A Case Study of Low Frequency Noise Assessed using DIN 45680 Criteria

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ABSTRACT

This paper describes a case study in which low frequency noise was suspected of causing disturbance in a semi-rural location close to an industrial estate. Previous attempts using conventional acoustic measurement techniques to resolve the case, or even prove the existence of a real acoustic problem, had proved unsuccessful.

In the present study, the authors applied a novel integrated acoustic/microseismic measurement system, and assessed the resultant data using criteria from the German national standard DIN 45680. Using this approach, the authors successfully resolved the low frequency noise problem and, after a test involving a sequential shutdown at a suspect industrial site, established the precise cause of the disturbance.

The paper thus supports the criteria in DIN 45680 as a predictor of annoyance due to low frequency noise and as an aid in resolving such problems. It also illustrates the flexibility of the combined acoustic/microseismic technique and the advantages of the method over conventional techniques.

1 INTRODUCTION

Environmental low frequency noise is a growing cause of annoyance and a potential hazard to health for many people [1].

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, psychosocial and mental health effects [1].

The primary effect due to low frequency noise appears to be annoyance [2]. Annoyance levels are particularly high in cases where masking effects due to other sources of background noise such as traffic are low [3]. Complainants therefore often dwell in otherwise quiet rural or suburban areas.

There is often an apparent contradiction in low frequency noise cases between individuals claiming to be suffering unbearable noise exposure and the inability of others to perceive any low frequency sound at all. This may be explained by the fact that contours of equal loudness of sound are very tightly spaced at low frequencies, so that for an individual, a slight increase in sound level of low frequency noise can cause a large increase in subjective loudness level [4]. In addition, 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. Sensitivity to low frequency noise also appears in some individuals to build up over time.

The number of industrial noise sources capable of creating low frequency noise is increasing, as plant and equipment sizes become larger. However, neither British nor International standards dealing specifically with low frequency noise problems exist as of yet.

This paper details a case study that illustrates the urgent need for improved diagnosis of low frequency noise problems. In order to enhance the prospects of successful diagnosis, a novel measurement methodology was used and assessment was made against objective criteria from a German national standard.

2 ASSESSMENT OF LOW FREQUENCY NOISE

Conventional methods of assessing environmental noise are based on A-weighted sound levels. The A-weighting filter largely de-emphasises low and high frequencies 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).

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 [4,5,6,7,8]. 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 [8].

Several authors have proposed alternative low frequency noise assessment techniques [4,9,10], 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 [5].

Piorr and Wietlake [5] 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:

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

The limits given by Piorr and Wietlake [5] formed the basis of the German national standard DIN 45680 [11]. These limits (for night-time monitoring) are given in Table 1.

This paper describes the use of criteria from the German national standard DIN 45680 to assess low frequency noise in a case study carried out in Britain. The current legal status of this approach in British law is unclear; nevertheless, DIN 45680 proved to be a valuable diagnostic tool in resolving the case study and as a predictor of annoyance due to low frequency noise. The authors are unaware of any applications of DIN 45680 in case studies reported in English language scientific literature, and it is hoped that the experience reported here will be of benefit to others.

3 MEASUREMENT METHODOLOGY

In order to enhance the prospects of successfully resolving low frequency noise problems, an integrated acoustic/microseismic technique was developed by the authors. The methodology, and the reasoning behind its development, is described in detail in a complementary paper [12]. A brief outline of the measurement strategy is given below.

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 floor-mounted 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 upstairs bedroom with a suspended wooden floor. Over a period of several days and nights, a large number of ten-second time histories were collected which could later be analysed in both time and frequency domains. Another seismometer was located on the ground floor slab; this was linked to a PC that recorded the ground floor vibration.

This set-up, which is shown in Fig. 1, allowed groundborne, airborne and internal (structure-borne) disturbances to be distinguished; this process is illustrated schematically in Fig. 2.

Individual time series events were analysed in both the time domain and (by digital Fast Fourier Transform) the frequency domain. The length of the events analysed (ten seconds) gave rise to narrow resolution in the frequency spectra (0.1 Hz), which was advantageous when matching recorded tones of potentially annoying character, with the operational frequencies of items of plant at nearby factories.

(Note that because the signals encountered in low frequency noise cases are often unpredictable and non-stationary in nature, each individual event was treated as a 'snapshot' and no attempt was made to average the events in either time or frequency domains. This gave rise to frequency spectra in which the background noise between the peaks of interest had a rather 'fuzzy' character.)

The night-time noise limits given in the German national standard DIN 45680 [11] (shown in other cases [5] to be a good predictor of annoyance due to low frequency noise) was used to assess the significance of the measured sound pressure levels in the present study. Third-octave band levels were calculated by summing the squared Fourier spectrum values in the frequency range for each band. In this way, the recorded sound levels could be compared with the DIN-recommended night-time limit for each third-octave band that contained sound of an 'unusual' nature [5] (i.e. highly tonal or fluctuating in level). DIN 45680 suggests conventional third-octave filtering, with levels averaged over one hour during the night (the 'loudest hour' [5]). Nevertheless, the third-octave band levels reconstructed from Fourier spectra for each recorded event proved to be an invaluable guide when assessing the degree of annoyance due to low frequency noise.

The British national standard BS 6472 [13] specifies maximum permitted levels of vibration in residential areas. These were used in the present study to assess the acceptability of measured night-time low frequency vibration levels in the dwellings under consideration.

4 CASE STUDY – INITIAL INVESTIGATION

4.1 Background

For several years, residents of a housing estate close to an industrial estate in a town in Britain, complained to their local council about a low frequency noise problem that they were experiencing in their homes. The semi-rural location has low background noise levels at mid-high frequencies, which may have enhanced the annoyance caused by low frequency noise.

The industrial estate contains several factories that were considered to be possible sources of the disturbance. The most likely source was thought to be a factory that is situated closest to the housing estate. For reasons of confidentiality, this will be referred to in the current paper as Factory F.

The noise 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 when the disturbance would be at its greatest.

Previous attempts by Environmental Health Officers from the local council to establish the cause of the complaints using conventional acoustic measurement methods, and without the use of a criterion such as in DIN 45680, had proved unsuccessful. Even after several detailed investigations there was no agreement amongst residents, local authority officials and factory proprietors, as to whether the noise was real or imagined. Over this period a considerable amount of antipathy had built up between the concerned parties. Whilst residents genuinely believed that they were suffering adverse health effects, industrialists were convinced that the 'motivation' for the complaints was to close down local industry. Meanwhile, local authority officials found themselves unable to perform their role of public protection.

The authors considered that the prospects of successfully resolving the case would be considerably enhanced by application of the combined acoustic/microseismic measurement technique, and assessment of the resultant data using DIN 45680 criteria.

Noise and vibration levels were initially monitored during several nights of unmanned monitoring at three properties in the housing estate. All three locations were the households of residents who had experienced disturbance in relation to the low frequency noise under investigation. To protect the identity of the residents, the houses have been designated H1, H2 and H3. The relative positions of these houses and Factory F can be seen on the sketch map in Fig. 3.

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. 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 holiday 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.

