University of Salford
A Greater Manchester University

Proposed criteria for the assessment of low frequency noise disturbance

February 2005
Contract no NANR45

Prepared for Defra by
Dr. Andy Moorhouse, Dr. David Waddington, Dr. Mags Adams

CONTENTS

SUMMARY

The aim of this study is to recommend a method for assessing low frequency noise (LFN), suitable for use by Environmental Health Officers (EHOs) in the UK. A general introduction to LFN is given, in which it is argued that a method of assessment is needed both from the sufferer's point of view, because there is currently not much to protect them against LFN, and from the Environmental Health Officer's point of view, where guidance is needed in determining whether a nuisance exists.

Criteria already in use in Germany, Sweden, Denmark, the Netherlands and Poland were reviewed and compared. Experience from these countries in applying the criteria was also reviewed, and was found to be generally positive.

A complementary set of field and laboratory studies was conducted in order to establish the best form for an assessment method. In the field studies, eleven cases of reported LFN were investigated, as well as five control cases where no complaints about LFN had been received. Analysis of recordings made over three to five days at each location distinguished three groupings: positively identified LFN, unidentified, and marginal. Three cases were positively identified, meaning that the various national criteria were exceeded and there was correlation between the resident's logged comments and the LFN level. Five cases were unidentified: the criteria were generally not exceeded, (except perhaps by traffic noise), and there was a lack of correlation between comments and noise levels. Three cases were marginal in that the LFN was marginal with respect to the criteria and did not correlate with comments. It was concluded that the criteria were successful at distinguishing cases where an engineering solution could be applied from those where no such solution could be found.

In the laboratory tests, a set of 'thresholds of acceptability' were established by asking 18 subjects to set the level of various low frequency sounds to a just-acceptable level for imagined day and night situations. The sounds presented consisted of a set of tones across the low frequency range, 'real' LFN extracted from field test recordings, and synthesised beating tones with varying degrees of fluctuation. LFN sufferers were found to be the least sensitive group in absolute terms, contrary to the common image of ultra-sensitive individuals. In relative terms however, they were the most sensitive group in that they set acceptability thresholds closer to their threshold of hearing. From the existing national reference curves, the Swedish curve showed the best agreement with the results. It was also demonstrated that fluctuating sounds are less acceptable than steady sounds for the same average acoustic energy and should be penalised. Furthermore, it was shown that 5dB is an appropriate penalty almost irrespective of the degree of fluctuation above a limiting value.

A method for assessing LFN suitable for use by EHOs is proposed. This consists of a reference curve based on 5dB below the ISO 226 (2003) average threshold of audibility for steady sounds, plus a means to establish whether a 5dB relaxation for steady sounds should be applied. It is expected that this will benefit EHOs by helping to identify cases where they are able to improve the situation by enforcing noise control measures. It is also expected that in a significant proportion of LFN cases it will not be possible to identify a 'hardware' solution. Consequently, it is suggested that further research be conducted into alternative solutions.

INTRODUCTION

In this section is given a brief introduction to the problem of low frequency noise (LFN). There is no need for more than a brief introduction since a comprehensive review was recently completed by Dr Geoff Leventhall et al. as part of a Defra funded project [Le03].

Low frequency noise is now a recognised problem in many countries in the world. Experience has been accumulating over more than 30 years, as a result of which a picture has built up of typical situations where disturbance occurs. A relatively small number of people are affected, but those who are tend to suffer severe distress. In most situations, only a single sufferer, or perhaps a couple living in the same property are affected. Occasionally, a cluster of complaints arises in a particular area, although typically only a small proportion of people living in the area will report problems. Although this picture is now becoming reasonably well-formed, this does not mean that the causes of such suffering is fully understood, and many cases still go unexplained.

There is a highly consistent vocabulary used by complainants, who may describe for example “pressure on the ears” or a sound like “a diesel engine idling in the distance”. Complainants frequently describe a sound that is intense, even deafening to them, while many visitors to their home may be unable to hear it. It is common that they also report a sensory perception of vibration (see for example [Mo02]) not perceived by others. Visitors typically include local Environmental Health Officers (EHOs, who have a statutory duty to prevent noise nuisance), water, gas and electric utilities, and others. This discrepancy between how the sufferer and other people perceive the sound can be one of the most baffling aspects of low frequency noise, and can leave the sufferer increasingly isolated and confused. Many times a complete breakdown in communications has occurred, the EHO being convinced that the complainant was suffering from tinnitus[1], and the sufferer equally convinced that the EHO was in collusion with whoever was thought to be causing the noise.

Nowadays, thanks to an increasing number of documented cases, there is more recognition of such cases, and a better understanding of how such situations could occur. Fewer sufferers are misdiagnosed as having tinnitus and the knowledge that other people around the world are involved in similar situations can be reassuring to both the sufferer and the EHO.

How is it that one person could describe a sound as loud while another cannot even hear the same sound? One possible explanation is based on the way the human hearing system operates at low frequency. The perceived loudness of low frequency sounds increases very rapidly with increasing acoustic energy. Therefore, low frequency sounds only just above the threshold of hearing[2] can be perceived as loud, even uncomfortably loud. Added to this is the fact that individual hearing thresholds

[1] Tinnitus: ringing in the ears which can occur when there is no external sound present

[2] Threshold of hearing: the level of the lowest sound that can be heard. This varies with the pitch or ‘frequency’ of the sound, the human ear being less sensitive at low frequency than at mid and high frequency.

vary, so that people with more sensitive hearing can hear sounds inaudible to others. Putting these two facts together we may find a situation where a low frequency sound is above one person's threshold, enough to sound relatively loud, whereas another person with less sensitive hearing cannot hear it. This situation does not arise with most other (not low frequency) sounds, because their perceived loudness increases much more slowly with increased acoustic energy. In other words 'normal' sounds need to have very much more acoustic energy than the hearing threshold before they become uncomfortably loud. The experience of low frequency sound can therefore be 'counterintuitive', i.e. it may contradict our more usual experience of sound.

This by no means explains all cases. However, an appreciation of the above subtleties is extremely important because the counterintuitive nature of low frequency sound makes it difficult to base accurate judgements on personal experience. Therefore, the more widely understood these ideas are the better.

An additional factor is that 'sensitisation' to low frequency sound often occurs over time, leaving the sufferer more aware of the sound and unable to shut it out or get used to it. Instead, the sound may grow in importance until it can become all-consuming. It is not fully understood why, but this effect tends to happen more with low frequency sounds than other sounds. Therefore, a brief visit to a property affected by low frequency noise does not always give an adequate impression of what it is like to live with the sound, making evaluation even more difficult.

The preceding paragraphs give the idea that the effect of low frequency sound is different in several ways to other types of sound. Although the number of cases is only a small fraction of total noise complaints, the distress suffered can be disproportionately severe. It is not uncommon for sufferers to sleep in a garden shed, a garage, a car or a hotel to escape the noise. Some move if they can. Complainants frequently describe loss of sleep and in the worst cases can contemplate suicide.

From the EHO's point of view, low frequency noise problems can take up a disproportionate amount of time and resources. They are notoriously difficult to tackle even for specialists with long experience of this type of problem and with good equipment. Added to this, not all acoustic instruments used by local authorities are suitable for low frequency noise evaluation since the vast majority of noise cases do not need a low frequency capability. Unfortunately many cases end up with a breakdown in communications between the EHO, who often goes to a great deal of trouble on the sufferer's behalf but is unable to detect the source of the problem, and the sufferer, who is convinced the EHO is doing nothing.

The success rate of solved cases is not high, and unsolved cases tend to remain 'open' for a long period, often several years. This is unsatisfactory both for the EHO, to whom such cases can become an open-ended burden on resources, and the sufferer, who may be left in a state of expectation but with no real prospect of a solution. Sadly, a relatively high proportion of such cases end up with an investigation by the Ombudsman, which puts both sides under a great deal of stress but rarely leads to a satisfactory solution.

Even when the local authority is convinced there is a statutory nuisance and is able to locate the source (they can only serve a notice if they know who is causing the problem) they are often reluctant to take the case to court. This is because there is a lack of authoritative guidance to support their case, and without such support the case is not at all certain to be successful. For this reason, local authorities have been known to find some other, less controversial grounds for serving a notice rather than base their case on the uncertain legal territory of low frequency noise. Therefore, the current situation is that local authorities need considerable resolve and, one might even say, some courage to consider a prosecution for low frequency noise.

From the above, it is clear that some authoritative guidance would benefit both the sufferer and the investigating EHO. This is needed both to help the EHO to identify genuine problems more quickly and to support enforcement when a nuisance exists.

Aim

Hence, we come to the aim of this report, which is to recommend a method for assessing low frequency noise, suitable for use by Environmental Health Officers in the UK.

It is most important that any such method is fair. If noise limits are set too high then a proportion of the population is not protected, and if set too low then an unfair burden is placed on industry (in cases where sources of low frequency noise can be identified they are usually industrial). In view of the well-known technical difficulties in assessing and evaluating low frequency noise, as well as the complexity of human reaction to sounds, this is not a simple task and needs to be done with considerable care.

The guidance is intended to cover low frequency noise from industrial, commercial and domestic sources, in particular rotating machinery but also including for example combustion noise and turbulence. Music noise is not included.

Review of existing criteria

In pursuing the aim of the project, we can take into account the growing body of experience about low frequency noise. Of particular relevance is the experience from other countries where low frequency noise criteria have been adopted. Therefore, the relevant authorities in countries with existing criteria were followed up in order to evaluate their experience. In this section is given a brief review of existing criteria, plus a summary of the reported experience from countries using them. Full discussions of the criteria are also given in references [Le03] and [Po03].

Sweden

The Swedish guidelines state that low frequency noise should be assessed by third octave band measurements in the range 31.5-200Hz. The sound pressure levels given in Table 1 and Figure 1 should not be exceeded in any third octave band.

A survey of local authorities in Sweden was carried out recently and it was ascertained that 62% of local authorities found the method to be better or much better than the previous method. Of the remainder, 35% said they did not know, and in most of these cases this was because they did not have the equipment needed to follow the procedures. Only one local authority (3% of the sample) said they thought the method was worse than the previous method. The positive response was received despite the fact that the method is more difficult to apply than the previous method, more time consuming and requires greater competence and equipment. This indicates that EHOs (at least in Sweden) see the extra effort involved in the assessment as a worthwhile investment.

Denmark

In the Danish method sound measurements are taken at several positions throughout the property in the low frequency third octave bands (see [Po03] or [Le03] for a description). Only the low frequency bands from 10-160Hz are included which, in a normal A weighted measurement, tend to be de-emphasised and dominated by higher frequencies. The measured third octave band values are then A-weighted and summed together to give a low frequency, A-weighted level, $L_{pA,LF}$. This value is then compared with limit values given below. There is no reference curve as such in the Danish method, but it can be compared with other criteria by assuming that the sound is all concentrated in one third octave band. This gives the values given in Figure 1and Table 1. In practice this extreme situation does not arise, so although this assumption allows us to compare with other criteria it gives values that are artificially high. Another feature of the Danish method that differs from the approach in other countries is that it specifies a 5dB penalty for impulsive sounds.

Maximum acceptable levels for $L_{pA,LF}$ are specified for certain areas:

Dwellings	evening/night (18h-07h)	20dB
Dwellings	day (07h-18h)	25dB
Offices/ teaching rooms		30dB
Other work rooms		35dB

Experience from the Danish Environmental Protection Agency indicates that the limits are rarely exceeded, but when they are, the Local Authority is usually able to locate the premises responsible for causing the noise and serve a notice or otherwise regulate the situation. These guidelines are not considered to be entirely satisfactory as they are relatively complicated for the EHOs to apply. Although there is little quantitative information on whether the limits are set at the right level the general feeling is that they are set are ‘close to OK’.

