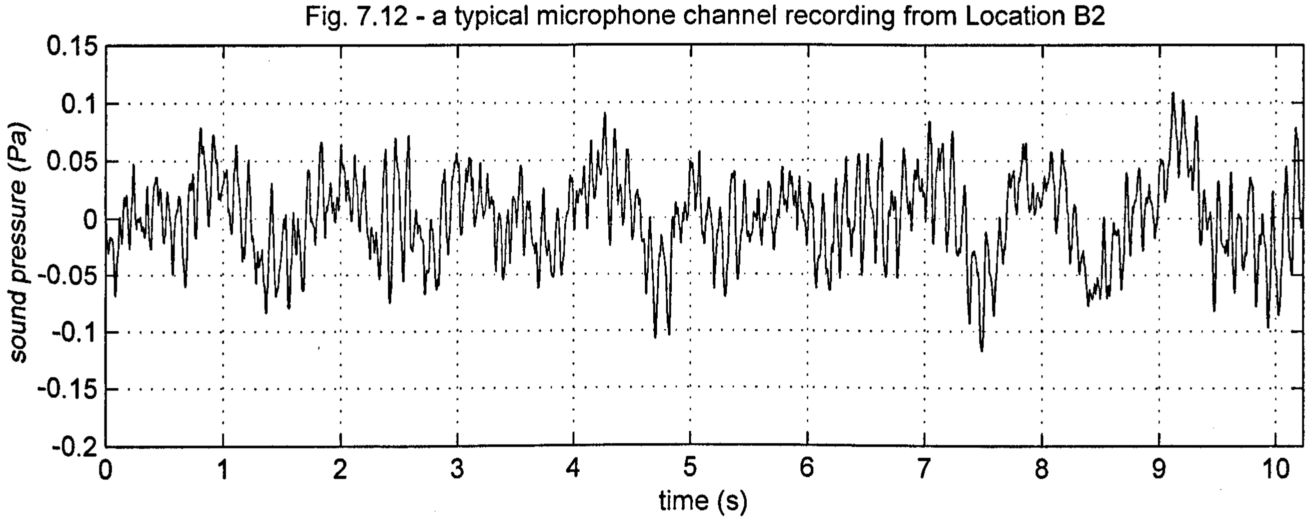
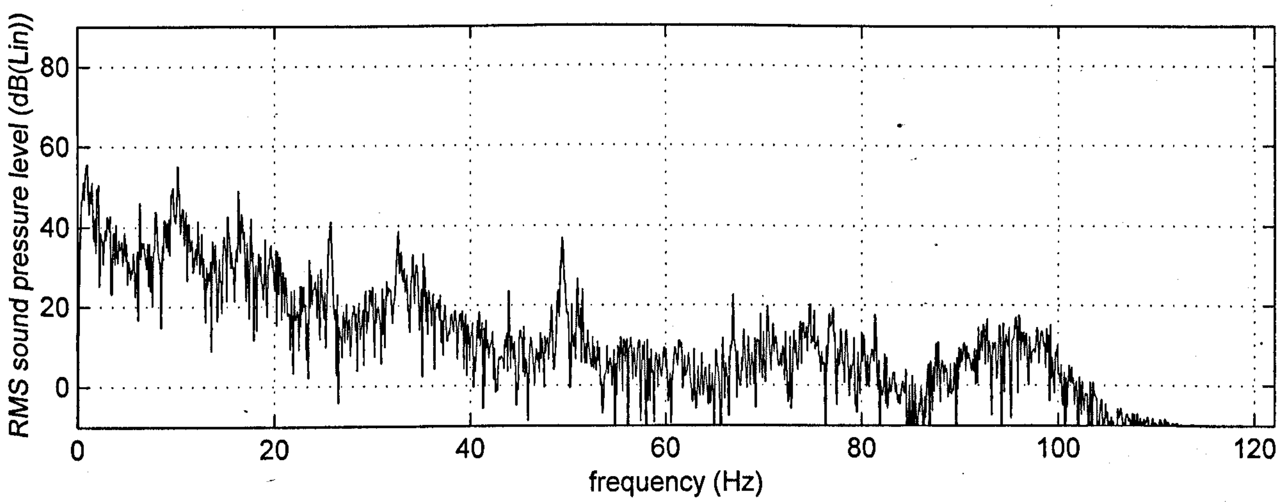


Fig. 7.12 - a typical microphone channel recording from Location B2





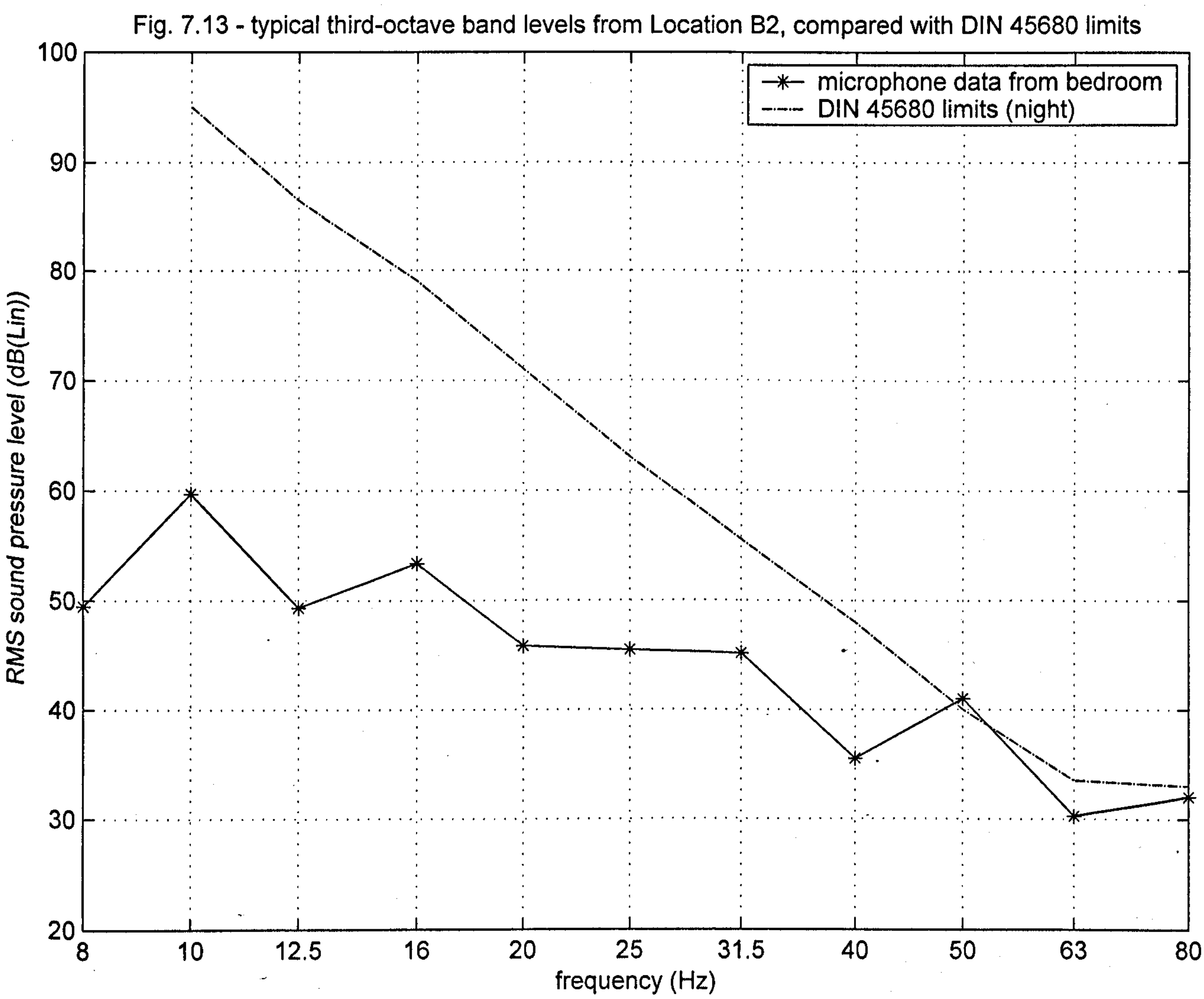


Fig. 7.13 - typical third-octave band levels from Location B2, compared with DIN 45680 limits
microphone data from bedroom
DIN 45680 limits (night)
RMS sound pressure level (dB(Lin))
100
90
80
70
60
50
40
30
20
8
10
12.5
16
20
25
31.5
40
50
63
80
frequency (Hz)

Fig. 7.14 - variations in 50 Hz third-octave band level during three nights and one day of monitoring at Location B2; a period of high cyclone fan output at Factory X is highlighted

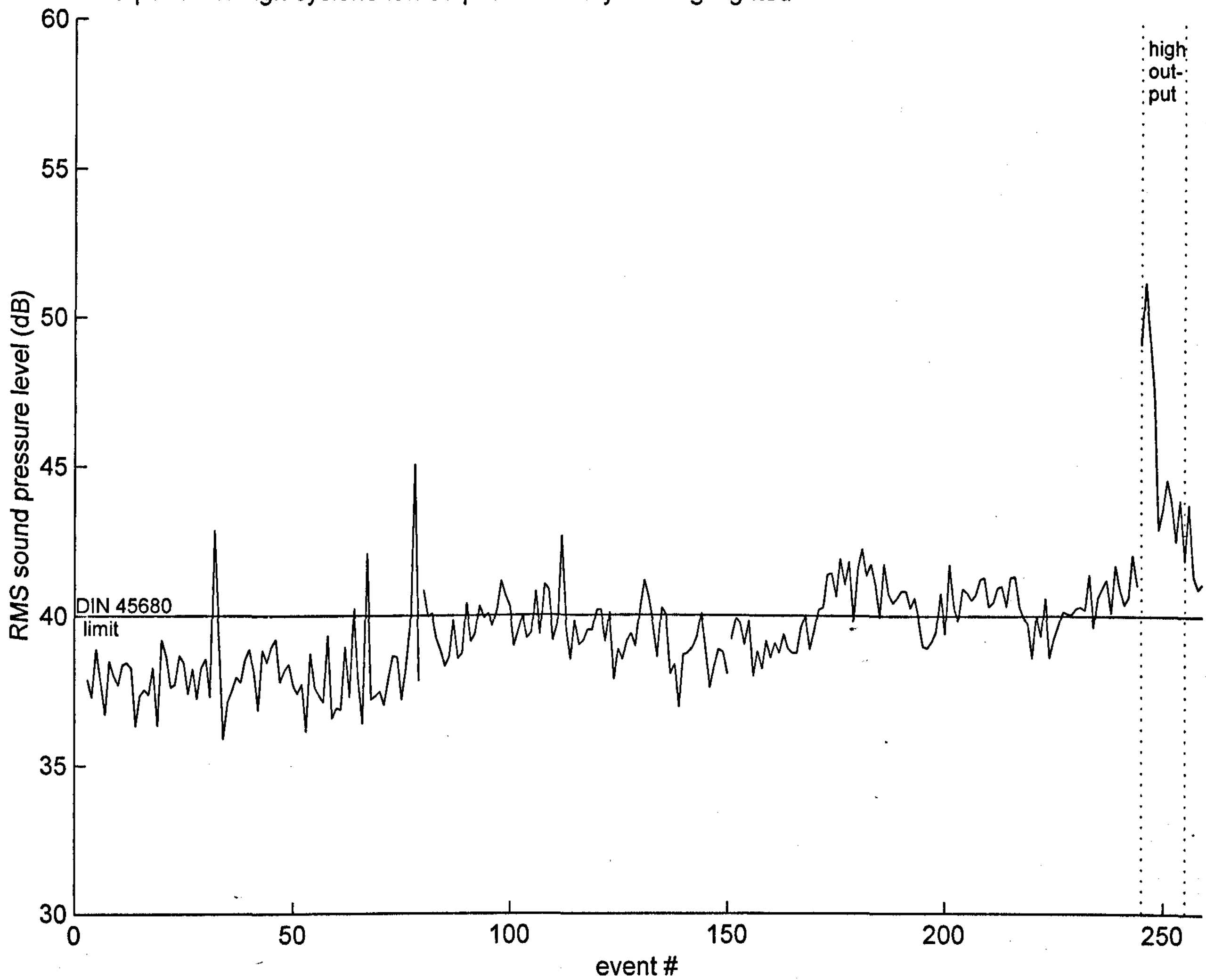


Fig. 7.15 - microphone channel recording from Location B2 during a period of high cyclone fan output

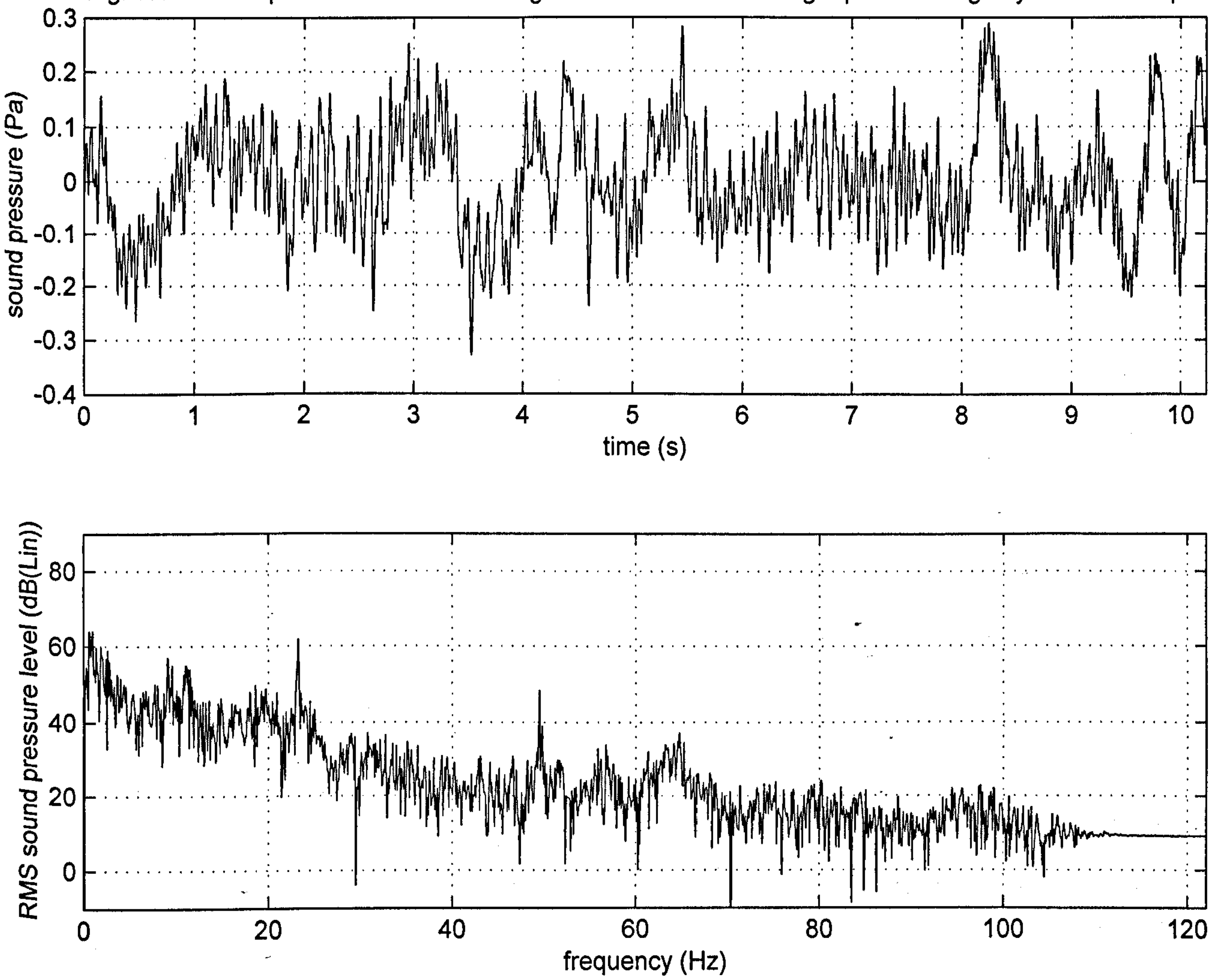


Fig. 7.16 - microphone channel recording from Location B2 during a period of low cyclone fan output

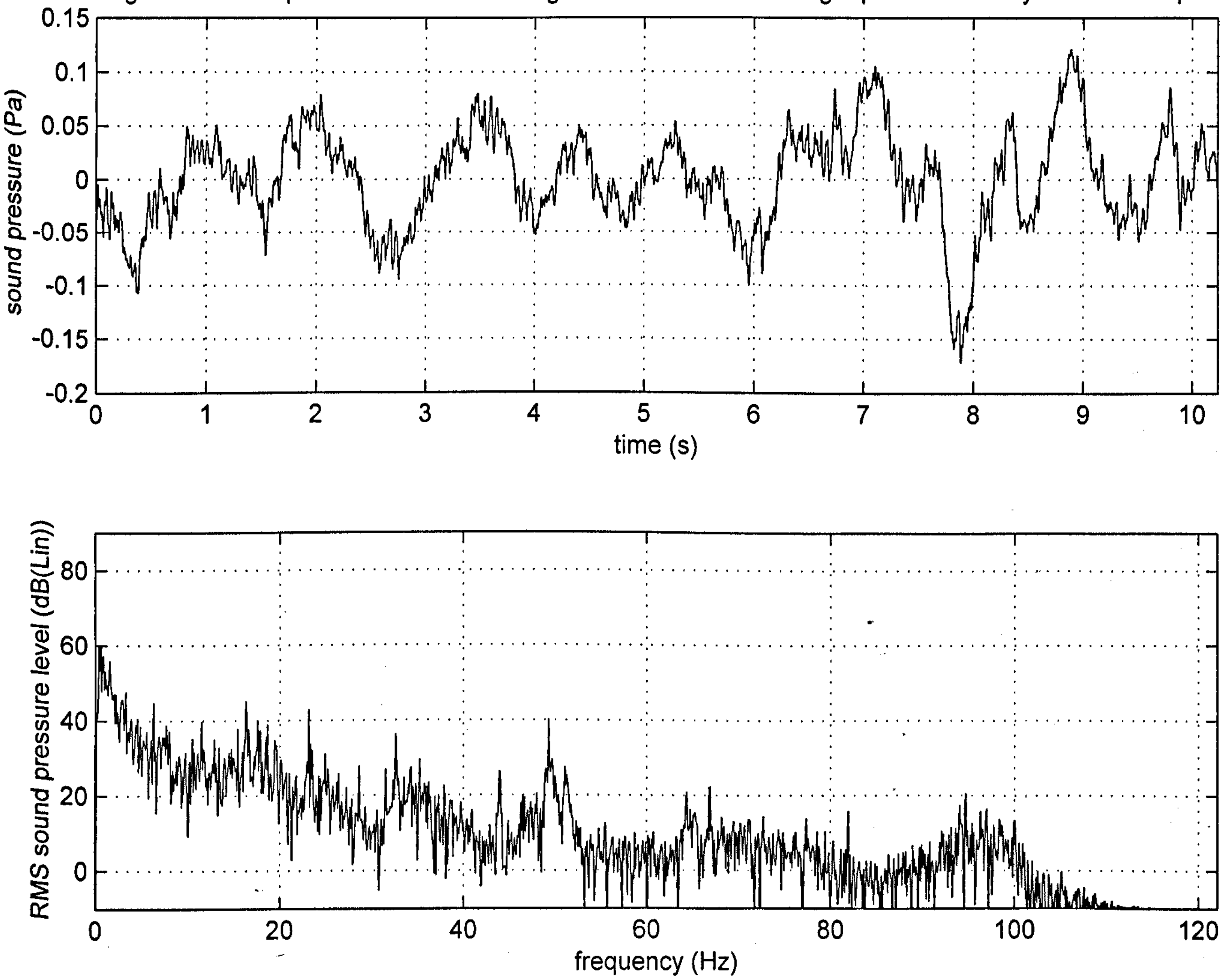


Fig. 7.17 - background noise at Location B1 during shutdown of Factory X, showing residual 48.5 Hz peak

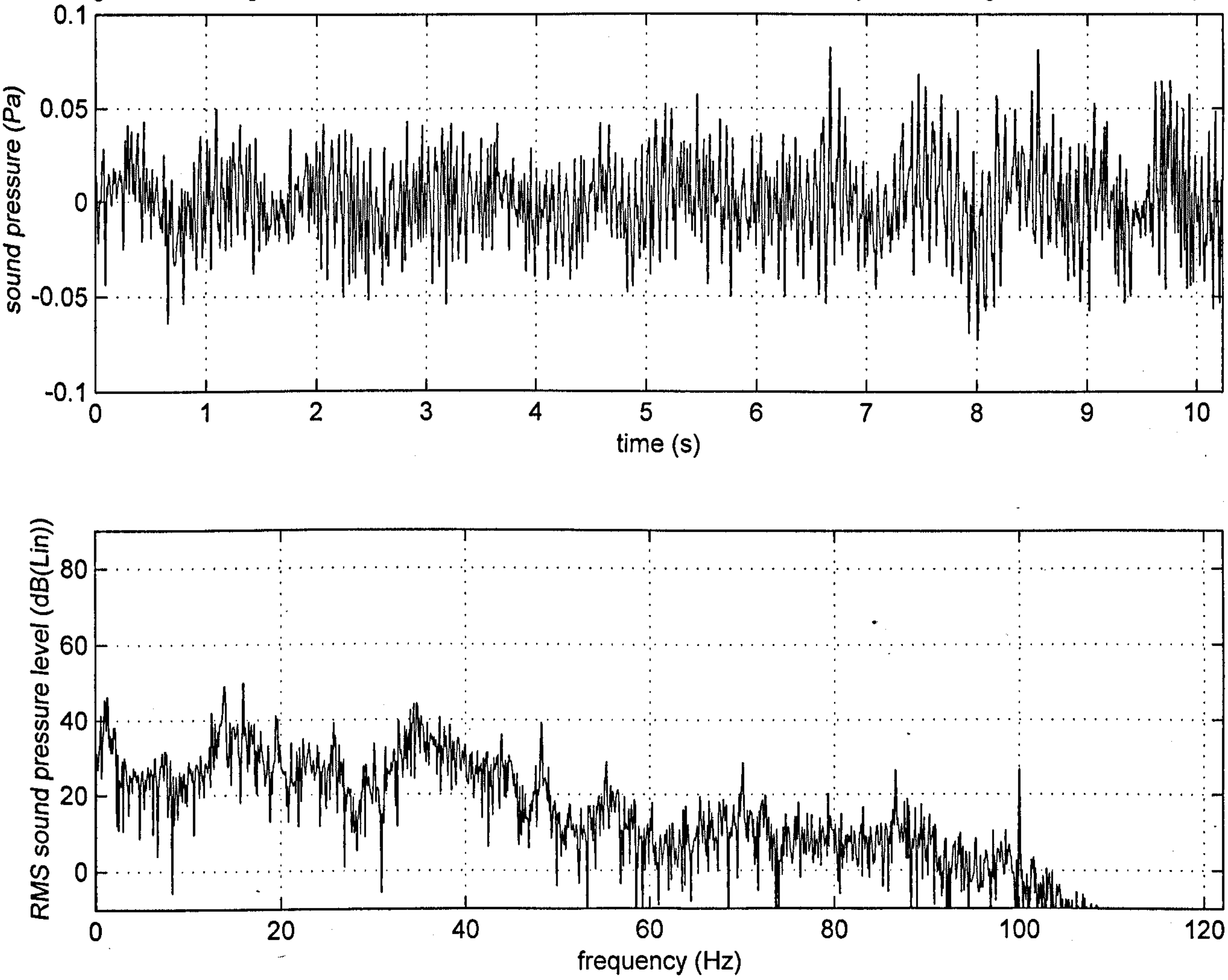


Fig. 7.18 - background noise in third-octave band levels at Location B1 during shutdown; still in excess of DIN 45680 limit at 50 Hz

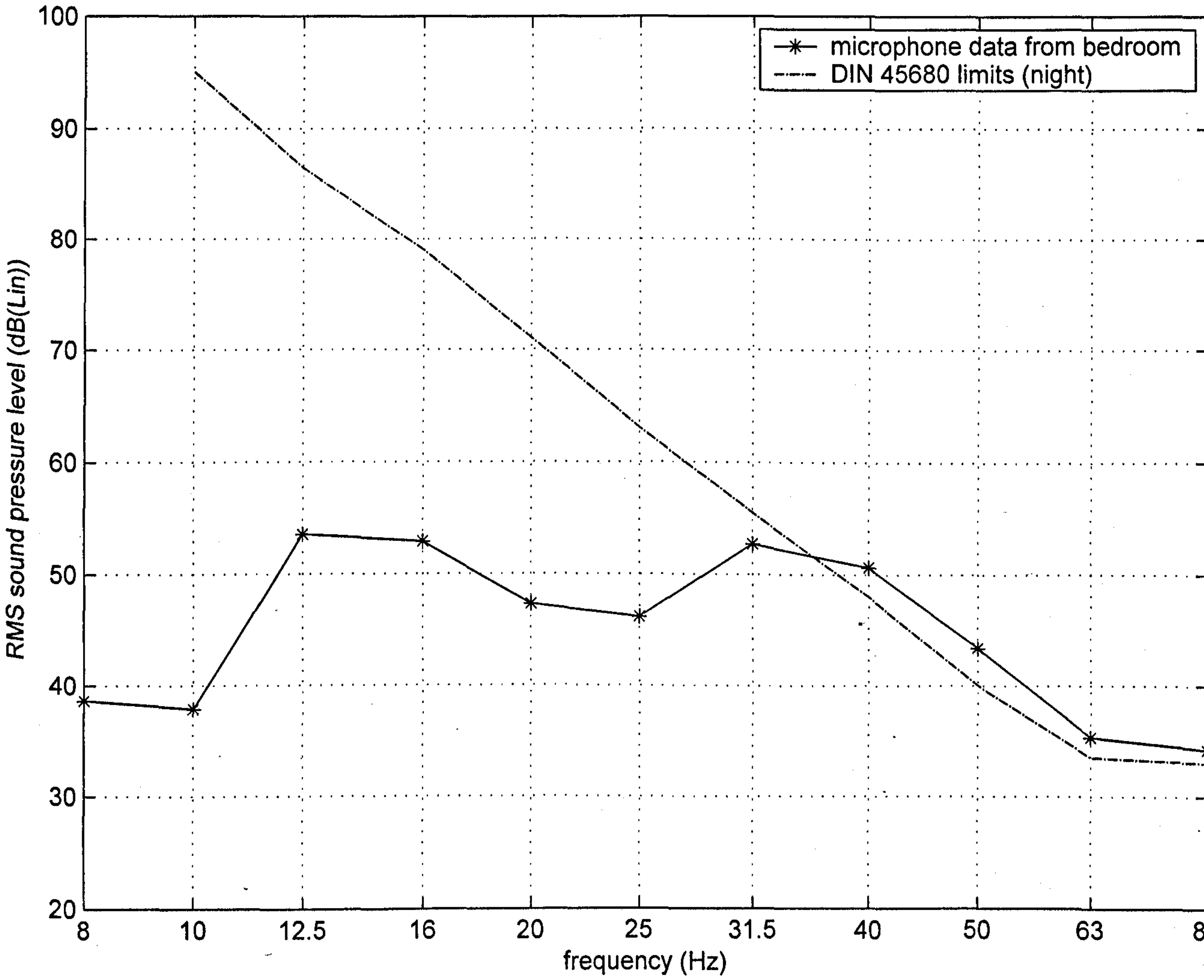


Fig. 7.19 - background noise at Location B1 during shutdown of Factory X; 48.5 Hz peak is absent

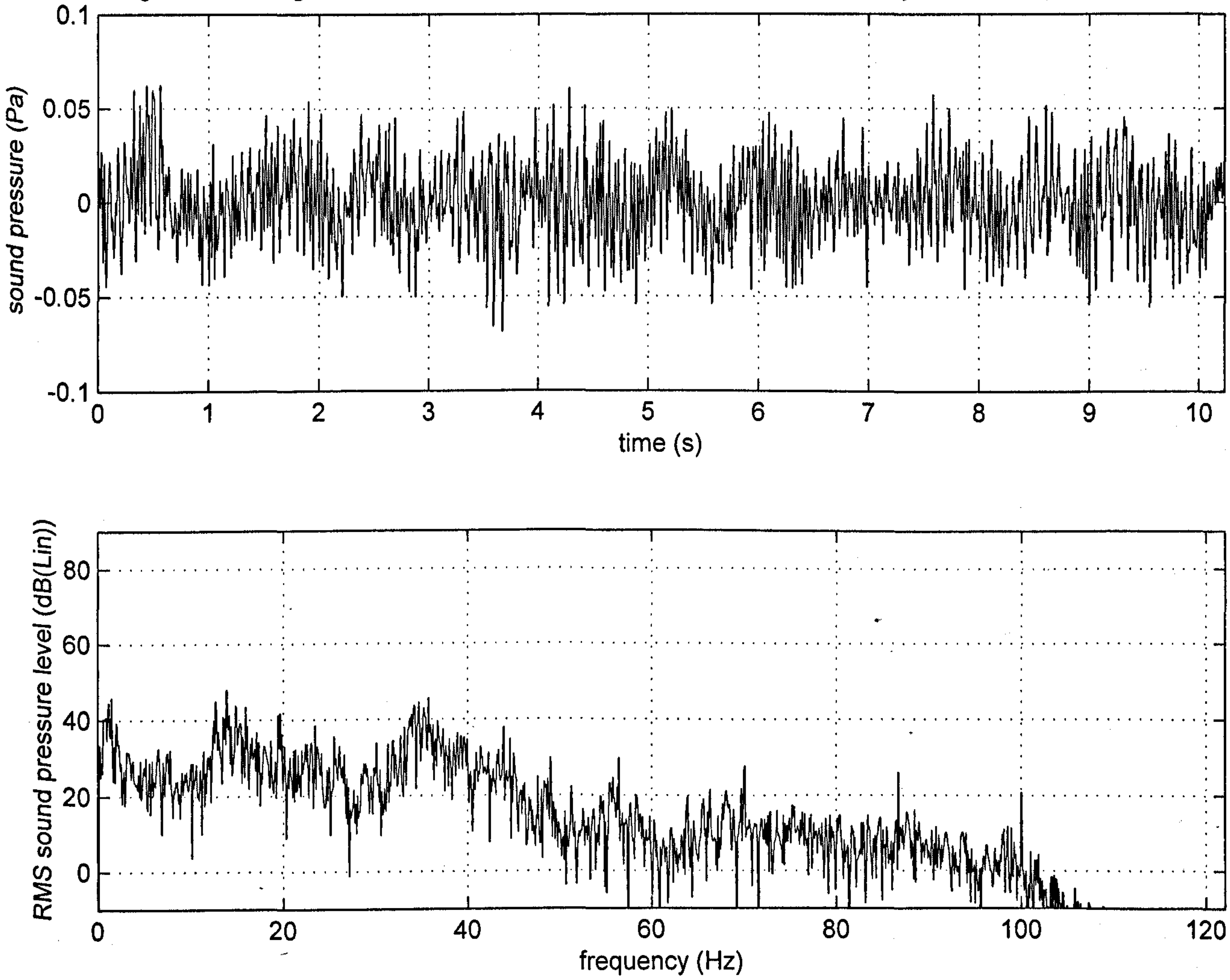


Fig. 7.20 - background noise in third-octave band levels at Location B1 during shutdown; close to DIN 45680 limit at 50 Hz