4.2 Analysis of Recorded Data

Hundreds of recorded events from each of the three houses were analysed in both time and frequency domains, from each channel of the *Vibrosound* (microphone, window-mounted accelerometer and three-component seismometer), as well as the ground floor slab vibration data.

Fig. 4 shows a typical event recorded at house H1 by the microphone channel of the *Vibrosound*. The raw ten-second time history and its corresponding narrowband frequency spectrum are displayed. Fig. 5 shows the same frequency spectrum, analysed in terms of third-octave band levels and plotted against the night-time limits (Table 1) recommended in DIN 45680 [11].

From plots such as these, it was possible to identify frequency bands 'of interest' with reference to DIN 45680. Particular focus was given to third-octave bands for which the DIN curve was exceeded and in which the sound displayed an 'unusual' character in the time and/or frequency domains. If both these conditions are met, then low frequency sound can be considered to be potentially annoying according to DIN 45680, as explained earlier.

The 40 Hz third-octave band consistently displayed a sharp peak at ~38 Hz, which stood proud of the surrounding spectrum by up to 20 dB at times (see Fig. 4). 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.

The 40 Hz third-octave band levels detected at house H1 were often slightly (1-2 dB) above the limit recommended in DIN 45680 (see Fig. 5). This fact, together with the highly tonal nature of the sound in this band, suggests that the low frequency sound in the 40 Hz third-octave band has the potential to give rise to annoyance.

Another notable feature of the recorded sound was strong 'bursts' observed in the time series containing ~12.5 cycles per second. These 'pulses' were typically 1-2 seconds in duration and were associated with a strong ~12.5 Hz peak in the frequency spectra. An example of this feature, which was present in about 1 in 5 recorded events, can be seen in Fig. 4. A secondary peak at ~13.9 Hz of similar amplitude was sometimes also observed in the frequency spectra, but was not associated with the above time series pulsing (events whose spectrum only contained the 13.9 Hz peak did not display tonal bursts in the time domain).

The 12.5 Hz third-octave band levels did not exceed the DIN 45680 limit for this band (see Fig. 5), when averaged over the entire ten-second events. However, the instantaneous peak-pressure-amplitude of the 12.5 Hz pulses at house H1 reached as high as 0.3 Pascal, which is equivalent to a root-mean-square sound pressure level of 80 dB, almost as high as the DIN 45680 limit for the 12.5 Hz band (see Table 1). It is therefore possible that the 12.5 Hz tonal pulses are both audible and annoying at the loudest part of their cycle.

Other third-octave bands (such as the 20 Hz band) contained strong tones but the overall band levels fell considerably below the DIN 45680 curve (see Figs. 4,5). Conversely, the 50 and 63 Hz third-octave band levels sometimes exceeded the DIN limits, yet the sound within these bands was not considered likely to cause annoyance as it was typically broadband in nature (possibly due to traffic), and was not therefore classified as 'unusual' (e.g. the 63 Hz band in Figs. 4, 5).

Thus the use of DIN 45680 criteria allowed the identification of features of interest, most likely to be responsible for the annoyance, and the ruling out of other regions of the recorded spectra. This narrowed down the 'detective work' considerably. In the particular case study described here, tonal sounds at around 38 Hz and 12.5 Hz (the latter associated with bursts in the time domain) were determined to be the most likely causes of the disturbance.

These features were commonly observed in the microphone channel data at all three houses where monitoring took place. However, the recorded amplitudes of the features were lower at houses H2 and H3: typically the 40 Hz third-octave band level at H2 was ~20 dB below the DIN recommended limit, whilst at H3 it was ~10-15 dB below. On the basis of the recorded levels, noise in the 40 Hz third-octave band would not therefore be expected to cause annoyance at these two locations.

The instantaneous peak-pressure-amplitudes of the 12.5 Hz bursts reached values of 0.2 Pa and 0.1 Pa at H3 and H2 respectively, equivalent to root-mean-square sound pressure levels of 77 dB and 71 dB. Assessed against DIN 45680 criteria (see Table 1), these pulses at houses H2 and H3 would not be expected to cause annoyance.

4.3 Source and Propagation Path Determination

The existence of the 38 Hz and 12.5 Hz tones at all three houses where monitoring took place suggests an external, rather than internal source for these features of the recorded sound.

The bedroom window vibration spectra from all three houses showed a strong peak at 38 Hz. No signal was detected at either 38 Hz or 12.5 Hz in the seismometer mounted on the ground floor slab at any of the properties. These findings suggest that the 38 Hz tone, and probably the 12.5 Hz pulsing, are due to airborne sound rather than groundborne vibration (see Fig. 2).

(This analysis – interpreting relative amplitudes from various transducer channels in terms of propagation path – is described in more detail in a complementary paper [12], and in a Ph.D. thesis [14] by one of the authors carrying out FEM modelling of acoustic enclosures.)

Slight variations in frequency of the 38 Hz tone observed over time are consistent with a machine source, whose rotational frequency varies slightly from a nominal running speed due to variable loading. The existence on some occasions of two distinct peaks at ~36 Hz and ~38 Hz, may suggest two distinct sources with similar rotational speeds.

The 38 Hz and 12.5 Hz tones exhibited both temporal and spatial variations in amplitude within all three houses. Spatial intra-house variations were detected by quickly scanning each property using a hand-held sound level meter with third-octave band filter set attached. This showed that variations of ~10 dB occurred in all frequency bands from 20 to 125 Hz throughout each property. This is to be expected for low frequency sound due to modal behaviour in rooms.

However, a general trend could be determined throughout the housing estate, namely that the recorded levels of the tones were 15-20 dB higher in house H1 than in H2 and H3. 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 (Fig. 3) shows that house H1 is situated to the north-east of H2 and H3, and closer to Factory F which lies north-east of the housing estate. Thus, the higher sound levels of the 38 Hz and 12.5 Hz tones at H1 are consistent with the source(s) of the tones being located to the north-east of the housing estate, possibly at Factory F.

(As monitoring did not take place simultaneously at all three houses, it must be assumed that the sound power of the source was constant over the entire monitoring period. Notes made by the residents did not suggest that any major changes in wind speed and direction occurred which could account for the variations in amplitude.)

House H2 is in fact slightly closer than H3 to Factory F, yet levels of the 38 Hz tone were on average ~5 dB higher at H3 than at H2. This is not inconsistent with a source to the north-east 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 H2 in which monitoring took place faces away from Factory F, whereas the measurement rooms in H3 (and H1) face towards it (see Fig. 3).

The general drop in level of the 38 Hz tone between H1 and H3 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).

A large drop in sound level of 15-20 dB 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 (Fig. 3), the distance between H3 and Factory F is approximately 3 times the distance between H1 and Factory F.

However, 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 H1) serves to shield the rest of the estate from sound emanating from sources to the north-east. This latter effect could partially explain the large drop in sound level in the measurement locations at the south-west end of the estate.

To summarise, the findings are broadly consistent with Factory F being the most likely source of potentially annoying, airborne tones detected in the housing estate at 38 and 12.5 Hz.