A report by Sorensen [So01] suggested that the 20dB limit for $L_{pA,LF}$ was strict if the noise was at the lower end of the range, i.e. 10-30Hz and unconservative for sounds at the higher end, i.e. around 160Hz. This was for multi-tone spectra as are often found with reciprocating engines in power plants, but is based on only two case studies and is not intended to give a firm, general conclusion.

A separate criterion for infrasound also applies in Denmark, although cases of infrasound are reportedly extremely rare. When the infrasound limits are exceeded then low frequency limits are often also exceeded at the same time. The low frequency limits are therefore seen as more important, whereas infrasound is not seen as an important environmental concern in Denmark.

Netherlands

This method is intended to determine whether suspected LFN is audible or not, rather than whether it should be classed as a nuisance [vB99a]. Audibility is based on hearing thresholds for the 10% most sensitive people in an otologically unselected population aged 50-60 years. These 10% thresholds are typically about 4-5dB lower than the average threshold for otologically normal young adults (18-25 years) as given in ISO226 [IS03].

Experience of the guidelines is generally positive. Consultants and EHOs are generally aware of them and use them to assess potential problems. It is reported that in not all cases where complaints occur is the threshold exceeded, and even in some of these cases there is not a clear correlation between the reported disturbance and the presence of the source. Arguably they are too low, because most complainants have a higher hearing threshold than that given in the limits, but this has not been systematically evaluated. Other investigators are more confident that the Dutch levels are neither too low nor too high.

Germany

In the German method [DI97], a simple preliminary measurement is recommended in order to determine whether the problem should be investigated further. If the difference dBC-dBA is greater than 20dB then third octave band measurements should be taken. The third octave readings are then compared with the values given in Figure 1 and Table 1. (The values in Table 1 and Figure 1 are equal to the reference curve up to 63Hz, but include corrections of +5dB at 80Hz, and +10dB at 100Hz. These are the amounts by which the reference curve may be exceeded by tonal sounds, so they have been added in the table to ease comparison). Different procedures apply if the noise is tonal or not. The noise is said to be tonal if the level in third octave band exceeds the levels in the two neighbouring bands by more than 5dB. A tonal noise that exceeds the values in Figure 1and Table 1 at night time is considered to be a nuisance. A 5dB increase in all bands is allowed for day time exposure.

If the noise is not tonal then a day time limit of 35dB is imposed on the A weighted equivalent level (10Hz-100Hz), where the A weighting is obtained by only using the third octave bands for which the threshold is exceeded. The night time limit is 25dB. The analysis required is therefore relatively involved for the non-tonal sounds.

Poland

The Polish method [Mi01] uses a reference curve defined over the range 10-250Hz, and denoted LA10 because at each frequency it has the value equal to a pure tone of 10dBA. It is shown in Table 1and Figure 1 and is the lowest of all the curves at 50Hz and below, and is also below the hearing thresholds as defined in ISO226 [IS03]. Low frequency noise is considered annoying when the sound pressure levels exceed the reference curve and simultaneously exceed the background noise level by more than 10dB for tonal noise and 6dB for broadband noise.

Although it may seem excessive to set a reference curve below the threshold of hearing, this was justified [Mi01] on the basis that subjects in a laboratory test could hear combinations of tones at lower levels than they could pure tones. Since the published thresholds are based on pure tones it was argued that LFN consisting of multi-tones (which it commonly does) may be audible at levels below the published threshold. However, this argument has not been incorporated explicitly in other national guidelines.

Comparison of national methods

The various reference curves are shown in Table 1 and Figure 1. Note that the Danish curve, is applied in a different way to the others, so it is not strictly correct to compare on a frequency by frequency basis. The impression that it is higher than other curves is therefore slightly misleading from the figure. Also, the Polish curve, which appears lower than others, is to be applied with an extra condition on background noise, and for this reason is closer to the other curves than appears. The Netherlands curve is intended only to predict audibility rather than acceptability, and so is lower. Therefore, the national reference curves actually show more agreement than appears from Figure 1and Table 1.

There are differences in the frequency range covered by the various curves. The lowest frequency is set at 10Hz in the Danish, Polish and German methods, although the German method includes an optional extension down to 8Hz. The Dutch and Swedish methods start at 20Hz and 31.5Hz respectively. Thus, there is not complete agreement on the lowest frequency that should be included. At the high end of the range, the German and Dutch methods stop at 100Hz, whilst the Danish, Swedish and Polish methods end at 160, 200 and 250Hz respectively. However, all the reference curves rise away from the threshold of hearing above 63Hz, so that the bands at the top of the range are significantly de-emphasised. Therefore, in effect there is more agreement than appears in that all methods give most importance to frequencies up to 100Hz.

In terms of the levels of the curves, there is almost complete agreement that sounds should be inaudible between 31 and 50Hz (a range where many reported problems occur). However, there are some differences in the interpretation of audible.

A review of the various national criteria was recently carried out by Poulsen [Po03]. He played various sounds to subjects in a laboratory and carried out an analysis to find which of the methods was the best predictor of their adverse reactions. He found that the best correlation was obtained for the Danish method, closely followed by the Swedish method. The Danish method was superior only when it came to evaluating impulsive noise such as from music. In this respect the Danish method includes a penalty of 5dB for impulsive sounds but there was no objective indication of when this should be applied. Since music noise is not included in this investigation the Swedish method can therefore be considered to be as good. The German non-tonal method also worked well.

In terms of ease of use, the methods requiring third octave band values to be summed (Danish, and German broad band method) are more difficult to apply. The summing operation itself is fairly straightforward and could be handled by the majority of

EHOs. However, the disadvantage is that this cannot easily be done in real time on site. This means the EHO evaluating the noise will not be able to get a feel for the problem by making a quick assessment on site. This is actually quite an important consideration since LFN problems are relatively uncommon, and EHOs often lack confidence in their assessments due to lack of experience. For these reasons, methods that specify a maximum third octave band value are preferred, because the investigator can see what is going on more quickly.

The Polish method is the only one to require an assessment of the background noise. This makes good scientific sense since it is often the case that background noise, e.g. from traffic, is dominant in the higher frequency bands (between 100 and 200Hz). Therefore, requiring the offending noise to be above background noise is a sensible way to avoid a false classification of a normal background noise as a problem low frequency. The drawback is that in practical situations it will rarely be possible to measure the background noise. This is because for a background noise measurement it is necessary to switch off the source being investigated. However, in a high proportion of LFN cases the source is not known. Indeed, one of the purposes of an assessment method would be to help to identify the source by narrowing down the problem to a particular frequency band. For these reasons the Polish approach of including background noise, although logically sound, is unlikely to be as useful to EHOs as other simpler methods.

Compared with other environmental noise standards it may initially seem too stringent to require levels of low frequency noise to be reduced to around the threshold of hearing. However, there is a growing experience that such low limits are needed to provide adequate protection from LFN. This is because of the strong reactions and the apparent difficulty in habituating to LFN. The fact that all national criteria (with the possible exception of the Danish one) are set at or below average hearing thresholds gives strong support to this idea. It should be remembered that the standard threshold is the median i.e., 50% of people are less sensitive and 50% are more sensitive. The standard deviation of the experimental subjects tends to be around 6dB. Thus, about 16% of people have a threshold which is 6dB or more lower than the median, which includes about 2% who have a threshold which is 12dB or more lower.

To summarise, on the basis of experience, the Swedish, Danish and Dutch (audibility) methods appear to have all been positively received. On the basis of a laboratory investigation the Danish, Swedish and German (non-tonal) methods were the best predictors of annoyance. From the point of view of ease of use the Swedish, Dutch and German (tonal) methods are most advantageous.

Hz	Germany	Denmark	Sweden	Poland	Netherlands	ISO threshold
8	103					
10	95	90.4		80.4		
12.5	87	83.4		73.4		
16	79	76.7		66.7		
20	71	70.5		60.5	74	78.5
25	63	64.7		54.7	64	68.7
31.5	55.5	59.4	56	49.3	55	59.5
40	48	54.6	49	44.6	46	51.1
50	40.5	50.2	43	40.2	39	44
63	33.5	46.2	41.5	36.2	33	37.5
80	33	42.5	40	32.5	27	31.5
100	33.5	39.1	38	29.1	22	26.5
125		36.1	36	26.1		22.1
160		33.4	34	23.4		17.9
200			32	20.9		14.4
250				18.6		11.4

Table 1: Reference curves used in the various national criteria, together with ISO threshold

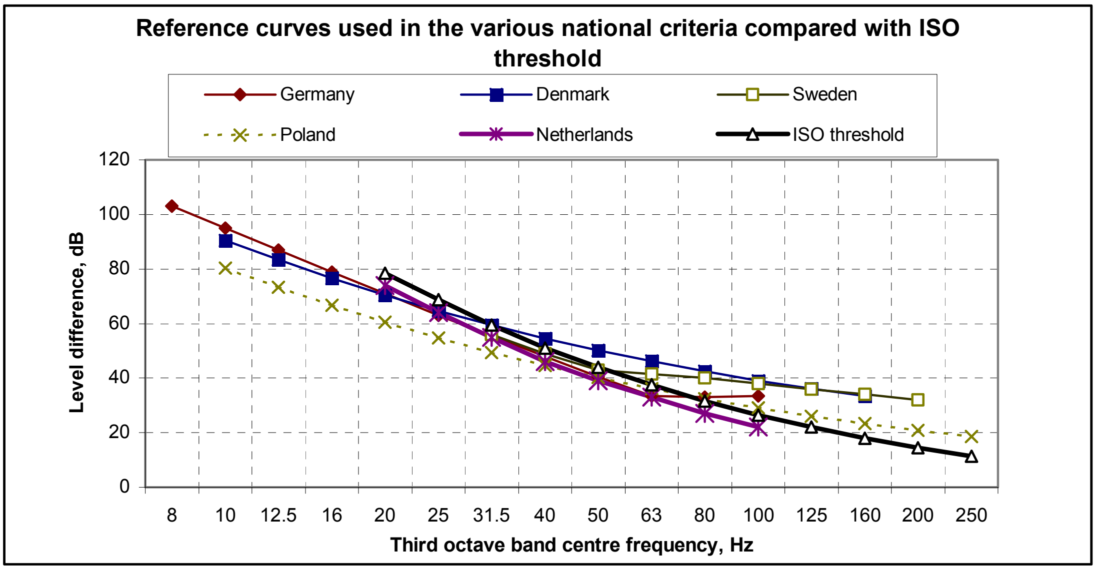

Figure 1

Research Methodology

From the above discussion it appears that a useful criterion can be based on a reference curve giving acceptable levels of sound at third octave band frequencies in the low frequency range. Some objective method to assess the effect of fluctuations, which appear to increase adverse reaction, would also be advantageous.

The form of the reference curve has been discussed above. Most existing curves are based on thresholds of audibility, which have been established for many subjects over many years, and provides us with the most comprehensive and reliable data about hearing in the low frequency range. Regarding fluctuations, there is much less data available. It is not possible to determine the effect of fluctuations through field studies; for one thing it would not be practicable to survey enough cases, and for another, there is too much variation between field studies, including the personal situation of the subjects, the length of exposure and the character of the sound. To establish the effect of fluctuations we need to measure the reactions of several people to the same sound, and this can best be done by setting up tests in the laboratory.

There are limitations in laboratory testing of low frequency noise. In particular, the disturbance in the field often includes an element of 'sensitisation' to exposure over extended time, and this factor cannot be reproduced in the laboratory. Nevertheless, the annoyance of a sound can be judged by most subjects after a few minutes exposure [Le03], so despite this limitation, laboratory testing is a well-established technique.

To summarise: in view of possible sensitisation over time, the only true test of a criterion is in real situations, but the only way to establish the effect of fluctuations is through laboratory testing. Therefore, the research methodology chosen is a combination of field and laboratory testing which are described in the following two sections.

FIELD STUDIES

The overall aim of the field studies is to provide support in the way of field data for a proposed criterion. Specifically this involved collecting data with which to test proposed criteria, and to provide audio recordings for use in the laboratory tests.