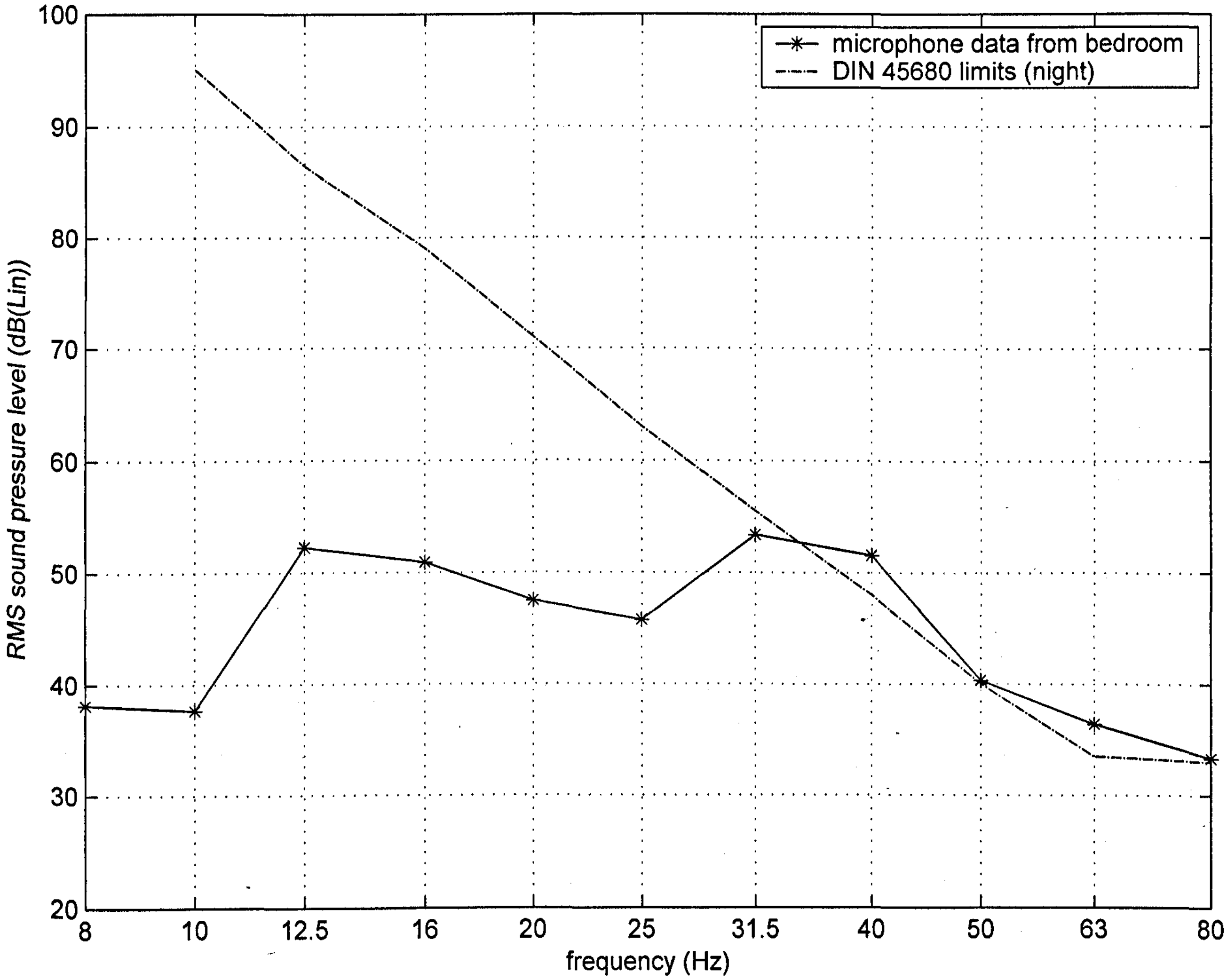


Fig. 7.21 - variations in 50 Hz third-octave band level at Location B1
during one night of the shutdown at Factory X

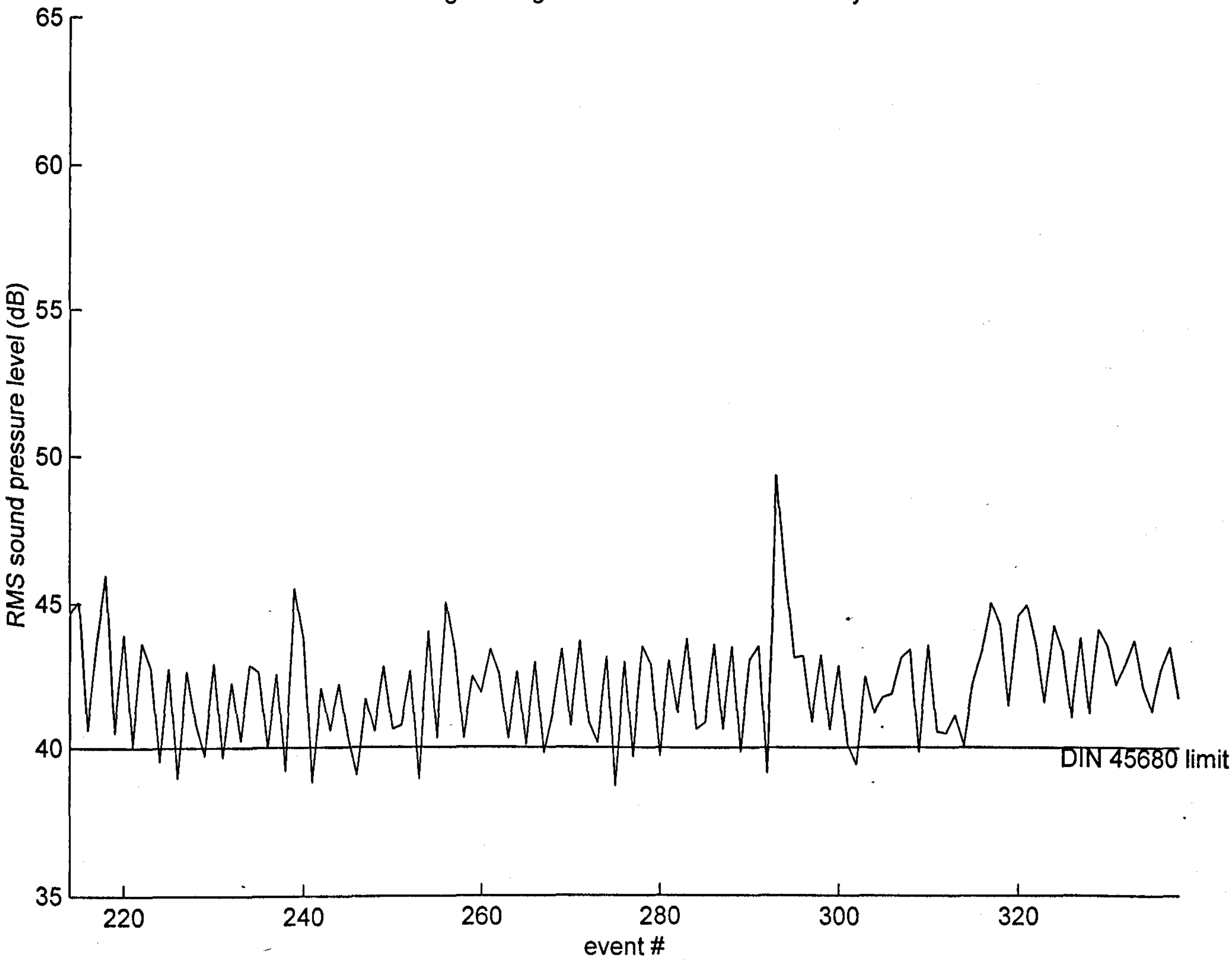


Fig. 7.22 - filtered east-west vibration of suspended bedroom floor at Location B1; shows a sharp increase in amplitude after 4 seconds

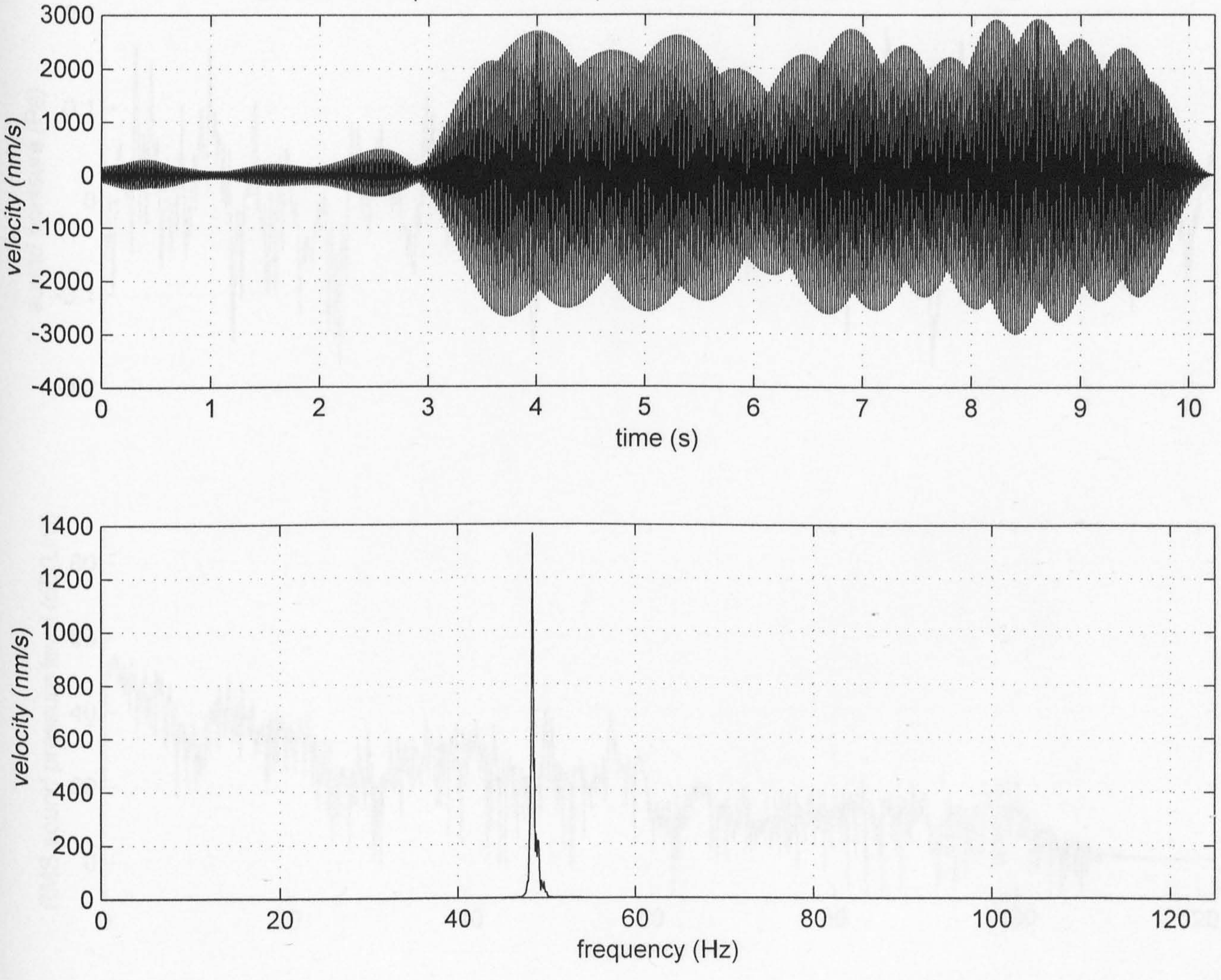


Fig. 7.23 - microphone channel output recorded at the same time as Fig. 7.22

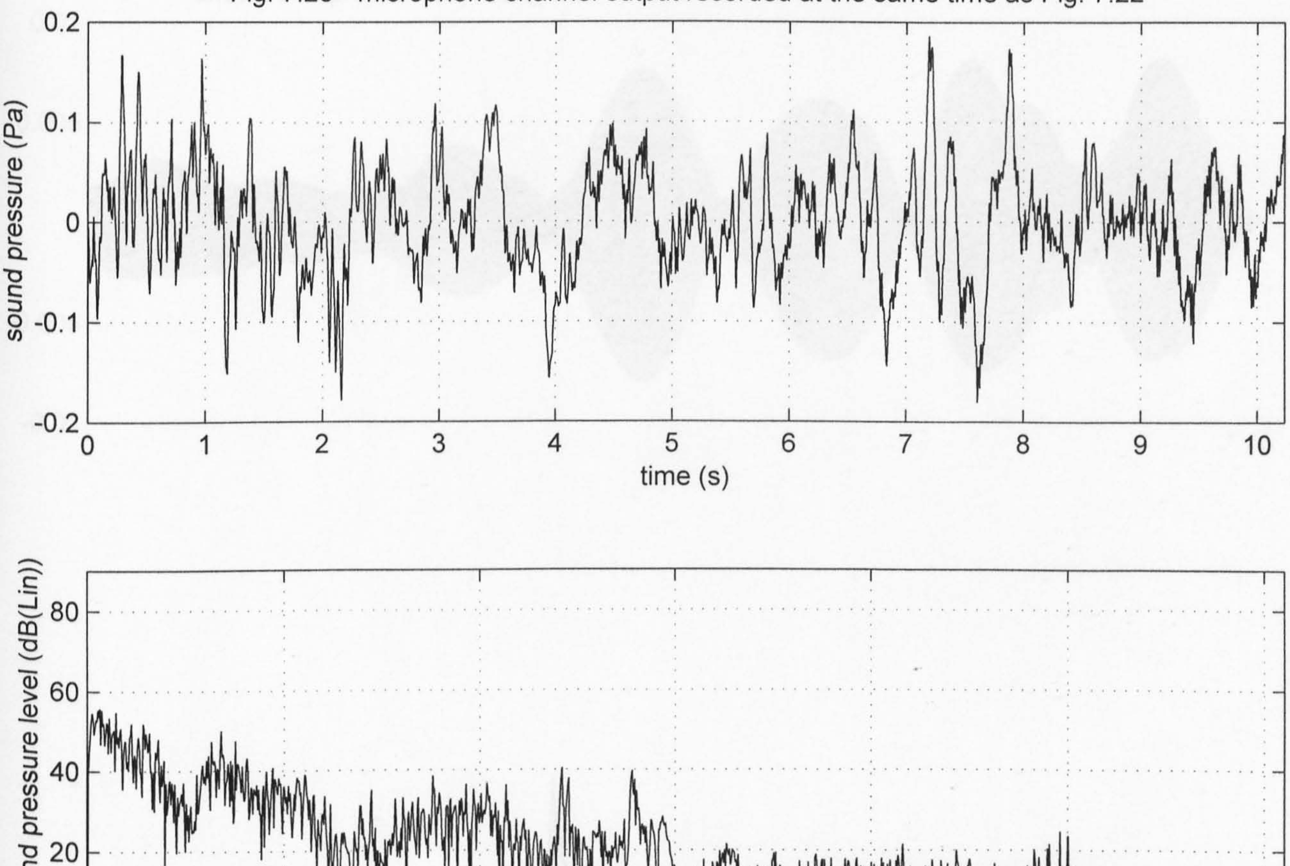


Fig. 7.24 - microphone channel output from Fig. 7.23 after application of a twelfth-octave bandpass filter; shows sharp onset of beating after 4 seconds

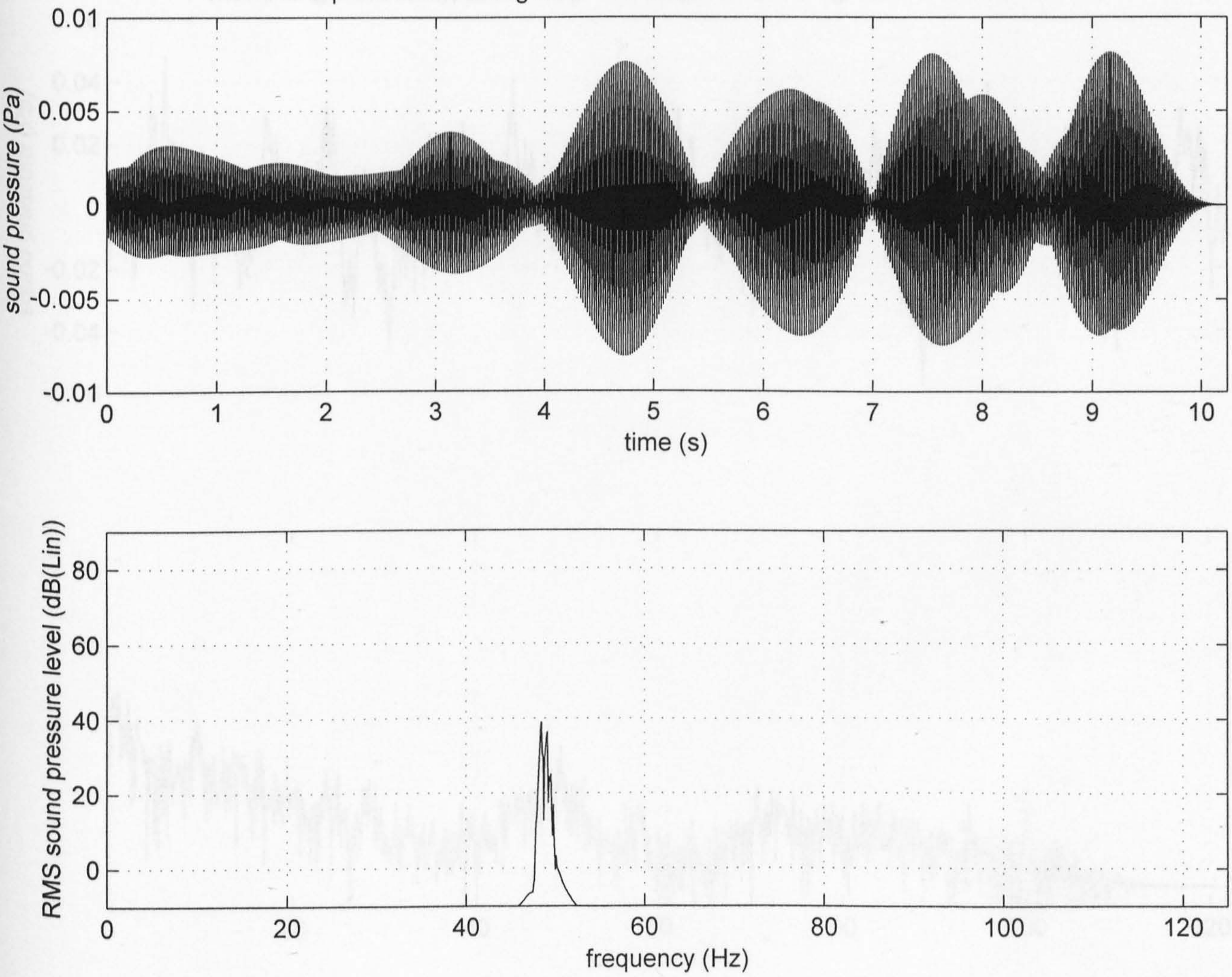


Fig. 7.25 - a typical microphone channel recording from Location B3

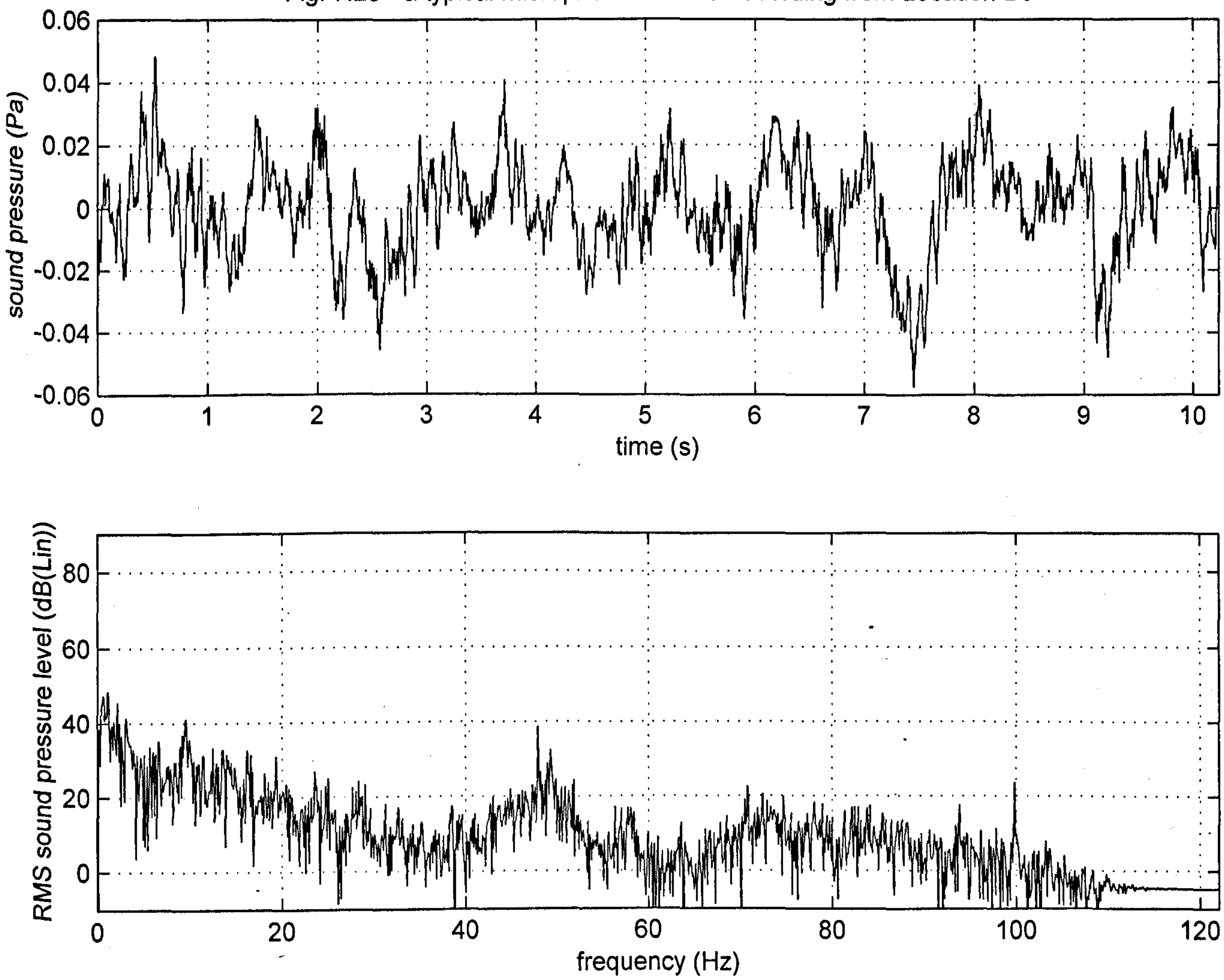


Fig. 7.26 - filtered microphone recording from Location B3, displaying strong beating

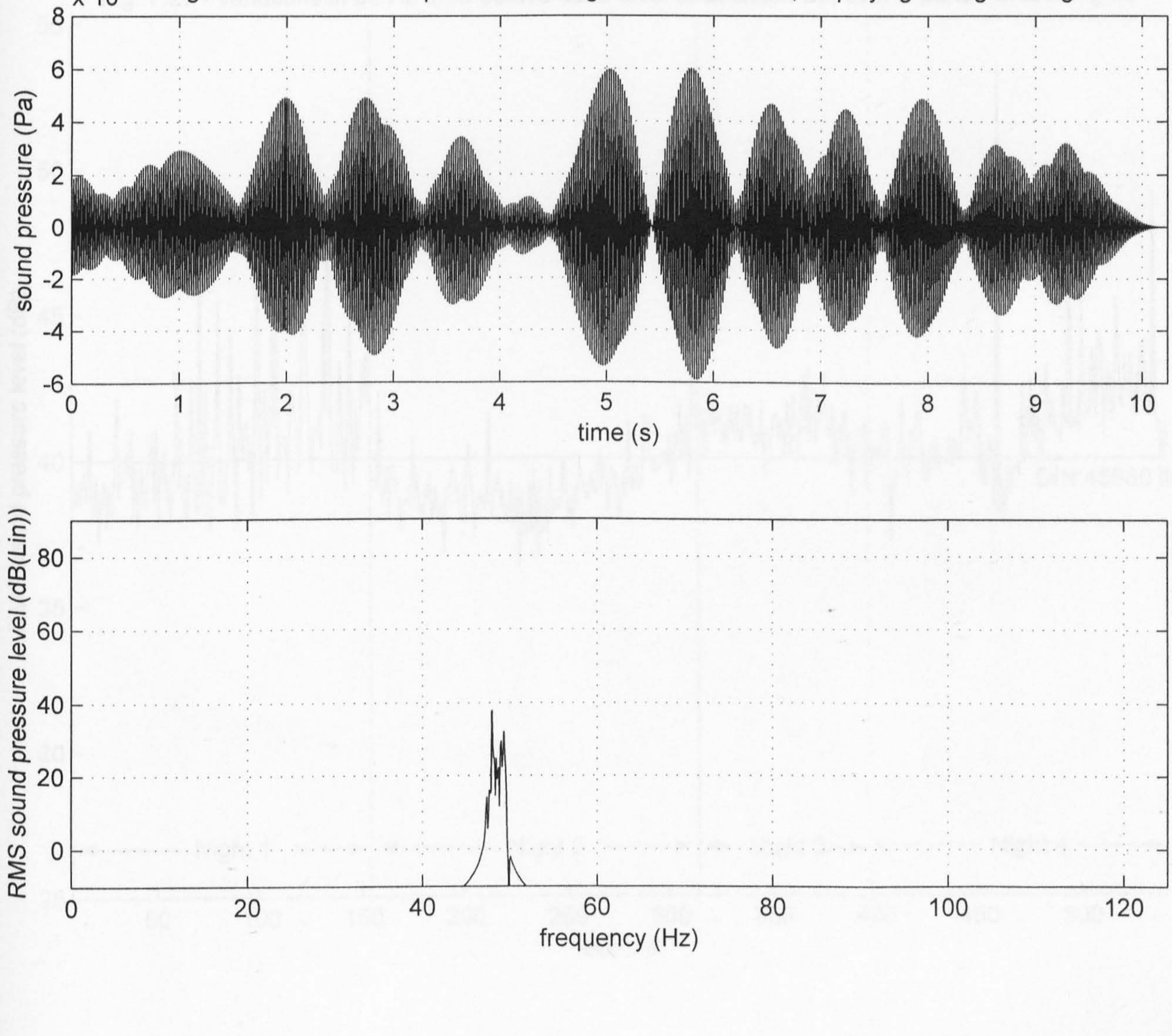


Fig. 7.27 - variations in 50 Hz third-octave band level at Location B3, over a period of four nights

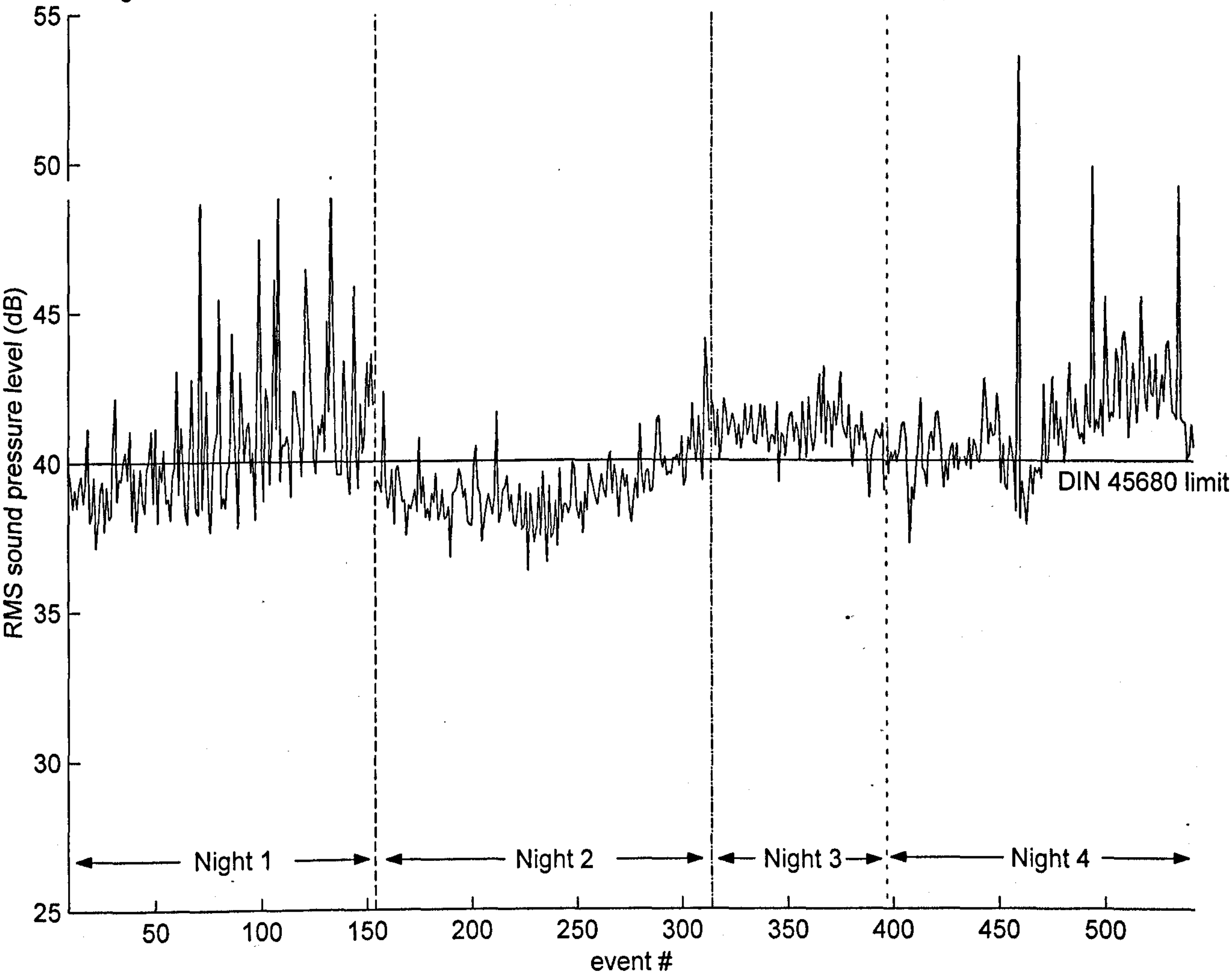


Fig. 7.28 - microphone recording taken at Location B3 during a windy period

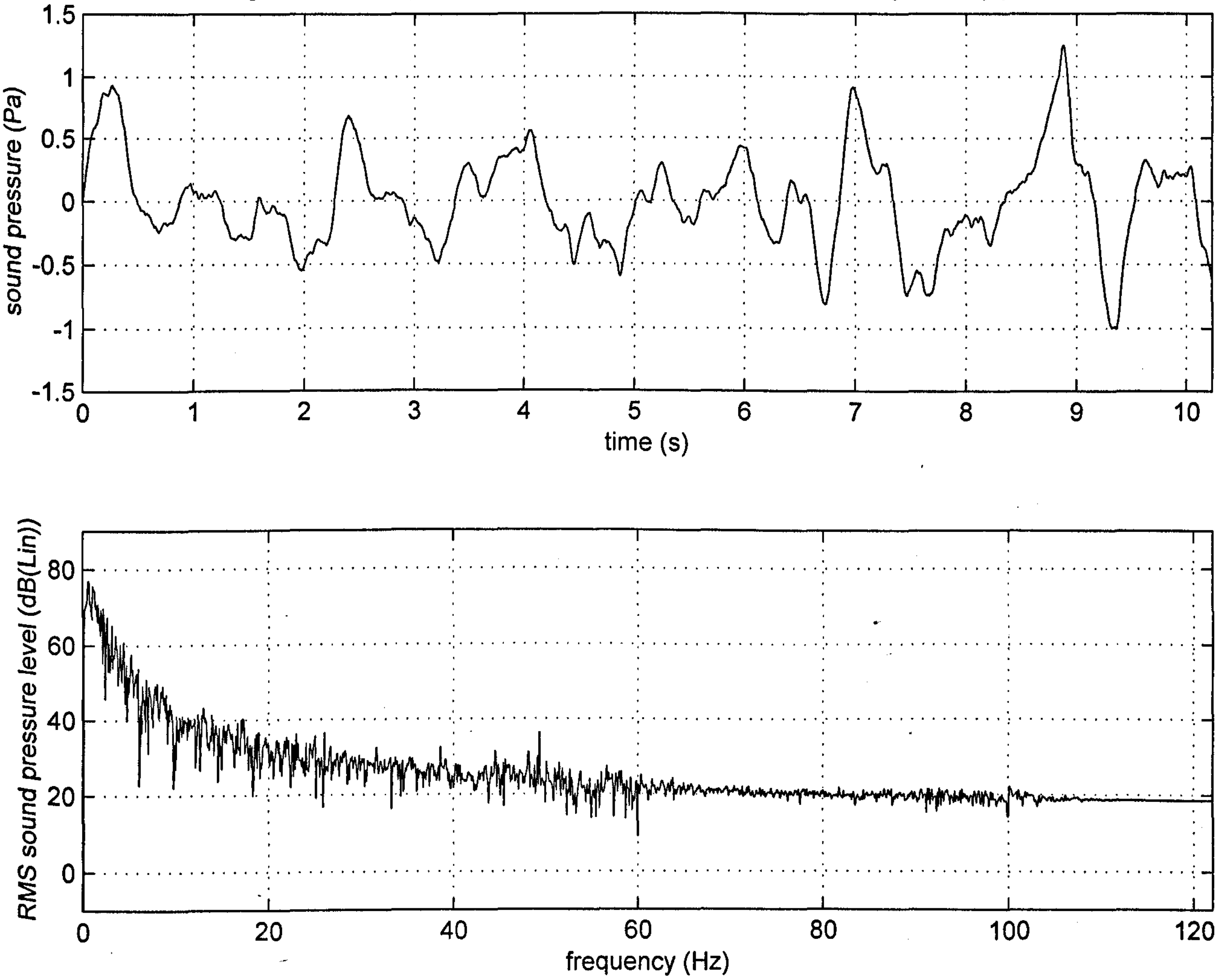


Fig. 7.29 - filtered microphone recording from Location B3, displaying strong beating with a slower beat frequency than Fig. 7.26