4.4 Other Findings from Recorded Data

Recorded vibration levels in the ground floor slab and the suspended bedroom floor at all three properties were at least two orders of magnitude below the limits permitted by BS 6472 [13], and were therefore imperceptible to humans. There also appeared to be no danger of structural damage to buildings, which provided reassurance to the residents.

Measurements taken over the Christmas period, when local industry including Factory F had shut down, showed that absolute levels of noise and vibration were greatly reduced. The 'unusual' features described above were not detected during this period; this is consistent with a local industrial source for the 38 Hz tone and 12.5 Hz pulsing.

4.5 Subjective Responses

The fluctuating character of the measured sound would appear to match the residents' subjective descriptions of the disturbing noise.

During the installation and removal of equipment at the start and end of the monitoring period at house H1, a low frequency throbbing sound could be perceived by the authors at a level close 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 also heard emanating from Factory F in rooms that face the factory.

The perceived level varied throughout the house, which is consistent with the variations in objective sound level demonstrated using a hand-held sound level meter. Residents of H1 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 H1 all reported that their house was very quiet throughout the Christmas period, with no external sounds perceptible except occasional traffic.

No low frequency sound was perceived by the authors at house H2. One of the authors stayed overnight at H2 to establish the effects of longer-term exposure to the sound field on the housing estate, but 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. On the other hand, the resident of H2 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.

No low frequency sound was perceived by the authors at house H3. A mid-frequency whine was audible in the bedrooms of the house, but as at H2 this lay outside the frequency range of interest and was not further investigated. Residents at H3 concurred that the entire monitoring period was relatively quiet; 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.

4.6 Evaluation of Subjective Responses using DIN 45680 Criteria

Most of the residents' and authors' subjective observations throughout the housing estate correlated well with variations in the 40 Hz and 12.5 Hz third-octave band levels.

Disturbance was recorded at house H1 where the DIN 45680 recommended limit was exceeded at 40 Hz. On some occasions, the DIN limit for the 12.5 Hz third-octave band may have been exceeded during the loudest parts of the pulsing cycle. The residents of H1 reported that the Christmas shutdown period was very quiet; the objective results confirm that absolute sound levels were greatly reduced over Christmas and the 'unusual' features described above were not detected.

The residents of house H3 reported the entire monitoring period to be quiet; the DIN 45680 limits for the 40 Hz and 12.5 Hz third-octave bands were not exceeded at H3.

The only exception to the trend that subjective loudness variations matched 40 Hz and 12.5 Hz third-octave band levels was at house H2, where the resident reported being disturbed throughout the measurement period including the Christmas shutdown. Measured sound levels at H2 were at least 10 dB below the DIN 45680 curve for all frequencies in the range 0-125 Hz, and the authors did not perceive any low frequency noise at H2. It is possible that the disturbance at H2 was due to a hearing condition such as tinnitus.

To summarise, the degree of annoyance due to low frequency noise was greatest where measured low frequency noise levels were highest, with the exception of one individual case. In fact, the DIN 45680 night-time limit for the 40 Hz third-octave band proved to be a good predictor of annoyance.

Finally, the reduction in levels of perceived annoyance across the housing estate during the Christmas shutdown period again suggests that a local industrial source is responsible for the disturbance.

5 CASE STUDY – SHUTDOWN EXPERIMENT

During the initial investigation, Factory F had been established as the most likely cause of complaints due to low frequency noise in the neighbouring housing estate.

A further 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 was 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 12.5 Hz bursts that had been determined by use of DIN 45680 criteria to be the most likely causes of annoyance.

Again, the results were analysed in an attempt to establish a correlation between subjective annoyance and measured sound levels with reference to the DIN 45680 recommended limits.

5.1 Test Procedure

A sequential shutdown experiment was conducted 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 house H1, 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 authors and staff at Factory F. During the course of an evening, 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. Evening time was chosen as a compromise between the worst case 'dead of night' and a time when factory staff were available to assist.

Recordings were taken simultaneously in the upstairs bedroom of house H1 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 H1 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.

5.2 Analysis of Recorded Data

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 house H1.

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. Figs. 6 and 7 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 emanated from Factory F and were transmitted into the house via an airborne propagation path. Figs. 8 and 9 demonstrate that the DIN 45680 recommended limit for the 40 Hz third-octave band was exceeded at H1 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 to ascertain which peak was the most important contributor to the

40 Hz third-octave band level, and which item of plant was responsible for causing each tone.

The 12.5 Hz bursts 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 that they emanated from a source within Factory F), were also kept under scrutiny for each successive event from the run-up period.

Figs. 10-12 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. This plot is shown in Fig. 13, which also details the points at which each item of plant was switched on. The DIN 45680 night-time limit 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.

Firstly, it can be seen from Fig. 13 that background levels in the 40 Hz band were ~13 dB below the DIN 45680 limit during the period when all plant was shut down.

In Fig. 10, 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.

Fig. 11 shows an event recorded soon afterwards in which a second peak had 'emerged' at 36.5 Hz, of similar amplitude to the 38.4 Hz peak. The item of plant known as "Bag Plant 2" (BP2) had just been switched on. A sharp peak at 13.7 Hz had also 'appeared', and the overall 40 Hz third-octave band level had increased to ~1 dB above the DIN limit.

Bag Plant 2 was therefore established as the source of sharp tones at 36.5 Hz and 13.7 Hz, and it had 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.)

Fig. 12 shows the first 're-appearance' of the 37.5 Hz peak, at a sound pressure level greater than either of the other two nearby peaks, and of high peak-pressure-amplitude bursts 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 pulsing at a rate of ~12.5 Hz in the time series. BP1 also provided the greatest contribution to the 40 Hz third-octave band level. (The nominal running speed of BP1 was 2295 rpm, equivalent to 38.25 Hz.)

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 available (0.1 Hz). A less narrow bandwidth, even twelfth-octave bands, may not have made the distinction between the peaks, and so the strong 37.5 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.

5.3 Subjective Responses

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 north-east end of the housing estate i.e. nearest to Factory F. Residents at the 'far' (south-west) 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 house H2, who had taken part in the earlier monitoring, reported disturbance at times when all plant was shut off; and also that the period of full output towards the end of the run-up was 'much quieter'. This appears to confirm the earlier conclusion that the disturbance was not due to an external source at this location.

The residents at the closest property to Factory F, house H1 (where monitoring was taking place) were logging subjective comments from the downstairs kitchen, which they considered to be the loudest part of the house. They heard "rotating (slow)" when BP2 was switched on, whilst they perceived the sound to be "rotating faster, louder" immediately after the switch on of BP1. The authors' 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 chimneystack and were therefore linked. It was recommended that the factory owners apply noise control treatment to both BP1 and BP2.

5.4 Summary of Findings from Shutdown Experiment

Several airborne tones at frequencies around 38 Hz, and pulsing at 12.5 Hz, were confirmed to be emanating from Factory F. 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. The sources of the 12.5 Hz bursts and a tone at 13.8 Hz were also identified.

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 house H1 exceeded the DIN 45680 limit for that band. This provides valuable circumstantial evidence that DIN 45680 is a good predictor of annoyance due to low frequency noise in a real-life situation.