Human reaction to sound is known to be dependent not just on the sound itself, but a complex array of other factors like personal associations of the sound. Therefore, in each field study the sound measurements were supported by questionnaires to determine whether sociological or other factors might influence the results.

Details of the tests

Selection of case studies

Cases were solicited through Environmental Health Departments by circular letter, and by specific approaches to Local Authorities known to have a problem in their area. More than forty cases were evaluated. EHOs who offered cases were approached by phone and asked for a detailed description of the case. In some cases it was also appropriate to approach the complainant at this stage. A few cases also came in by word of mouth directly from sufferers.

Cases where several complaints occurred in a cluster were selected in preference over those where a single complainant lived alone. This was because it is easier to justify the complaints as reasonable if there are more than one. Also, it is well-known that ‘mystery’ cases often arise where no problem can be identified from recordings, and it was thought that selecting clusters would help to avoid such cases.

Cases where there was a long history to the problem, particularly if there had been modifications to a noise source during that time, were generally avoided. This is because such cases can become overlaid with complications that make it more difficult to know if the responses are purely due to the noise. For example, a number of cases were received in which a low frequency noise source had been identified and noise control work had been carried out to the satisfaction of most residents, but where a smaller number had continued to complain afterwards. One possible cause of this is that the complainants had become sensitised whilst the noise was present. Whilst such sensitisation is a genuine part of low frequency noise cases, it becomes more difficult to classify the response as typical and so stronger conclusions could be obtained by excluding such cases.

Cases where the complainant was felt to be reasonably objective and perceptive in their judgement of the sound were selected where possible.

EHOs and sufferers alike were generally keen to participate. Both groups were told that we were not intending to solve their particular problem, but rather to contribute to improved methods of evaluation in general. We adopted a policy that data collected would not be released to either party, since this could have caused political complications. Whilst all were generally anxious to solve their problem (which in most cases had defied resolution), they were generally happy to participate on the grounds that the results might help others in the future. Participants, both EHOs and sufferers, were generally extremely co-operative and helpful.

Measurement setup

Although the majority of environmental noise standards specify that sound measurements should be conducted outside, it is now generally agreed that low frequency noise can only meaningfully be evaluated inside. All national standards specify indoor measurements. Therefore, all measurements were carried out inside complainants' homes.

A single microphone was positioned at a point in the room where the sufferer indicated the sound was present. In most cases an unoccupied room was used. In two cases an unoccupied bedroom was not available, so an occupied room was used, although this was avoided if at all possible. In order to minimise data storage, recordings were taken only when the sufferer said the noise was at its worst. In all cases the noise, although usually present during the day, was reported worst at night. Therefore, recordings were usually made between 21h00 and 09h00 when interference from other sources is reduced. In some cases, at the request of the resident, recordings were also made during the day. However, the most valuable recordings were all from the night time period due to minimum interference from other sources. The equipment was left to monitor unmanned for between 3 and 5 days.

Equipment

Measurements were taken using 01dB Symphonie systems. The signal from the single microphone was simultaneously captured on two data channels which enabled all the required parameters (dBA, dBC, third octave band levels and audio) to be monitored simultaneously. The microphone and measurement chain were calibrated down to 1Hz against a traceable standard in the UKAS accredited Calibration Laboratory at Salford University immediately prior to the tests. In each location audio recording plus a wide range of indicators, including one third octave band levels down to 1Hz were taken. Data was streamed directly to hard disk and subsequently downloaded to DVD disks for archiving.

Instructions to participants

Subjects were asked to complete a log sheet (see Figure 2) giving comments on how they perceived the sound at particular times.

Please complete the following log sheet filling in the date and time when you hear the noise being studied, rating the noise along the scale from 'Not at all disturbing' to 'Intolerable' and adding any other comment you feel may be important. It is useful to us to have information about when you are not disturbed as well as when you are. Please use as many sheets as necessary.

Date and Time	Rating (please place a tick along the line)	Comments
	Not at all disturbing |----|-----|-----|-----|-----|-----|-----|-----| Intolerable	

Figure 2: Log sheet given to subjects in the field studies

The terms 'disturbing' and 'intolerable' were used deliberately. Most studies of environmental noise use the term 'annoyance' to judge the severity of the response. However, the descriptions and vocabulary used by low frequency noise sufferers does not generally suggest that 'annoyance' is their main concern about the LFN. The term 'disturbing' is considered to represent the response of a typical sufferer more accurately and so was used on the log sheets. Again, the term 'intolerable' was used deliberately to help identify periods of extreme, unacceptable exposure, as perceived by the sufferer, from the recordings.

Interviews

In addition to making physical recordings of the sounds within complainants' residences it was necessary to obtain a significant amount of personal data about the individuals themselves. This was important in order to obtain an overview of the background to the LFN complaint that might have a bearing on the responses. Details were collected about each individual's residential and occupational histories, their general health, details of the noise they are exposed to, suspected sources of the noise, effects of the noise on themselves and their health, and any measures they have taken to cope with or avoid the noise.

Using a comprehensive one-to-one structured interview schedule we obtained detailed personal information from 12 LFN sufferers. All 12 sufferers answered all questions without hesitation and were forthcoming and open when answering questions relating to their general and mental health and when providing detailed information about their noise problem. This section reports on the specific questions asked and the information obtained.

Current and previous occupations

Details of current and previous occupations were gathered in order to determine whether people had a work-related exposure to LFN. This could be relevant if theories of sensitisation to LFN are verified. Additionally, it was important to establish whether there was any employment-related connection to the main suspected source of the LFN.

Only one complainant reported any previous work-related exposure to LFN and had worked in the industrial works section at British Rail for 28 years since an apprenticeship over 40 years ago. This had entailed exposure to heavy drop forges, pneumatic air guns and general industrial machinery noise. This complainant made some earmuffs as nothing was provided at the time. No other complainants reported working in environments that could be considered likely to expose them to LFN.

None of the complainants named a previous employer as the likely suspect of the LFN to which they are exposed.

Current and previous address

Details of current and previous addresses were gathered in order to determine how long complainants had resided at their current address and whether their residence predated exposure to LFN. Additionally, it enabled clarification to be sought on health related matters in later questions.

Two complainants stated that the LFN was detectable when they first moved into their house but all others had many years of no exposure prior to the onset of the problem. This ranged from 4 ½ years to 38 years.

Respondent's routine

Details of daily routines were collected in order to determine when the house was busiest and quietest. Given that recording equipment was placed in the home for up to 7 days it was necessary to determine when quality recordings might be obtained. Knowing bedtimes and waking times enabled the recording devices to be set to record at appropriate times.

Determining what woke the complainant during the night was important to determine the amount of sleep deprivation associated with exposure to LFN. In some cases it was not the noise that awoke the complainant but subsequent awareness of it prevented them returning to sleep. Asking what the complainant did when wakened in the night was to determine whether any additional coping strategies were employed at that time. Later in the report we discuss the main coping strategies used by complainants not just those employed in the night-time.

All bar one respondent wakes during the night and 75% of all respondents claim it is the noise that wakes them. Over half of complainants get up and walk about when they wake up and a quarter look around the house or out the window to try to determine the source of the noise that has disturbed them. Other activities include putting on the television, using the bathroom, making a drink, taking a sleeping tablet or putting in earplugs. A third of all respondents sometimes just lie in bed listening to the noise without taking any other action, although they may take action on other nights.

Health

Complainants were asked personal questions about their general health to help determine what health related problems they suffered from. Initially, at the beginning of the interview, complainants were asked to self-report symptoms they suffered from, both related to and unrelated to the LFN problem, to give them the opportunity to list what they considered the most significant health issues in their lives.

In order to determine whether complainants might have a hearing problem they were asked whether they had ever had their hearing tested, how long ago this took place, and the outcome. They were also asked whether they were satisfied with the outcome. This was done in order to rule out hearing problems as a cause of the problem. Not every complainant had had a recent hearing test done. Complainants were also asked if they had ever suffered from tinnitus.

A quarter of complainants said they had known hearing problems. One had a 60% hearing loss in one ear with the other ear normal. Another had age-related hearing loss with a loss in the higher frequencies, and one had a blockage due to sinusitis which produced a whistling in the ear.

Half of complainants had never had a hearing test and only 2 had had one within the previous year.

All knew what tinnitus was when asked whether they had suffered from it. All bar one said they had never suffered from it and one said they were not sure as they did sometimes get a whistling in their ear. This was attributed to sinusitis.

Finally a list of other symptoms was read out to the complainant and they were asked to state whether they suffered from any of them. It was made clear that they should say whether they suffered from the symptom whether or not they attributed it to exposure to LFN. The list of symptoms was obtained from the published literature on LFN exposure with particular reference to Leventhall (2003) [Le03].

Respondents who practiced successful coping strategies were asked to report health problems at the time when the noise was at its worst. Our intention was to obtain a list of symptoms experienced by sufferers although we do not have sufficient data or expertise to determine aetiology. Further research in this area is required.

The table below shows the results of this line of inquiry listed in the order in which the questions were asked. 92% of complainants suffer from sleep disturbance, 83% suffer from stress and 67% have difficult falling asleep. 42% suffer from insomnia and 33% from depression. 33% suffer from palpitations although none claim to have heart ailments. 58% suffer from headaches and 25% from migraines. 42% have high blood pressure. Perhaps most seriously, 17% have felt suicidal.

Health	Number of respondents	Percentage of respondents
Tinnitus	*1	8%
Stress	10	83%
Loss of concentration	6	50%
Sleep disturbance	11	92%

Difficulty falling asleep	8	67%
Frequent irritation	5	42%
Nausea	1	8%
Nervousness	6	50%
Insomnia	5	42%
Chronic fatigue	2	17%
Anxiety	8	67%
Frustration	9	75%
Depression	4	33%
Indecision	1	8%
Tiredness	7	58%
Exhaustion	3	25%
Dizziness	2	17%
Sinusitis	3	25%
Glaucoma	0	0%
Pressure or pain in ear or body	7	58%
Body vibration or pain	6	50%
Palpitations	4	33%
Heart ailments	0	0%
Frequent ear vibration	2	17%
Eye ball or other pressure	3	25%
Pains in neck	5	42%
Backache	2	17%
Migraine	3	25%
Headaches	7	58%
Subdued sensation	1	8%
Shortness of breath	2	17%
Abdominal symptoms	3	25%
Shallow breathing	3	25%
Chest trembling	1	8%
Hypertension	5	42%
Stitch	1	8%
Difficulty reading	4	33%
Difficulty watching tv	4	33%
Difficult listening to radio	1	8%
Head injury	2	17%
Dental disease / surgery	5	42%
Eye surgery	0	0%
Suicidal	2	17%

* respondent attributed whistling in ear to sinusitis rather than tinnitus

Table 2: Numbers of respondents reporting various symptoms

The list of health questions included details of surgery and dental treatment undergone in order to identify any possibility that symptoms may be related to head injuries or dental surgery. 42% of complainants mentioned some form of dental surgery the most invasive of which was root canal treatment received by one individual. The other reports refer to tooth extraction, dentures and crowns. Two individuals reported head injuries and these can both be discounted as sources of noise complaints. One head injury was whiplash from an accident a year previously (this respondent has suffered from LFN for 14 years), the other was from collapsing two years previously due to an incorrectly prescribed dosage of medication which resulted in requiring stitches across the head (this respondent has suffered from LFN for 5 years).

Details of other people who hear the LFN

Sufferers were asked about anyone else who heard the LFN to which they were exposed as previous research has shown that LFN may be detectable by some people and undetectable by others. All of our sufferers reported that other people had heard their noise but that not everyone who came to their residence was able to hear it. Overall a wide mixture of 'others' could hear the noises including family, neighbours, friends and other visitors to the house. Many also reported people saying that they thought they could live with the noise – i.e. it didn't bother them as much as it did the complainant.