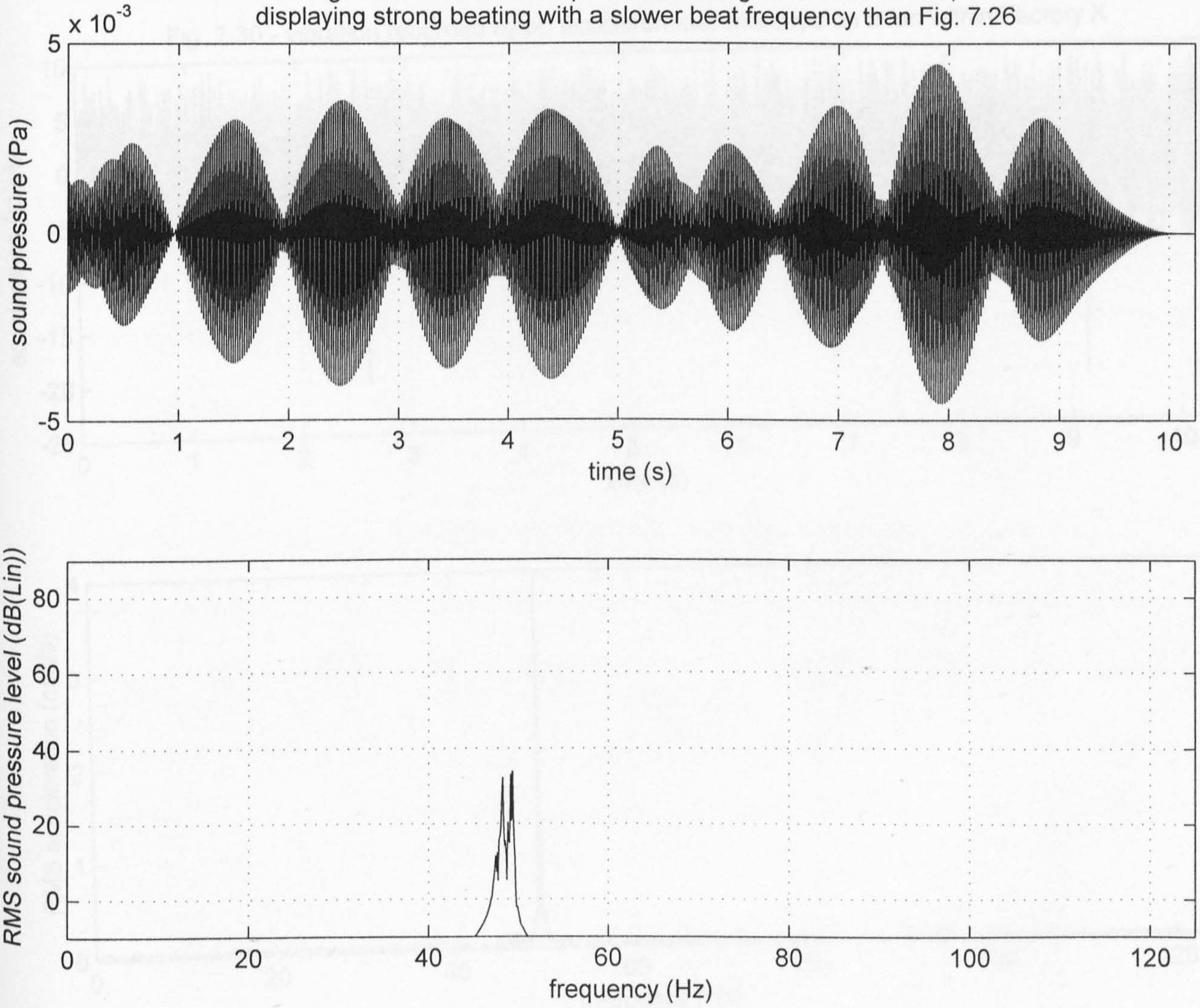
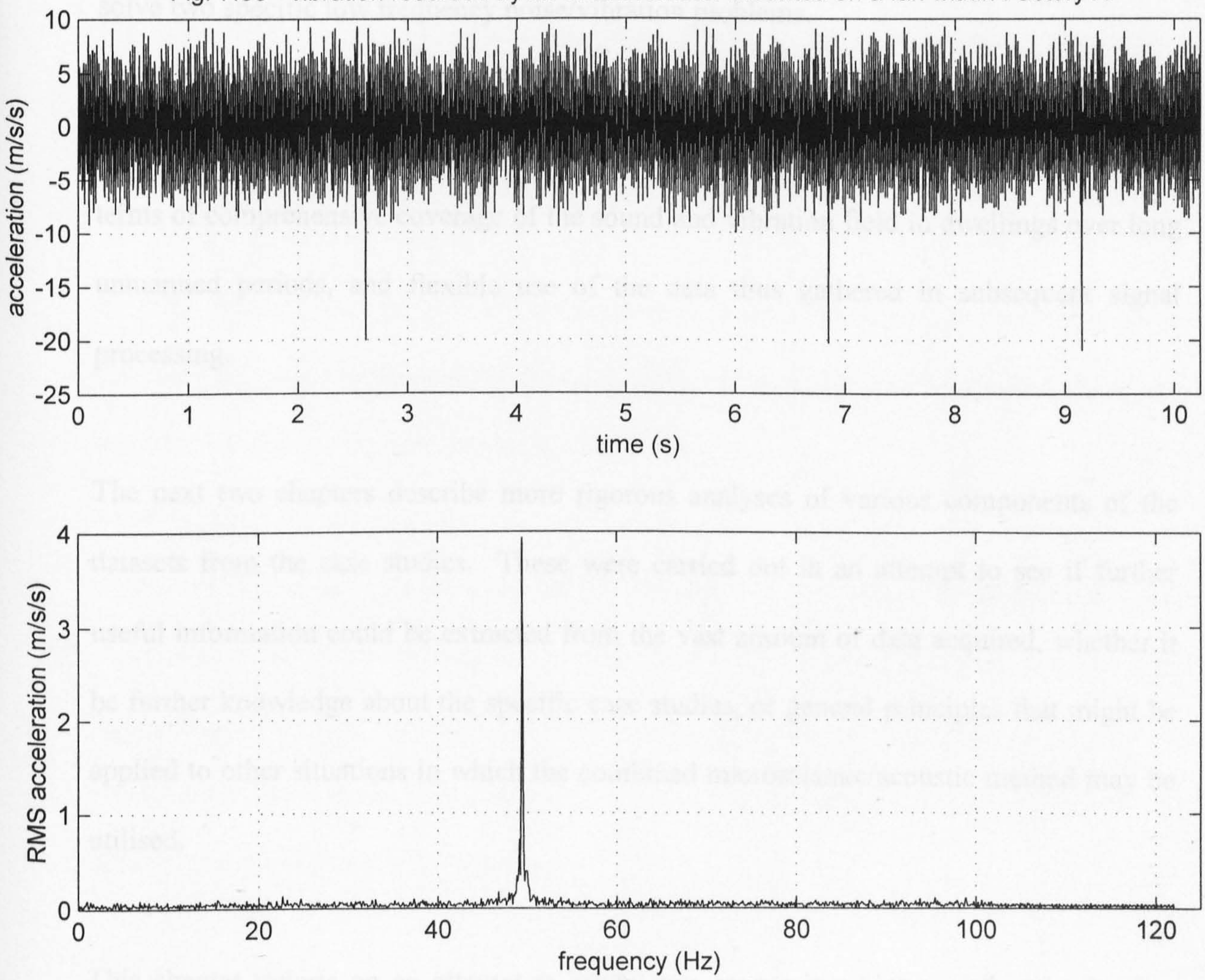


Fig. 7.30 - vibration recorded by an accelerometer mounted on a fan within Factory X



8 APPLICATION OF FINITE ELEMENT METHOD MODELLING TO THE RECORDED DATA

Chapters 6 and 7 described two case studies in which the combined microseismic/acoustic measurement technique was utilised in the context of attempting to solve two specific low frequency noise/vibration problems.

The case studies demonstrated some of the advantages of the integrated technique, in terms of comprehensive coverage of the sound and vibration field in dwellings over long unmanned periods, and flexible use of the data thus gathered in subsequent signal processing.

The next two chapters describe more rigorous analyses of various components of the datasets from the case studies. These were carried out in an attempt to see if further useful information could be extracted from the vast amount of data acquired, whether it be further knowledge about the specific case studies, or general principles that might be applied to other situations in which the combined microseismic/acoustic method may be utilised.

This chapter reports on an attempt to model two rooms in which sound and vibration monitoring had been carried out during the case studies, using a Finite Element Method (FEM). It builds on some of the signal processing tools described in Chapter 5, and draws on the acoustic theory detailed in Chapter 2.

8.1 AIRBORNE SOUND PROPAGATION MECHANISM

During the earlier case studies, intuitive assumptions were made about the propagation behaviour of features of the recorded sound and vibration spectra. Measured tones in a room were classified as airborne, groundborne, internal or externally-sourced, based on the relative levels of vibration at the tonal frequency in a bedroom window pane, suspended bedroom floor, ground floor slab and the sound pressure level within the bedroom. This procedure is detailed in Section 5.3, and illustrated in Figure 5.8.

A Finite Element Method was used to try to validate these semi-quantitative assumptions. This is only possible because of the wide array of data that were collected using the combined acoustic/microseismic technique.

Figure 8.1 shows a sketch of a simple mechanism that was placed under scrutiny. An external pressure wave incident on the façade of a house sets a bedroom window into forced vibration. The window's displacement is expected in profile to follow a half-sine wave pattern, with nodal lines at the edges. This may be assumed to be the case in two dimensions in the plane of the window.

The window pane then acts as a piston, radiating sound energy into the air volume within the room. The measured sound pressure level at a microphone within the room results from the in-and-out motion of the window.

Given the wide array of data, it may be possible to confirm this as the primary mechanism by which sound energy enters the room by modelling the acoustic system using a Finite Element Method (FEM). A response function for window-to-air vibration may be calculated, and applied to the measured vibration levels in the window to give a predicted sound pressure level at the position of the microphone. This may be compared with the measured sound pressure level at the same position, and good agreement can be taken to indicate that excitation of the room volume is predominantly by the mechanism modelled i.e. by transmission from outside through the window.

In practice, the window may not act as shown in Figure 8.1. Its behaviour will depend on the frequency of an incoming wave, as this will determine whether the panel responds to the excitation in modal patterns, whether it is mass-controlled or stiffness-controlled (see Section 2.4).

For the purpose of this modelling we need not be greatly concerned with how the window is behaving (i.e. why it displays the vibration spectrum that it does), as we are primarily interested in simply determining the response function between that vibration spectrum and the microphone sound pressure level.

However, the potential for resonant behaviour was pertinent to the original choice of accelerometer position, as if it had been placed at a nodal point for a particular window mode (see Section 2.4) then the measured vibration levels in the window would have underestimated the amount of energy entering the room at the corresponding frequency. This would have led to an under-prediction of the measured sound pressure level at that frequency. The exact choice of accelerometer position is discussed later.

8.2 FEM MODELLING USING SYSNOISE

A computer package called SYSNOISE was used to FEM model the system described above.

Firstly, a program called PATRAN was utilised to create a three-dimensional mesh model of a room whose dimensions matched a real room chosen from the case studies. The model room was split into elements (as shown in Figures 8.2 and 8.3), whose size (and therefore the number of elements selected in each dimension) was determined by the maximum frequency under consideration. According to Astley (1998), at least six elements are required to correctly represent the pressure over a wavelength. The modelling was carried out for a frequency range of 0-125 Hz, so the smallest wavelength of 2.72 m gave an upper limit for element size of 0.45 m. In practice, this led to between 4 and 8 elements being chosen for each axis of the model room.

The mesh model was imported into SYSNOISE, where the room modes were calculated based on parameters such as the dimensions of the room and standard air physical characteristics.

The outer boundaries (walls, floor and ceiling) of the room model were each assigned damping coefficients (admittance), depending on whether the corresponding surface in the field was of lightweight or heavyweight construction. Bies and Hansen (1988) give typical values for absorption coefficients, α, of various constructions. Maluski and Gibbs (1999) used frequency-invariant values of α=0.02 for a masonry wall, α=0.15 for a lightweight partition.

The SYSNOISE package works on the basis of input values for admittance, Y, which were calculated from the absorption coefficient α using the following formulae:

$$Y = 1/Z$$

[Formula 8.1]

$$Z = \frac{[1 + \sqrt{(1-\alpha)}]}{[1 - \sqrt{(1-\alpha)}]}\rho c$$

[Formula 8.2]

where Z is the normal impedance at normal incidence, ρ is the air density and c is the velocity of sound in air. This assumes that the (complex) admittance is dominated by its real component and is positive and frequency invariant, which is a reasonable assumption at low frequencies (Beranek, 1940).

A window was then modelled as a vibrating rectangular piston, whose dimensions were chosen to approximately match the size, shape and position of the actual window for which vibration measurements were available. A panel is limited to an integral number of element lengths or widths.

Figures 8.2 and 8.3 show the room meshes used in SYSNOISE to model the monitoring rooms at Locations A1 and B1 respectively. In each figure a vibrating panel is shown (in black) that represents the window of the corresponding real room.

A constant velocity was assigned across the whole surface of the vibrating panel, and across a frequency range 0.1-125 Hz. The latter was chosen to match the frequency range of the Vibrosound data as measured in the case studies. The former is a simplification of the more likely pattern of window displacement as described earlier (a half-sine wave fixed at the edges); the consequences of this for the accuracy of the model will be discussed later.

A FEM analysis was then processed in SYSNOISE for the chosen room/window configuration, as a result of which the sound pressure level at a specified field point within the model room could be determined. A field point was chosen to match the microphone position within the real room under consideration, and a response function determined between the (constant) vibration level in the window panel and the sound pressure level at the field point.

The response function was then exported from SYSNOISE into the Mathematics software package *Matlab*, in the format $20*\log_{10}(P/v)$ where (P/v) is the ratio of air pressure to panel velocity (in units of $Pa.(m/s)^{-1}$) as a function of frequency. Figure 8.4 shows an example of a SYSNOISE response function.

By applying the response function to the measured vibration levels in the window pane of the modelled room, a predicted sound pressure level could be calculated and compared with the actual sound pressure levels recorded simultaneously by the Vibrosound, at the chosen microphone position within the room.

8.3 ASSIGNING DAMPING VALUES TO THE FEM MODEL

Finite element modelling of rooms at low frequencies is a process that has been well validated (Maluski and Gibbs, 2000; Pietrzyk, 1997). The major source of uncertainty lies in assigning damping values, but once the correct damping has been incorporated into the model reasonably accurate predictions are possible. Theoretically, zero damping gives rise to infinitely high modal peaks (in practice the peaks are sharp but finite, due to processing limitations of the computer). Conversely, applying an absorption coefficient that is too high has the effect of flattening out the modal peaks, as all the energy is absorbed so standing waves cannot be set up (this is known as the anechoic condition).

The approach adopted by Maluski and Gibbs (1999) is to adjust damping in the FEM model until agreement is obtained with a measured transfer function. This procedure has been applied to results from the case studies. However, it must be borne in mind that the sound pressure spectrum in the room is the sum of sound pressure from both internal and external sources, and therefore will give at best a noisy transfer function. Nevertheless, it has been shown that applying realistic damping values to the walls resulted in a reasonable agreement in the signature (spectral shape) of the measured and predicted transfer functions.

An alternative method of increasing the level of absorption of sound energy in a model room is to introduce furniture into the model. However, Maluski and Gibbs (2001) developed an FEM model to investigate the effects of furniture on the low frequency sound field in dwellings, and found that the effect of furniture may be disregarded at frequencies below 100 Hz. The introduction of furniture into the model was therefore not attempted in this study.

8.4 RESULTS OF FEM MODELLING

FEM modelling of the relationship between vibrations and sound pressure level in a room was carried out for two different rooms, one from each of the two case studies described earlier in this thesis. The bedrooms at Locations A1 and B1 were chosen. At A1, measurements had been taken in a fairly small room in which the frequency of interest lay below the first room mode; on the other hand in Location B1 a larger room had been monitored which had fundamental room modes around the frequency of interest.

These two rooms were selected, as they represent two fundamental categories into which low frequency noise problems may be separated. In one respect the former is a simpler case to solve when trying to determine the character of a low frequency noise that is propagating into a room from an external source. On the other hand it may be that in the latter case it is the interaction between the external sound and a room mode that is causing or exacerbating the nuisance. Of course, different rooms within a single house may fall into each category.

8.4.1 Location A1 - Window-Room Interaction

Figure 8.5 shows a sketch plan of the bedroom at Location A1 (from Case Study A, Chapter 6). Table 8.1 shows the acoustic modes for this room up to 150 Hz.

The closest match achieved between predicted and measured sound pressure level curves, based on the window vibration data from a single event, is shown in Figure 8.6. This is representative of the data from Location A1; other events that were subject to the same modelling process yielded similar results for similar parameters.

To achieve this match, two outer walls were assigned absorption coefficients of α=0.02, whilst two internal walls, the wooden floor and plaster ceiling were given coefficients of α=0.3. These are within sensible limits for the respective material types.

Across the frequency range 20-100 Hz, the 'signatures' of the two curves match reasonably well i.e. the peaks and dips occur at approximately the same frequencies (49 Hz fundamental mode, 77 Hz, 88 Hz), and with the same gradients. Note that peaks in the spectra at around 38 Hz and 12.5 Hz are due to external signal, and not room modes.

This suggests that the room modes were accurately modelled and the absorption coefficients applied to the surfaces of the model were fairly representative of those in the real room.

The matching signatures are consistent with, or at least do not contradict, the mechanism outlined in Figure 8.1 of sound entering the room from outside via the window pane acting as a piston.

The match was not perfect, however. The model under-predicted the measured sound pressure levels by ~5-10 dB across the frequency range 20-100 Hz. Under-prediction was slightly greater at 60 Hz (~15 dB). A discussion of possible reasons for the difference in absolute level follows later.

Note that the under-prediction increases below 20 Hz. In particular, there is a sharp peak in the measured spectrum at 12.5 Hz, whose sound pressure level is under-predicted by the model by around 50 dB.

The 12.5 Hz tone should be familiar from Chapter 6, where its absence from the window vibration spectrum and its unidentified propagation path were previously noted. FEM modelling has confirmed the result obtained in Chapter 6 that a mechanism other than window vibration is responsible for propagating 'acoustic' energy at 12.5 Hz into the room.

(The apparent large over-prediction below ~5 Hz is an artefact of the data processing.)

A sensitivity analysis was conducted in which the position of the microphone and window were varied. The results were shown to be insensitive to variations in microphone position within about 10cm as might be expected from the wavelengths involved. On the other hand, variations of up to 20dB were observed when the distance between the microphone and window was varied.

Residual Under-Prediction:

The 5-10 dB discrepancy between measured and predicted sound pressure levels may be explained by several factors.

The choice of accelerometer position may not have been representative of the 'average vibration level' position for the window. SYSNOISE assigned an equal vibration level across the entire window pane, whereas the displacement under forced vibration is more likely to follow a half-sine wave, as explained earlier. The area under a half-sine wave (of width pi radians) is equal to 2 radians; a planar displacement of height 2/pi, width pi radians will give the same overall volume velocity. The 'mean' position along the more realistic half-sine wave displacement occurs where the height equals 2/pi i.e.

$$\sin \omega = 2/\pi$$

This gives

$$\omega = 0.69 \text{ rad}$$

which is 22% as a proportion of the width of the window (pi radians).

The same result is arrived at by a three-dimensional consideration of the window. Thus an accelerometer placed somewhere between 1/5 and 1/4 of the way across the length and width of the window, is a suitable position for measuring the average vibration levels of the window as a whole.

In practice, the accelerometer position chosen was approximately 1/5 of the way across the windowpane in both dimensions. This also minimised the chance of the transducer being placed at a nodal point of the window. However, slight variations in accelerometer position will affect the measured vibration levels for a constant level of excitation.

Differences between the actual and modelled window panel size and shape may also account for differences between the measured sound pressure level, and that predicted on the basis of the observed window vibration levels. Small variations in window dimensions were not possible within SYSNOISE without restructuring the entire model using a more highly discretised mesh. This was prohibitively costly in terms of memory usage and computing time.

Another explanation for the residual under-prediction of the model is the potential existence of alternative transmission paths.

For instance, some of the acoustic energy entering the room may be passing through the wall surrounding the window (facing the source). An approximate calculation may be used to determine the ratio of energy flows through the window and surrounding wall (assuming mass-law behaviour):

For a given frequency, the amount of acoustic energy passing through a panel is inversely proportional to the square of the surface mass of the panel, and directly proportional to its surface area:

Typical surface mass of glass window:	15 kg/m^2
Typical surface mass of outer wall:	380 kg/m^2

Ratio of wall surface mass/window surface mass:	25
Ratio of wall surface area/window surface area:	8

Ratio of acoustic energy through window/wall:	$(25)^2/8 = 78$
In dB:	$10*\log_{10}78 = 19$ dB

(Material properties were taken from Sharland, 1998.)

This suggests that the window is the primary route through which acoustic energy passes through the façade wall, confirming it as the 'path of least resistance'. However, the assumption of mass-controlled behaviour is questionable at the frequency range of interest. This depends on the first structural modes of the window and wall (see Section 2.4), which are not known with certainty as they depend on many parameters including panel thickness, material properties, edge conditions (clamped or simply supported) and whether the whole façade of the house acts as a single unit in response to the incident low frequency pressure waves, or whether internal boundaries cause it to act as several individual plates.

Furthermore, some energy may also be entering through the roof cavity/ceiling. This and other potential propagation paths have not been considered in detail.

8.4.2 Location A1 - Floor-Room Interaction

The aim of the primary FEM modelling at Location A1 was to confirm that sound energy measured in the bedroom resulted from external airborne sound propagating through the window. This was achieved to a reasonable degree of success, although a number of other possible propagation paths and potential errors in the model were identified.

The Vibrosound datalogger also recorded vibration levels of the first floor simultaneously to the sound pressure level data. This allowed a second application of FEM modelling to be carried out, in which the suspended wooden floor of the room was treated as a simple vibrating panel instead of the window. This led to a second predicted sound pressure level curve, based on the vertical component of the first floor seismometer data, that could also be compared with the measured microphone spectrum.

This model involved similar errors to the previous window model, regarding whether or not the chosen seismometer position on the floor provided representative (mean) values for the floor vibration levels. It did not take into account the effects of beds and other furniture situated on the floor, on the distribution of vibration levels detected in the floor. Nor did it consider that joists under the floorboards may be acting to discretise the floor.

Figure 8.7 shows a typical result obtained using the vibrating floor model, based on the same event as shown in Figure 8.6.

In terms of both signature and absolute level, the match between predicted and measured spectra is worse than for the spectra predicted on the basis of the window vibrations. Measured sound pressure levels are under-predicted by ~15-30 dB.

Applying a range of realistic parameters to the modelling did not yield as close a match between predicted and measured sound pressure levels, based on the floor vibration model, as was achieved based on the window pane vibrations. This finding was shown to be repeatable throughout a number of the recorded events.

This suggests that vertical vibration of the suspended wooden floor is a less probable source of the acoustic energy entering the room, than vibrations in the window pane.

There is, however, some similarity between the shapes of the predicted and measured curves; this may be explained as the vertical floor vibration resulting from excitation by the air in the room.

It should be noted that the levels of vertical vibration at 12.5 Hz in the upper floor at Location A1 are not sufficiently high to be a cause of the airborne tone at that frequency. The propagation mechanism for the 12.5 Hz fluctuations observed in Case Study A therefore remains unexplained.

8.4.3 Location A1 - Summary

A reasonably good match was achieved for the bedroom of Location A1 between the signatures of the predicted sound pressure level curve, based on FEM modelling of window vibration levels, and the measured SPL curve, in the frequency range 20-100 Hz.

There was an under-prediction of 5-10 dB in absolute level, which may have been due to errors in model parameters or propagation paths other than the window contributing to the sound field in the room.

Nevertheless, external airborne sound waves exciting the window pane into piston-like behaviour was considered to be the most likely mechanism for propagation of low frequency sound into the room. This includes the prominent tone at 38 Hz, identified in Chapter 6 as a source of annoyance to the residents of the house.

This mechanism did not, however, explain the presence of a strong tone at 12.5 Hz associated with pulsing in the time domain.

Vertical vibration of the bedroom's suspended wooden floor was shown to be a less probable cause of low frequency noise in the room. It is more likely that low frequency sound in the air was acting on the floor, exciting it into motion, although this was not modelled.

8.4.4 Location B1

Figure 8.8 shows a sketch plan of the bedroom at Location B1 (from Case Study B, Chapter 7). Table 8.2 shows the acoustic modes for this room up to 150 Hz.

The sound and vibration data from Location B1 were subject to a similar FEM modelling process with sensitivity analysis, as was applied at Location A1.

However, it was not possible to achieve a very satisfactory match between the predicted and measured spectra across the whole frequency range of interest (0-100 Hz), despite the use of a wide range of values for the various model parameters.

The closest match achieved between predicted and measured sound pressure levels, based on the window-mounted accelerometer data from a typical event record, is shown in Figure 8.9.

For the model that gave rise to Figure 8.9, one external and one party wall were considered to be of heavyweight construction and were assigned absorption coefficients, α=0.02. Two internal walls and the floor and ceiling were given suitable damping coefficients for lightweight constructions, α=0.2.

There was a significant under-prediction of ~30 dB at around 25 Hz, and an over-prediction at 42 Hz of ~10 dB.

Figure 8.10 shows a predicted sound pressure level curve based on the vertical motion of the suspended floor, and the measured sound pressure level for the same event.

The signature match between the two curves in this case is even worse than for the window-based prediction model.

It may be speculated that the room is more difficult to model in this case because of the higher modal density of the room in the frequency range 0-100 Hz, compared with the smaller bedroom at Location A1.

However, the FEM modelling did yield a good match between predicted and measured sound pressure levels in a specific frequency band, which had previously been subject to scrutiny during the case study.

Two distinct tones had been detected in Location B1, at 48.5 Hz and 49.3 Hz, that were found to be giving rise to strong fluctuations in air pressure by beating together. It was established that this was responsible for the annoyance to the occupants.

An interesting result was observed by 'zooming in' on Figures 8.9 and 8.10 at the frequency range 46-52 Hz, giving rise to Figures 8.11 and 8.12.

These plots show that the sound pressure level of the sharp peak at 49.3 Hz was correctly predicted (to within 1-2 dB) by the window-based FEM model (Figure 8.11). The floor-based FEM model under-predicted the level of the 49.3 Hz tone by around 20 dB (Figure 8.12). This suggests that this tone had an external airborne source; the tone was eventually discovered to be caused by a fan located at a nearby factory.

Conversely, the sound pressure level of the 48.5 Hz peak was under-predicted by ~12 dB based on the window vibration spectrum for the event (Figure 8.11), whereas the floorboard vibration model correctly predicted the level of the tone to within < 1 dB (Figure 8.12). The peak in the floor vibration spectrum at 48.5 Hz rises ~25 dB above background vibration levels (as the floor-air response function is fairly smooth in this region).

The FEM modelling suggests that the 48.5 Hz tone detected at Location B1 was structure-borne, and emanating from a source within the house itself. In fact, it was unequivocally demonstrated to result from a refrigerator in the kitchen immediately below the bedroom.

The result demonstrated above was shown to hold for several other events in which the 48.5 Hz tone was present in the airborne sound spectrum at Location B1 i.e. events recorded whilst the fridge was 'on'.

Thus the FEM modelling of the window and floorboard vibration models were validated for a region of the sound spectra at B1 in which peaks were present whose propagation mechanism had been established in the earlier case study, and whose sources were known to be stable (at least over the length of individual event records).

Other regions of the spectra (typically broadband) were not well predicted by the model, as less was known about the source of the (typically broadband) low frequency sound, which could have been due to a random combination of internal and external sources.

It may be surmised that whenever a steady tonal source of low frequency sound (external or internal) is present throughout a period of monitoring by the integrated acoustic/microseismic technique, then Finite Element Method modelling (based on the window- or floor- vibration models respectively) will correctly predict the sound pressure level of the tone.

8.5 SUMMARY OF FINDINGS FROM FEM MODELLING

Finite Element Method modelling of the sound and vibration data recorded during two case studies was conducted based on two possible mechanisms for sound entering the rooms, namely:

- from an external source via a piston-like action in the window;
- from an internal source via a suspended wooden floor structure.