Sound levels at house H1 during full output were similar to those measured during the earlier monitoring period. Assuming that sound levels at houses H2 and H3 during full output were comparable with earlier levels (i.e. ~10 dB below the DIN-recommended limit), the subjective responses from the far end of the estate (suggesting low levels of perceived disturbance) are also broadly supportive of the DIN 45680 criteria.

It is noteworthy that levels exceeding the DIN criterion by only a few dB produced a strong increase in the number and vociferousness of complaints. This is in marked contrast to mid and high frequency problems where, for example, exceeding an NR/NC criterion curve by a few dB in one frequency band would often scarcely be noticed. This is a consequence of the bunching together of equal loudness contours at low frequencies (as mentioned in the Introduction), and indicates that low frequency sound tends to be judged as either 'acceptable' or 'unacceptable' with very little margin of transition between these two states. In terms of practical assessment, this implies that even small transgressions of the criterion curve should be considered potentially significant.

6 OUTCOME OF CASE STUDY

Remedial work for the suspect item(s) of plant was recommended. The owners of Factory F brought in consultants who applied noise control treatment to the relevant plant, following which the level of complaints received by the local council dropped considerably.

7 CONCLUDING REMARKS

The case study detailed above provides valuable 'real life' evidence of the effectiveness of the German national standard DIN 45680 [11] as an aid to resolving low frequency noise problems that may otherwise be difficult to solve. It also illustrates the flexibility of the integrated acoustic/microseismic technique and the advantages of the method over conventional techniques.

Measured sound levels were assessed with reference to DIN 45680 criteria to establish the existence of a physical acoustical cause for the annoyance that had given rise to complaints.

DIN 45680 (interpreted by Piorr and Wietlake [5]) states that a low frequency noise is potentially annoying if it exceeds a prescribed limit (the limits are given in terms of third-octave band levels) and is of an 'unusual' character (i.e. tonal, fluctuating). Applying these conditions to the recorded sound pressure data allowed the identification of features of interest, most likely to be responsible for the annoyance, and the ruling out of other regions of the recorded frequency spectra. This narrowed down the 'detective work' considerably.

A long period of monitoring was carried out during a controlled shutdown and run up of plant at the factory suspected of being responsible for the annoying low frequency noise. Subjective logs of disturbance were noted by the residents of the housing estate during this experiment. Narrowband frequency analysis of the measured data allowed the distinction of different sources for several tones that were very close in frequency.

DIN 45680 was demonstrated to be a reasonably good predictor of annoyance, based on third-octave band levels constructed from the recorded time histories and on the subjective assessments provided by residents of the estate and the authors. Due to the closeness of the equal loudness contours for low frequency sound, levels only 1-2 dB above the criteria should be considered potentially significant.

As a result of the case study, the authors recommended that noise control measures be implemented on specific items of plant at the factory. The low frequency noise problem throughout the housing estate abated after this remedial work was carried out on the suspect items of plant.

8 ACKNOWLEDGEMENTS

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Table 1 – DIN 45680 night-time low frequency noise limits

f (Hz)	10	12.5	16	20	25	31.5	40	50	63	80	100
L_{nt} (dB)	95	86.5	79	71	63	55.5	48	40	33.5	33	33.5

Fig. 1 – equipment set-up [15]

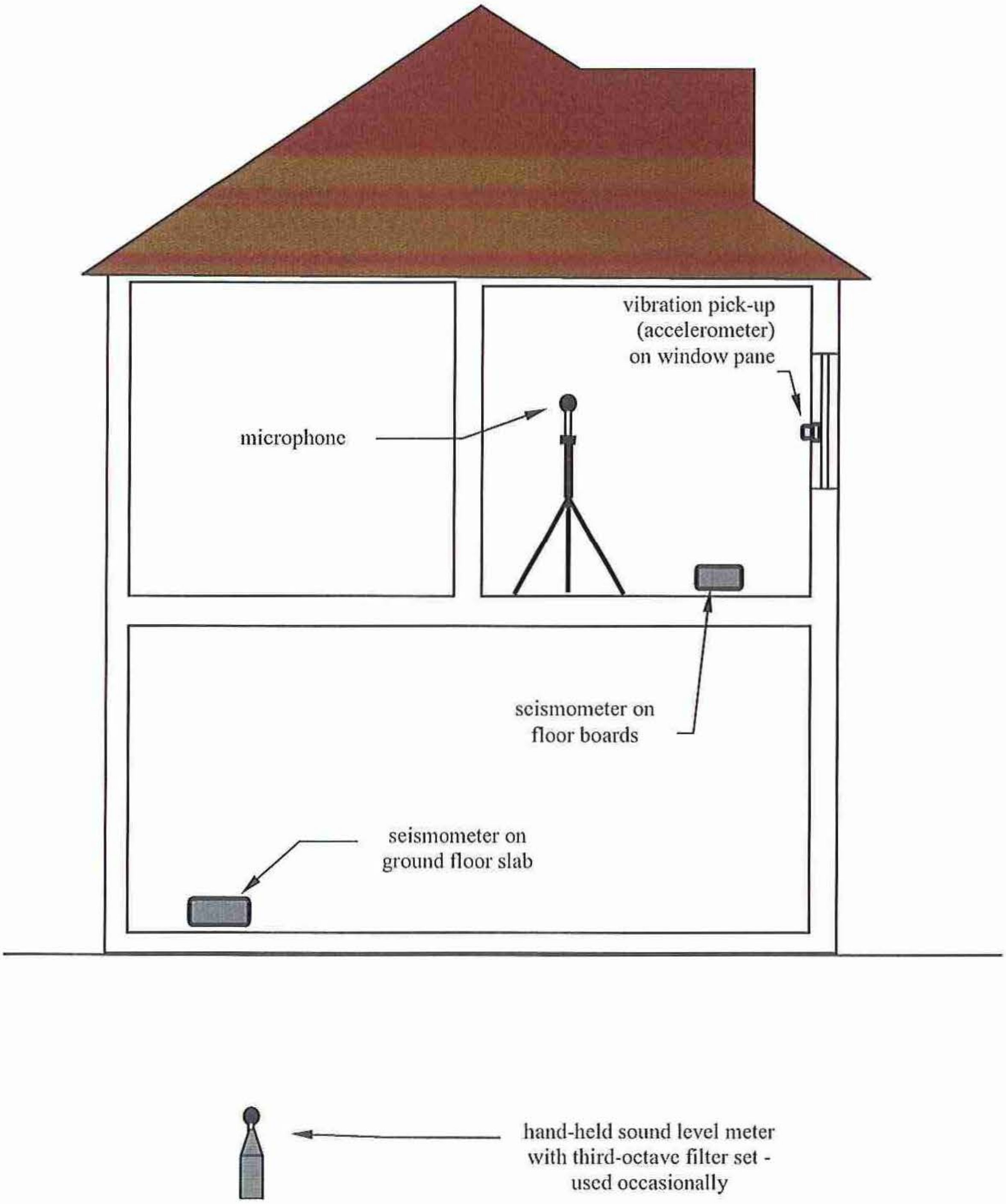

Fig. 2 - identification of transmission paths and external/internal sources of low frequency noise/vibration [15]