Further to this we asked whether the noise annoyed every person who heard the noise equally. This was in order to determine whether people had their own explanations or theories about why they were bothered but others were not. Responses to this included observations about other people being too busy to be bothered by it, having more going on in their homes (family, children, loud music etc), and worrying about the value of their home if they made a complaint and then couldn't sell their property. Other people wondered whether they were more sensitive to LFN than others or whether they were simply able to hear sounds at lower frequencies than other people.

Previous addresses

Sufferers were asked whether they had experienced similar LFN problems at their previous address (even if this was a very long time ago) or at any time in the past prior to the onset of the complaint in question. Our intention was to find out whether they had been bothered by LFN when they were younger, although a negative response to this question does not signify that younger people do not detect LFN.

Two complainants stated that they had had similar noise problems at previous addresses. One of these was related to traffic noise, which caused the windows to vibrate causing a hum. This was rectified with secondary glazing. The other was attributed to living amongst factories and the complainant expected to hear noise at that location.

Additionally complainants were asked whether their sleeping patterns were the same at their previous address in order to see whether their current pattern was a constant throughout their life. This question elicited more discussion of changes in lifestyles and work patterns than answers related to LFN.

Location of noise in and around the property

Details of where in the property the sufferer heard the noise were gathered in order to determine the best location to leave the recording equipment. Knowing whether the noise was more detectable in particular positions in rooms enabled a more precise location to be found, thus allowing the best obtainable recording.

Complainants were asked whether the noise was better or worse with the window open as the literature suggests that LFN is exacerbated in enclosed rooms due to windows and walls filtering out higher frequency sounds. It is sometimes experienced that opening the window ameliorates the LFN problem, although only 25% of respondents reported this. 50% of respondents said it made no difference whether the window was open or closed.

Noise descriptions

Complainants were asked to describe in their own words the LFN to which they were exposed. Subsequent to this they were read a list of further descriptions, from the literature on LFN, to see if any of them also matched their noise. In an effort not to put words into the complainants' mouths they were asked for their own descriptions first.

In addition to the descriptions commonly used by complainants to describe LFN, as reported in the literature, other descriptions used by our respondents included: 'like a car ticking over'; 'a distant hum'; 'like a refrigerator building up again after the door has been opened and closed'; 'like a central heating boiler'; 'a whine like a jet engine or turbine'; 'a whistle'; 'a short beat and a long beat'; 'like a lorry with the engine going'; 'like a meter winding down'; 'like a spin dryer'; 'like being in a microwave'; 'like a kettle warming up'; 'like aircraft high overhead'; 'a deep roar'; 'like a compressor unloading'; 'like emerging from a tunnel'; 'like fishing boats going to sea at night'; 'like air roaring up a chimney'.

Sources of LFN

Complainants were asked if they knew the source of the noise. While a third of cases said they did know the source they were only able to narrow it down to a site (a particular commercial or industrial premises) rather than to a specific process or piece of equipment. Two thirds of cases did not know the source but had a variety of theories, usually with a favoured suspect. Details of how the source or potential source of the noise was identified were gathered and these included visiting the sites in question or obtaining information about when new equipment was brought online at the sites.

Complainants were asked formal questions about the history of their LFN problem. While it was felt unnecessary to obtain the complete detailed history of the relationship between the complainant, the EHO concerned and the suspected source of the LFN enough information was sought to establish how long the LFN had been present and what steps had been taken to identify and rectify it. These histories often identified long running problems with considerable involvement of the EHO. Sometimes ameliorating procedures were put in place which either rectified part, but not all, of the problem, or seemed to remedy the problem only for it to start up again in subsequent years.

Exposure to LFN

In order to obtain good recordings of the LFN complainants were asked what time of the day the noise was worst. It was expected that this would be at night time when background noises are reduced although this was not always the case. Often complainants attributed bad times to particular periods in the cycle of the equipment or process considered to be the most likely source. A number of complainants mentioned how wonderful it was when the noise stopped – sometimes for a fortnight over Christmas or summer (which they attributed to the plant in question closing down for holidays) – only they were on edge all the time expecting it to start up again at any time.

For the majority of respondents (83%) the LFN was continuous, i.e. it was always there. The remaining two respondents said their noise was intermittent, with silent periods in between.

Ambient noise level in home – expectation and control

Respondents were asked how they would describe the background noise level in their home taking the LFN out of the equation. Given that other sounds may mask LFN we wanted to ascertain the extent to which masking sounds were present. All described their home as 'Quiet' or 'Very Quiet'. This raises questions about expectation and whether some people have higher expectations of intrusion of noise from external sources. However, some sufferers stated that they didn't mind aircraft flying overhead or the sound of the road outside their home because they knew it was intermittent and other stated that it was knowing the source that was important to them as it gave them a sense of control.

Subjective reaction

Complainants were asked to state in their own words how the noise made them feel. Put this way the question allowed for a repetition of the health symptoms the complainant suffered from or a further description of their emotional response to the noise. Many complainants spoke of the frustration they experienced, their lack of control, and the lack of help or success from agencies they expected to have power over the situation.

Noise avoidance

Details of any measures that had been taken to try to avoid the noise were obtained. The importance of this was to identify the extremes to which people have gone to avoid the noise as well as to identify measures that worked and could therefore prove useful strategies for other sufferers.

Half of the sufferers interviewed have tried earplugs and some still use these at night. Others said that they exacerbated the problem or made no difference. Headsets or ear defenders have been tried by a third of sufferers, sometimes in tandem with earplugs. Some complainants said that using head phones when watching TV aided their concentration which was otherwise diminished.

Three quarters of the complainants had tried sleeping in different rooms in their house with varying degrees of success. For those who found that one façade of the house was worse than another moving to a 'back' room proved successful. However others found no respite despite trying to sleep in the living room, the hallway, the kitchen, the cellar and/or the balcony. Some attempted putting foam under the bed legs, with no effect, while others slept with their head pointing towards the middle of the room rather than against the wall, with some effect.

One respondent said they would go away to a holiday home they owned in order to avoid the noise and would extend their vacation because they hated coming home. Nearly half had considered selling their home, some had even put it on the market, but all were concerned about their duty to tell potential buyers about the LFN problem. Those that had tried to sell found it impossible once potential buyers were aware of the LFN problem.

A quarter of the sufferers said they tried to concentrate on other things in order to divert their attention from the LFN. Techniques that came under this category include practicing yoga and other stress reduction techniques.

A quarter of sufferers regularly took prescribed sleeping tablets in order to sleep and found these very successful. Others were not willing to take sleeping tablets.

Creating additional noise to mask the LFN was tried by some, again with varying success. Using a 'tinnitus machine' worked extremely well for one complainant who had discovered this on the internet. Similarly an air purifier worked for another complainant. Another had found playing 'white noise' on the radio helped them sleep. However, playing the radio or TV during the night had limited success although more during the day.

All respondents were asked if they had any additional comments that they felt were relevant to their problem but which had not been covered in the interview. No new information was obtained in this way.

General comments on interviews

The results presented above indicate that all the complainants used in the study have ongoing problems which they associate with low frequency noise, and which have a fairly serious impact on their lives. None have a history of suffering from these problems at previous residences, and none have had an employment or other discernable relationship with the company or organisation suspected as the source of the low frequency noise about which they complain. Furthermore, as far as can be judged by an experienced interviewer, the complaints were genuine, and there was no hint of ulterior motives, such as wanting to get rid of local industry.

Responses to the problem of exposure to low frequency noise ranged from an annoyed interest to feeling suicidal. Coping strategies ranged from wearing earplugs through sleeping in different rooms to attempting to sell the house. Not all respondents had found a strategy that worked for them at the time of the interviews although we were able to pass on information about how other sufferers coped.

Measurement results and analysis

A large amount of data was recorded for each case study. This was considered necessary, since from experience, the equipment must typically be in the property for several days to capture a period when the complainants report hearing a representative 'bad' noise. One of the problems of LFN analysis is how to make sense of such a large amount of data. The details of the analysis varied from case to case, but the usual steps were as follows:

a. Several periods were selected from the subject's log about the time they said the noise was particularly bad (the period was chosen to encompass the time given by the occupant, but to exclude events such as doors closing etc. as detected by ear)
b. For each such period a sonogram was drawn to display the 1/3 octave spectrum. This was examined to see whether any events could be identified that correlated with the respondent log. The sonogram option may not be available to most EHOs, but a third octave band spectrum could be used instead.
c. From the third octave band plot, the single third octave band that exceeded the audibility threshold by the highest margin was selected
d. A narrow band plot was also made to see if there were any obvious tonal frequencies in this band
e. A plot of the sound level in this third octave band was then plotted against time so as to show what, if anything, happened at the time identified as being bad.

In all but two cases it was possible to identify suitable periods described by the subject as particularly bad. In Case 8 the subject did not make a detailed log, asserting simply that their noise was present all the time. In Case 6 there was some question as to whether it was the subject themselves or a spouse who had compiled the logs. For these cases we selected the worst case situation by a combination of looking at the spectra and analysis 'by ear' of the audio recordings.

In this section are presented two cases which are illustrative of the other cases. A summary of the results of other cases is shown in Appendix 1.

Case 20

Figure	Times identified by respondent selected for presentation below
Figure 5	03h00 "Bad throb, headache, felt sick"
Figure 8	00h30 "Very bad rumble"
Figure 8	08h15 "Very bad throb"
Location	Rural
Source	Distant industrial
Microphone position	Corner of downstairs living room

The narrow band plot in Figure 3 is from the around the time indicated as bad by the complainant, and shows a clear pronounced peak at about 36Hz. Sounds at this frequency, if of high enough intensity to be audible, would be heard as a low booming. However, the presence of this peak by itself is not enough to demonstrate a problem, we need to compare it with the threshold of audibility and with national criteria. This is done in the third octave band plot, Figure 4, taken at around the same time, on which is also shown the ISO threshold of audibility. The 40Hz band is above the threshold by more than 20dB, and is the most likely candidate to cause a problem.

Having clearly identified the 40Hz band as the likely source of the problem, a plot of the variation in the level of this band with time is shown in Figure 5. The time given by the complainant is marked, and clearly corresponds with a time when the level in this band was raised. Also shown in this figure for comparison are the limits from the Polish and Danish national criteria, which are respectively the lowest and highest values of any of the national criteria for this band. Note that the Danish curve is not strictly intended to be used as a reference curve in this way, and so the value plotted is if anything on the high side. Even without taking this into account, the levels are above the curve, and therefore above all the national criterion curves.

Figure 6 shows the dBA and the dBC levels plotted during the night. dBA is the usual indicator for environmental noise, and filters out low frequencies. dBC does not filter out low frequencies. The amount by which the dBC level exceeds the dBA level therefore gives an approximate indication of the low frequency content in the sound. The difference is up to about 30dB, so the preliminary check used for the German standard would show the need for a more detailed investigation. Note that after 07h00 the A weighted level rises significantly whilst the dBC level remains about the same. This is due to activity of the residents getting up and making some sound in the house. Thus, the sound is predominantly low frequency, except when there is ‘people noise’ in the house.

Figure 7 shows the third octave band spectrum at another time indicated by the complainant as particularly bad. It is similar to Figure 4 with the 40Hz band about 15dB above the threshold of audibility. The time history in Figure 8 shows that levels exceed the Danish limits (and therefore all other national criteria) in the 40Hz band throughout the night, and are particularly high at times indicated.

Therefore, in this case there is a clear correlation between times when the noise exceeded guidelines and when the complainant reported being particularly disturbed.