This analysis highlights one of the advantages of simultaneously recording time histories of sound and vibration levels on several channels. The results corroborated the main findings of the case studies regarding propagation paths of the key spectral components.

The results suggest that it may be possible to deduce the source and propagation path of a recorded tone by testing out the window- and floor- vibration mechanisms to look for good agreement between predicted and measured sound levels.

8.6 REFERENCES

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Sharland, I., (1998): *'Woods Practical Guide to Noise Control'*, 7th Impression, Woods of Colchester Limited.

Fig. 8.1 – cross-section through a window displaced in a half-sine wave pattern by an external incident wave; the displacement of the pane radiates sound energy into the room (displacement is exaggerated for emphasis)

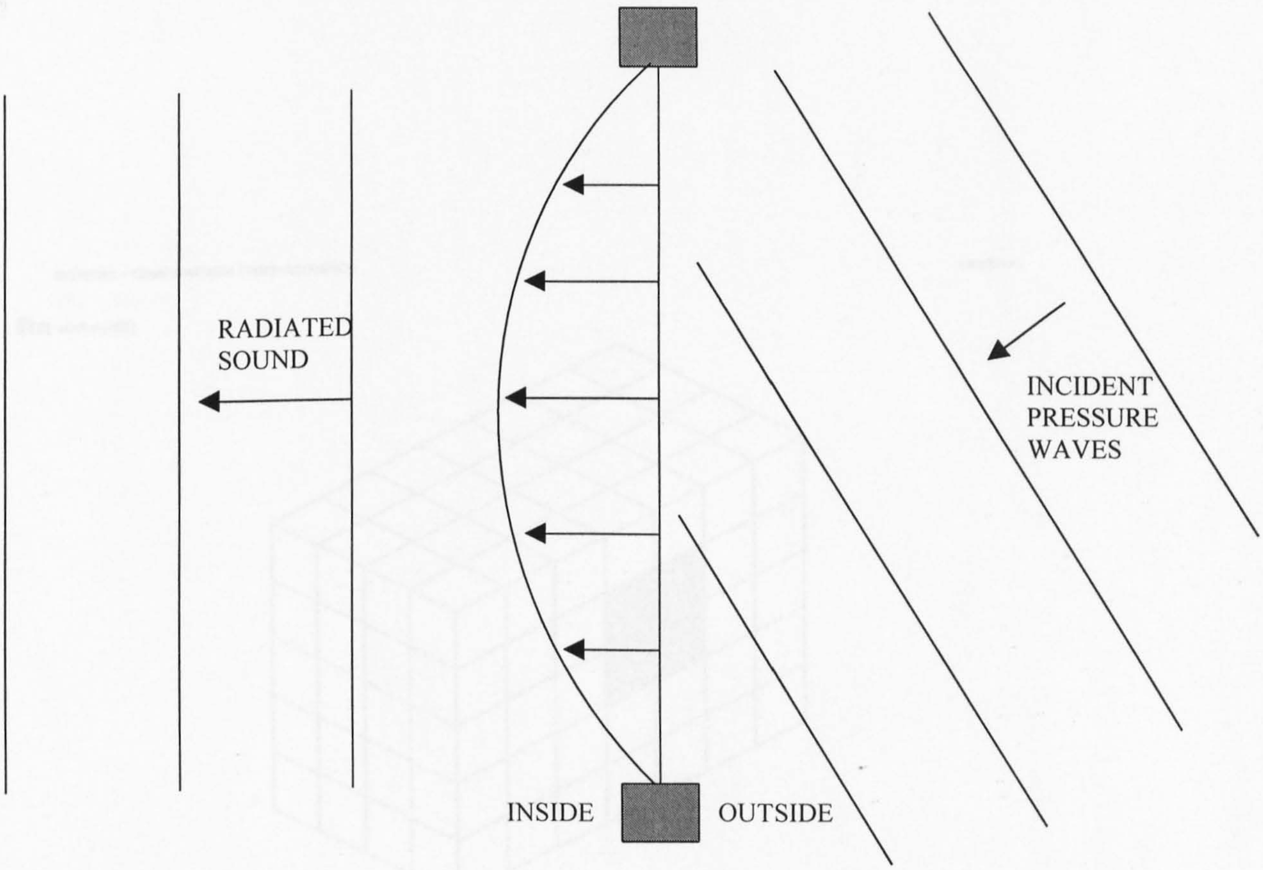


Fig. 8.2 – room mesh and window panel used in FEM modelling of the bedroom at Location A1 within SYSNOISE

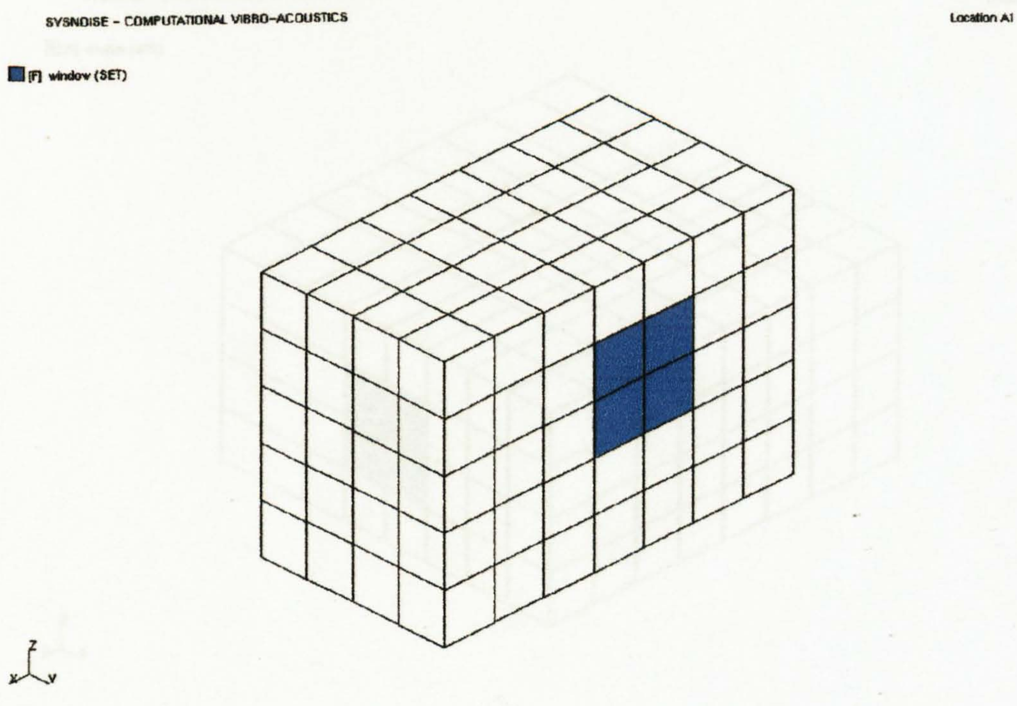


Fig. 8.3 – room mesh and window panel used in FEM modelling of the bedroom at Location B1 within SYSNOISE

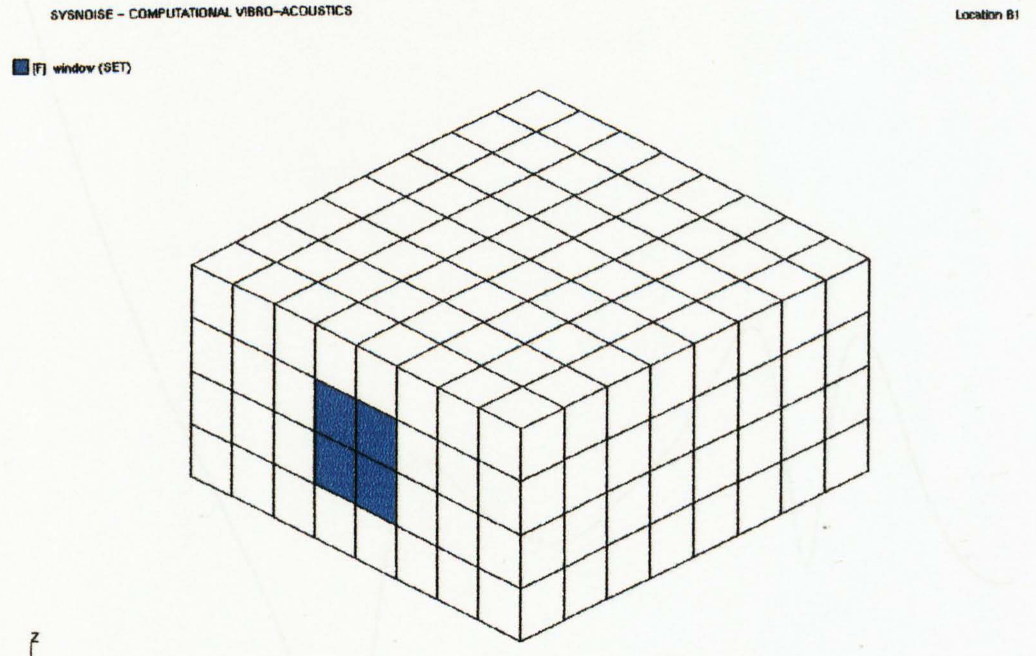


Fig. 8.4 - an example of a SYSNOISE window-air Response Function, from Location A1

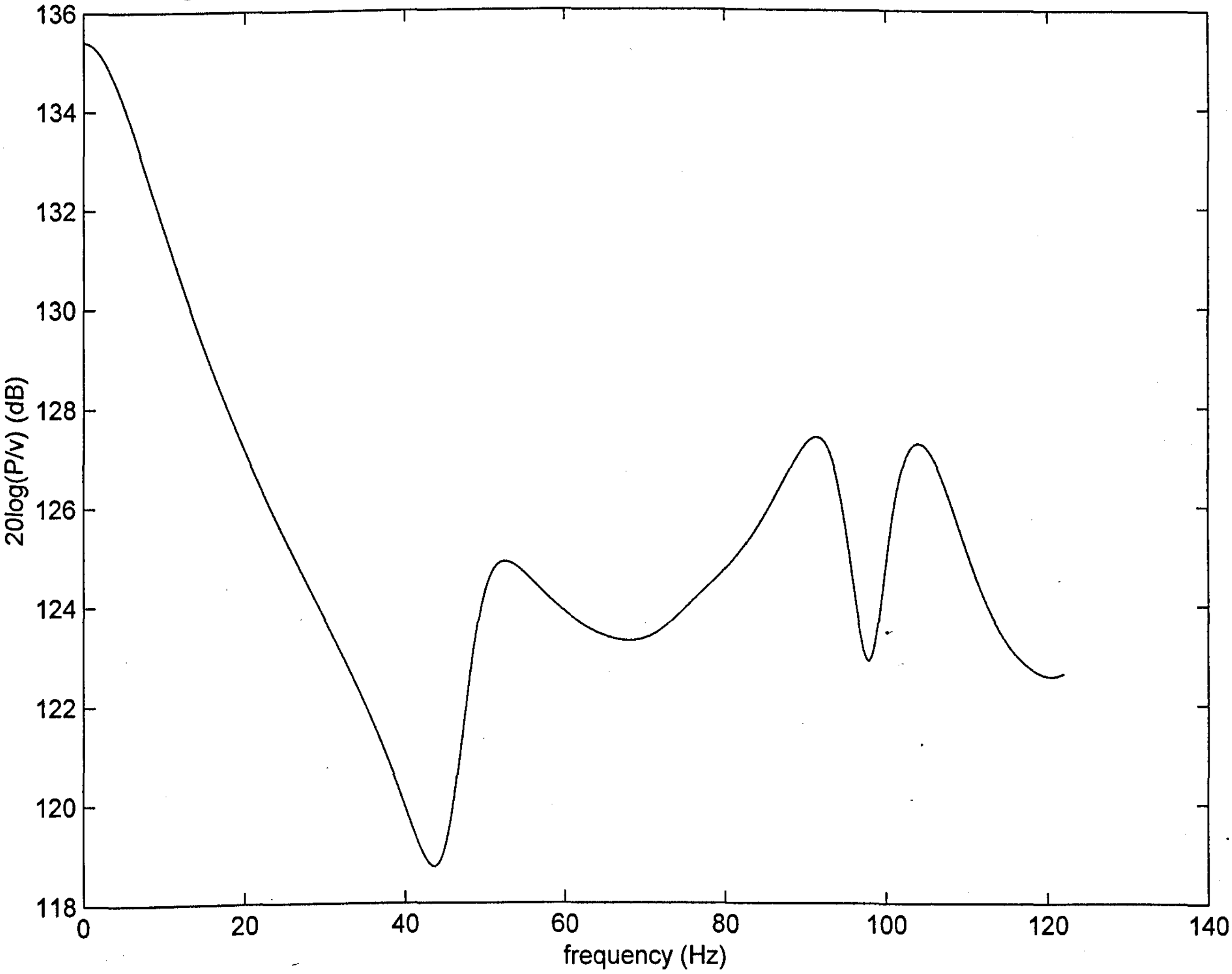


Fig. 8.5 - sketch plan of the bedroom at Location A1 modelled using FEM

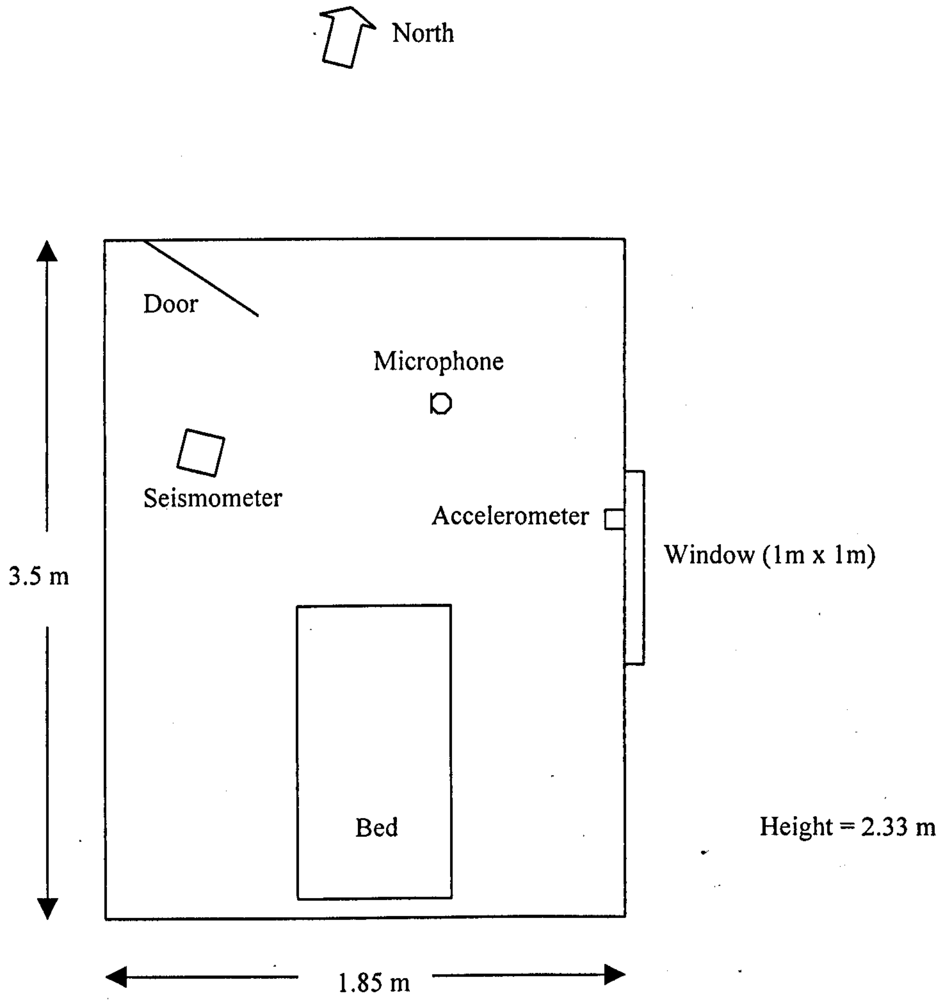


Table 8.1 – acoustic modes of the bedroom at Location A1

n_x	n_y	n_z	f (Hz)
0	0	0	0
1	0	0	49
0	0	1	73
1	0	1	88
0	1	0	92
2	0	0	97
1	1	0	104
0	1	1	118
2	0	1	122
1	1	1	127
2	1	0	134
3	0	0	146
0	0	2	146

Fig. 8.6 - FEM-predicted and measured sound pressure levels acquired using the bedroom window as a sound source at Location A1

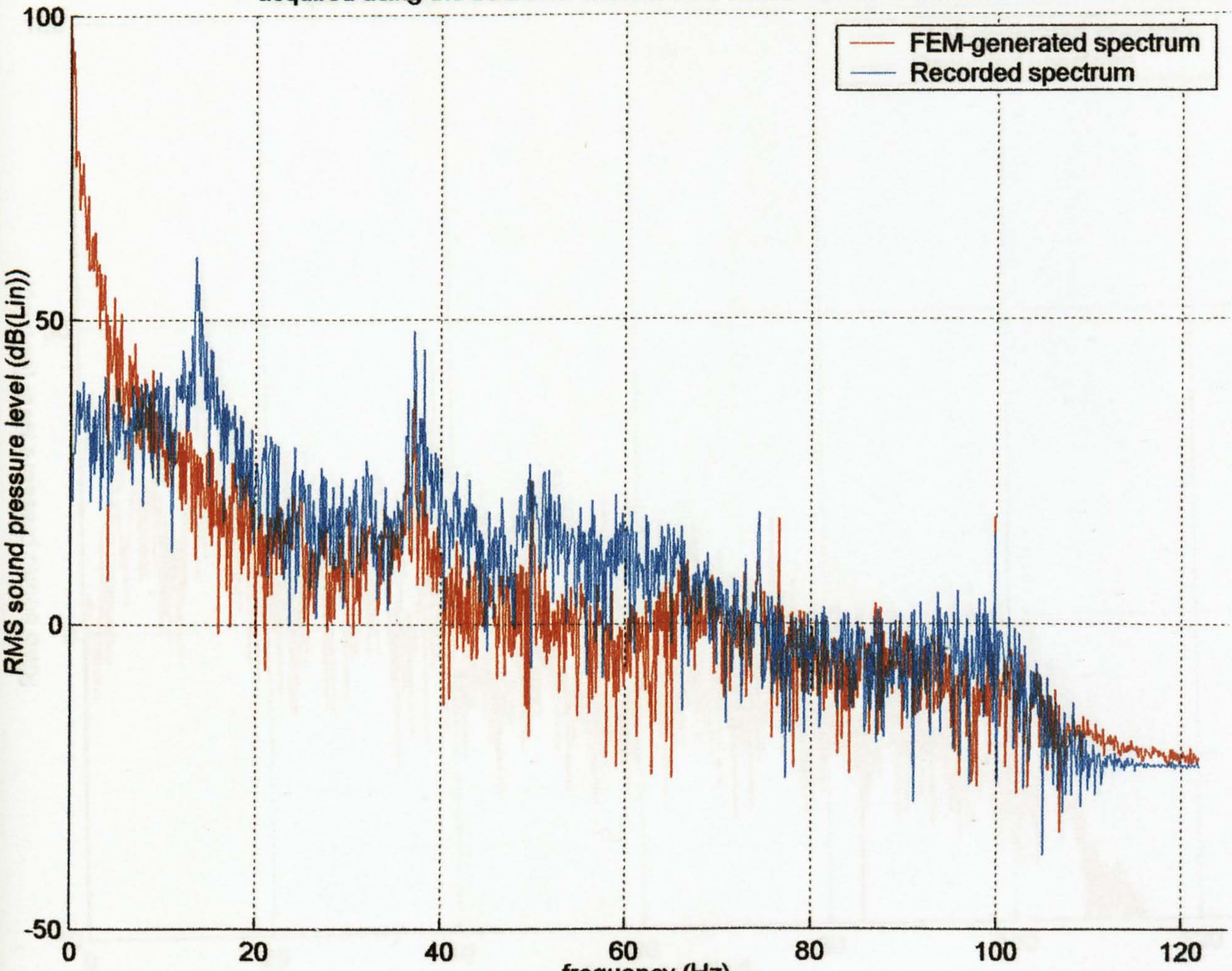


Fig. 8.7 - FEM-predicted and measured sound pressure levels acquired using the bedroom floor as a sound source at Location A1

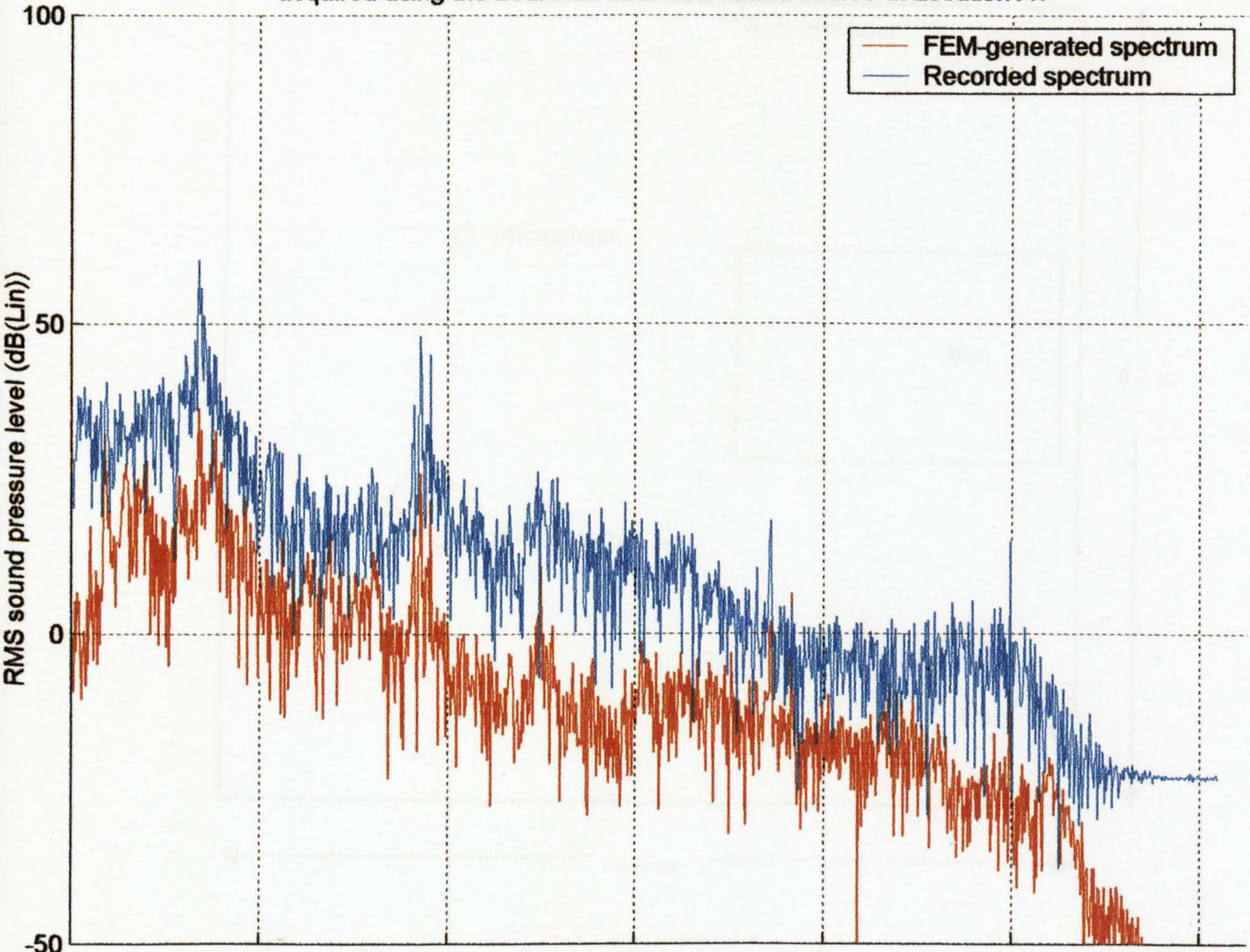


Fig. 8.8 - sketch plan of the bedroom at Location B1 modelled using FEM

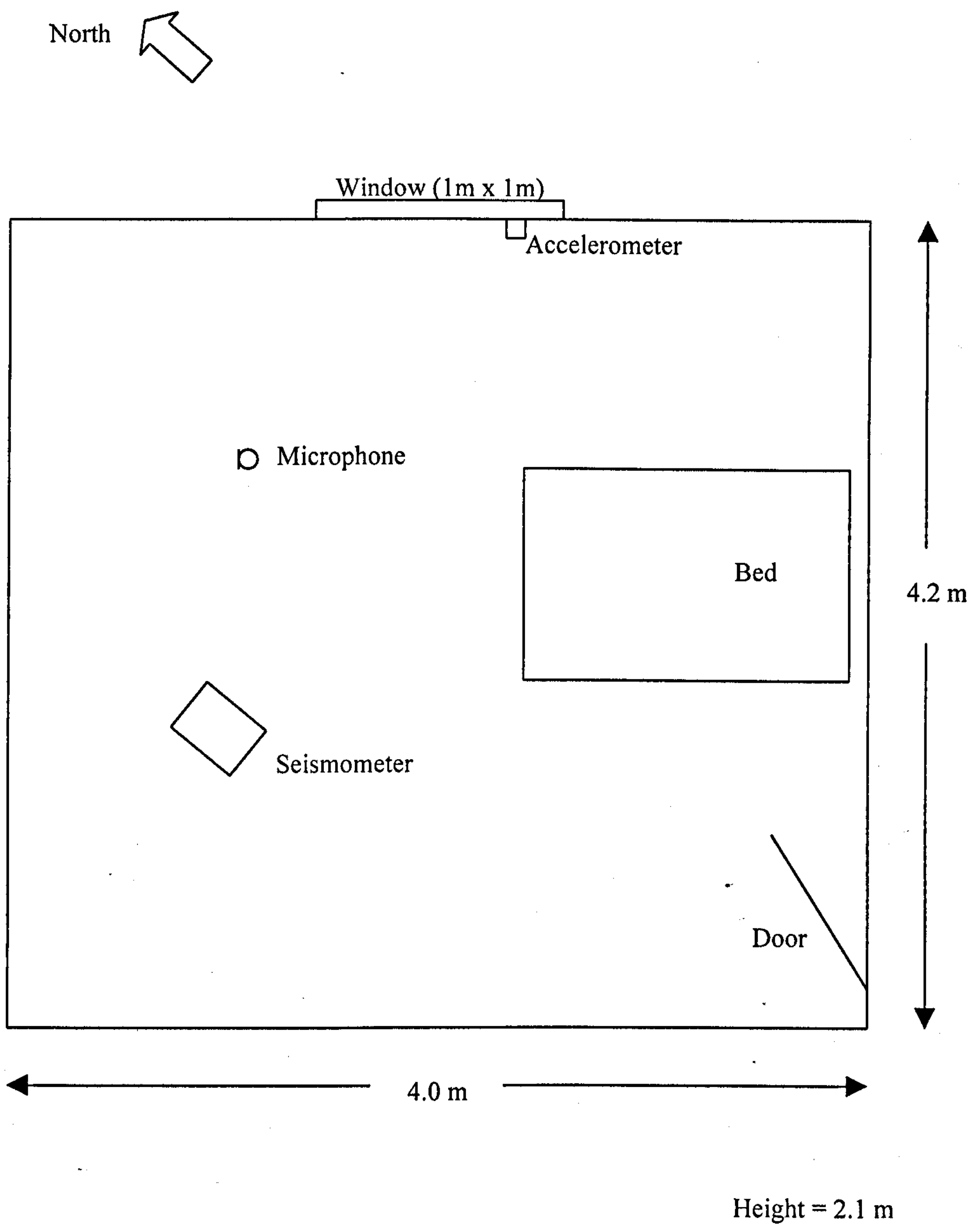


Table 8.2 – acoustic modes of the bedroom at Location B1

n_x	n_y	n_z	f (Hz)
0	0	0	0
1	0	0	41
0	1	0	43
1	1	0	59
0	0	1	81
2	0	0	81
0	2	0	85
1	0	1	91
0	1	1	92
2	1	0	92
1	2	0	94
1	1	1	100
2	0	1	115
0	2	1	118
2	2	0	118
3	0	0	122
2	1	1	122
1	2	1	125
0	3	0	128
3	1	0	129
1	3	0	134
2	2	1	143
3	0	1	146
3	2	0	149

Fig. 8.9 - FEM-predicted and measured sound pressure levels acquired using the bedroom window as a sound source at Location B1

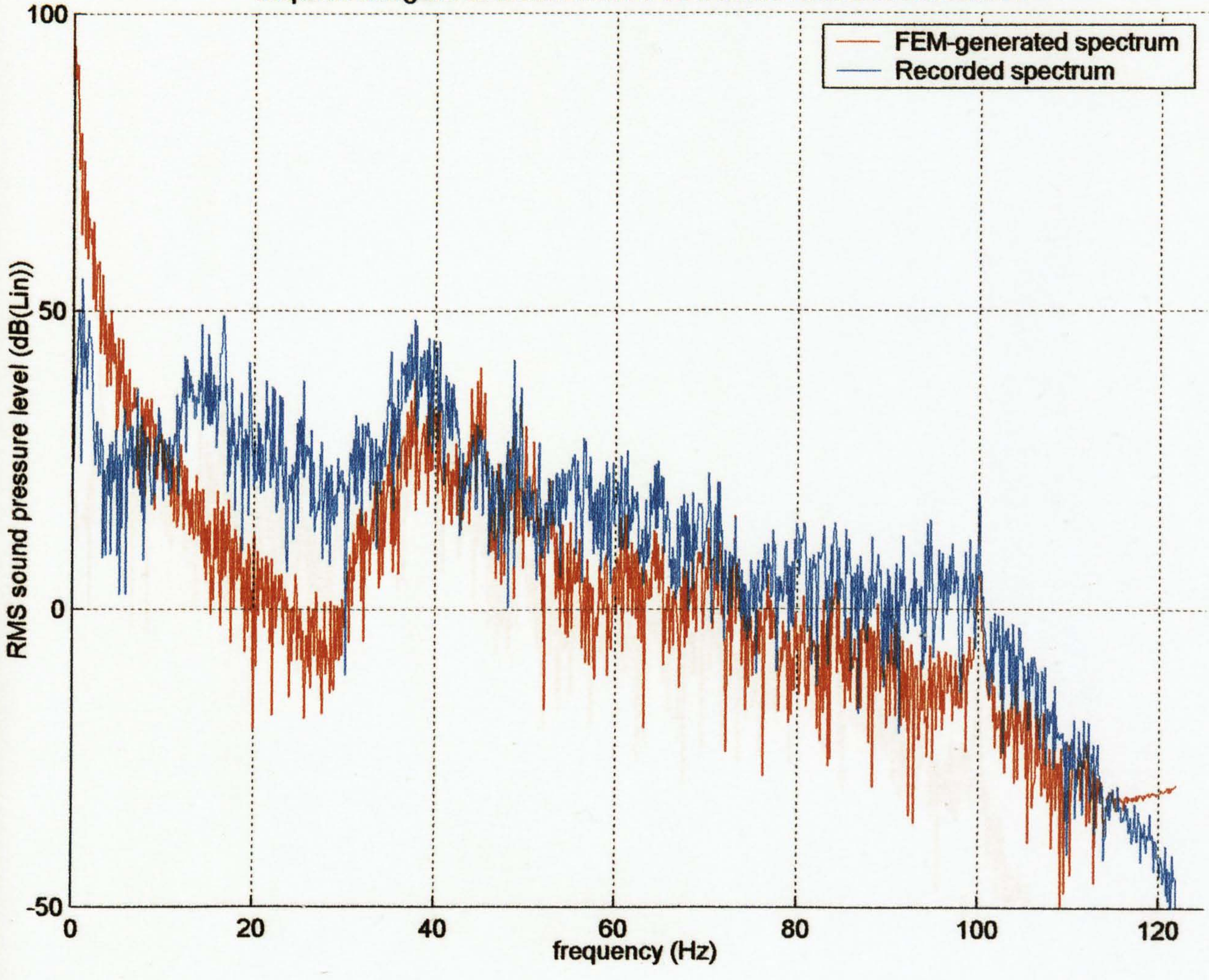


Fig. 8.10 - FEM-predicted and measured sound pressure levels acquired using the bedroom floor as a sound source at Location B1