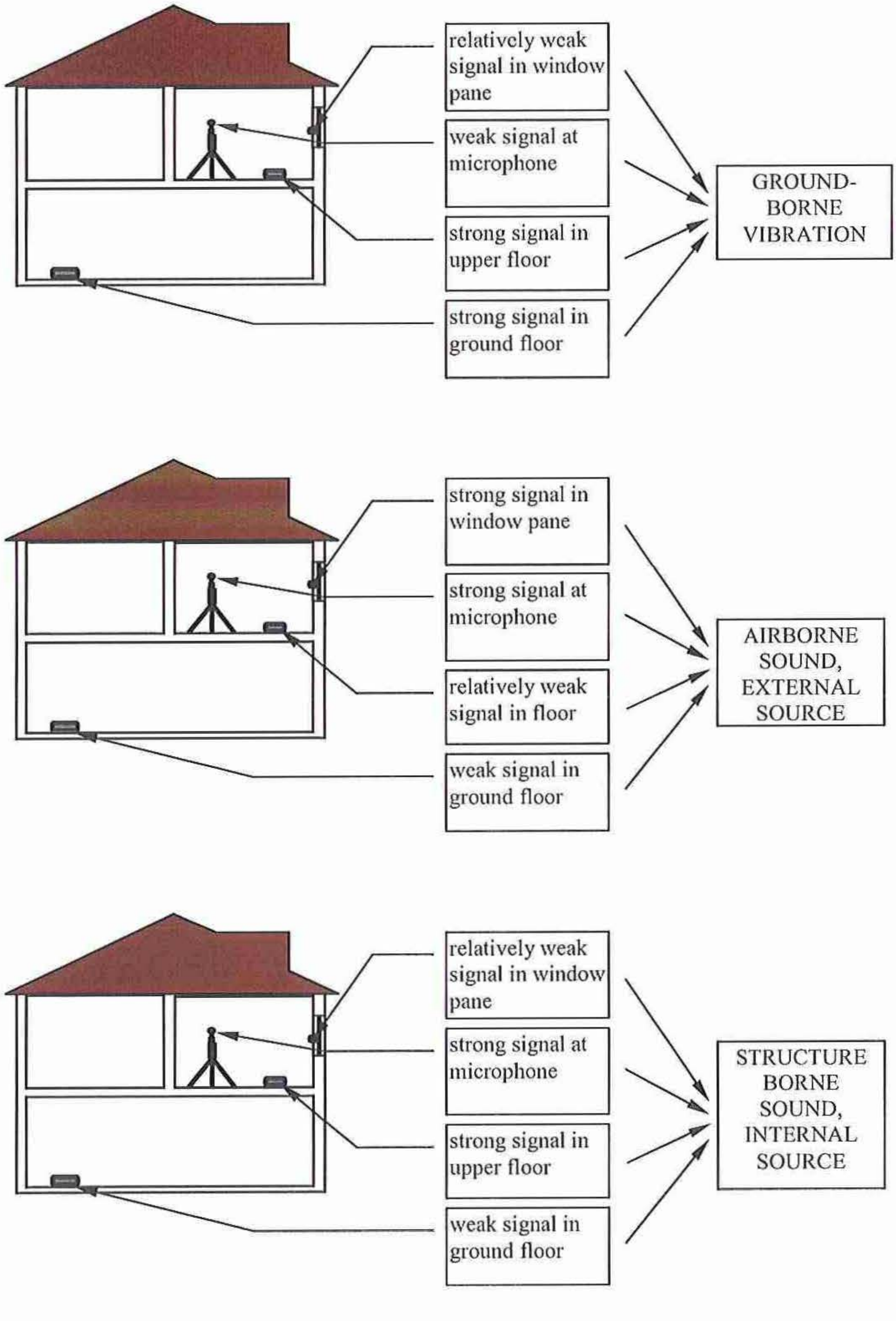

Fig. 3 – schematic map of the area under investigation in the case study, showing a factory suspected of causing a low frequency noise problem and three houses where monitoring took place (houses not to scale)