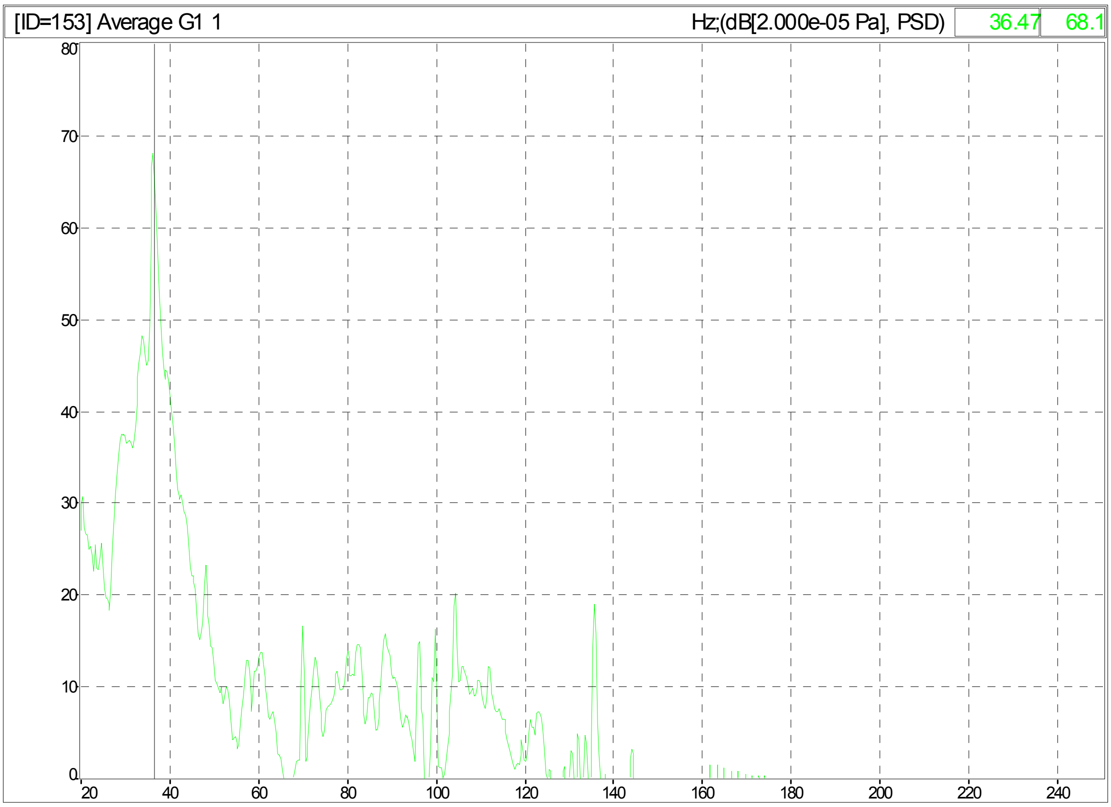

Figure 3: FFT of 9m30s audio record starting 02h28m from measurement Case20_040508_210000.cmg

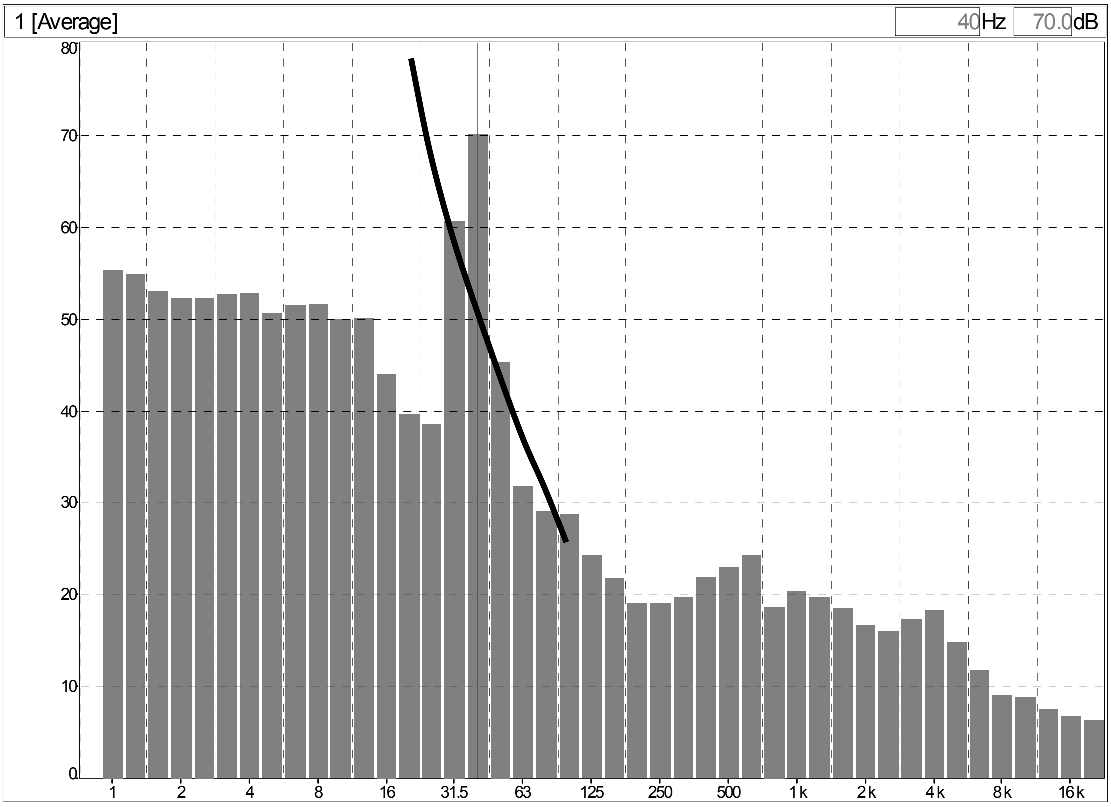

Figure 4: Mean 1/3 octave band spectrum 9m30s starting 03h00m from measurement Case20_458_210000.cmg

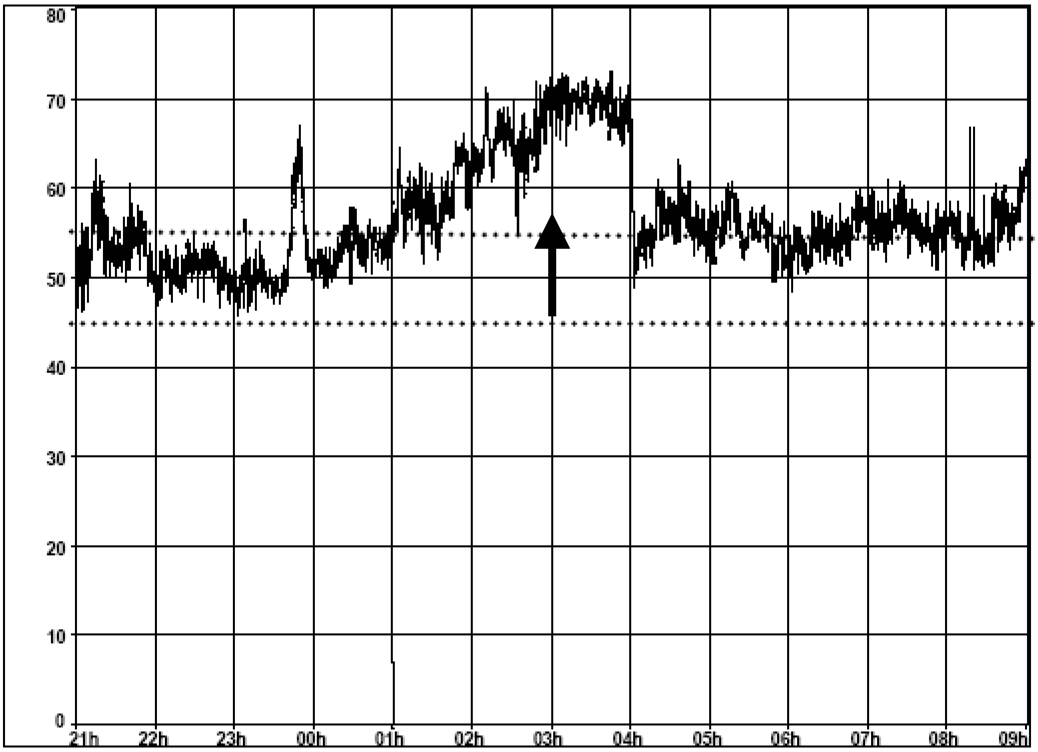

Figure 5: Time history showing 40Hz 1/3 octave spectrum band from measurement Case20_458_210000.cmg together with lower Polish 44.6dB and Danish 54.6dB limits

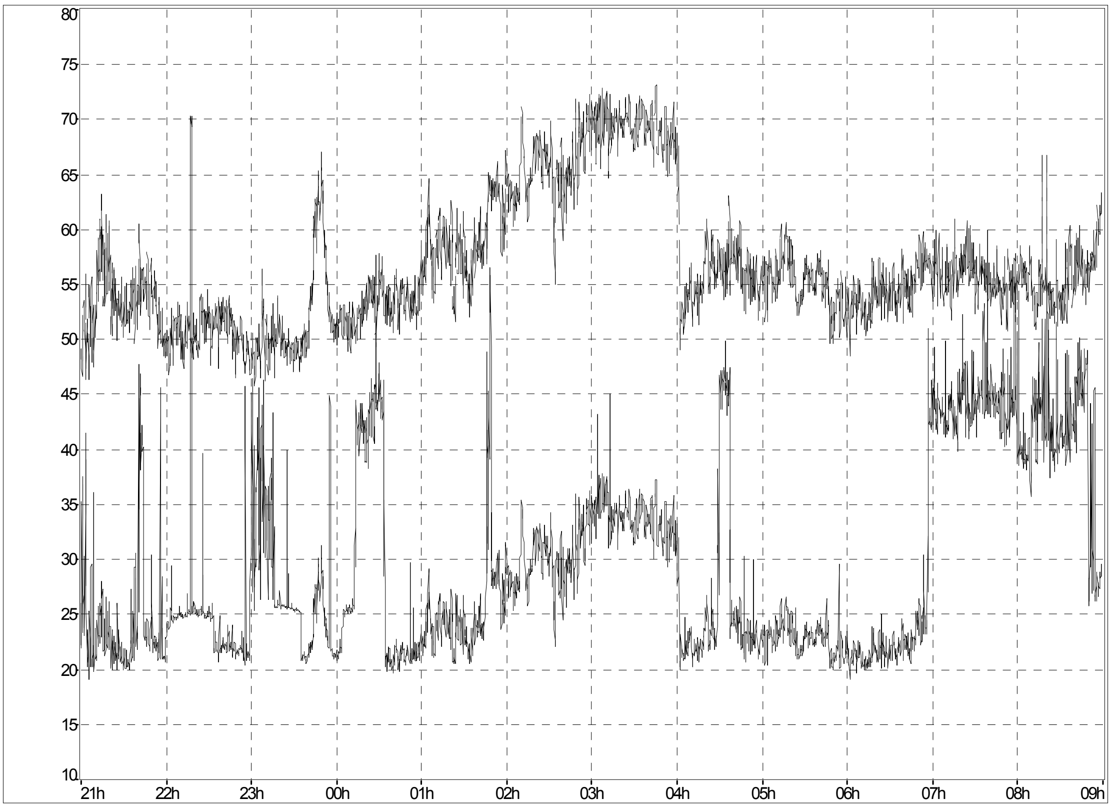

Figure 6: Time history showing 40Hz 1/3 octave spectrum band from measurement Case20_458_210000.cmg together with dBA levels. The dBA level illustrates normal household noise.