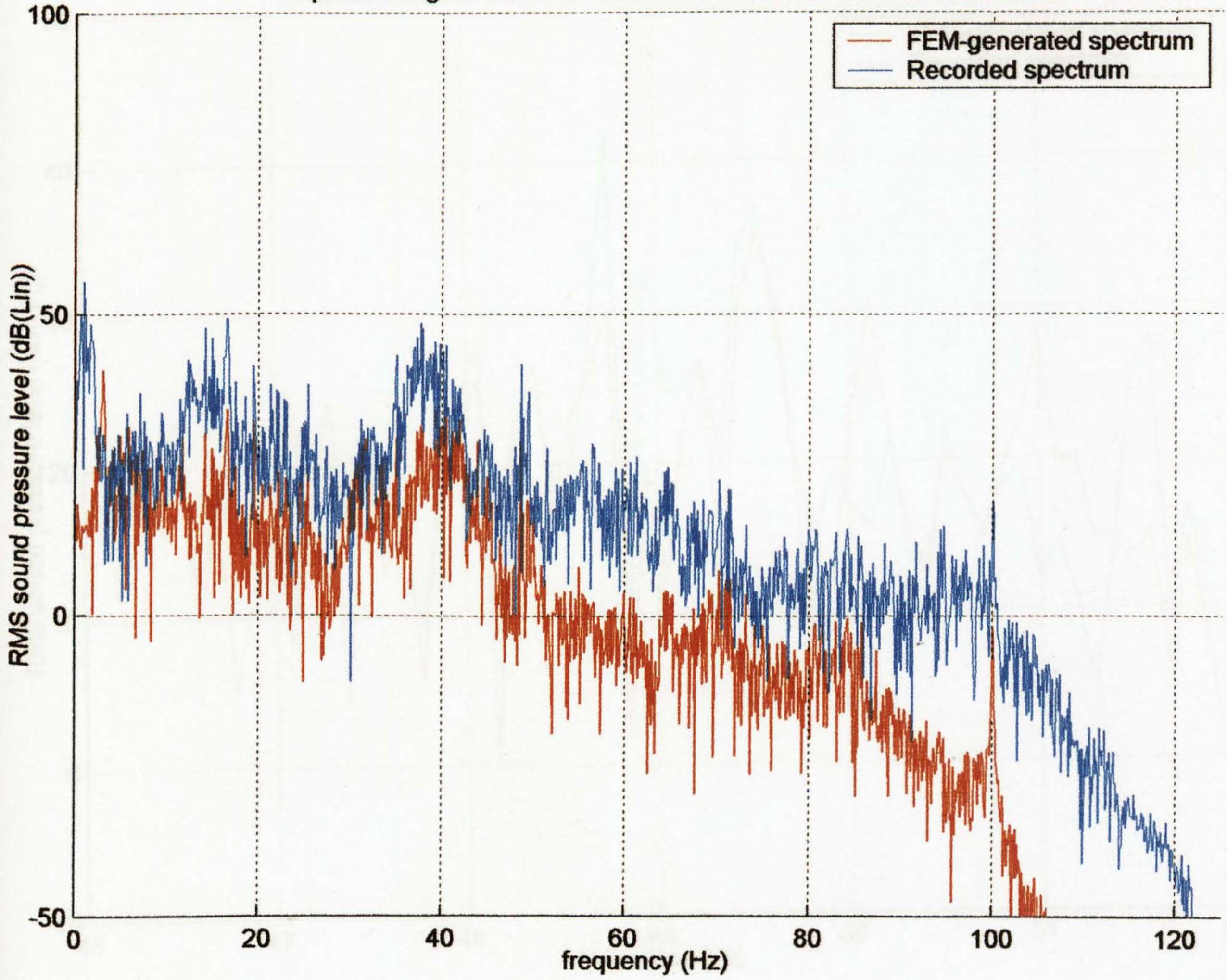


Fig. 8.11 - close-up of Fig. 8.9 in the frequency range 46-52 Hz (window-based FEM modelling at Location B1)

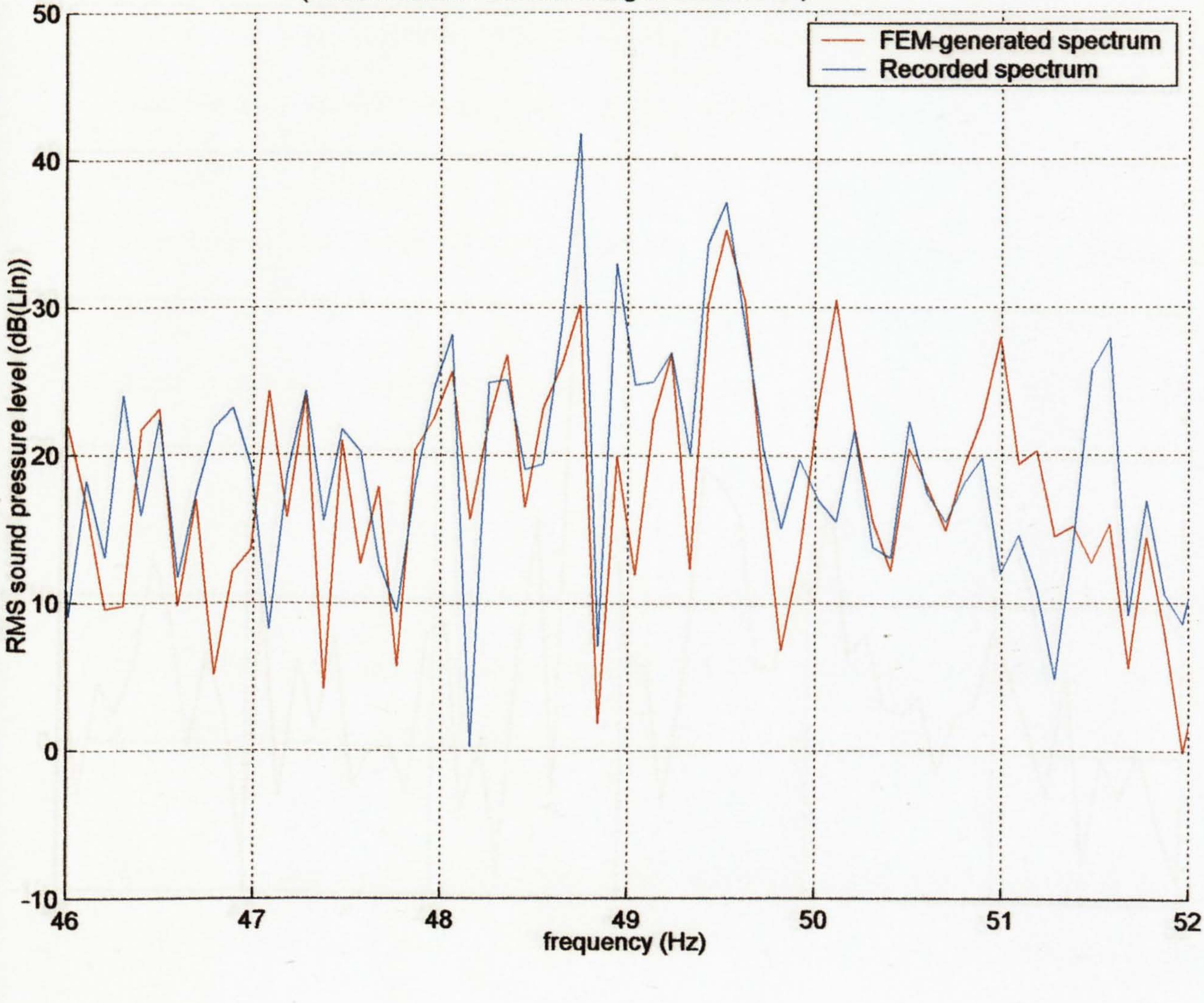
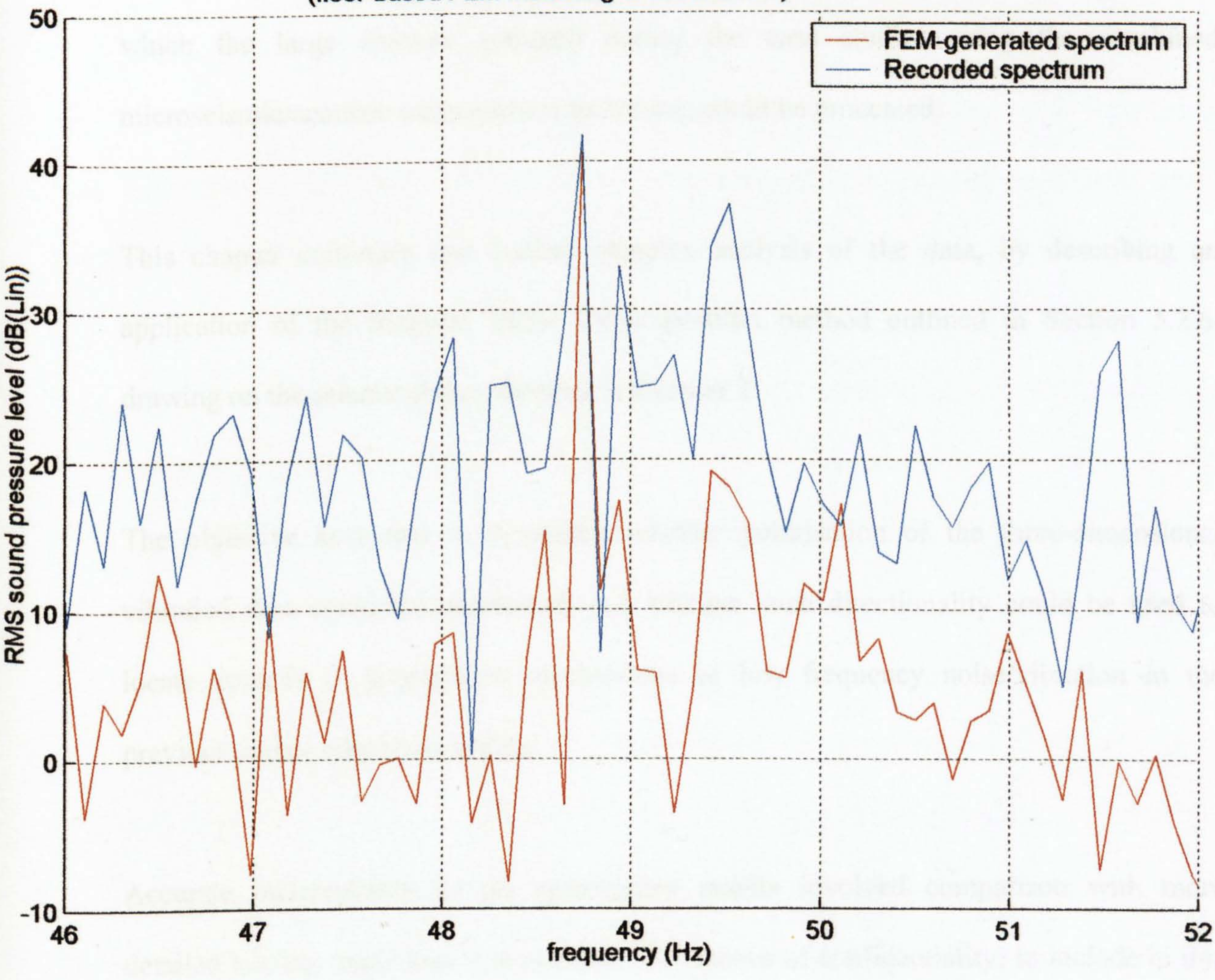


Fig. 8.12 - close-up of Fig. 8.10 in the frequency range 46-52 Hz
(floor-based FEM modelling at Location B1)



9 POLARISATION ANALYSIS OF THE RECORDED DATA BY A SINGULAR VALUE DECOMPOSITION METHOD

The previous chapter followed on from Chapters 6 and 7 in exploring further ways in which the large datasets gathered during the case studies using the combined microseismic/acoustic measurement technique, could be processed.

This chapter continues that further complex analysis of the data, by describing an application of the Singular Value Decomposition method outlined in Section 5.2.6, drawing on the seismic theory detailed in Chapter 2.

The objective here was to determine whether polarisation of the three-dimensional vibration data could be ascertained, and whether such directionality could be used to locate sources or propagation mechanisms of low frequency noise/vibration in the previous and/or other case studies.

Accurate interpretation of the polarisation results involved comparison with more detailed locality maps than it is possible (for reasons of confidentiality) to include in this thesis.

9.1 APPLICATION OF THE SVD METHOD TO CONTINUOUS SIGNAL

Section 5.2.6 describes the Singular Value Decomposition method in detail, including an example of its application to a single seismic (P-wave) arrival of high signal/noise ratio. The standard way in which SVD analysis is carried out is to assume that the chosen time window contains only a single arrival (Jackson et al., 1991).

However, data collected by the ground floor seismometer in the case studies reported in this thesis, displayed ground vibrations of a different type, namely continuous tonal vibration at very low levels.

This section describes an attempt to apply the SVD method to the three-component seismometer data recorded in the ground floor slab in Case Study A (Chapter 6), despite the fact that the signal in these cases was composed not of individual separable events, but of continuous vibration.

It is likely that the data recordings contained low amplitude waves of various types, including both Rayleigh and Love surface waves, as well as background noise. This was particularly true because the vibrations were recorded within a few hundred metres of the likely source (Factory F), so separation of phases by dispersion (see Section 2.3) was unlikely to have taken effect even if ground vibration had been of discrete (rather than continuous) nature.

However, some useful analysis could still be carried out. When the horizontal NS and EW components (unrotated) of the 'loudest' (highest signal/noise ratio) events recorded at Location A1 were initially plotted against each other, they appeared to display a general polarisation along a NE-SW axis at a frequency of 4 Hz. This was consistent with the earlier assumption in the case study that a 4 Hz tone recorded by the ground floor seismometer was propagating through the ground from Factory F (which is located approximately northeast of A1; see Figure 6.1).

Figure 9.1 shows a typical example of a 'loud' period from an event. The x- and y-axes represents motion to the east and north respectively. A narrow-band filter has been applied to emphasise the polarisation at 4 Hz, which can be seen to be aligned to a NE-SW orientation.

The Singular Value Decomposition method (Formulas 5.2-5.4) was applied to several of these 'loud' bursts, giving eigenvectors, $\mathbf{v}_1$ with azimuths, θ=45°±10° and very shallow elevation values, φ=0°-2°.

(Positive values of θ derived from this analysis represent anticlockwise angles from the east (x-axis).. ϕ represents the angle of the motion vector out of the x-y plane, positive for positive z-values.)

This suggested that the major principal axis ($\mathbf{v}_1$) of the ground vibration was horizontal and pointing towards the likely source. Furthermore, one of the other principal axes (it was actually $\mathbf{v}_3$ rather than $\mathbf{v}_2$) was almost vertical (i.e. had an elevation of almost 90°), and both $\mathbf{v}_1$ and $\mathbf{v}_3$ components displayed a sharp peak at the same frequency (4 Hz; its amplitude was greatest in the horizontal direction parallel to $\mathbf{v}_1$). The third principal axis did not contain a peak at this frequency. Finally, vertical profile plots ($\mathbf{v}_3$ versus $\mathbf{v}_1$) appeared to show an elliptical locus to the motion.

Figure 9.2 shows the same event as Figure 9.1, but with the vertical component plotted against the horizontal component parallel to the major principal axis. An elliptical locus can clearly be seen, especially when an animated plot is observed.

Based on knowledge of the properties of Rayleigh waves (Section 2.3), certain assumptions were made about the 4 Hz tone, followed by an attempt to justify those assumptions.

Rayleigh motion involves an elliptical locus in a vertical plane, the ellipse having a horizontal major axis; this appeared to be the case for the 4 Hz tone.

It was therefore assumed that the motion along $\mathbf{v}_1$, $\mathbf{v}_3$ was indeed due to a Rayleigh wave propagating from the factory site to the northeast (i.e. azimuth θ=225°). Motion parallel to the third principal axis $\mathbf{v}_2$ was assumed to be uncorrelated noise, even though its magnitude was slightly greater than that of the signal parallel to $\mathbf{v}_3$.

Two further properties of Rayleigh waves were used to corroborate these assumptions.

The mean phase difference between the components of the rotated data parallel to $\mathbf{v}_1$ and to $\mathbf{v}_3$ was calculated at the frequency 4 Hz and was established to be around 90°, as would be expected for a Rayleigh wave. Note that the filtering process used did not affect the phase differences derived from the data, because the *Matlab* routine *filtfilt* causes precisely zero phase distortion (see Section 5.2.5).

Furthermore, the polarity of the motion was retrograde (assuming the Rayleigh wave was travelling southwest, away from the factory) i.e. the ground surface reached its highest point as it moved towards the northeast at its fastest horizontal velocity.

Figure 9.3 was created from the same recording as before, but only 1-2 cycles at 4 Hz are plotted for reasons of clarity. An arrow-head has been added to indicate the polarity of the motion. The positive x-axis represents motion to the northeast.

The vibration in the third dimension (horizontal, perpendicular to the major principal axis) showed no such phase relationship with either of the two 'Rayleigh' components and therefore consisted entirely of random noise and/or other, independent phases.

Note that only with the best available data was this kind of analysis achievable. Prior knowledge of the likely source formed part of the assumptions made; source location may not have been achieved using the seismic data alone. Even the 'loudest' (i.e highest signal/noise ratio) events displayed considerable levels of noise perpendicular to the plane of the elliptical Rayleigh-type wave.

However, it should also be pointed out that the ground vibrations at 4 Hz, although detectable by the sensitive equipment used, were at levels several orders of magnitude below the limiting values given in BS 6472 (1992).

It may be hypothesised that if a case study were encountered in which ground waves were detected at sufficiently high vibration levels to exceed BS 6472 limits, then the signal-to-noise ratio of the ground waves would also be considerably higher. The uncertainty on the polarisation direction acquired using this type of analysis would then be lower, and a reliable source direction could be based upon it.

It was thus demonstrated that it is possible to extract meaningful polarisation information, even for continuous vibration from a steady source and with a low signal/noise ratio. However, the unusual application of the SVD method to this type of data meant that some aspects of the method had to be adapted in order to maximise the prospects of extracting useful information from the data.

9.2 ADAPTION OF THE SVD METHOD TO TWO DIMENSIONS

Because of the complicated interaction between different phases that was suspected to be occurring in the seismometer data, the formulas given in Section 5.2.6 for rectilinear and elliptical signal/noise ratios (Formulas 5.5, 5.6) did not prove to be good predictors of the 'degree of polarisation' of the recorded events.

There was a poor correlation between events with high signal/noise ratios (of either type), and events that appeared to be highly polarised when seen in plan view and which therefore gave a good indication of direction to source.

An approach was therefore developed that did not try to distinguish between different ground wave phases but merely looked for any predominant polarisation in the x-y plane, and attempted to quantify this.

The *Matlab* function *svd* can perform a singular value decomposition on an input matrix of n columns. Thus the procedure may be applied to two components of vibration data, as well as three components.

For a number of (time-domain filtered) recorded events at certain frequencies, the major principal axis $\mathbf{v}_1$ was established by use of the standard three-dimensional SVD method, to be almost horizontal. For these events it was considered that a two-dimensional SVD method could be developed, using only the NS and EW horizontal components of the data, and that the azimuth determined by this 2-D approach would not vary much from the azimuths obtained via the standard 3-D SVD method.

[Events with a high-elevation (i.e. sub-vertical) principal axis $\mathbf{v}_1$ may yield large errors between the azimuths determined by the two methods, as the projection of the eigenvector $\mathbf{v}_1$ onto the x-y plane may not be significantly greater than the projections of the minor but sub-horizontal eigenvectors $\mathbf{v}_2$ and $\mathbf{v}_3$ onto that plane.]

The 2-D SVD method simply considered the EW and NS components of the data, $\mathbf{x}_x$ and $\mathbf{x}_y$, and performed an eigenanalysis on the 2 x 2 cross-energy matrix $\underline{\mathbf{M}}$, as for the three-dimensional case. This yielded two eigenvectors in the x-y plane, $\mathbf{v}_1$ and $\mathbf{v}_2$, their corresponding eigenvalues, λ_1 and λ_2, and singular values equal to the square roots of the eigenvalues, σ_1 and σ_2 (see Section 5.2.6). A rotated data matrix $\underline{\mathbf{K}}$ (l x 2) was then obtained using Formula 5.4, as before.

$\mathbf{v}_1$ was then considered to be the least-squares best estimate of the direction of propagation of a ground wave (which could be a P-wave or Rayleigh wave, depending on whether it is accompanied by any vertical motion, out of the x-y plane, but this does not affect the current analysis). Motion parallel to $\mathbf{v}_2$ was assumed to be pure noise (of energy σ_2^2) and there was considered to be an equal component of noise (σ_2^2) along $\mathbf{v}_1$. The signal/noise ratio of this two-dimensional SVD analysis was then given by

$$\text{signal/noise} = \frac{\left(\sigma_1^2 - \sigma_2^2\right)}{2\sigma_2^2} \qquad \text{[Formula 9.1]}$$

9.3 DEVELOPMENT OF AN ALGORITHM TO ASSESS 'DEGREE OF POLARISATION'

The simplified two-dimensional SVD analysis and formula for signal/noise ratio calculation derived in Section 9.2, were applied to recordings (or time-filtered recordings) for which the horizontal levels of vibration were clearly shown to dominate over the vertical component i.e. events for which $\mathbf{v}_1$ was almost horizontal.

Comparison of azimuth values for the major principal axis $\mathbf{v}_1$ based on the 2-D and 3-D SVD transforms showed very little discrepancy (1-3°), as expected.

Empirical values were determined for 2-D signal/noise ratio values from which events could be categorised, based on their 'degree of polarisation'.

Plots that 'appeared' to be 'highly polarised' when seen in plan view (x-y plane) had 2-D signal/noise ratios of 10 or more (with some extremely polarised events giving signal/noise ratios as high as 50).

Plots that showed 'fairly poor' or 'fairly good' polarisation in plan view, had 2-D signal/noise ratios between 6-10.

Plots with 2-D signal/noise ratios less than 5-6 showed 'poor' polarisation or none at all (the latter resembling filled-in circles).

(Note that this categorisation was initially based on the author's subjective judgement, but by application to a large number of events the rules-of-thumb that had been developed appeared to be reinforced.)

This approach transpired, for these type of events (ones containing continuous vibrations in many phases), to be a better, more useful predictor of the 'degree of polarisation' (and hence the confidence level in the azimuth value derived from SVD analysis of horizontal data only) than the rectilinear or elliptical signal/noise ratios derived from 3-D SVD analysis, that are designed to be applied to isolated arrivals.

One series of events, when filtered around the 12 Hz frequency band, displayed motion that was dominated by the vertical component. It was confirmed by calculation of 2-D and 3-D SVD eigenanalysis that values of the azimuth, θ of the principal axis showed large discrepancies between the two methods (~10-30°). This was to be expected for events whose principal eigenvector $\mathbf{v}_1$ had elevations, ϕ of around 85°, for reasons that were mentioned in Section 9.2.

However, the 2-D signal/noise ratio formula [Formula 9.1] developed above, when applied to these 12 Hz bandpass-filtered events, yielded relatively low signal/noise ratio values, ranging between 0.2 and 4. This placed the events in the empirical category 'poor/no polarisation'.

This suggests that the novel algorithm developed by the author to determine 'degree of polarisation' (i.e. the level of confidence in azimuths derived based on horizontal vibration data alone), may be used with confidence even if the elevation, ϕ of the primary axis is high or unknown.

9.4 RESULTS OF POLARISATION ANALYSIS

Because of the development of Formula 9.1 and the categorisation outlined in Section 9.3, it was possible to quantify quickly the subjective observation that certain recorded events plotted in 'plan view' (NS component against EW) appeared to be highly polarised whilst others did not. This speeded up the process of going through large numbers of event records trying to discern trends in degree of polarisation, whilst also establishing confidence in the values of θ obtained which it was hoped might help to pinpoint source directions.

9.4.1 Ground Floor Slab – 4 Hz Tone

As shown in Section 9.1, the 4 Hz signal recorded in the ground floor slab at Location A1 displayed polarisation along a NE-SW axis at times. The 2-D signal/noise ratio for the event used as an example previously (Figure 9.1) is ~9 i.e. 'fairly good' polarisation. Other events from Location A1 yielded 2-D SVD signal/noise ratios up to 20 ('high degree of polarisation'), with similar values of θ.

The 4 Hz tone had also been detected in the ground slab at the other two houses where monitoring had taken place during Case Study A. Theoretically, if a similar quality of polarisation results were established at the other two houses, then the mean values for θ (azimuth to source) derived from each house may be used to pinpoint the precise source of the 4 Hz groundborne tone within Factory F. This would be achieved by a triangulation method.

However, the configuration of the estate (Figure 6.1) is such that Locations A2 and A3 are almost co-linear with Location A1 and Factory F. This is not an optimised array for the triangulation method, which works best if two of the monitoring positions subtend an angle of 90° at the source.

In any case, the degree of polarisation observed at Locations A2 and A3 for the 4 Hz groundborne tone was not as convincing, giving 2-D SVD signal/noise ratios of ~1-4 ('poor' or no polarisation).

This could be because of the reduced amplitude of the 4 Hz ground vibration recorded at A2 and A3 (which is in itself an indication that the source lies to the north-east of the housing estate).

9.4.2 First Floor – 4 Hz Tone

Vibration at 4 Hz was also detected in the horizontal components of the seismometer mounted on the suspended floor upstairs at Location A1. The degree of polarisation and any azimuths displayed at 4 Hz in the bedroom floor were assessed, and compared with the established ground slab behaviour at this frequency.

The hypothesis under scrutiny here was that the whole house was behaving as a rigid mass in response to a passing 4 Hz Rayleigh wave emanating from the northeast, and 'riding' over the wave as one. If this were the case, the polarisation directions obtained from the first floor data at 4 Hz would be expected to be similar to those from contemporaneous events in the ground floor slab i.e. motion aligned along a NE-SW axis.

In fact, this was not shown to be the case. The first floor vibrations, filtered at 4 Hz, were dominated by horizontal components but otherwise the motion in the first floor did not fit this model. Polarisation plots of the vibration at 4 Hz resembled a filled-in circle.

For example, Figure 9.4 shows an event recorded by the first floor seismometer at the same time as the NE-SW polarised ground slab motion in Figure 9.1, in plan view. The best-fit azimuth for this event was -27° i.e. ESE-WNW, and the 2-D SVD signal/noise ratio for polarisation was 1 ('poor').

This suggests a more complex mechanism than whole-house rigid body response, is responsible for the transfer of vibrational energy at 4 Hz from the ground to the first floor. Bending waves in the walls are one possibility, but it is not possible to say for certain. Wall-mounted accelerometers may have elucidated this, but were not employed during the monitoring. (There was no apparent 4 Hz signal in the window-mounted accelerometer.)

9.4.3 Ground Floor Slab – 38 Hz Tone

One of the dominant features of the airborne sound spectra recorded during Case Study A was a sharp tone at 38 Hz, which had been correlated with the subjective disturbance at Location A1. This was clearly an 'interesting' frequency, and it was considered possible that the ground floor vibration spectra might yield further information about it.

If it could be shown that the predominantly airborne 38 Hz tone also had a small groundborne component, then it might be possible to observe directionality for that component, and thus determine the direction to the source. This would be a very useful application of a seismometer in an acoustic problem, and may provide a more practical alternative to acoustic intensity techniques for source location, which must be conducted in a free-field i.e. outside (Vasudevan and Leventhall, 1989).

Therefore, an attempt was made to determine whether any 38 Hz signal was buried in the noise floor of the ground slab seismometer recordings, and whether narrowband filtering and Singular Value Decomposition analysis of any such signal might yield a directionality. In fact, this did not turn out to be the case. 2-D Singular Value Decomposition signal/noise ratios were ~1, and no polarisation of the signal could be discerned. Although a very tiny signal was picked up at 38 Hz by the ground floor-based seismometer (at amplidues ~20 nm/s), this was thought to be due to the airborne pressure waves at that frequency acting on the side of the seismometer box. It was concluded that the airborne tone at 38 Hz in this case was reaching the house via an exclusively airborne propagation path.

This of course does not negate the value of attempting to establish a minor groundborne component of a predominantly airborne tone, even if the results were negative. Nor does it preclude the possibility that in other case studies such dual-path propagation may take place.

9.4.4 First Floor – 38 Hz Tone

Finally, the author investigated whether polarisation could be observed in the first floor vibration spectra at the 'problem' frequency of 38 Hz in data from Case Study A.

The expectation was that the vertical seismometer component would be dominant at this frequency, due to excitation of the floor by the strong airborne signal. However, the results showed horizontal polarisation stronger than had been observed to date.

Figures 9.5 and 9.6 show a typical first floor seismometer recording from Location A3, narrowband filtered around 38 Hz, in plan view and in profile (vertical component versus a component parallel to the azimuth of the principal axis of vibration). The first floor vibrations are clearly very polarised, and the 2-D SVD signal/noise ratio is around 300. The principal axis has a shallow elevation of -9° and an azimuth of 26°. Similar results were observed throughout the records from Location A3.

The first floor vibration data at 38 Hz from Location A1 gave similar results, though the degree of polarisation was not as extreme (signal/noise ratio ~20). Typical principal axis orientation values from Location A1 were $\theta = 12°$, $\varphi = -36°$.

Location A2 did not exhibit clear polarisation at 38 Hz in the first floor vibration measurements.

However, monitoring took place at Locations A1 and A3 in rooms that look out onto the Factory F, whereas Location A2 faces away from the factory and is shielded by neighbouring houses. The objective sound pressure levels measured at 38 Hz were also lowest at Location A2.

Despite initial impressions, the axes of polarisation derived from Locations A1 and A3 do not point towards Factory F. Comparison of a map of the area (Figure 6.1) with the values of principal axis azimuth (θ) from A1 and A3, show that the strong polarisation directions at each house are orientated perpendicular to the façade that looks out onto Factory F.

It would seem that the polarisations of the first floor vibrations at 38 Hz in Locations A1 and A3 are determined by the building response to the external pressure wave incident on the building façades. The mechanism involved is unclear. The external sound waves may be setting the whole house into a kind of 'shearing' action perpendicular to the wall facing the source, or they may be exciting flexural waves running up and down the wall from which the floor is suspended.

In any case, the horizontal motion observed in the suspended floor is aligned parallel to one of the axes of the house. The implications of this are that an accurate determination of source direction is not possible on the basis of the first floor polarisation data alone.