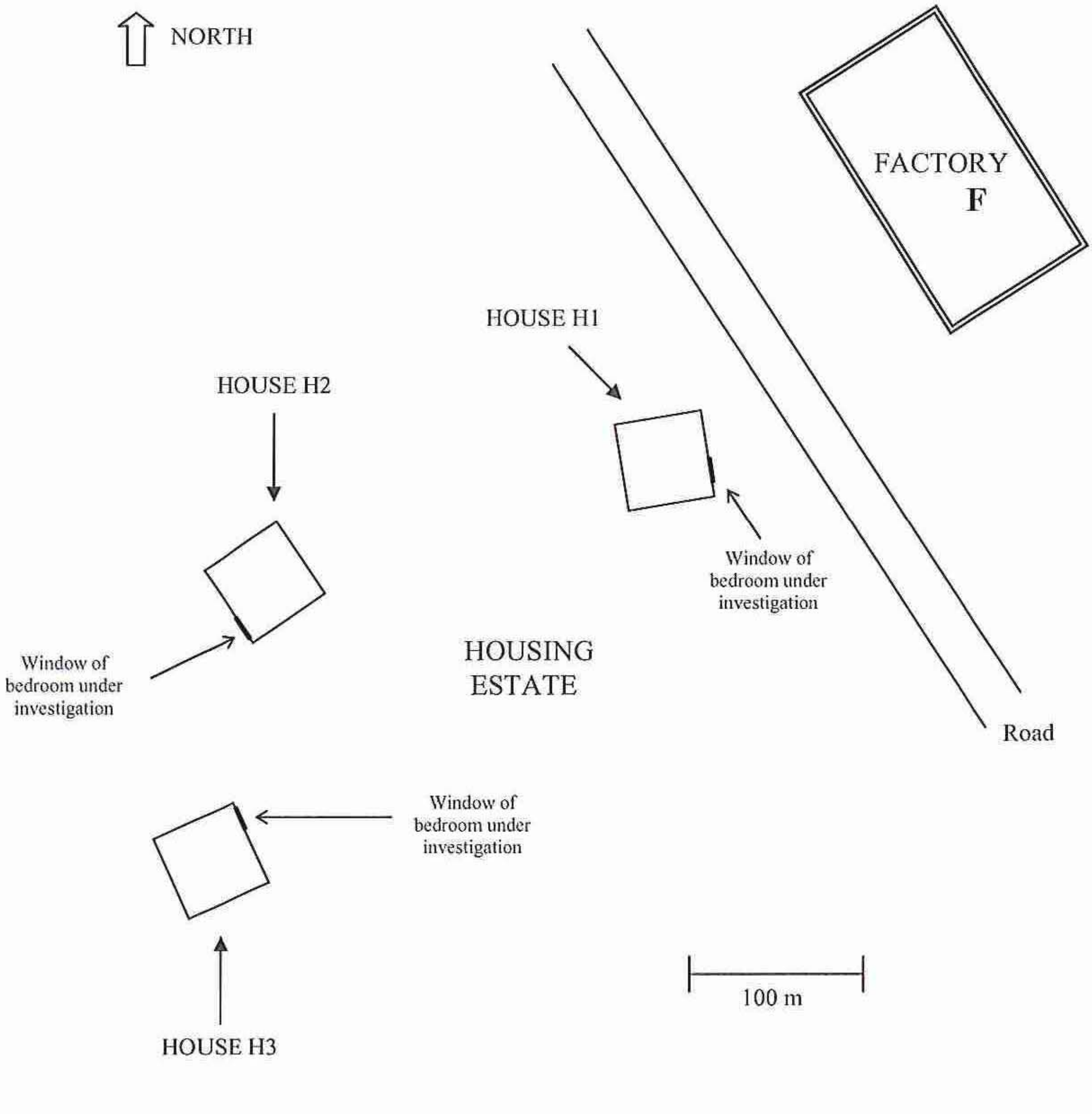

Fig. 4 - a typical microphone channel recording from house H1

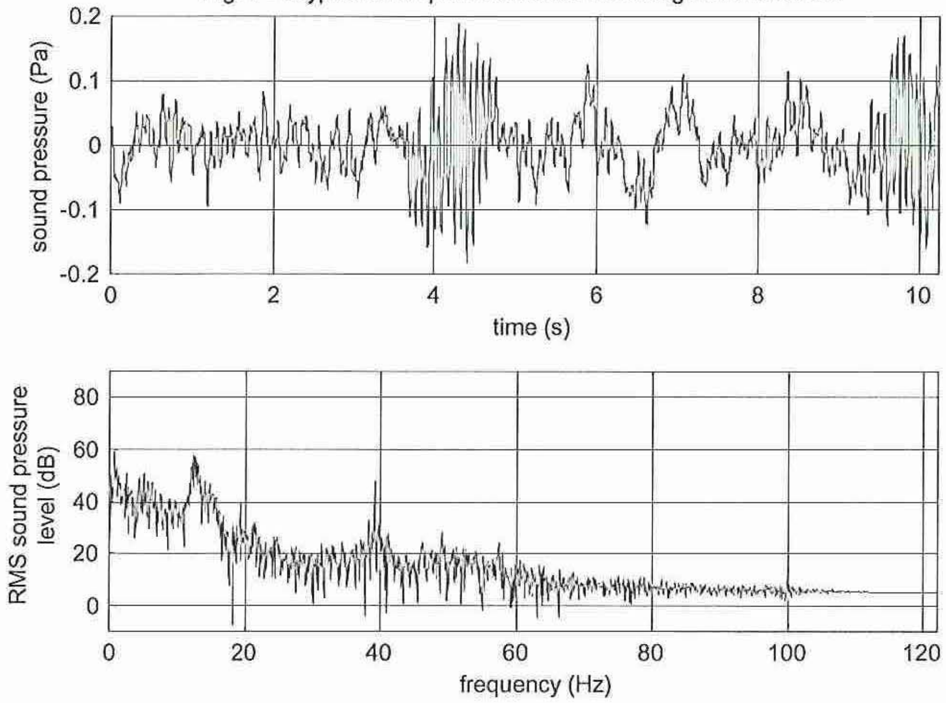

Fig. 5 - typical third-octave band levels from house H1, compared with DIN 45680 limits