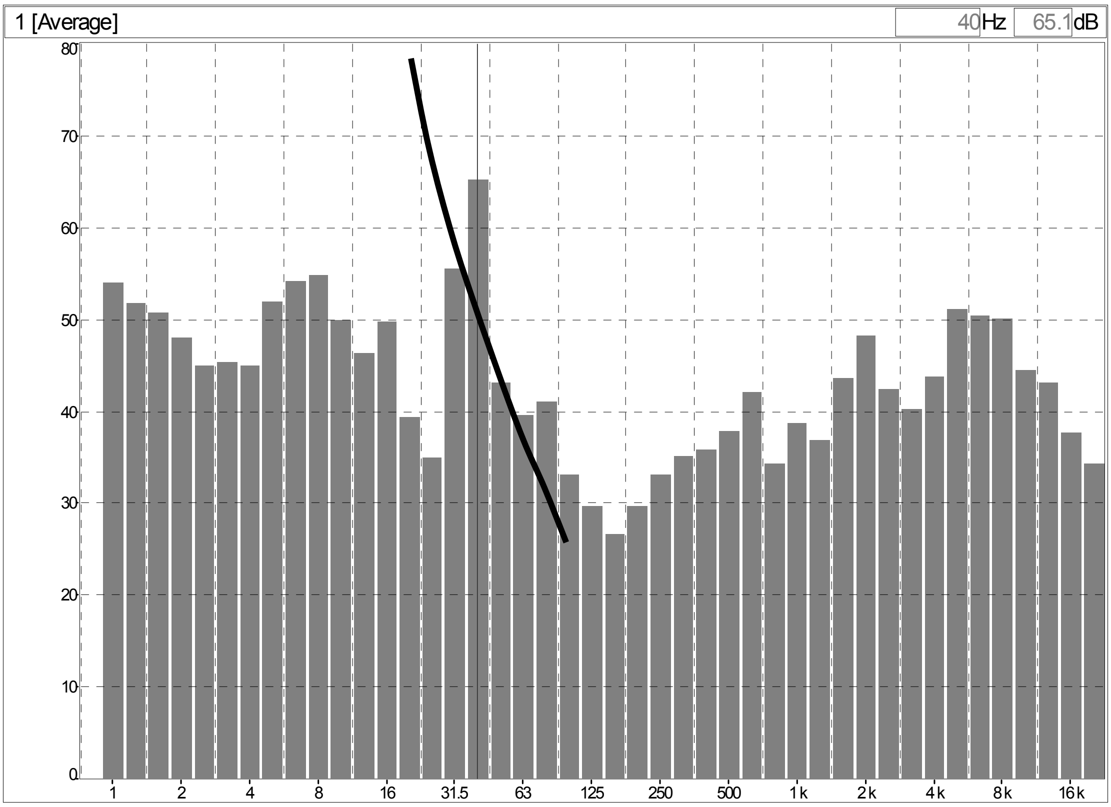

Figure 7: Mean 1/3 octave band spectrum 9m30s starting 08h10m from measurement Case20_459_210000.cmg

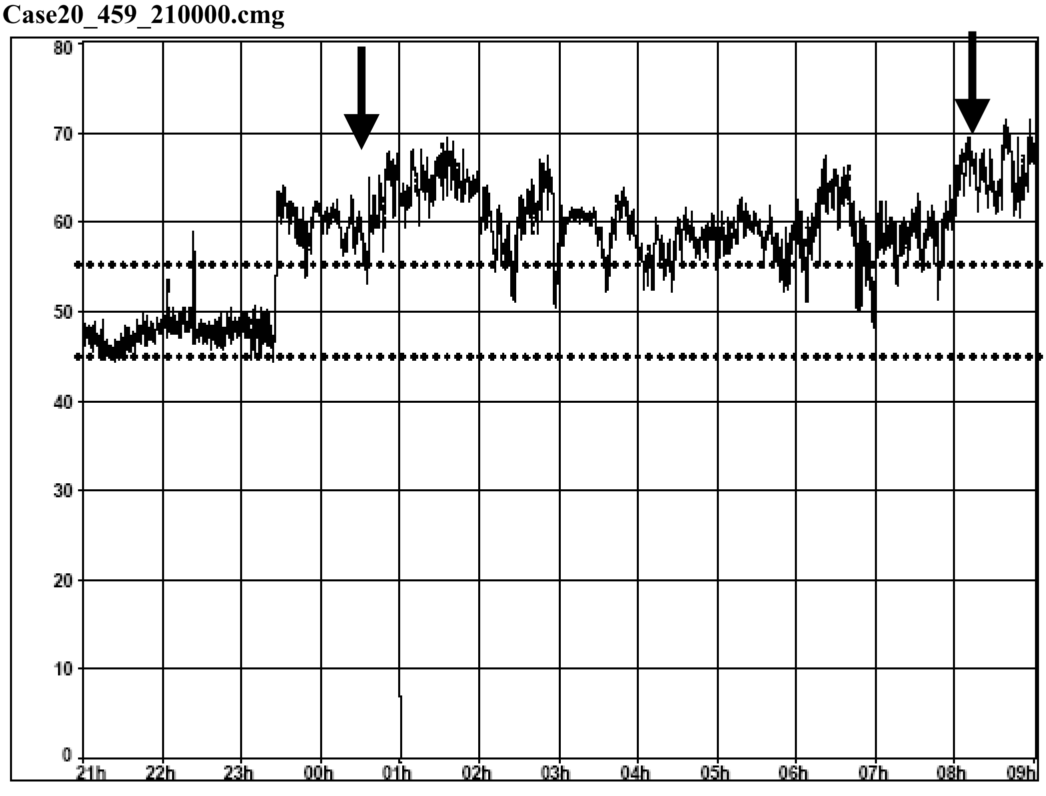

Figure 8: Time history showing 40Hz 1/3 octave spectrum band from measurement Case20_459_210000.cmg together with lower Polish 44.6dB and Danish 54.6dB limits

Case 2

Figure	Times identified by respondent as 'Intolerable' selected for presentation below
Figure 11	23h45 5 on scale. 'Hum louder through the night'
Figure 14	07h00 2 on scale 'Hum as usual'
Location	Suburban
Source	Suspected industrial.
Microphone position	By closed doubled glazed window in upstairs front bedroom

Figure 9 shows the narrow band recording from Case 2 at a time indicated by the complainant as a score of 5 on the log sheet scale of 8 (Figure 2). This was the highest that they recorded throughout the tests. Figure 10 shows the third octave band plot with the ISO threshold of hearing superimposed. The only notable feature on both plots is a peak at 10Hz, but this is more than 40dB below the threshold of hearing as published in the German standard (the ISO published values do not extend down to 10Hz). The 80Hz band might be just audible, and the 100Hz band exceeds the audible threshold by about 6dB, so could be audible. However, none of the bands up to 80Hz exceeds any of the national criteria. The 100Hz band level is at a similar level to the Polish curve, but would not exceed it when background noise was taken into account as is required in the Polish method. Thus, none of the national criteria were exceeded for this time.

The dominant source in the 80and 100Hz bands was road traffic noise. It is fairly common to find audible noise in these bands due to traffic. This could be determined by ear, and from the profile of the sound levels during the night (Figure 11) which is typical for traffic. Figure 11 also shows the time the comment relates to. It can be seen that this occurs at a time when the noise levels in this band are falling. (The occasional 'spikes' on this plot are due to internal movement or occasional events in the neighbourhood, and are not associated with any steady noise of LFN type). The description of the noise as 'hum louder through the night' does not correlate with the noise levels in this band.

Thus, for this time:

- none of the national criteria were exceeded
- the description given by the complainant does not correlate with the observed variation in noise levels in the only band likely to contain audible sound
- the noise in this audible band was due to road traffic.

The narrow band spectrum for another time is shown in Figure 12. There is a small peak at 75Hz, which also shows up in the third octave spectrum Figure 13 (the source is not known but is thought to be internal). This band is an average of more than 5dB above the two neighbouring bands and slightly exceeds the German night time limit of 33dB. The time history in Figure 14 shows a similar typical profile of traffic noise (again, the spikes are single events, not LFN). Noise levels are rising at the time of the comment, but the complainant gives a score of only 2 on the scale of 8. These findings do not correlate with the above comments from the earlier time where the German criterion was not exceeded and a higher disturbance score was given.

Several other times and comments were evaluated, but we were unable to find a relationship between noise levels and the comments. The cause of complaints in this case therefore remains a mystery. In terms of the aims and objectives of this project it provides a clear example of a case that could not be solved by engineering noise control. This is true firstly because the only noise that could be identified was road traffic noise. Secondly, even if a source could be found, the lack of correlation between the respondent's comments and the presence of any raised noise levels suggest that reducing noise levels would not resolve the complaints.

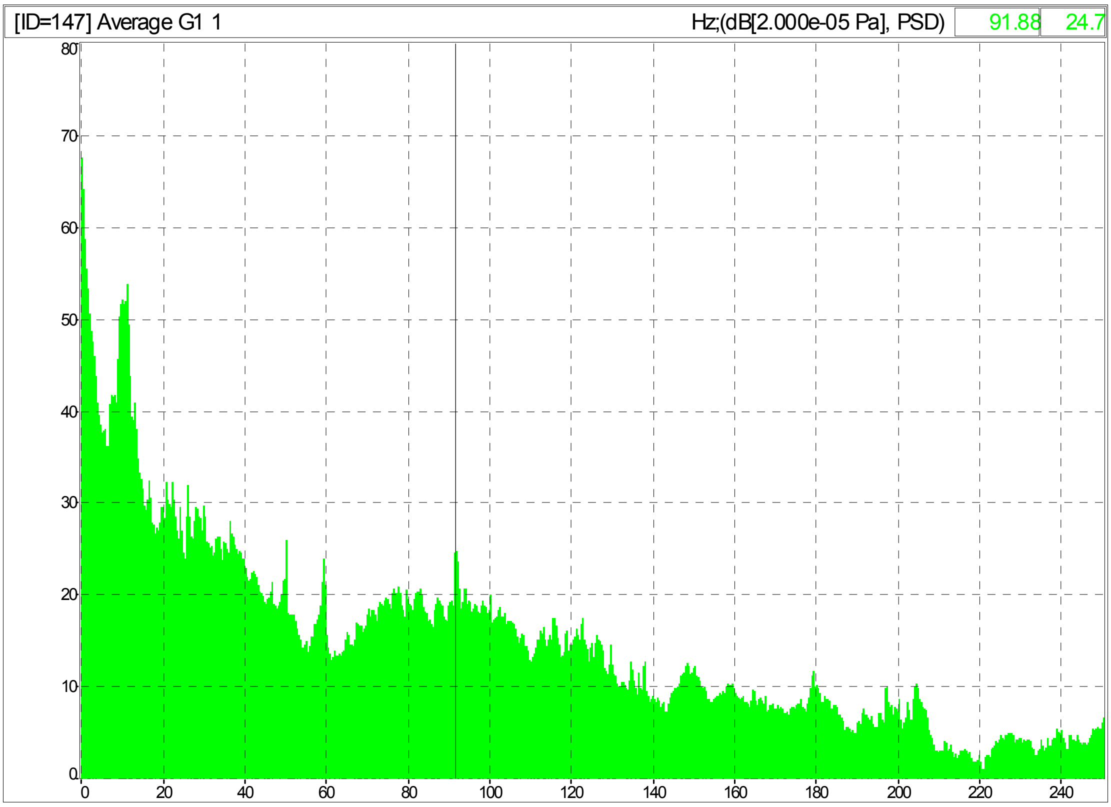

Figure 9: FFT of 9m30s audio record starting 23h45m from measurement Case2_433_104426.cmg