9.5 SUMMARY OF FINDINGS FROM POLARISATION ANALYSIS

Polarisation analysis of the data recorded by the integrated acoustic/microseismic technique was conducted utilising a Singular Value Decomposition method.

The SVD matrix transform was adapted for application to recordings of continuous vibration and two-dimensional analysis of the two horizontal seismometer components. An algorithm was developed to enable subjective impressions of the degree of polarisation to be established on a firm basis. This gave confidence in the derived values of azimuth i.e. direction to source.

This analysis highlights another use of simultaneously recorded time histories, this time from three mutually orthogonal velocity transducers. Time domain filtering was useful in distinguishing the polarisation of specific tonal components of the vibration.

The analysis was applied to the data from Case Study A to try to establish propagation directions and mechanisms of key spectral features.

Rayleigh-type motion in the ground at 4 Hz was observed at levels well below the threshold of human perception. It is possible that other case studies could involve similar modes of groundborne vibration at higher amplitudes, in which case more accurate determination of propagation direction and source location may be achieved using this type of analysis.

The 38 Hz tone that was previously identified as a cause of disturbance to residents was confirmed to be entering the houses via an exclusively airborne path.

Building response to the external pressure waves at 38 Hz in two of the houses excited the suspended upstairs floorboards into horizontal motion normal to the house façades. Polarisation of the suspended floor vibration was therefore not found to be useful for precise determination of the source of the problematic airborne tone.

9.6 REFERENCES

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Vasudevan, R. and Leventhall, H., (1989): *'Annoyance Due to Environmental Low Frequency Noise and Source Location – a Case Study'*, Journal of Low Frequency Noise and Vibration, Volume 8(2:30-39).

Fig. 9.1 - polarised ground motion at 4 Hz, displayed in a horizontal plane

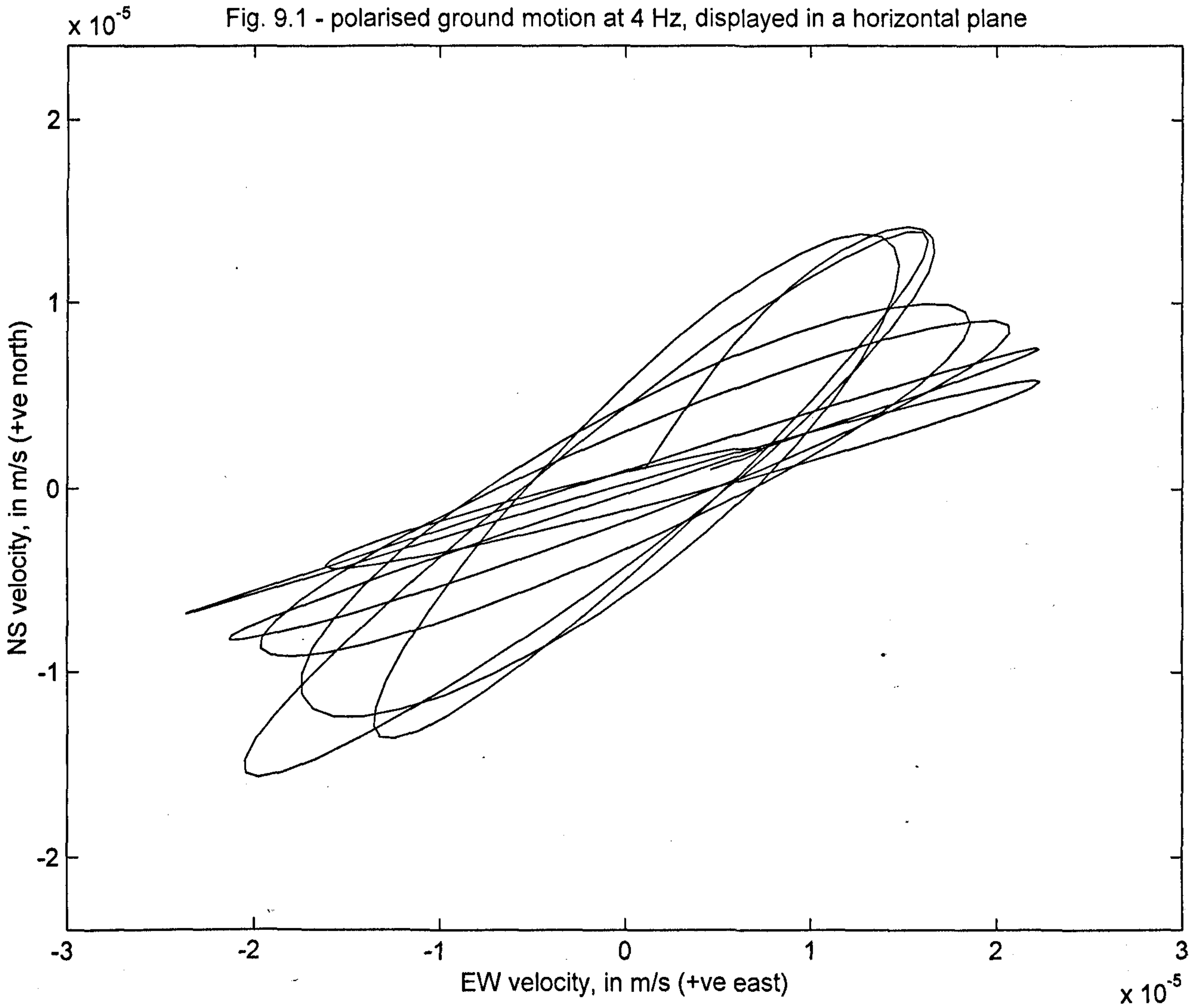


Fig. 9.2 - polarised ground motion at 4 Hz, displayed in profile

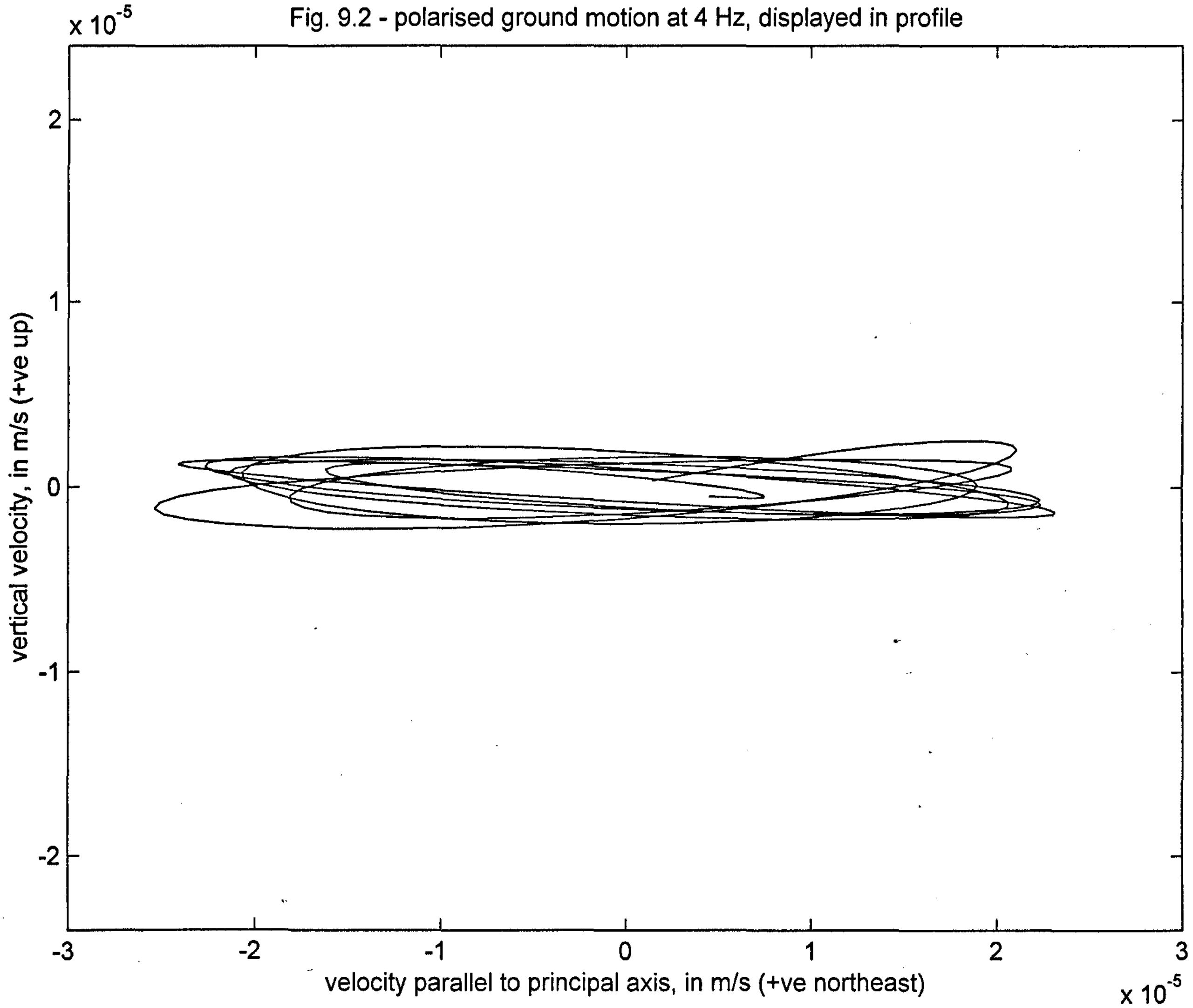


Fig. 9.3 - Rayleigh-type ground motion, following a retrograde elliptical locus in a vertical plane

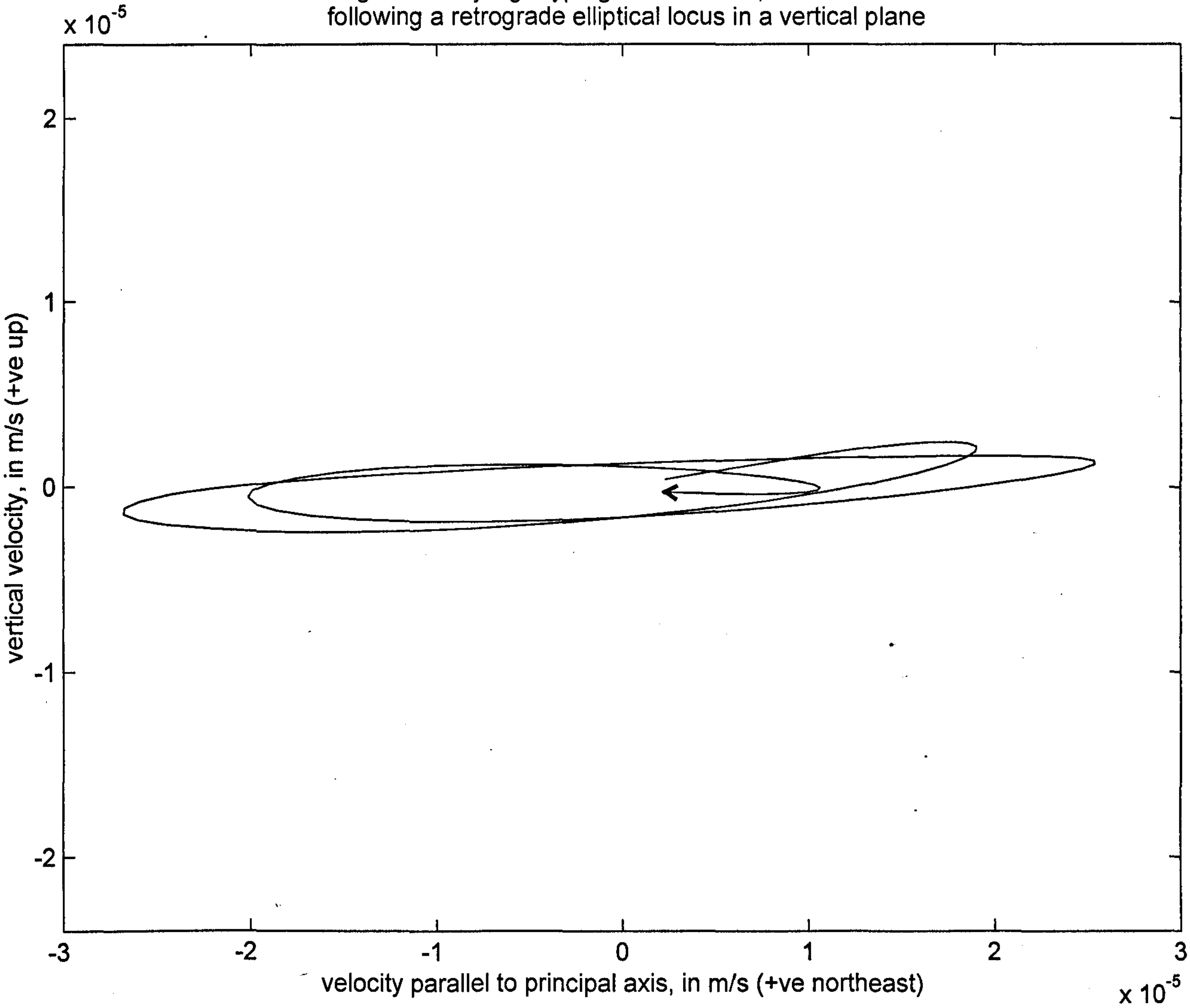


Fig. 9.4 - non-polarised motion in a suspended upper floor, displayed in a horizontal plane

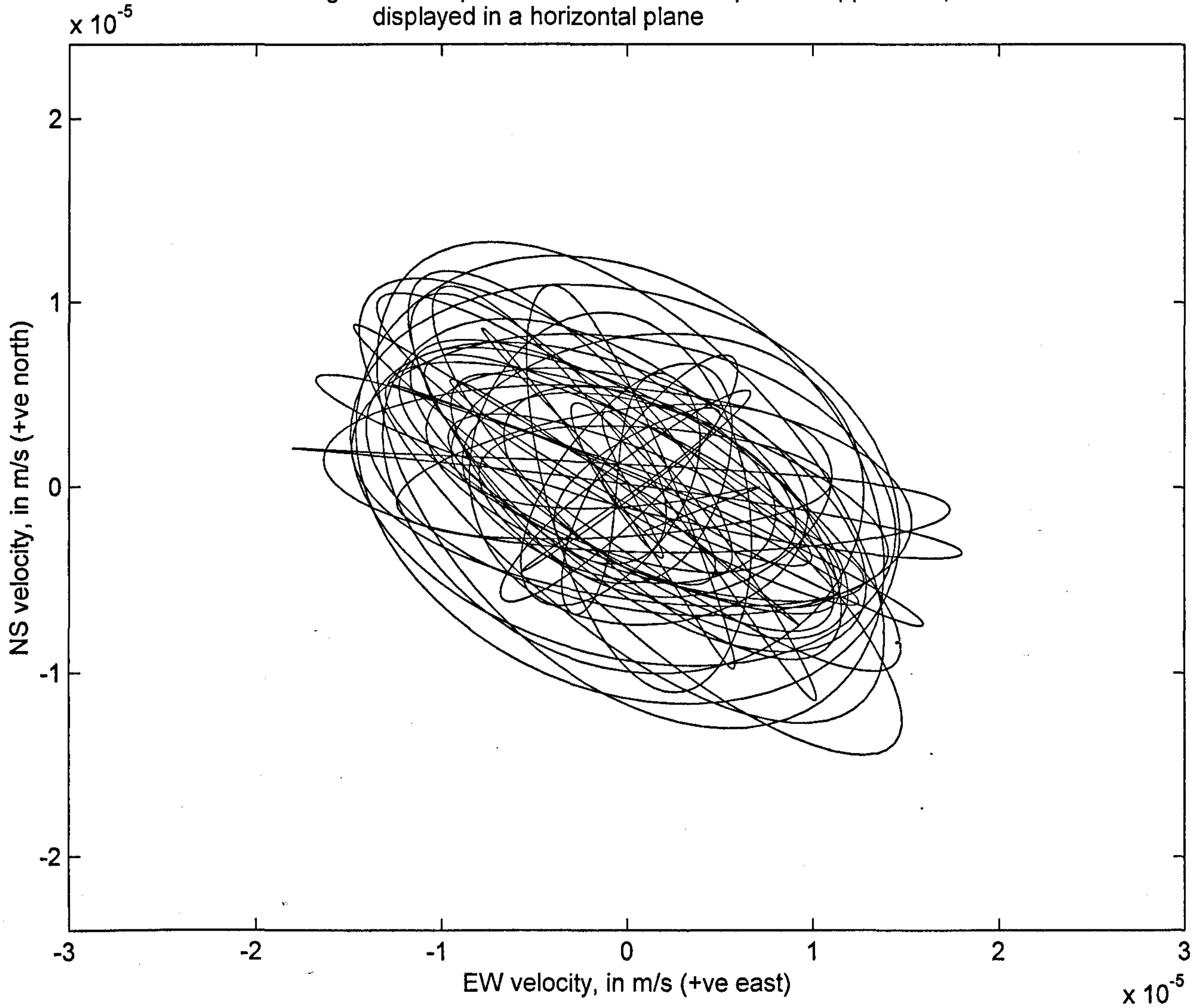


Fig. 9.5 - highly polarised horizontal motion in a suspended upper floor at 38 Hz

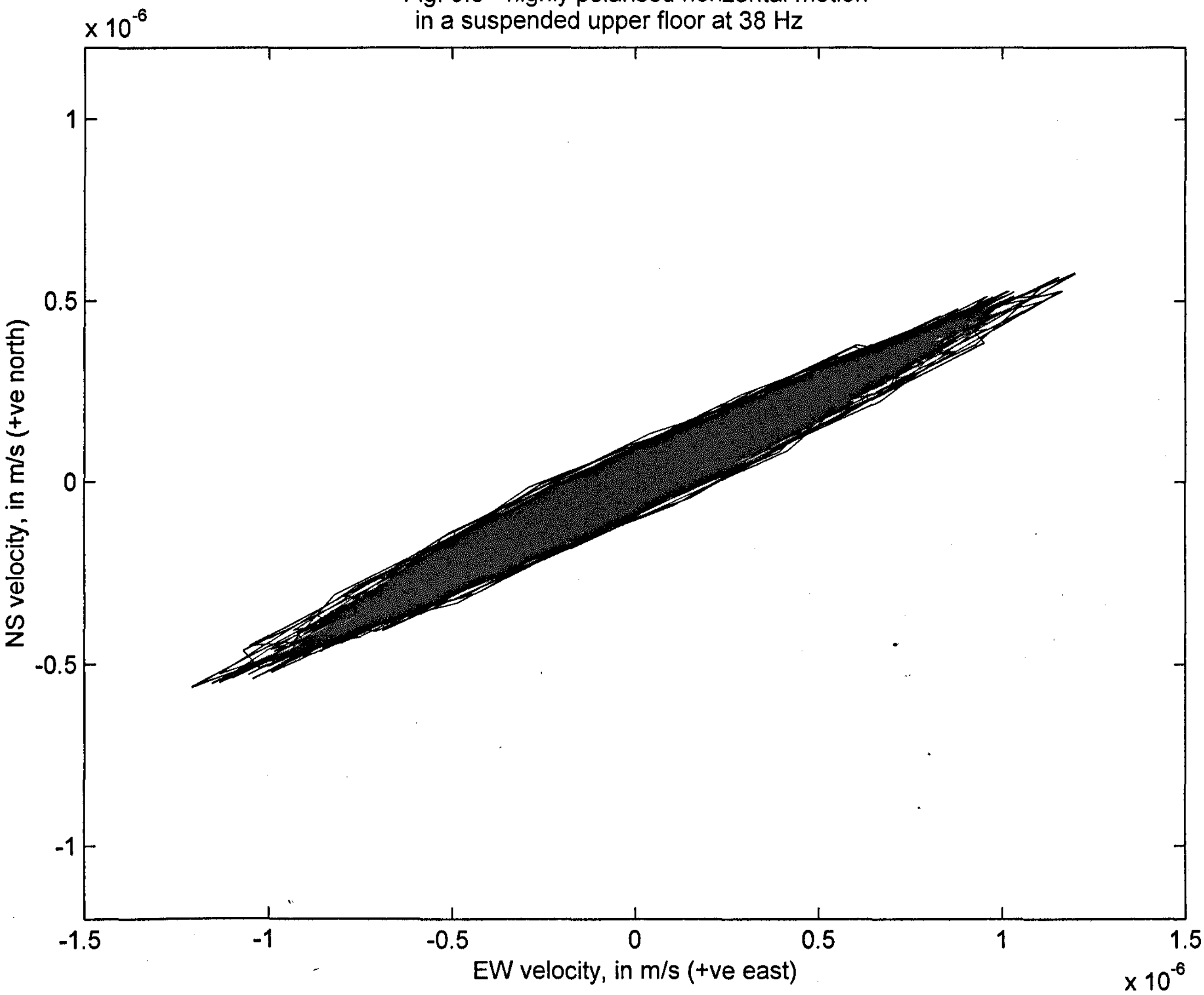
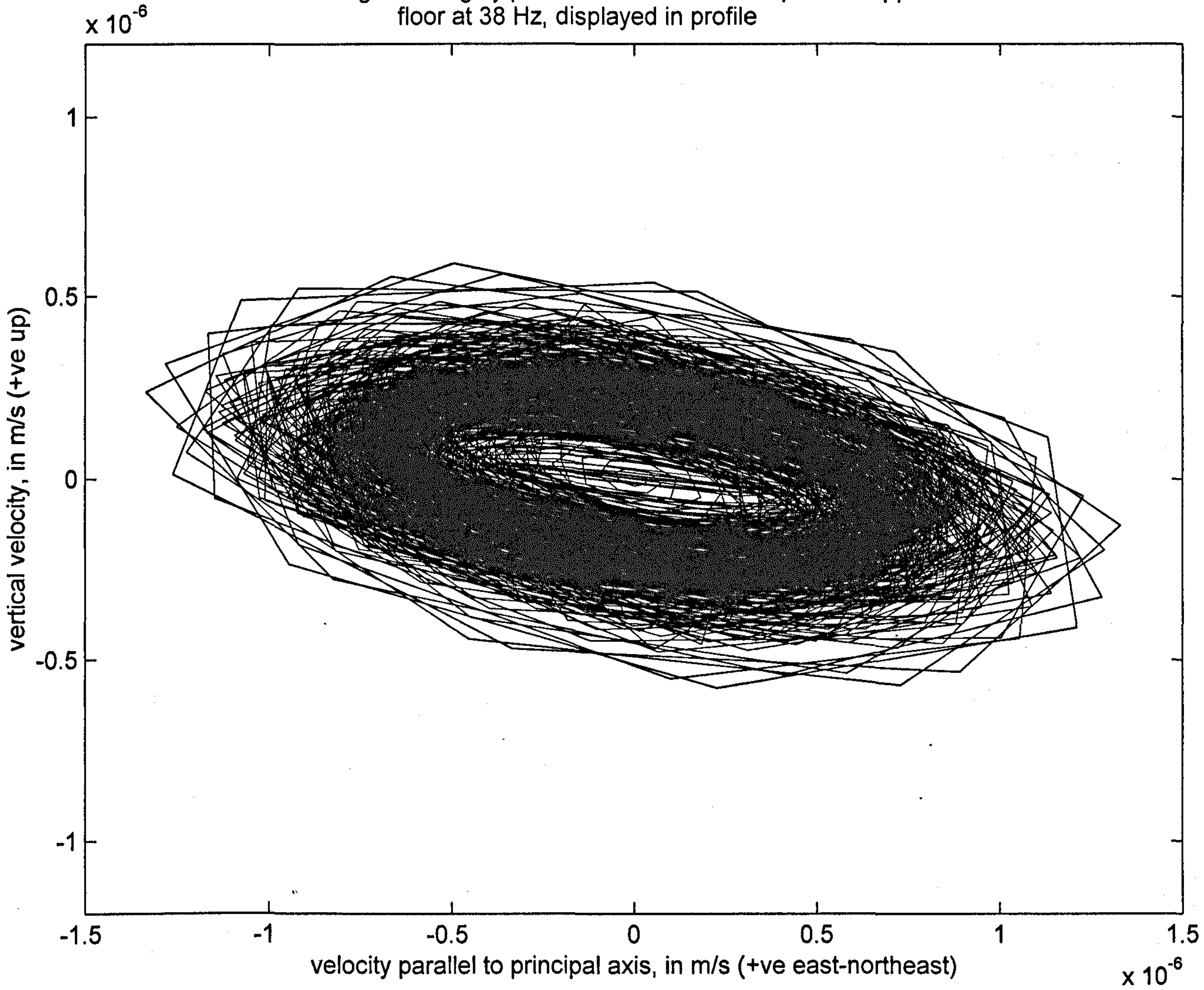


Fig. 9.6 - highly polarised motion in a suspended upper floor at 38 Hz, displayed in profile



10 CONCLUDING REMARKS

An integrated acoustic and microseismic approach to monitoring low frequency noise and vibration was developed. The measurement system that was assembled combined acoustic and microseismic transducers with microseismic data capture capabilities.

The advantages of the technique were assessed in two major field trials, involving the collection of large quantities of sound and vibration level data. The data were subject to rigorous investigation in a wide range of subsequent laboratory analyses.

It was concluded that the extent of knowledge about low frequency noise/vibration problems that can be extracted from data acquired using the combined technique, is greater than the total information available by applying each of the two disciplines independently i.e. "the whole is greater than the sum of the parts".

A secondary conclusion was that the German national standard DIN 45680 is a good predictor of the level of annoyance caused by low frequency noise.

10.1 ADVANTAGES OF EXPERIMENTAL TECHNIQUE

Long-term monitoring is possible using the integrated technique, which increases the prospects of solving intermittent, unpredictable low frequency noise/vibration problems. Data acquired over several days may be compared with logs of subjective loudness level and/or production records to aid source determination. By analysing the recordings in conjunction with contemporary meterological data, it may be possible to distinguish variations in measured levels due to environmental factors, from those due to changes in power output at the source.

The simultaneous recording of sound pressure, window vibration and floor vibration levels allows direct comparisons of the levels in each channel to be made. From this, information about the propagation path of the low frequency noise/vibration may be inferred.

Recording ground floor vibration levels allows the potential for damage (either to humans or to building structures) due to groundborne vibration to be ruled in or out.

The experimental method of recording time histories over long periods for subsequent analysis means that a wide array of useful signal processing is possible. Important time-varying characteristics of a noise may be observed, which would not be detected by use of standard acoustic methods that involve time-averaging of the measurements.

Subtle changes may be detected in the frequency domain because of the fine frequency resolution that is achievable using the technique. When tones close to 50 Hz are detected, mains 'hum' may be ruled out as a possible cause by studying the output from an unused channel of the Vibrosound in the frequency domain.

It may be possible to determine the source and propagation path of a recorded tone in a room by using FEM modelling to test out two possible mechanisms for sound entering the room, namely:

- from an external source via a piston-like action in the window;
- from an internal source via a suspended wooden floor structure.

This analysis highlights one of the advantages of simultaneously recording time histories of sound and vibration levels on several channels.

A Singular Value Decomposition matrix transform of three mutually-orthogonal components of measured vibration levels, may allow observation of polarised motion. This is another potentially valuable application of multi-channel data recorded using the integrated technique.

Polarised Rayleigh wave ground floor motion may yield a direction of propagation, and hence source of the Rayleigh waves, to be ascertained if the signal/noise ratio is sufficiently high.

Polarised motion in the suspended upper floor of a house due to the response of the house to incident sound waves, is likely to be aligned along an axis of the house and is therefore not useful as an indicator of the propagation direction or source of the airborne sound.

In case studies it was shown that transmission into the buildings was predominantly airborne. No cases were encountered involving groundborne transmission at levels perceptible to humans. Although no firm general conclusion can be drawn from individual cases, these findings may suggest that most or even all low frequency noise problems are due to airborne rather than groundborne transmission.

10.2 SHORTCOMINGS OF EXPERIMENTAL TECHNIQUE

The Vibrosound recording system used in the field trials did not yield continuous coverage of sound and vibration level variations during the trials, although more advanced system are now available that do provide this.

The seismometer mounted on the ground floor slab was connected to an independent PC-based data recording system and therefore was not precisely synchronised to the rest of the channels of data recorded by the Vibrosound system. This meant that precise ground floor-to-first floor transfer functions could not be calculated.

Long-term monitoring is not always possible in the exact room where disturbance occurs most (usually the main bedroom of a house), without causing inconvenience to residents. The sound field between rooms may differ because of modal behaviour, and this may impede attempts to correlate subjective levels of disturbance with objective recordings.

Data from the Vibrosound must be downloaded onto a PC before they can be observed. It is not possible to obtain quick readings, as given by a sound level meter. The use of a sound level meter may complement the Vibrosound recording system.

10.3 SUGGESTIONS FOR FURTHER DEVELOPMENT OF THE TECHNIQUE

An updated version of the integrated acoustic/microseismic technique could be developed using more modern microseismic data acquisition tools that would allow continuous coverage of sound and vibration levels in a house and a higher number of input channels. Ground floor vibration levels could then be recorded in parallel with the suspended first floor vibration data, allowing direct calculation of a transfer function between the two.

Further channels could be attached to accelerometers mounted on the walls and ceiling to allow more detailed routes to be modelled for low frequency noise and vibration propagating through the house. More microphone channels could be utilised.

10.4 SUGGESTION FOR FURTHER APPLICATION OF THE TECHNIQUE

To date, the integrated acoustic/microseismic technique has only been tested out in case studies in which it transpired that the dominant propagation path of the low frequency waves causing disturbance, was through the air (although this had not been known at the outset).

It would be a useful application of the integrated technique to apply it in a case where disturbance is known to be caused by low frequency groundborne waves. This would further validate (or otherwise) the applicability of the technique to a wide range of situations in which a low frequency noise and/or vibration problem is suspected.

APPENDIX

Published Papers:

Rushforth, I., Styles, P., Manley, D. and Toon, S., (1999): *'Microseismic investigations of low frequency vibrations and their possible effects on populations'*, Journal of Low Frequency Noise, Vibration and Active Control, Volume 18 (3:111-121).

Rushforth, I., Styles, P. and Moorhouse, A., (2000): *'Industrially induced low frequency noise & vibration in residential buildings'*, Proceedings of the Institute of Acoustics, Volume 22 (2:33-42).

Microseismic Investigations of Low Frequency Vibrations and their possible effects on Populations

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ABSTRACT

Environmental low frequency noise and vibration (or "hum") is a growing annoyance and potential health hazard to many people, according to surveys conducted by the UK's Low Frequency Noise Sufferer's Association. This paper describes attempts to measure the "hum" using microseismic methods. Sensitive three-component seismometers and high resolution digital dataloggers were employed in the homes of "hum" sufferers, and three-dimensional vibrational data were recorded overnight. Frequency analyses were then performed on the time series data using Fast Fourier Transform methods.

In one case study, a clear signal was observed corresponding to a fundamental vibrational frequency peak of 10 Hz. At least one harmonic frequency peak (30 Hz) was also apparent. It is suggested that local industry of some kind (with machinery running overnight at an operating frequency of 10 Hz) may be responsible for this ground-borne disturbance.

In another house occupied by "hum" sufferers, no notable ground velocities were recorded overnight with the seismometer mounted on ground floor concrete foundations. Significant levels of vibration were only observed in an upstairs bedroom, by placing the instrument on floorboards which appear to be excited by acoustic waves in the room. It is inferred that in this case the "hum" is predominantly air-borne; again, local industry is a likely source.