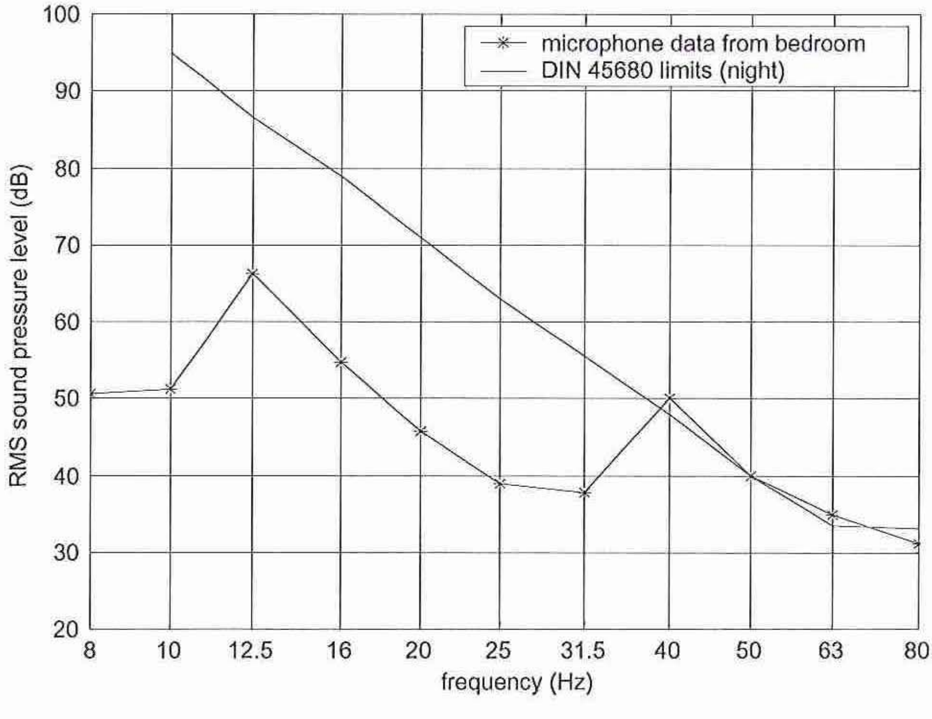

Fig. 6 - event recorded at H1 immediately prior to shutdown of Factory F

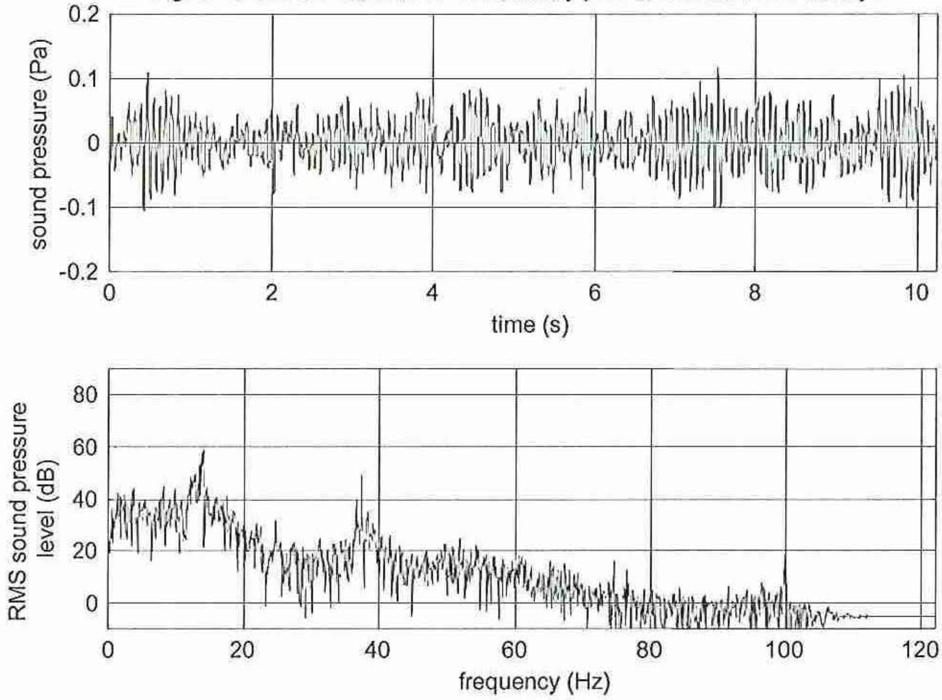

Fig. 7 - event recorded at H1 immediately after shutdown of Factory F

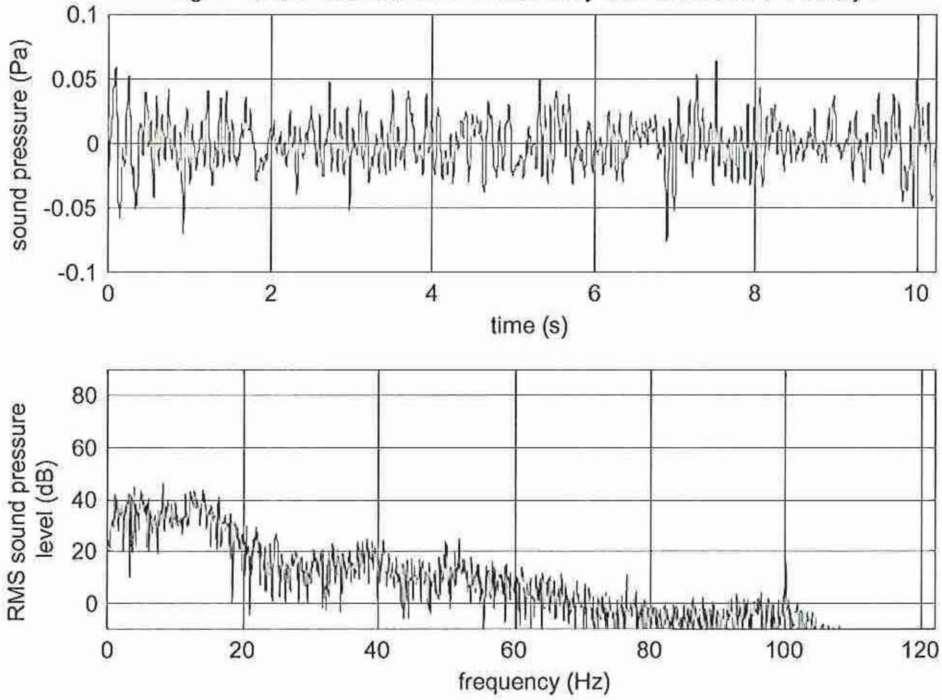

Fig. 8 - event recorded at H1 immediately prior to shutdown, plotted as third-octave bands levels against DIN 45680 limits

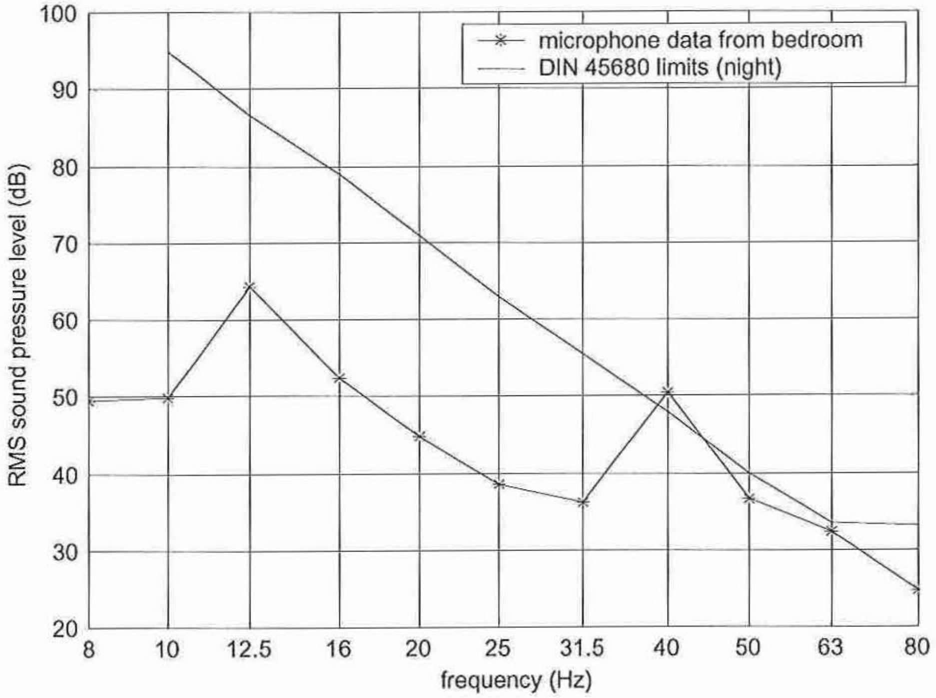

Fig. 9 - event recorded at H1 immediately after the shutdown, plotted as third-octave bands levels against DIN 45680 limits