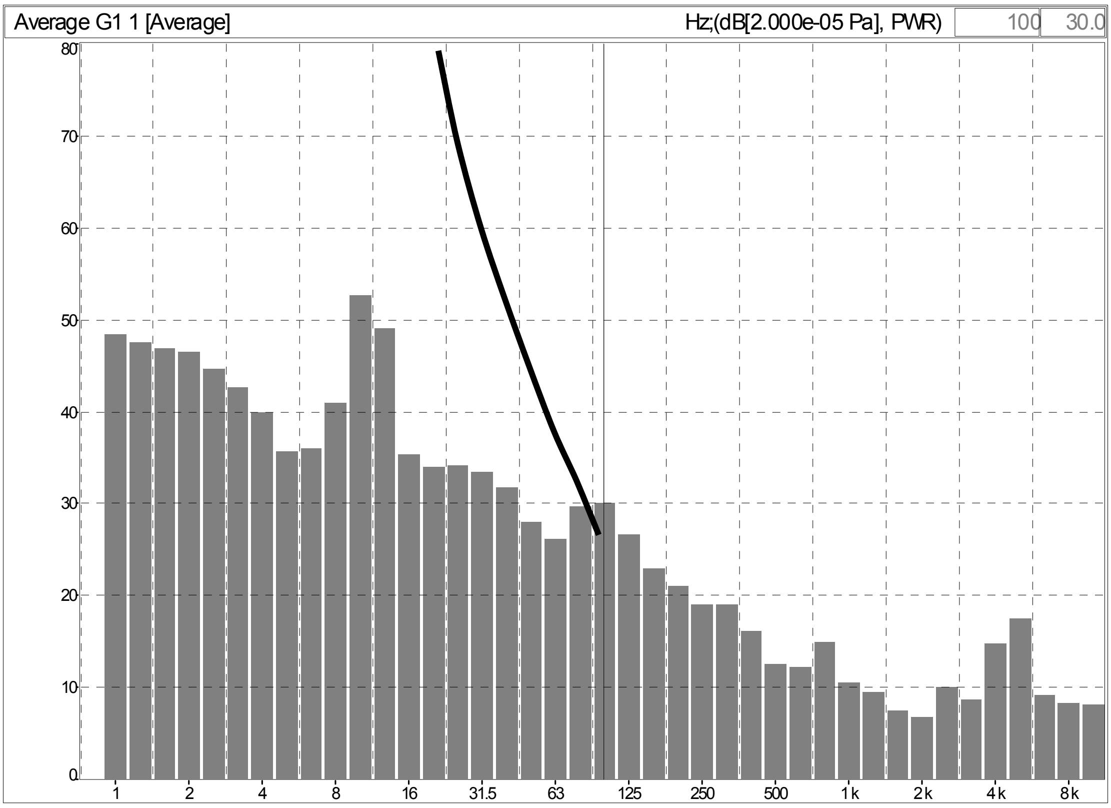

Figure 10: Mean 1/3 octave band spectrum 9m30s starting 23h45m from measurement Case2_433_104426.cmg

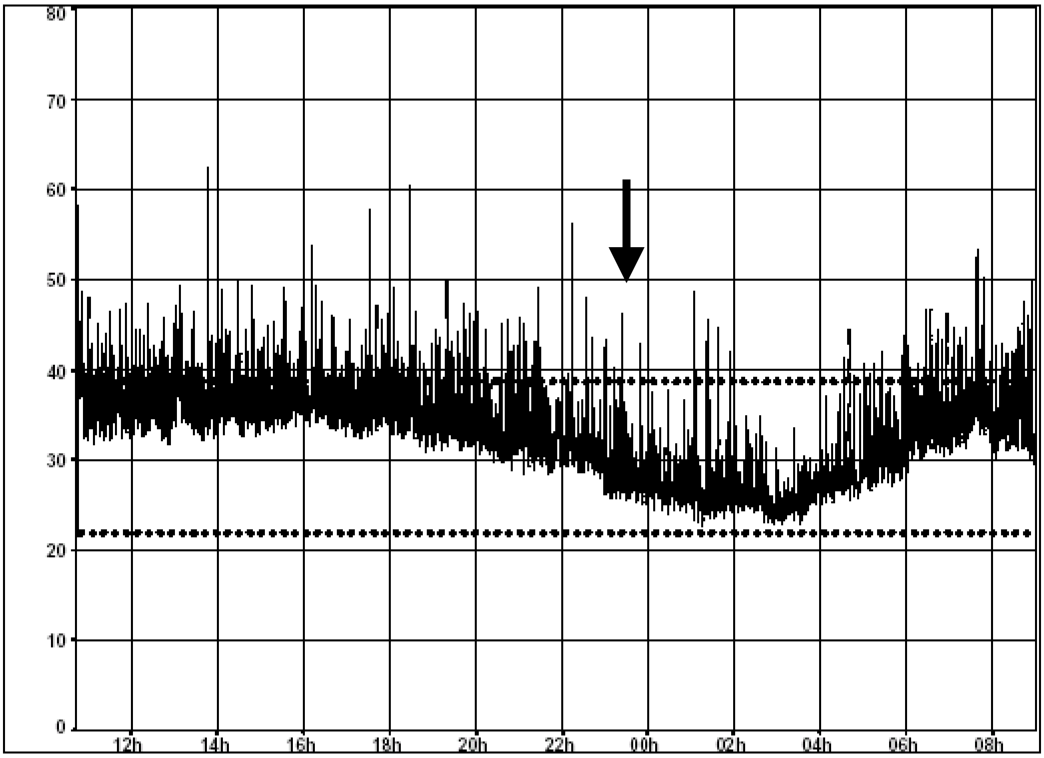

Figure 11: Time history showing 100Hz 1/3 octave spectrum band from measurement Case2_433_104426.cmg together with lower Dutch (audibility) 22dB and Danish 39.1dB limits

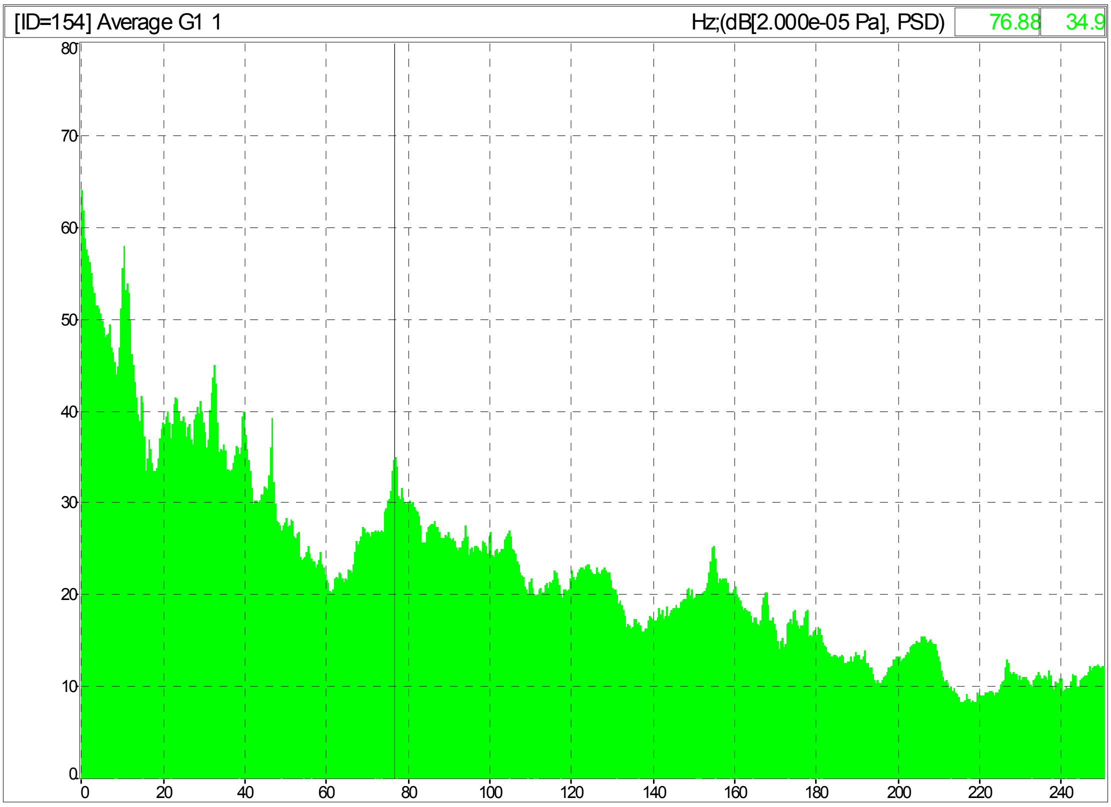

Figure 12: FFT of 9m30s audio record starting 07h00m on 01/03/04 from measurement Case2_4229_210000.cmg

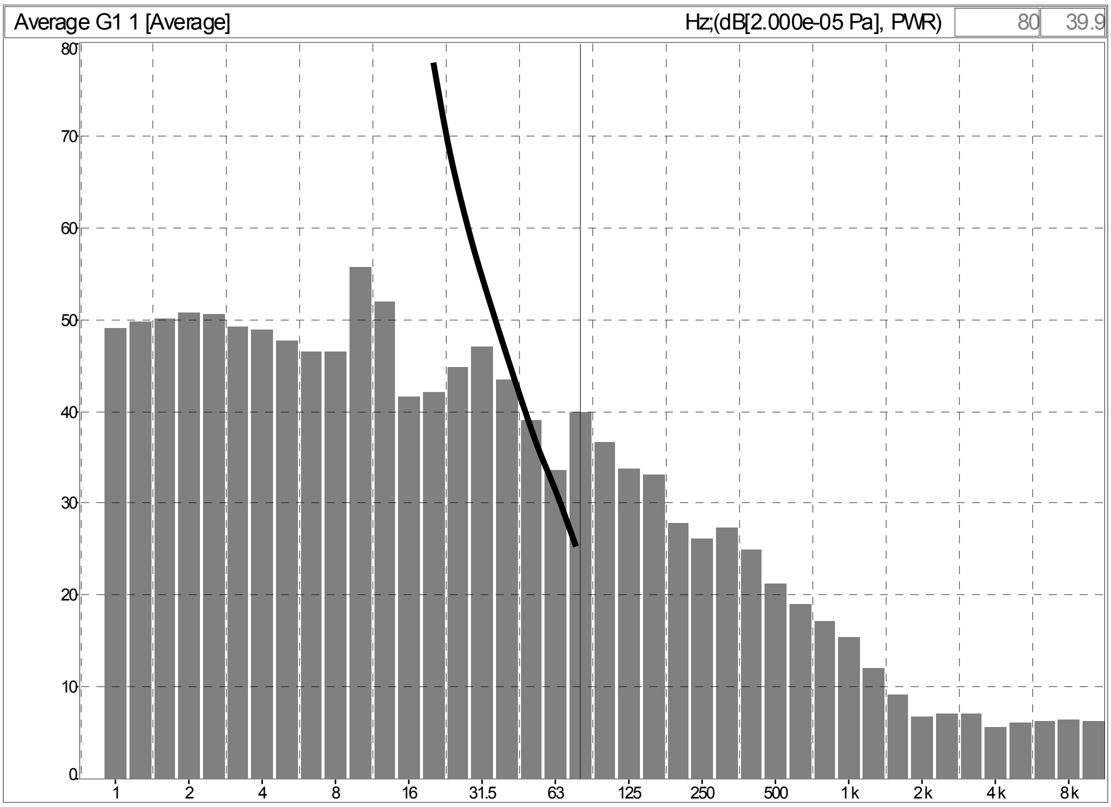

Figure 13: Mean 1/3 octave band spectrum 9m30s starting 07h00m on 01/03/04 from measurement Case2_4229_210000.cmg

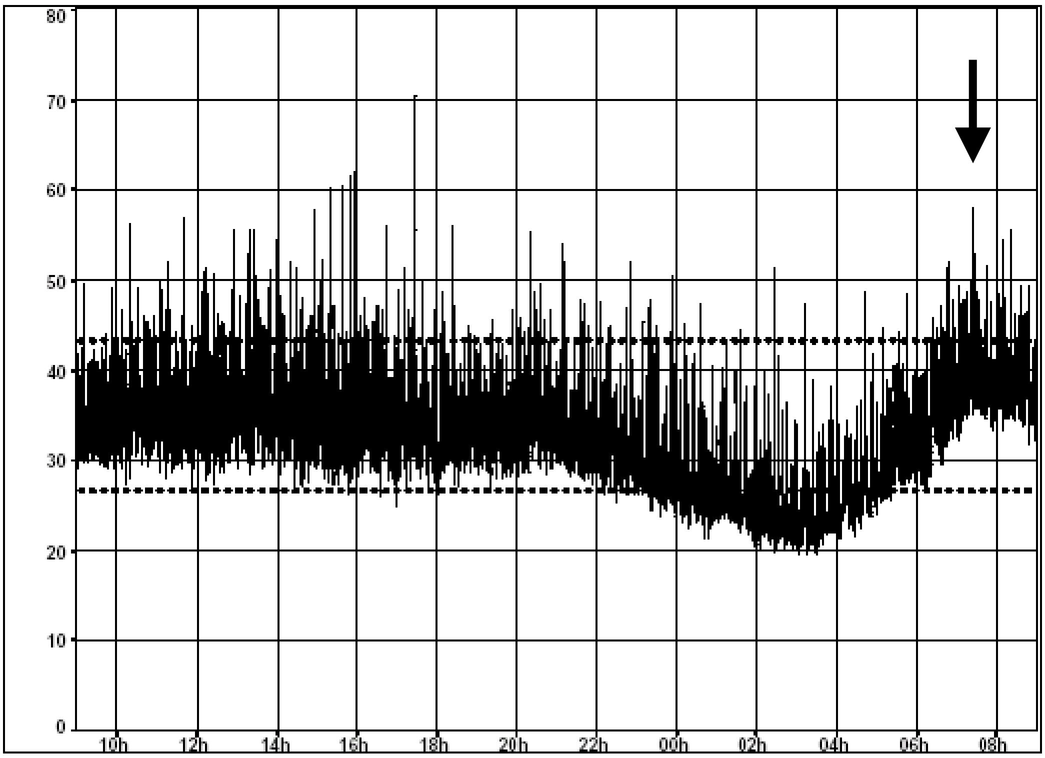

Figure 14: Time history showing 80Hz 1/3 octave spectrum band from measurement Case2_4229_210000.cmg together with lower Dutch (audibility) 27dB and Danish 42.5dB limits

Similar analyses were carried out from measurements at nine other residences. Some of the figures used in the analysis are given in the Appendix. The overall findings are summarised in Table 3.