Low frequency "hum", both acoustic and ground-borne, is a very real problem which causes sufferers great distress. It is possible to measure the "hum" and determine its frequency characteristics using microseismic techniques. Urgent revision of current legislation is needed to limit industrial output levels of low frequency noise/vibration, especially at night time.

INTRODUCTION

The number of complaints registered by members of the public about low frequency environmental noise/vibration has increased rapidly in recent years, both in the UK and world-wide. Whilst this has coincided with a general growth in industry, neither the nature nor the source(s) of these "hum" phenomena are yet fully understood. However, questionnaires (Appendix A) carried out by the UK Low Frequency Noise Sufferers' Association (LFNSA) suggest that in many cases the disturbances may not be entirely acoustic in origin, but might propagate through the ground as microseismic waves. As the human body's resonant frequencies cover the range 1-80 Hz (ISO 2631: 1978), it is clear that such low frequency vibrations have the potential to cause great distress to, or even affect the health of, affected individuals (as reflected in the questionnaires – Appendix A).

This study endeavours to measure the "hum" over the frequency range 0-80 Hz using highly sensitive seismometers, to determine its characteristics and attempt to distinguish ground-borne and air-borne low frequency vibrations.

INSTRUMENTATION

The vibration data were measured using a high-sensitivity Lennartz LE-3D/1 three-component seismometer. This has a flat frequency response between 1 and 80 Hz, thus no calibration was required across this frequency range.

Data were recorded onto 20 MB PCMCIA Flash Cards using a six-channel Vibrosound SP1 24-Bit A/D converter. The Vibrosound has a dynamic range of > 118 dB and allowed velocities as small as ~1 nm/s to be observed.

Each recorded event consisted of 10 seconds of data, thus frequency analysis using MATLAB Fast Fourier Transform software achieved a frequency resolution of 0.1 Hz. The sampling rate of the Vibrosound A/D converter was set to 250 Hz; the Nyquist frequency was thus 125 Hz, well above the frequency range of interest (0-80 Hz).

MICROSEISMIC INVESTIGATIONS: TWO CASE STUDIES

Microseismic monitoring was carried out at two households occupied by "hum" sufferers: 261 Sommerfield Road, Woodgate Valley, Birmingham (6-7 May 1997), and 63 Ty Draw, Little Church Village, S. Wales (12-13 March 1997).

The equipment was set to record one event (10 s of data) automatically every five minutes throughout the night, when background noise/vibration levels were low. Wherever possible the seismometer was placed on a solid, flat surface (e.g. a concrete ground floor), in order to obtain a good vibrational coupling with the building foundations/bedrock. Additional recordings were made the next morning, at various positions around the buildings, using a manual triggering device. In all cases, the seismometer was oriented with respect to true North.

During each visit, verbal communications with the "hum" sufferers was noted down in order to determine such factors as geographical and geological setting of the dwelling, "hum" variations and characteristics, any medical (especially hearing) problems resulting from or pre-dating the onset of the problem, any previous independent scientific attempts to measure the disturbance, sufferers' theories on possible local industrial sources of the disturbance, etc. One observation which came out of this study is that many "hum" sufferers claim to be able to "feel" the disturbance as much as they can hear it. This makes the question of whether the "hum" is air-borne or ground-borne a very pertinent one.

RESULTS & DISCUSSION

261 Sommerfield Road:

This is one of a row of terraced houses in a level region of SW Birmingham, and is underlain by Carboniferous clay.

The seismometer was set up to record in the downstairs kitchen on hard linoleum overlying a concrete floor (this seemed the most suitable position, although the "hum" can be perceived throughout the whole house according to the residents). Some of the results obtained were rather interesting. (All results displayed below are for vertical component vibrations, which showed the strongest signals in this instance, although three components of motion were always recorded).

Figure 1a shows the time series data recorded at 00:10 BST on 7/5/97, and presents a strong signal of period ~0.1 s and ground velocities of over 2000 nm/s. The Fast Fourier Transform of this, displayed in Figure 1b, reveals an extremely sharp peak velocity at 10 Hz (over 1300 nm/s), as well as lesser peaks at 30 and 50 Hz. These could represent the 2nd and 4th harmonics of the 10 Hz vibration, although the 50 Hz peak is likely to be at least in part due to electrical noise picked up in the circuits of the instruments (this is a common feature in all the data).

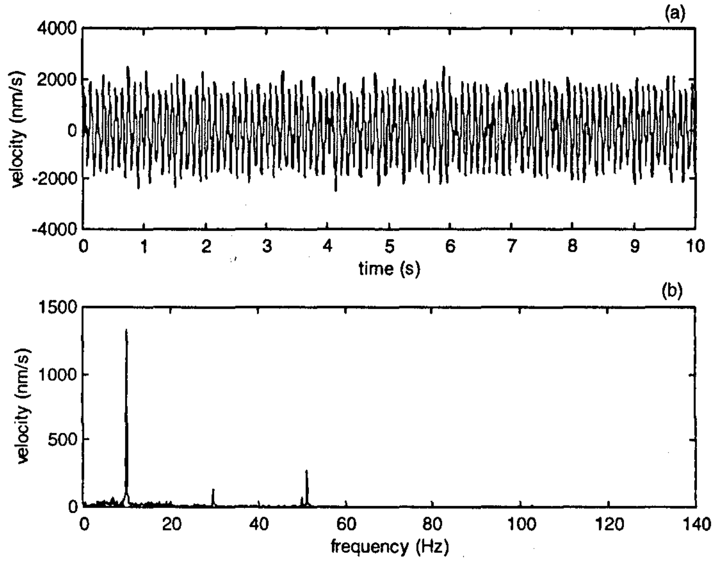

Figure 1. Z-component microseismic recording at 261 Sommerfield Road on 7/5/97, at 00:10 BST. (a) Time series and (b) Frequency spectrum.

For comparison, Figure 2 shows data from a period (01:06 BST) when the 10 Hz signal was not picked up. Noticeably, the 50 Hz electrical noise peak (280 nm/s) dominates over the background vibration levels (~20 nm/s).

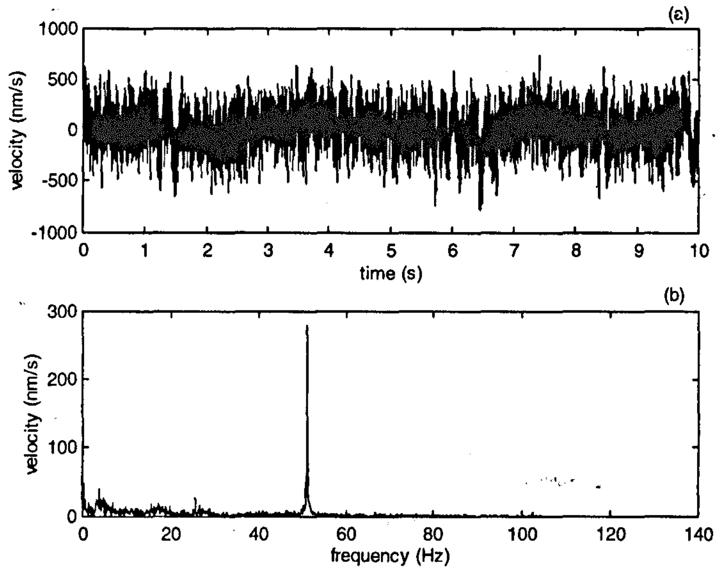

Figure 2. Z-component microseismic recording at 261 Sommerfield Road on 7/5/97, at 01:06 BST. (a) Time series and (b) Frequency spectrum.

Figure 3a (data recorded at 07:30 BST) presents even stronger vibration levels (~100000 nm/s) of similar character to those recorded earlier (at 00:10). However, although the FFT (Figure 3b) reveals an extremely large vibration level at 10 Hz (~6000 nm/s), this peak is not as sharp as it was previously, with more of a broadband character, and no harmonics of 10 Hz are clear above background noise levels.

It should be mentioned at this point that, given the hard nature of the surface on which the seismometer is mounted and the high velocity levels recorded, the vibrations observed are unlikely to be caused by acoustic waves, and so the signal in this case appears to be ground-borne.

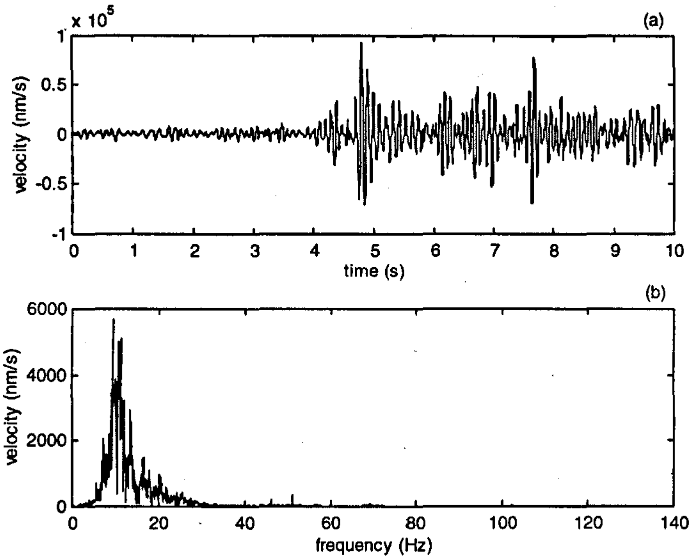

Figure 3. Z-component microseismic recording at 261 Sommerfield Road on 7/5/97, at 07:30 BST. (a) Time series and (b) Frequency spectrum.

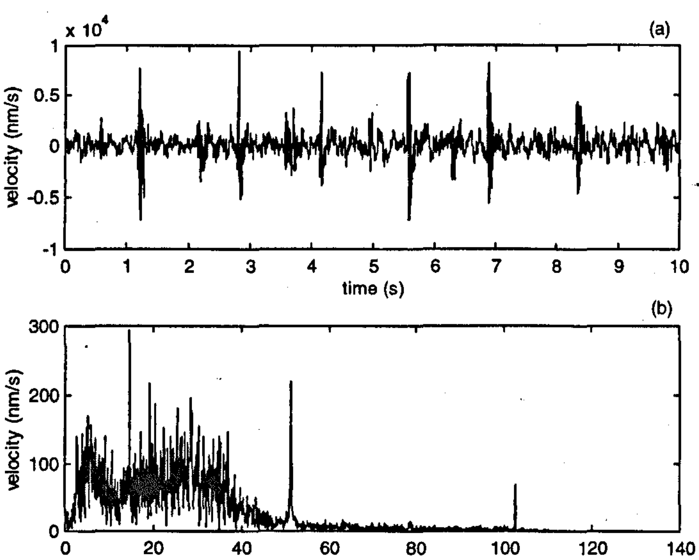

Figure 4. Z-component microseismic recording at 261 Sommerfield Road on 7/5/97, at 98:00 BT. (a) Time series and (b) Frequency spectrum.

A different type of perturbation is present in the Sommerfield Road data shown in Figure 4. The time series consists of very sharp impulses, spaced at irregular intervals of 0.5-1.5 seconds, and the FFT displays a very broadband signal, with no peaks of velocity greater than 300 nm/s. This event was recorded at 08:00 BST, shortly before the Vibrosound was switched off, and the impulsive jolts are probably due to the footsteps of the waking occupants of the house. This is effectively noise in the data, and it is easily distinguishable, both in the time and frequency domains, from the strong signal seen in Figures 1 & 3.

Discussion with the occupants revealed that several potential sources for the 10 Hz vibrations lie within 2 km of the house, including gas and water pumping stations, an electric power station, a motorway and a factory with compressor. It has not yet been determined which of these, if any, is responsible. (However, the nearby motorway would not produce vibrations of such tonal characteristics as was observed, and indeed noise from the motorway apparently sometimes masks the "hum", providing relief to the sufferers).

63 Ty Draw:

This house, which is situated on the corner of a sloping cul-de-sac in a hilly area, overlies sandstone bedrock within the Carboniferous Coal Measures.

The seismometer was positioned to record in the downstairs lavatory on a hard concrete floor, which appeared to be the best surface for receiving microseismic signals. However, the resultant vibration levels (all three components) were very low, even though the "hum" was in this case audible to the author. Once again, all data displayed below represent Z-components of the 3-dimensional vibrations recorded.

Figure 5 shows a typical event recorded during the night (at 06:13 GMT on 13/3/97), with velocities of <300 nm/s in the time series, and 50 Hz electrical noise in the instruments swamping the extremely low background vibrational levels (<30 nm/s) of individual frequencies on the FFT.

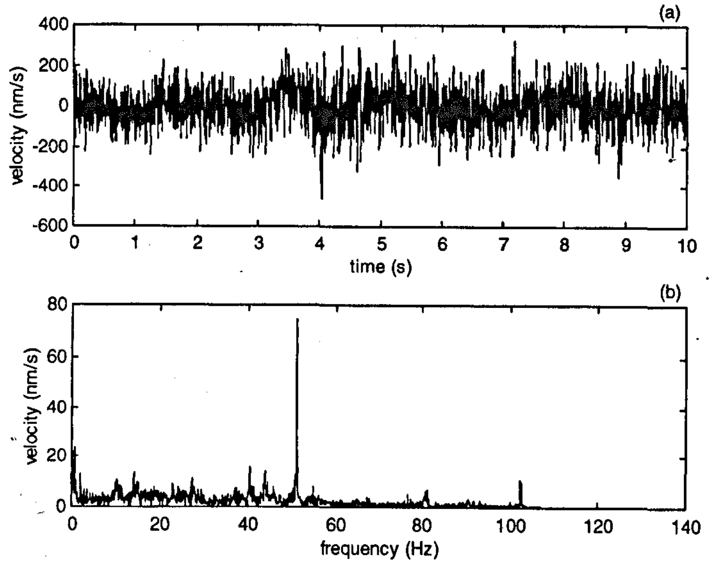

Figure 5. Z-component microseismic recording at 63 Ty Draw (downstairs lavatory) on 13/3/97, at 06:13 GMT. (a) Time series and (b) Frequency spectrum.

At 06:53 GMT, some sort of disturbance occurred giving ground velocities of ~6000 nm/s (Figure 6a), but the FFT (Figure 6b) indicates that the perturbation was extremely broadband (over 10-40 Hz) and not very tonal (unlike the "hum" described by the occupants), and still consisted of very low amplitude frequency domain peaks (<180 nm/s). This event was probably caused by the passing of early morning traffic nearby.

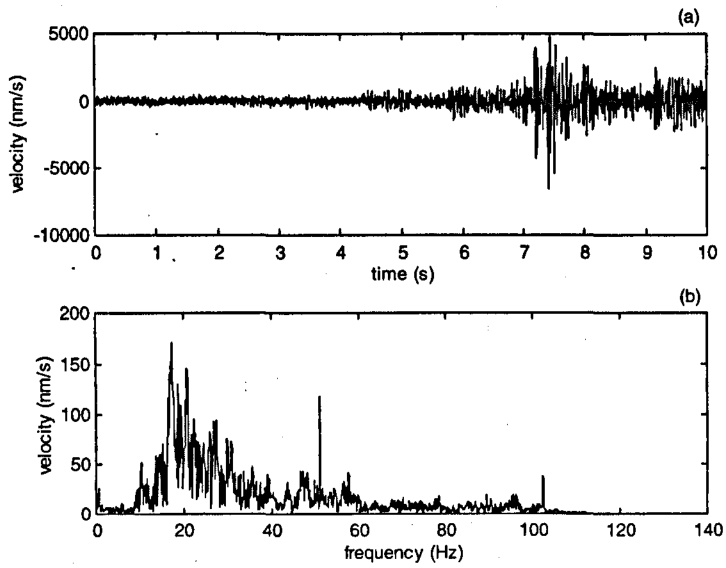

Figure 6. Z-component microseismic recording at 63 Ty Draw (downstairs lavatory) on 13/3/97, at 06:53 GMT. (a) Time series and (b) Frequency spectrum

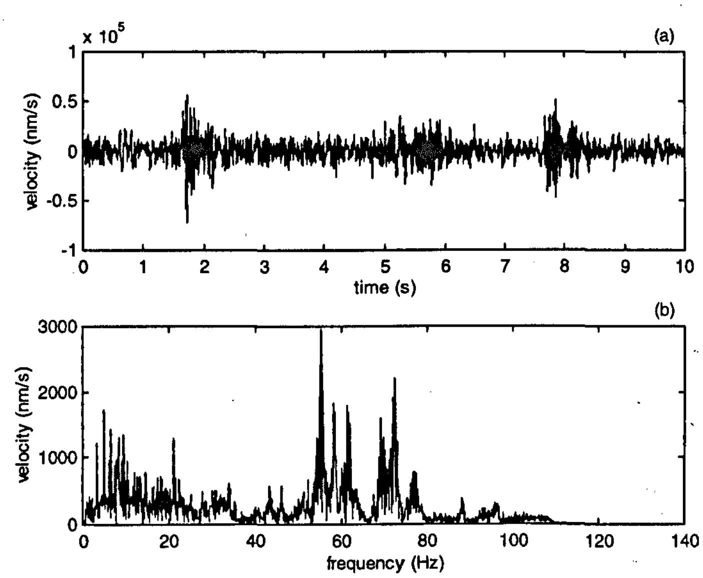

Figure 7. Z-component microseismic recording at 63 Ty Draw (upstairs bedroom) on 13/3/97, at 08:46 GMT. (a) Time series and (b) Frequency spectrum.

The next morning, the seismometer was placed on bare floorboards in an upstairs bedroom, one of two East-facing rooms in which the "hum" is perceptibly louder than elsewhere. Figure 7 displays the results, recorded at 08:46 GMT. Vibration velocities were much higher than observed earlier (~60000 nm/s). Frequency analysis reveals strong (~1000 nm/s) peaks, separated by

~1.6 Hz, over the frequency range 0-20 Hz. These may be harmonics of some sort; they could relate to the source of the "hum" or to traffic driving by. Peaks of velocity ~2000 nm/s are also seen around 57 and 73 Hz; the room dimensions are 3 x 3.6 metres, and these peaks seem to correspond to eigenfrequencies of acoustic standing wave resonances in the room.

In any case, it seems clear that the high velocities recorded in the bedroom are caused by acoustic waves exciting the floorboards in vibration. A large industrial estate lies 2km East of the house, and this or some other nearby sourece seems to be responsible for a predominantly air-borne "hum" encountered at Ty Draw.

CONCLUSIONS

Several elements have emerged from this study:

- The low frequency "hum" does not propagate exclusively by either ground-borne or air-borne mechanisms, and so there is a need for both microseismic and acoustic research into the problem;
- It is possible to record low frequency acoustic tones using seismometers, where floor structures have been excited into vibrational modes by acoustic waves;
- The vibration levels experienced by "hum" sufferers are low (when compared with, for example, the levels (Figure 8) stated in BS 6472: 1992), but it is possible with highly sensitive seismometers to discern tonal and other characteristics of the "hum", which may eventually yield a diagnosis of the cause in some instances. It may then be possible for those responsible to take remedial action, in order to allow some relief to sufferers;
- Whilst the "hums" perceived by sufferers may not exceed the vibration levels stated in BS 6472 (Figure 8), it has become clear that many people's health and quality of life are affected to their detriment by low frequency noise and/or vibration. There is therefore an urgent need for a British Standard that gives guidelines relating to acceptable levels of continuous low frequency vibration in homes, particularly where this is tonal in character. Similarly, the weighting curves currently applicable to measurements of low frequency and 'infrasonic' noise (Bruel & Kjaer, 1984) need modification.

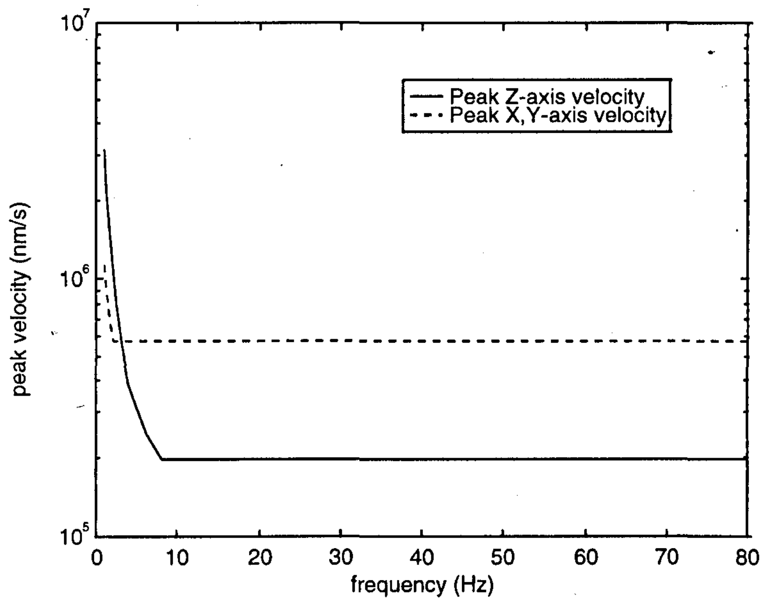

Figure 8. Plot showing BS6472 maximum permitted levels of continuous vibration for residential areas at night.

FURTHER MICROSEISMIC WORK

- Further work needs to be done to establish the causes/sources of the low frequency vibrations detected. Tonal frequencies, once established in the recorded data (e.g. 10 Hz at Sommerfield Road), may be compared with the operating frequencies of industrial machinery in the surrounding region. It is important to bear in mind, though, that low frequency waves may propagate over large distances (several kilometres) with little attenuation;
- More research needs to be done into the interaction of waves (both ground- and air-borne) with building structures (floors, walls, windows, etc.);
- A good vibrational coupling between seismometer and mounting surface is important in microseismology, and this must be accomplished especially for outdoor work;
- It may eventually be possible by using an array of three-component seismometers, to determine the directionality of low frequency environmental vibrations, and thus pinpoint accurately and directly the source of a "hum" disturbance.

ACKNOWLEDGEMENTS

The authors would like to thank the various members of the UK Low Frequency Noise Sufferers' Association who assisted in the undertaking of this research. The hospitality of Ms Jones and the Gardners was particularly appreciated.
Ian Rushforth acknowledges the N.E.R.C. for the funding of a studentship.

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APPENDIX A: A STUDY OF RESPONSE OF SUBJECTS TO LOW FREQUENCY VIBRATION CALLED "THE HUM"

Dr D M J P Manley, Chairman, LFNSA UK

1991 Survey of Members of the UK Low Frequency Noise Sufferers' Association
(104 replies out of 164 questionnaires distributed)

Age + Male or Female	28% male 72% female	Average age is 60 years old.
Have you suffered over 20 years?	7%	63% have suffered less than 10 Years
Have you suffered over 10 years?	30%	
Consulted your doctor?	62%	
Do you have Tinnitus and hear The "hum"?	29%	
Can you be sure the noise is outside the head and ears?	91%	Perhaps your local Tinnitus Association would be interested in this result.
Have you reported it to your local Environmental Health Dept?	70%	
Good or bad response?	29% good.	
Any readings done?	25%	
When the "hum" intensity is low is there any other LFN that is Troublesome (at night time)?	25%	
Is it a *continual* all night long LFN without any breaks of more than a second?	71%	High percentage of disturbed nights.
Effects on Health		
Nervousness	50%	
Headaches	47%	
Disturbed sleep	83%	
Lack of concentration	64%	
Depression	54%	
Blurred vision for some time after waking	31%	

1997 survey of 35 LFNSA Members from the Questionnaire in News Sheet No. 7
1. I wish to know about factors concerning where you live and also any other locations where you have experienced LFN at high volume:
a) Do you describe the land as level or hilly (what gradient, please)?
b) Do you know what type of rock you live on (sedimentary information)?
c) Do you live on the crest of a ridge, hill, edge or eminence?
d) Location of any nearby factories, manhole access to gas or water pipes, etc.?
e) Any other suspected source of LF noise, including your theories.

1a) 80% of replies were on level ground, none on very high ground.
1b) 70% referred to chalk and clay base – good transmitters of LF vibration.
1c) Nearly all replies did not live on a ridge.
1d) Several manholes were referred to – mainly British Gas, but several questionnaires referred to electricity substations and two to radio transmitters.
1e) A range of possible sources of "hum" were suggested:

The whole pattern does show a majority verdict that refers to resonances in underground pipes of some sort, as a source for the "hum". British Gas transmission pipes were the most commonly quoted example. One has to bear in mind that not only are there gas pipes present in industrialised regions, but also water mains and other chemical pipes as well as sewers.

To increase the difficulties of conclusive evidence, it was found that several people were detecting low-powered LF noise from such sources as refrigerator motors, central heating motors, lift motors (in flats), ventilation motors and even electrical hum from meters and transformers. All these noises are predominant in the 40 – 200 Hz frequency spectrum and are very local. People have attempted to capture the "hum" using small motors and this is easily recognised by the trained acoustician.

Many subjects thought that electrical fields may be a cause. The author has investigated a very large short and medium wave transmission site and questioned workers and visitors at the site – no reports of effects of LF radiation were reported, similarly with people working near high-powered microwave terminals and particularly satellite stations where enormous pulsating radio radiation is predominant.

2. I wish to know of any serious illness you may have and whether there is any recorded deafness, as well as your age bracket (e.g. "fifties") and gender.

2. A surprising and helpful fact has emerged – that is that 80% of the replies from people that have some form of deafness, have quoted that one ear is affected, demonstrating that many sufferers have asymmetric hearing that is not balanced. This may have great relevance to the mechanism of "hum" perception.

The age range is from 44 to 84 with an average age of 67-68 and median of 66. High frequency hearing sensitivity is known to deteriorate with age, leaving one relatively more sensitive to low frequency noise as one gets older.

65% of sufferers were women; 35% were men. Elizabeth Griggs in 1991 did a survey showing then that 72% were women and 28% were men. Both surveys show that women suffer more than men, but it must be borne in mind that the average life expectancy of women is higher.

3. It has been extremely useful to view LOGS of when the hum is detected and whether it has been very loud (Strength 5), loud (Strength 4), moderate but not disturbing (Strength 3), just detectable (Strength 2) or not detected (Strength 1).

If you have many sheets to such a log, please let me have a sample of then of the very worst cases of annoyance and cases of relative quiet.

3. COMMENT: Poorly answered.

4. a) Do you find the weather, e.g. fog, rain or snow, affects your feeling?

b) *Do you find that LFN is always stronger indoors and weaker outside?*
c) *Do you get a modulation, e.g. a warble or pulsation?*
d) *How would you describe what you feel?*
e) *Does the hum have any musical note?*
f) *In which room of your house do you feel the hum most?*
g) *When did you first detect the hum (date if possible)?*
h) *Has an EHO or acoustician taken noise-spectra traces and please may I see them?*
i) *How has this hum affected your general health?*
j) *Any other technical comments.*

4. This was the most interesting.

4a) showed clearly that foggy weather showed maximum "hum", also when it was very hot or very cold. N.B. One would expect acoustic waves to be more heavily attenuated in foggy conditions.

4b) showed a 97% consistency that the "hum" was only heard indoors.

4c) Modulation and pulsation were clearly indicated in 70% of the cases, and I suspect the 30% that did not answer this question did not understand it.

4d) Answers often described a hissing sensation; vibrations in one's bones was a common response.

4e) Only one answer stated that the "hum" had a musical note; majority of over 80% of replies indicate that they could not feel or hear a musical note – suggesting LF waves of no discernible pitch.

4f) people answered that the "hum" was worst in the bedroom, although 30% stated LF waves of no discernible pitch.

4g) The spread of dates when the "hum" was first occurred varied from 1959 to 1996 with the MEDIAN being 1989 – most popular column was 1995. This information shows that recent industrial developments, such as the installation of national gas transmission pipes, may not be the only source of the "hum".

4h) Environmental Health Officers were called in most cases and many detected the "hum" but NONE did anything about it!

4i) 80% of people mentioned loss of sleep and difficulties in sleeping – clear indications that the "hum" is worst at night time.

4j) Much additional data has been sent and was most helpful. It is clear that many logs were taken and the "hum" appeared at different intensities and different times. There is however one factor that is most important – every case I have seen shows that sufferers experience the "hum" worst when the ambient background noise level is LOW (e.g. inside the house at night), and therefore masking effects are important in determining whether or not the "hum" is audible at any given time and location.

INDUSTRIALLY INDUCED LOW FREQUENCY NOISE & VIBRATION IN RESIDENTIAL BUILDINGS

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1. INTRODUCTION

This paper describes a system developed to provide comprehensive coverage of the sound & vibration spectra within the residences of low frequency noise/vibration sufferers situated near to industrial sites. Case studies are employed to illustrate the effectiveness of the integrated acoustic/microseismic approach.

Standard acoustic techniques alone have often proved ineffective at tackling low frequency problems, yet seismic techniques alone are insufficient in many cases to prove that a statutory nuisance exists. By combining the two disciplines, the chances of determining the source of the disturbance and the propagation path (airborne, groundborne or both) is greatly enhanced. Remedial work can then be undertaken to alleviate the problem.

A German national standard (DIN 45680) was utilised in the case studies to assess the measured levels of airborne noise. This proved to be a good predictor of annoyance.

2. EXPERIMENTAL TECHNIQUE

2.1 Equipment

Data were logged on a six channel Vibrosound 24-bit A/D recording system with a bandwidth of 0-125 Hz. The a.c. outputs from a three-component seismometer, microphone and window-mounted accelerometer were fed into the Vibrosound. This system was set up to provide recordings of the sound and vibration levels in an unoccupied bedroom. Over a period of several days and nights, ten-second time series events were collected which could later be analysed in both time and frequency domains. Another seismometer was also located on the ground floor slab; this was linked to a PC that recorded the ground vibration and allowed groundborne and airborne disturbances to be distinguished. (*Figs 1 & 2).*

2.2 Analysis

Individual time series events were analysed in both the time domain and, by Fast Fourier Transform, in the frequency domain. The length of the events analysed (ten seconds) gave a resolution in the frequency spectra of 0.1 Hz. The presence of characteristic frequency components or impulsive events helped to match the disturbance to specific machinery parts in nearby industrial sites, particularly where rotating machinery with fixed operating frequencies were present. In this way, a process of elimination could be carried out to decide which elements of the site(s) were to blame for the noise nuisance leading to complaints, and what course of action could be taken to reduce the overall noise/vibration levels in the residences of the complainants.

2.3 Standards Used To Assess Noise/Vibration Levels

The British national standards designed to deal with industrial noise pollution problems may not always be adequate in dealing specifically with low frequency noise, being based on A-weighted sound pressures in which low frequencies are significantly de-emphasised. In the research outlined in this paper, the German national standard DIN 45680 [reference 1] was used to ascertain whether or not the sounds recorded were of an acceptable level and/or nature. DIN 45680 places particular emphasis on tonal and impulsive/fluctuating low frequency noise, and has been reported to be a reasonable predictor of whether or not a low frequency noise is likely to give rise to complaints in residential areas [reference 2]. In the analysis third octave bands were constructed by applying a root-mean-square method to the sound pressure-frequency spectra, so that the dB(Linear) levels of the bands could be compared with the DIN-recommended levels.

BS 6472 [reference 3] is the British national standard in which recommended levels of vibration in residential areas are laid down. There is some controversy over the levels given, particularly for intermittent vibration. It is thought by some researchers to be too liberal, in terms of acceptable night-time low frequency vibration levels in the home [reference 4]. However, no viable alternative has yet been devised.

3. CASE STUDY A

3.1 Initial Investigation

Measurements were made at three households on a housing estate near to an industrial site over a period of one month. In addition, the residents were asked to log their subjective impression of how the disturbance varied over the monitoring period.