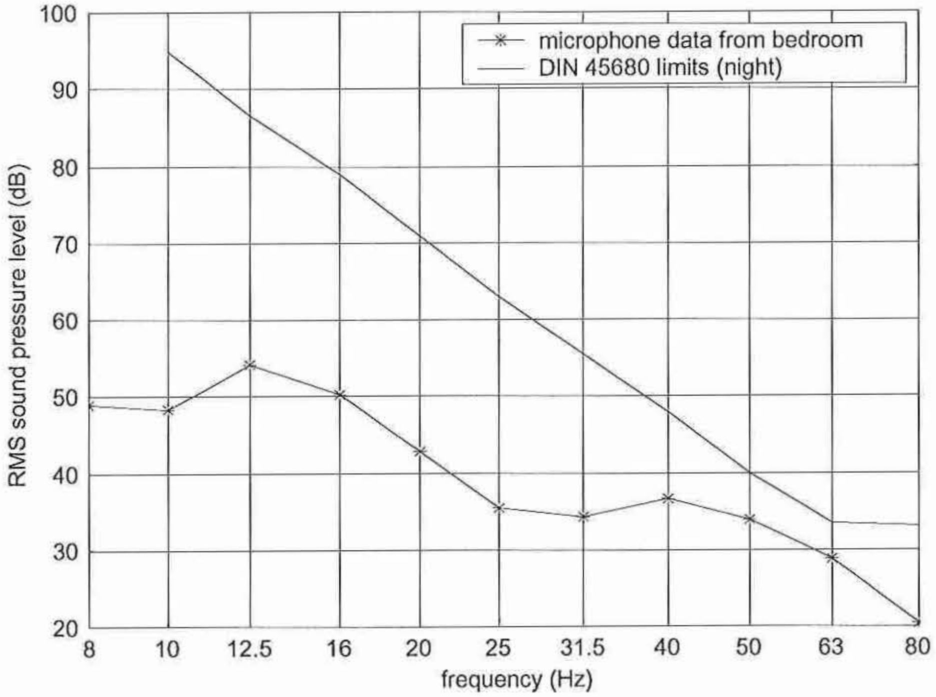

Fig. 10 - event recorded at H1 shortly before Bag Plant 2 switched on

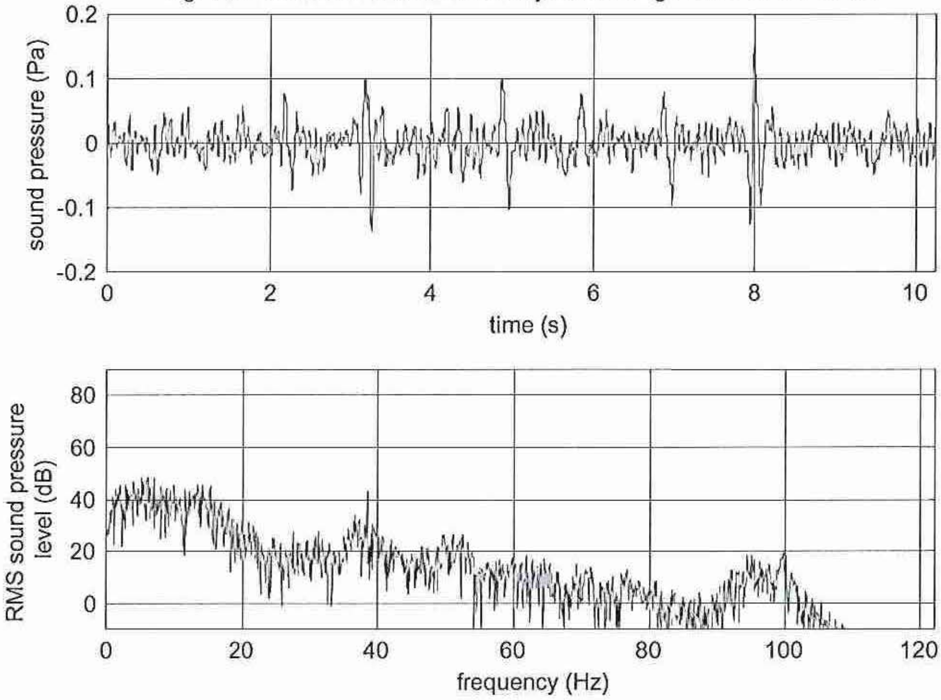

Fig. 11 - event recorded at H1 shortly after Bag Plant 2 switched on

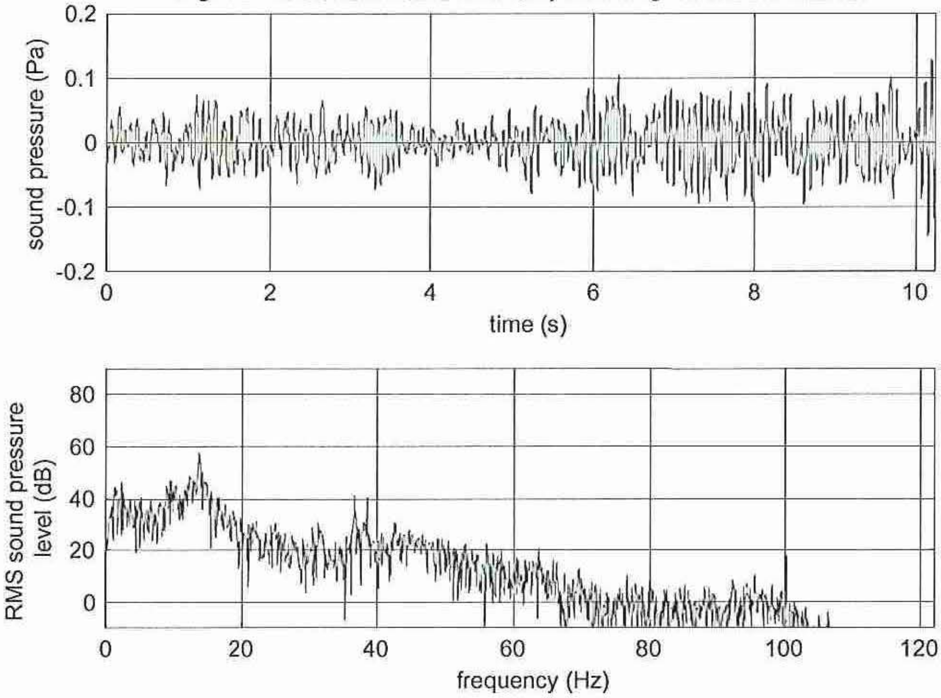

Fig. 12 - event recorded at H1 shortly after Bag Plant 1 switched on

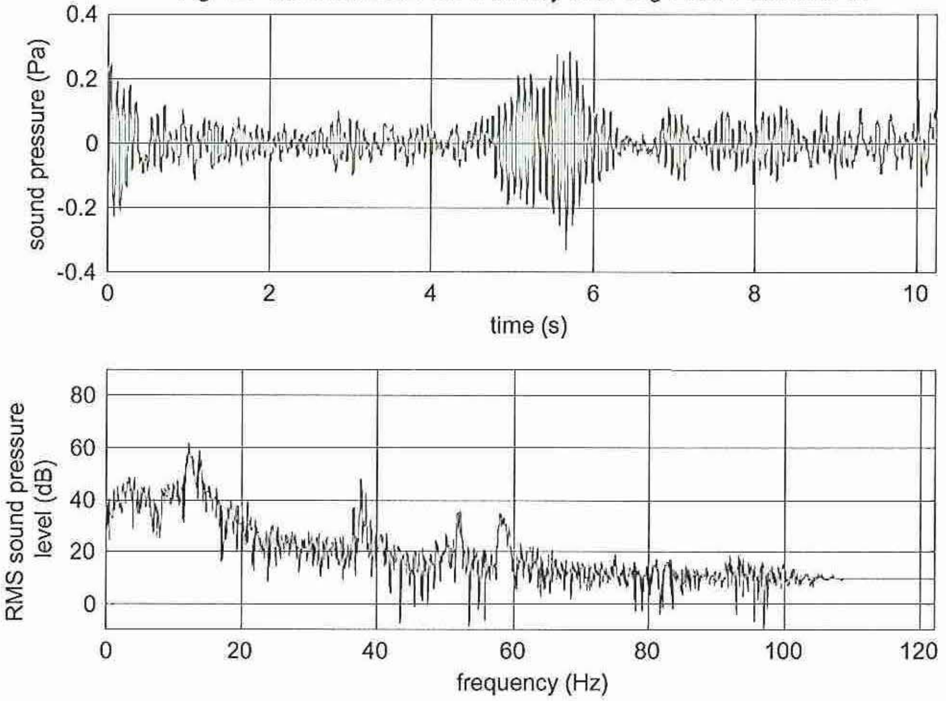

Fig. 13 - variations in 40 Hz third-octave band level throughout the shutdown experiment, with details of plant activity (C1 CT = Caster 1 Cooling Tower; C2 CT = Caster 2 Cooling Tower; BP1 = Bag Plant 1; BP2 = Bag Plant 2)