FFT analysis of the time series data showed the presence of fluctuating low frequency tones on the estate (see *Fig 3*). These were apparent in the data recorded by the microphone and window-mounted accelerometer channels of the Vibrosound.

Two of the tones (12.5 Hz and 38 Hz) were sometimes at a dB level that would be considered disturbing according to the German national standard DIN 45680 (see *Fig 3*). The variation of amplitude of the tones with distance was consistent with them emanating from the nearby industrial site. It was found that in the 40 Hz third octave band, which contains the 38 Hz tone, the RMS sound pressure levels most often exceeded the recommended DIN level in the household whose occupants reported most disturbance during the monitoring period (that is, the house nearest to the suspect site).

No excessive groundborne vibration levels were recorded in the households; night-time levels were generally more than two orders of magnitude below those prescribed in BS 6472. This, combined with the high amplitudes measured by the window-mounted accelerometer, led to the conclusion that the disturbance had an airborne transmission path.

A further study was proposed with a view to pinpointing the source.

3.2 Sequential Shutdown Experiment

Following on from the previous study, a sequential shutdown experiment was arranged one evening in conjunction with the local council and the suspect industrial site. Each item of machinery was shut down in turn, and then switched on again in turn, whilst sound & vibration levels were monitored at the nearest household to the industrial site. In addition, residents of the housing estate made detailed notes on their subjective experience of the level of disturbance throughout the experiment. The residents were not told which items of plant were operational at any given time, though this information was logged and provided to the investigating team for analysis.

Results of this test confirmed the findings of the previous study i.e. that during full operation of the plant, a fluctuating low frequency noise was present in the house of tonal character. Peaks of 12.5 Hz and 38 Hz were prominent in the frequency spectra. The periods when the 40 Hz third octave band exceeded the DIN-recommended dB level, correlated reasonably well with the times when the residents reported that they could hear a noise similar to the one that led to the complaints. *Figs 3 & 4*, which were constructed respectively from data recorded just before and just after total shutdown, illustrate these points.

The disturbance was again shown to have an airborne transmission path and the variation in level from when all machinery was in full operation to when all was shut down, showed beyond reasonable doubt that the industrial site under study was the source of the noise. In addition, the source was traced to two particular items of plant (fans with operating frequencies around 38 cycles per second which were operational during the time of *Fig 3* but not *Fig 4*); these were selected for implementation of noise control measures.

3.3 Further Investigation

A third experiment is proposed for this case study, to take place after noise control measures have been implemented. This would test the effectiveness of the noise control measures, in terms of reducing the low frequency noise levels and subjective disturbance at the housing estate.

4. CASE STUDY B

4.1 House Measurements

The technique outlined above was used in another, similar case study. Equipment was set up in an unoccupied bedroom of a house near an industrial estate where the residents had complained about a local low frequency noise/vibration problem. This noise was described as having a 'throbbing' character. Monitoring took place over a period of four consecutive nights. Again, the residents made notes outlining their subjective impressions of the intensity of the disturbance throughout that time.

FFT analysis of the microphone time series data yielded two significant peaks in the frequency spectrum around 50 Hz, namely 48.1 Hz and 49.3 Hz (*Fig 5(b)*). On the two nights perceived as 'relatively noisy' by the residents, the amplitudes of these peaks were such that the RMS sound pressure level for the 50 Hz third octave band tended to exceed the level recommended in DIN 45680 by about 1-2 dB (*Fig 5(c)*). Conversely, on the two nights described by the residents as 'reasonably quiet', the 50 Hz third octave band had a dB level which fell below the DIN curve by typically 2-3 dB.

Furthermore, the close proximity of the two frequencies (the peaks are 1.2 Hz different in frequency) raised the possibility that they were 'beating' together to create the fluctuating sound levels. This was compatible with a 'throbbing' occurring at around 1 cycle per second as described by the residents, and also as perceived by the authors on site. A digital Butterworth band-pass filter was applied to some of the ten second events from the microphone channel, to create time-domain filtered records for the 50 Hz third octave band; these illustrate the fluctuations due to 'beating' quite well (*Fig 6(a)*). This also illustrates the flexibility of the methodology used and described in this paper.

Once again, excessive vibration levels were not picked up in the ground floor slab of the house. Vibration levels at night, when traffic was minimal, were at least an order of magnitude below those recommended in BS 6472. Thus it was again concluded that the transmission of the disturbance was airborne.

4.2 Factory Investigation

With the co-operation of the proprietors, a factory close to the household where the measurements had taken place was investigated to see if the source of the 48.1 Hz and/or 49.3 Hz tones could be located. It was found that a fan within the factory had an operational frequency around 49 Hz; indeed, an accelerometer mounted on the fan casing showed there to be a peak present in the vibration spectrum at precisely 49.3 Hz. No source of the 48.1 Hz peak was found. However, it is hoped that if noise control measures were to be carried out on the fan identified, the other peak might have 'less to beat against' and thus the problem might at least be reduced.

5. CONCLUSIONS

The case studies outlined above demonstrate the advantages of taking an integrated acoustic/microseismic approach when tackling low frequency noise/vibration problems. A lot of useful information can subsequently be obtained by recording raw data in the time domain which can then be processed in numerous ways. Both time series and frequency spectra can be constructed and other informative analysis such as filtering may be carried out. The relatively long event lengths (10 s) give rise to frequency spectra with high frequency resolution (0.1 Hz) which aids source determination. The wide range of instrumentation used (three-component seismometers, microphones and accelerometers) gives great scope for analysis and allows transmission paths to be ascertained.

The German national standard DIN 45680 proved to be a reasonably good predictor of whether a particular low frequency noise in a residential area is likely to give rise to complaints, particularly where that low frequency noise is strongly tonal and/or fluctuating/impulsive in character. DIN 45680 may be a useful tool for researchers or local authorities investigating similar problems.

6. REFERENCES

[1] DIN 45680 : 1997. Messung und Bewertung tieffrequenter Geräuschimmissionen in der Nachbarschaft.

[2] D PIORR & K H WIETLAKE (1990). Assessment of Low Frequency Noise in the Vicinity of Industrial Noise Sources, *Journal of Low Frequency Noise & Vibration*, 9(3).

[3] BS 6472 : 1992. Evaluation of Human Exposure to Vibration in Buildings (1 Hz to 80 Hz).

[4] Personal communication, Dr David Manley, Low Frequency Noise Sufferers' Association.

Figure 1 *EQUIPMENT SET-UP*

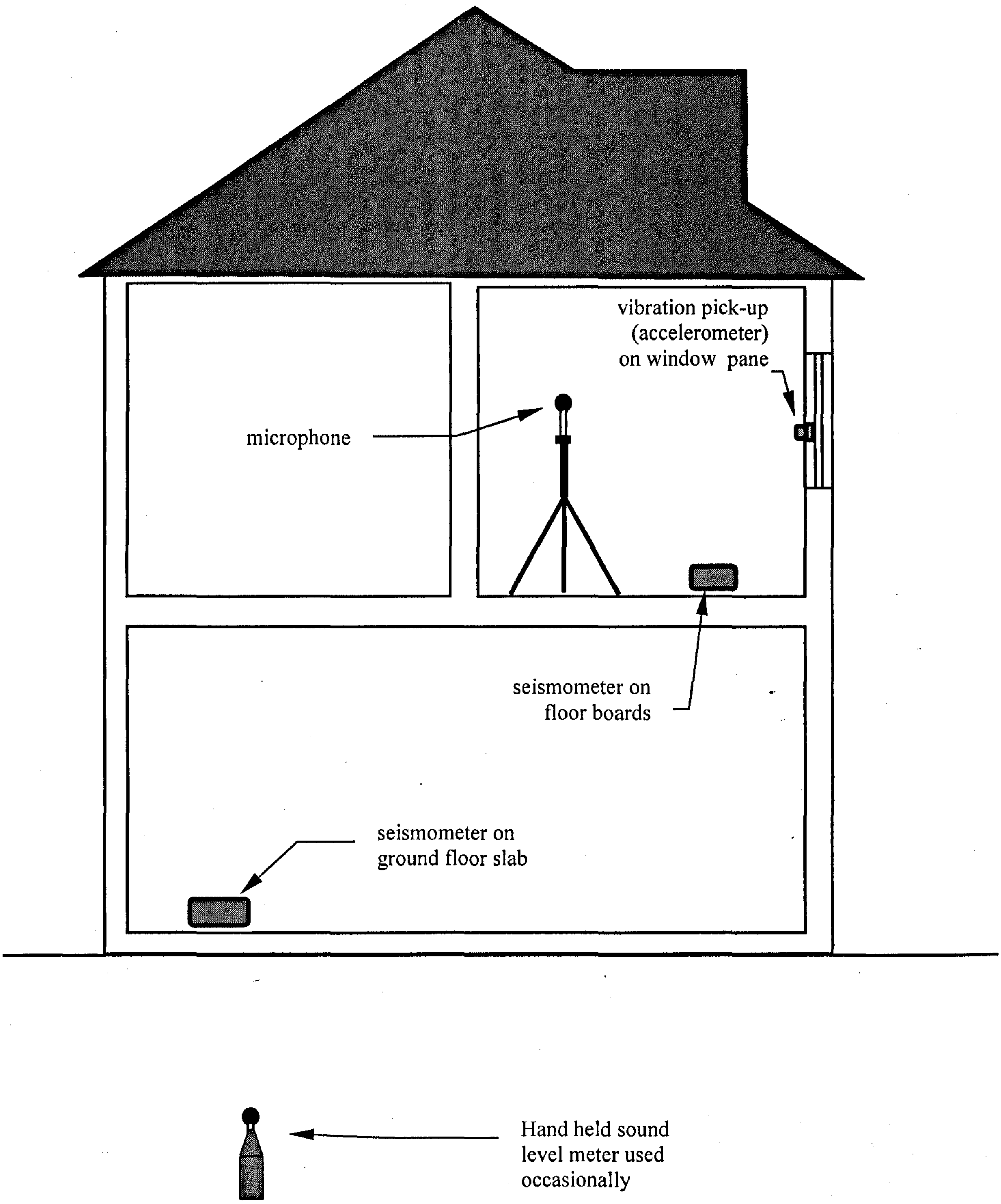


Figure 2 *IDENTIFICATION OF EXTERNAL AND INTERNAL NOISE/VIBRATION SOURCES AND TRANSMISSION PATHS*

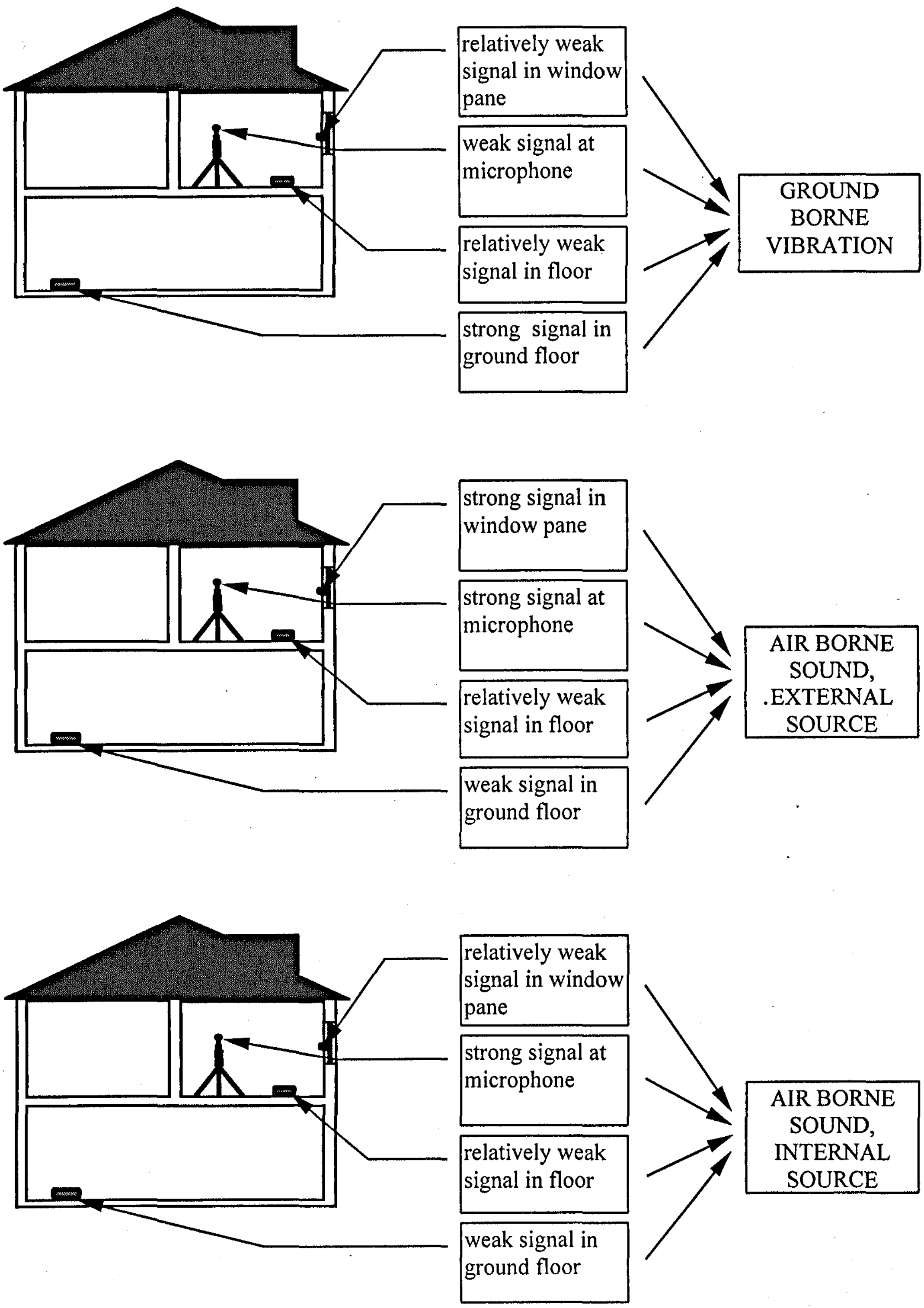


Figure 3 **CASE STUDY A:** *SOUND LEVELS AT HOUSEHOLD NEAREST TO INDUSTRIAL SITE DURING SHUTDOWN EXPERIMENT, SHORTLY PRIOR TO TOTAL SHUTDOWN. RESIDENTS DESCRIBED HEARING A 'PULSATING NOISE' AT THIS TIME. FANS WHICH WERE LATER SELECTED FOR NOISE CONTROL IMPLEMENTATION WERE ACTIVE.*

(a) time history, showing 12.5 Hz pulsing;
(b) narrow band spectrum, showing peaks at 12.5 Hz and 38 Hz;
(c) third octave band spectrum compared with DIN 45680 night-time limits.

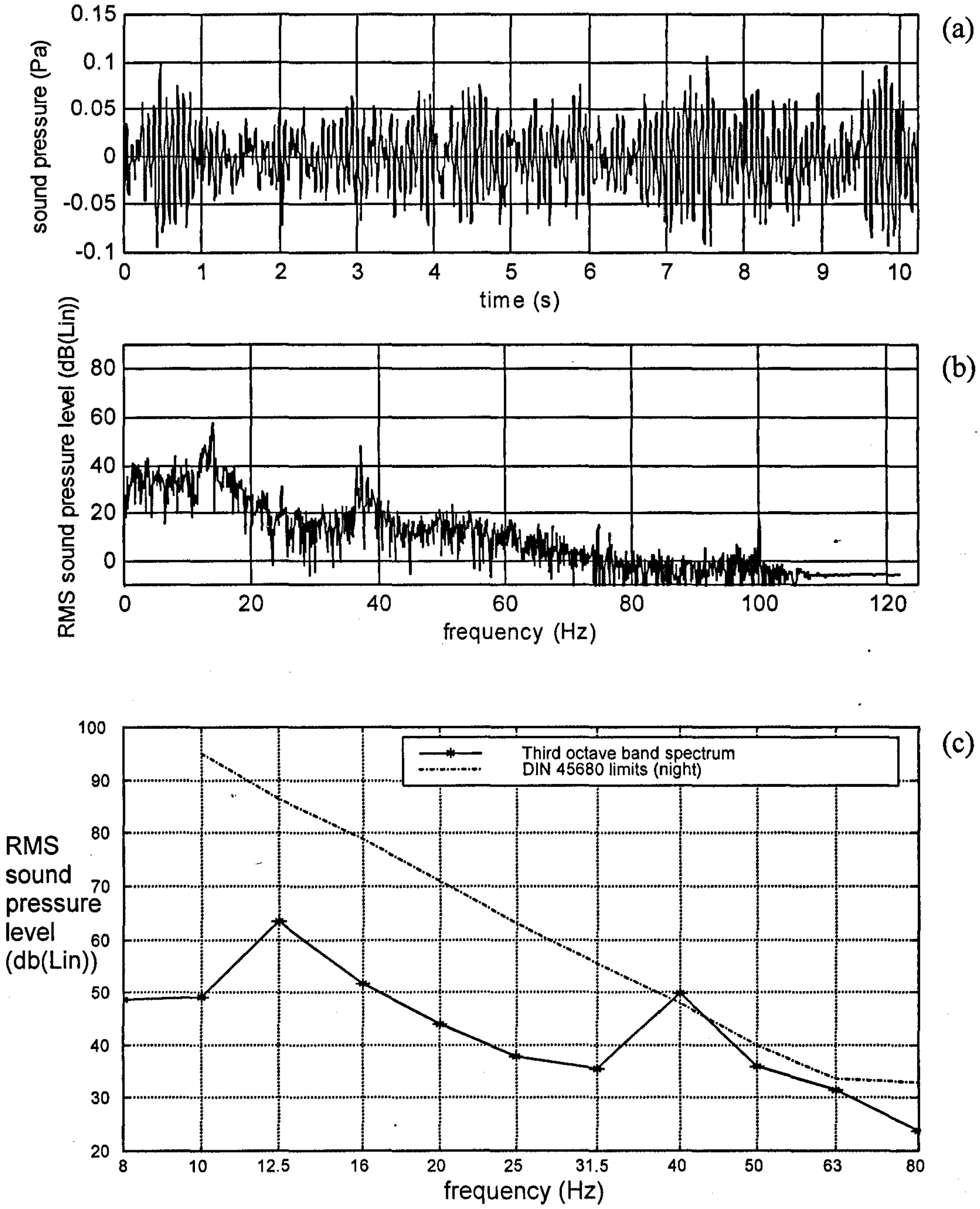
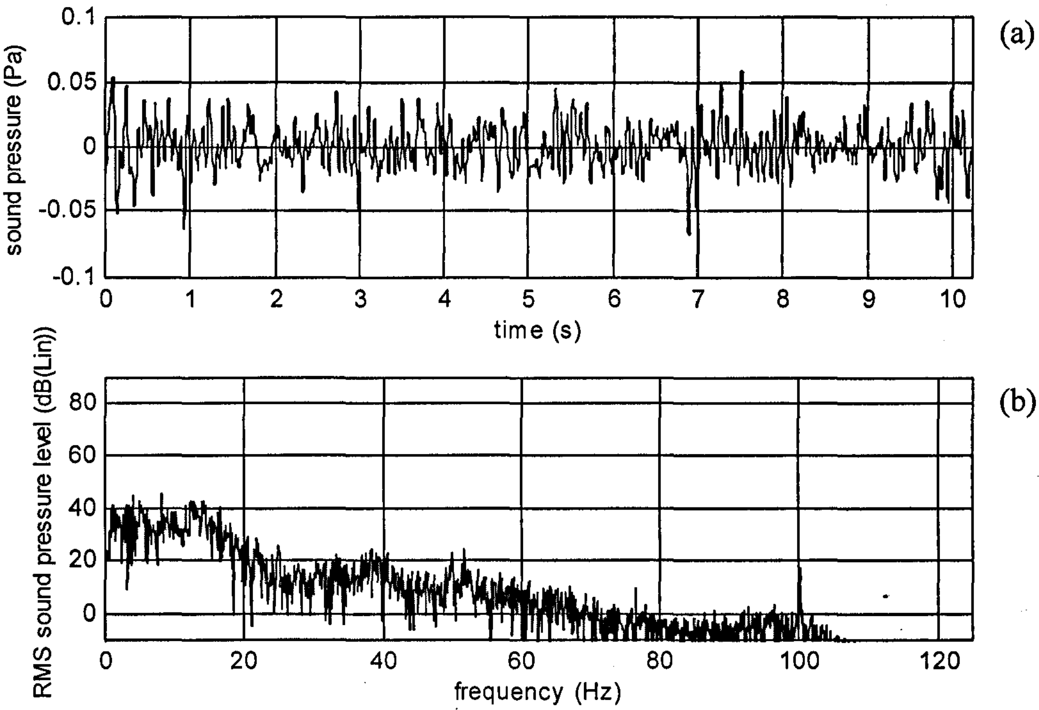


Figure 4 ***CASE STUDY A:*** *SOUND LEVELS AT HOUSEHOLD NEAREST TO INDUSTRIAL SITE DURING SHUTDOWN EXPERIMENT, SHORTLY AFTER TOTAL SHUTDOWN. RESIDENTS STATED THAT DISTURBING NOISE HAD STOPPED. FANS THAT WERE LATER SELECTED FOR NOISE CONTROL IMPLEMENTATION HAD BEEN SWITCHED OFF BY THIS TIME.*

(a) time history, 12.5 Hz pulsing is absent;
(b) narrow band spectrum, 12.5 Hz and 38 Hz peaks are absent;
(c) third octave band spectrum compared with DIN 45680 night-time limits.



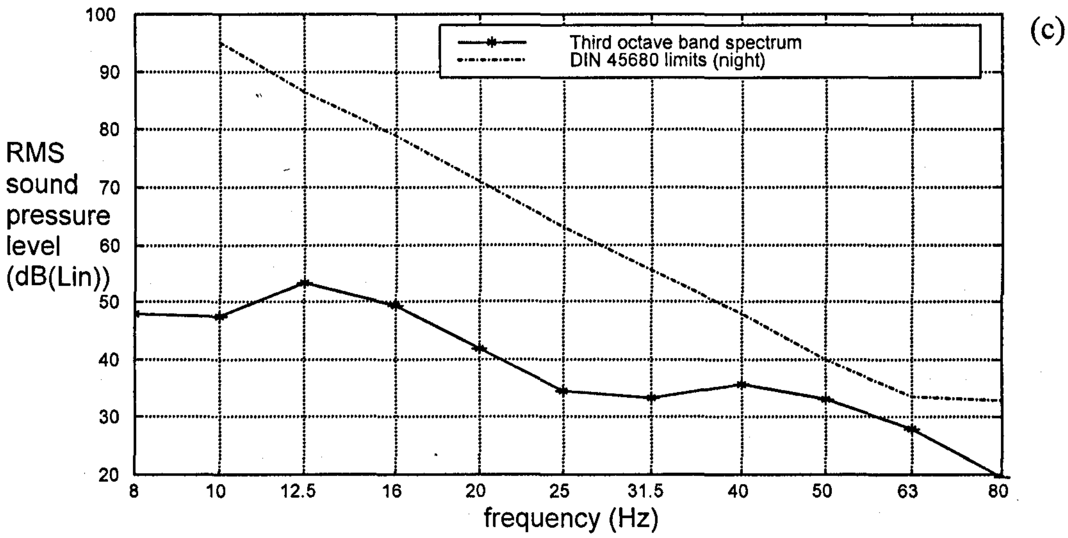
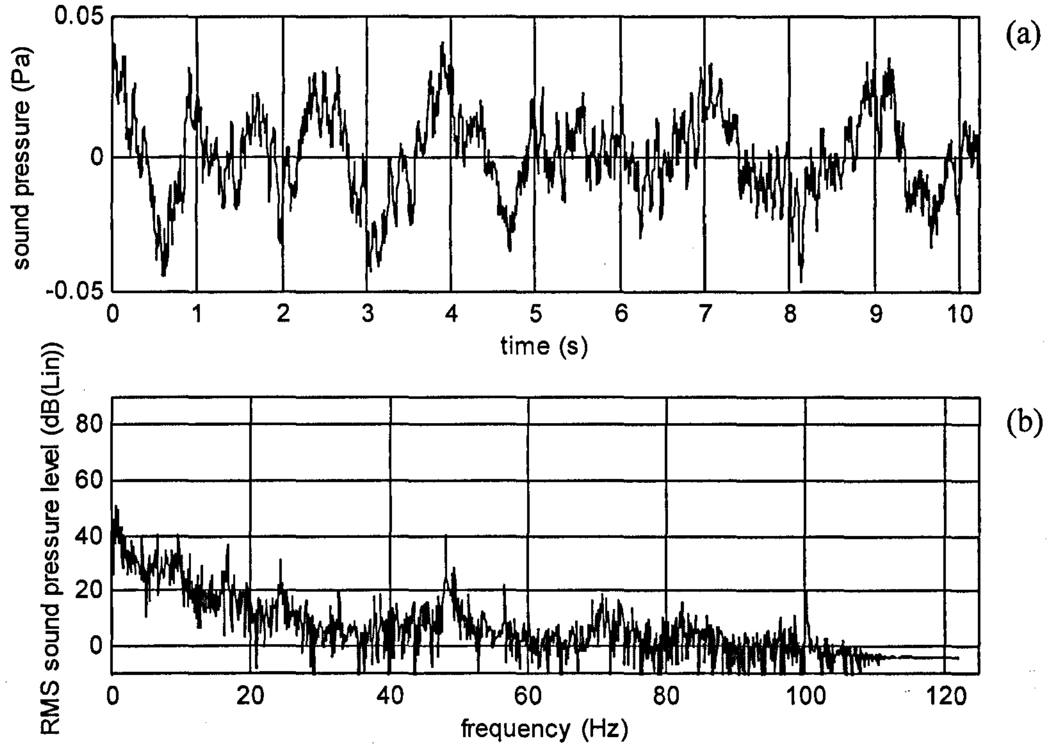


Figure 5 ***CASE STUDY B:*** *TYPICAL SOUND LEVELS AT A HOUSE NEAR TO AN INDUSTRIAL SITE, WHERE THE RESIDENTS COMPLAINED ABOUT A LOW FREQUENCY 'THROBBING'.*

(a) *time history;*
(b) *narrow band spectrum, showing prominent peaks at 48.1 Hz and 49.3 Hz;*
(c) *third octave band spectrum compared with DIN 45680 night-time limits.*



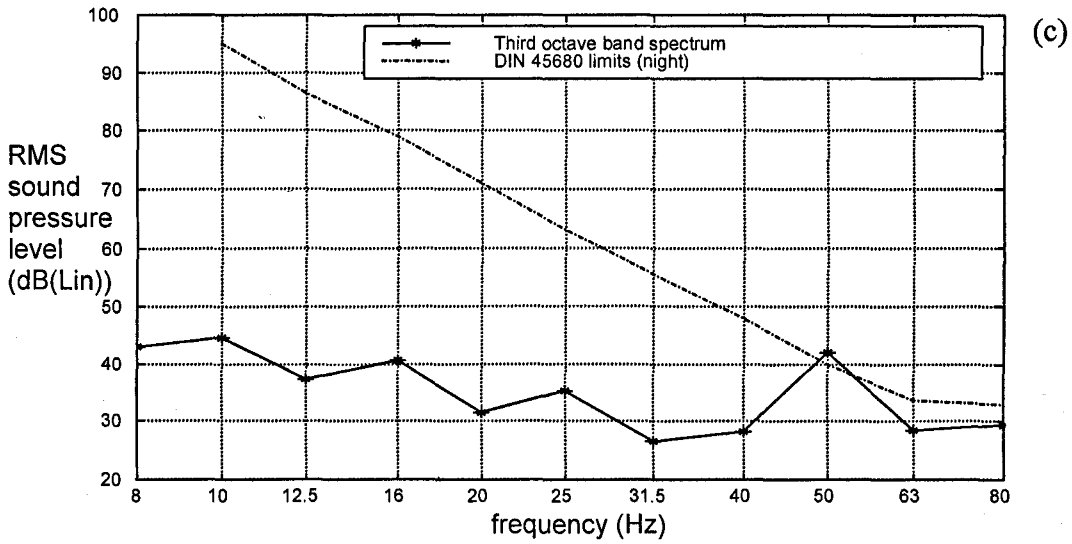
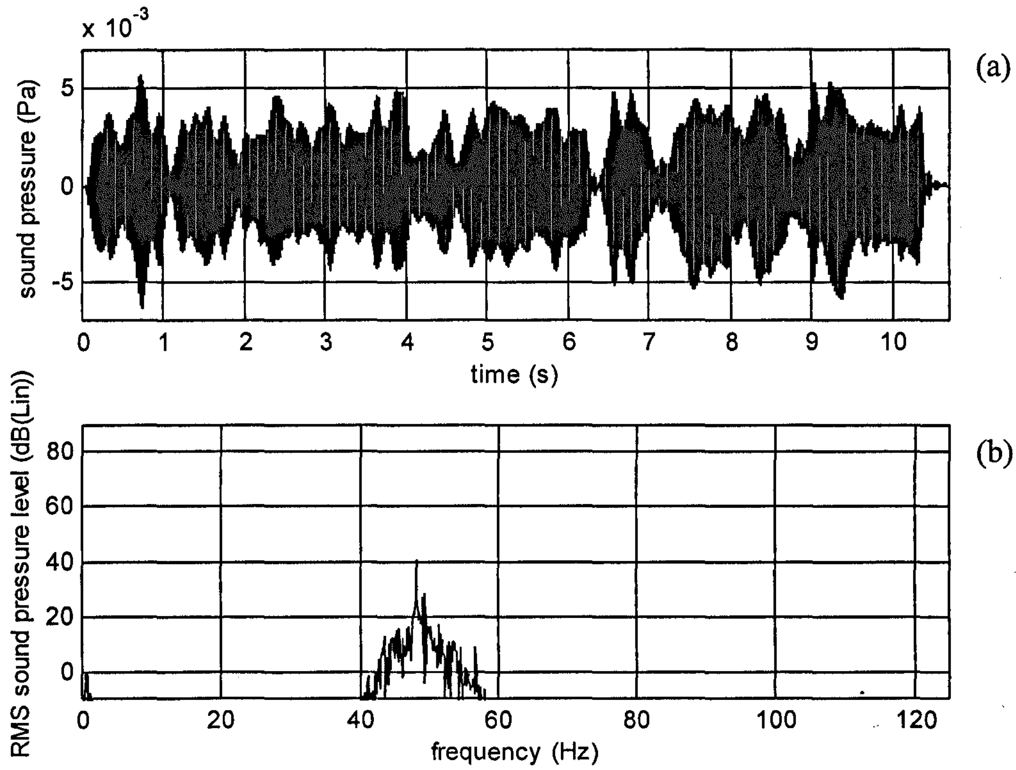


Figure 6 ***CASE STUDY B:*** *THIS FIGURE SHOWS THE SAME 10 SECOND EVENT RECORD AS PRESENTED IN FIGURE 5, AFTER THE APPLICATION OF A DIGITAL BUTTERWORTH BAND-PASS FILTER.*

(a) time-domain filtered record for the 50 Hz third octave band;
(b) filtered narrow band spectrum, showing prominent peaks at 48.1 Hz and 49.3 Hz.



NOTE THE FLUCTUATIONS AT A RATE OF AROUND 1 CYCLE PER SECOND; THIS BEATING MAY EXPLAIN THE 'THROBBING' NOISE PERCEIVED BY THE RESIDENTS.