Case	Peak 1/3 octave band (Hz)	Respondent suspected source	Correlation of respondent log with suspected source	Source indicated by analysis	Correlation of log with analysis indicated source
2	100	Industrial	No	None	N/A
	80				
5	63	Industrial	No	None	N/A
	63				
6	50	Industrial	No	None	N/A
	100				
7	80	Industrial	No	None	N/A
	80				
8	50	Industrial	No log	Industrial	N/A
	50				
13	100	Do not know	N/A	None	N/A
	100				
16	100	Do not know	No	Air traffic and domestic equipment	Yes
18	50	Industrial	No	Domestic equipment and possibly air traffic	Yes
19	100	Industrial	Yes	Industrial	Yes
	50				
19a	63	Industrial	Yes	Industrial	Yes
	63				
20	40	Industrial	Yes	Industrial	Yes
Control 1	63	Traffic	Yes	Traffic	Yes
	40	Domestic equipment	Yes	Domestic equipment	Yes
Control 2	50	Domestic equipment	Yes	Domestic equipment	Yes
Control 3	63	Traffic	Yes	Traffic	Yes
Control 4	160	Industrial	Yes	Industrial	Yes
	100	Traffic	Yes	Traffic	Yes

Table 3: Summary of findings from case studies and control cases. The multiple entries refer to different events studied.

A number of control cases were also examined using the same techniques. These were residences where low frequencies would be expected in the spectrum, but where there had been no reports of disturbance, for example city centre residences and houses with direct line of sight to a busy motorway. The findings are also summarised in Table 3. Of particular note from these results is that in Control Case 1 the criteria would have been exceeded due to a domestic central heating pump in the dwelling, although there was no complaint about LFN.

General comments on field studies

The case studies fall into three categories:

a. Positively identified LFN – in these cases the national criteria were exceeded and respondent logs correlated with recorded sound from an external source of LFN
b. Unidentified – in these cases the national criteria were not generally exceeded, (except perhaps by traffic noise or sound from internal domestic equipment) and respondent logs did not correlate with any source
c. Marginal – in these cases a source of LFN could be determined but was borderline with respect to the criteria.

The case studies falling into these categories are identified in Table 4

Table 4: Categorisation of case studies

Positively identified	Case 20 Case 19 Case 19a
Marginal	Case 16 Case 18 Case 8
Unidentified	Case 6 Case 13 Case 7 Case 5 Case 2

In positively identified cases an engineering solution could be put into place, and in view of the correlation with respondent logs, would be likely to remove the source of the problem. In unidentified cases engineering solutions would not be possible, firstly because no source could be identified, and secondly, even if it could, the lack of correlation with the complainant logs suggest that the problem would not be solved by reducing sound levels. In two out of three of the marginal cases the suspected source involved air traffic, which would be beyond the control of a local authority.

Therefore, it appears that the national criteria are generally successful in distinguishing between cases where the EHO is likely to be able to bring about a solution from those where they are not. However, as control cases show, there is not always a complaint when the criteria are exceeded. These conclusions are significant in terms of the aims of this study; they imply that the criteria can be useful indicators, provided they are not applied in a rigid way.

Most of the ‘problem’ and ‘marginal’ sounds were in the 40 and 50Hz bands. In these bands the national reference curves are in reasonably close agreement, so the same conclusion would be arrived at irrespective of the criterion used.

It was noted that in all cases the background noise levels in the residences were extremely low apart from the LFN, if present. This is typical and has been observed by various researchers (see for example [vB99b]). Such low levels of natural masking noise are thought by some to be a factor contributing to the disturbance of LFN.

It is also noticeable that there were no cases in which the noise was reported to be present only during the day. This does not mean that the noise was absent during the day, most respondents said they could hear it during the day but that it was worst at night. However, in every case the noise was reported to be present at night. This contrasts with common experience, where a random batch of complaints about general industrial noise (not LFN) might be expected to include some complaints about industry that does not operate at night but causes disturbance only in the daytime. This observation does not contribute to the main aims of this report, but it is mentioned as being relevant to help explain the phenomenon.

A certain amount of judgement is involved in identifying LFN. One of the most useful aspects of the criterion curves is to help identify problem frequency bands (see also [Ru02]). A useful technique, which is now becoming more widely available, was found to be to take audio recordings along with sound level measurements. It is a common problem that the investigating person is hampered by not being able to hear the sound themselves. Audio recordings can be played back at a higher (audible) level and are useful to distinguish between various noise sources. Combined with third octave and narrow band spectra, together with the criterion curve improves the chances of being able to identify sources.

LABORATORY TESTS

Objectives of the tests

Much previous work, (including most national guidelines) is based on the idea that the acceptability or otherwise of a low frequency sound can be evaluated in relation to a frequency-dependent reference curve. This well-established approach will be adopted here. Such a curve can be called the 'threshold of acceptability': sounds with a higher intensity would be considered unacceptable, and those with a lower intensity acceptable. (The idea is similar to the familiar 'threshold of hearing' which indicates the level at which sounds become just audible rather than acceptable.) The overall aim of the laboratory tests is to establish a threshold of acceptability for day and night time and for sounds of various characters.

It has already been mentioned that it is not possible to reproduce realistic field conditions in a laboratory test. In particular, the length of exposure does not give an adequate impression of what it is like to live with the sound. Therefore, the laboratory tests should not be used to establish absolute levels for a reference curve. However, absolute levels have been fairly well established in the various national criteria and by reference to published hearing thresholds, so this is not needed. What is needed is to establish an optimum shape for the curve since the various national guidelines differ in this respect. This will be the first objective of the laboratory tests.

Clearly, as with thresholds of hearing, the threshold of acceptability would be expected to vary from one person to the next. It might also vary between day and night time, and could show variation depending on the character of the sound as well as its intensity. In particular, the degree of fluctuation in a sound has previously been identified as an important parameter affecting the acceptability [Po03] [Le03].

The objective of the laboratory tests is therefore to establish 'thresholds of acceptability' for sounds with varying degrees of fluctuation, for day and night exposure.

Overall methodology for laboratory tests

There are two general approaches to testing in the laboratory: the method of limits and the method of adjustment.

In the method of limits a number of fixed sounds is played to the subject, who is asked to give each one a 'score' to indicate how much it annoys them, how pleasant they find it etc. In the method of adjustment, the level of the sound is adjusted until it achieves a certain response from the subject, for example it is adjusted so that they can just hear it (this is how hearing thresholds are tested). In both methods one is looking to find a correlation between an objective quantity (as measured by the acoustic instrumentation) and a subjective quantity (as indicated by the subjects).

The method of limits is the best-established method for measuring reactions to environmental noise (see for example Poulsen and Mortensen [Po03]). One advantage for this study is that we could argue it is closer to real cases in that sufferers of low frequency noise have no control over the sound, (other than to move to another room or building). A disadvantage is that, since we are interested in establishing the effect of fluctuations on the threshold of acceptability, we need as many sounds as possible to be around the threshold level. This may not work out if we are fixing the level of the sounds for all subjects since each individual will have a different threshold. This leaves the possibility that some tests might not give useful data.

The method of adjustment could be used by asking subjects to adjust the level of the sound so that it is just acceptable for an assumed situation, like trying to get to sleep. (see for example Inukai et al. [In00] who carried out a series of tests on Japanese subjects). The effect of fluctuations, if any, on the threshold of acceptability can be judged directly from their responses to sounds of different character.

Therefore, the method of adjustment is well suited to the objectives of the tests and was adopted. There are further advantages in that the comparisons can be done more quickly than with the method of limits, so that more significant data can be obtained from each subject in the time available. Furthermore, since the method gives the threshold of acceptability directly it avoids the need for statistical analyses required by the method of limits.

Details of the tests

Having decided in the previous section on the basic approach, in this section the following details are described:

- selection of sounds
- choice of subjects
- length of tests
- listening room set-up
- calibration of listening room
- audiometric tests
- test procedure.

Selection of sounds

The following options were available:

- sounds from field recordings
- synthesised sounds
- a combination of real and synthesised sounds.

The advantage of real sounds is that they are more easily accepted as realistic. The advantage of synthesised sounds is that they can be controlled so that only one aspect of the sound is varied at once. Specifically, this would allow us to control the amount of fluctuation whilst keeping other characteristics of the sound constant. The final set presented to subjects comprised a combination of real and synthesised sounds which was developed and refined during a series of preliminary tests.

It was decided to use at least some sounds from the field studies for realism. However, it was not sensible to compare sounds from different case studies because a number of factors vary, such as the frequency and character of the sounds. In order to isolate the effects of fluctuations we needed to compare subject reactions to a number of sounds in which all parameters (tonality, frequency content etc.) were kept constant except the amount of fluctuation. After some searching we found a set of sounds that met this requirement fairly closely. In case 20, the suspected source was about a mile away, so that the fluctuation in the sound varied with wind and other factors. We were able to select a number of short recordings from the five-day record in which the source was essentially the same, but the degree of fluctuation of the sound varied. From this set, the best five samples were chosen by a combination of analysis and preliminary listening room tests. In fact there was some variation in frequency content between the samples, but since this was not detectable by ear it was decided that they could be considered essentially the same except for the type and strength of fluctuation. This allowed us to combine the realism of actual sounds with the controlled fluctuations that would otherwise have had to be synthesised. The test sounds were therefore strongest in the 40Hz third octave band.

The sounds had to be carefully prepared. Segments of a few minutes with varying degrees of fluctuation were identified by evaluating the standard deviation of the sound pressure level (this is a measure of the variance in sound level, see later) over the three nights of recording. It was verified that the sounds were ‘clean’, i.e. with the industrial source only and without extraneous noise, such as traffic, which could have confused the picture. From this set, a smaller set of five sounds was selected in which the frequency of the sounds was as close as possible. In preliminary tests it was found that most of the sounds drifted in level over a period of a minute or so, making it difficult to establish a proper threshold. Hence, a ten second sample of each sound was taken and ‘looped’ so as to produce a recording of 3 minutes duration but with a homogenous content throughout. The ‘joins’ between the looped segments were disguised by cross fade techniques so that even expert listeners could not tell that it had been looped.

Waveforms of the five real sounds are shown in Figure 15[*].

[*] The sounds can be heard on http://www.acoustics.salford.ac.uk/lfn.htm

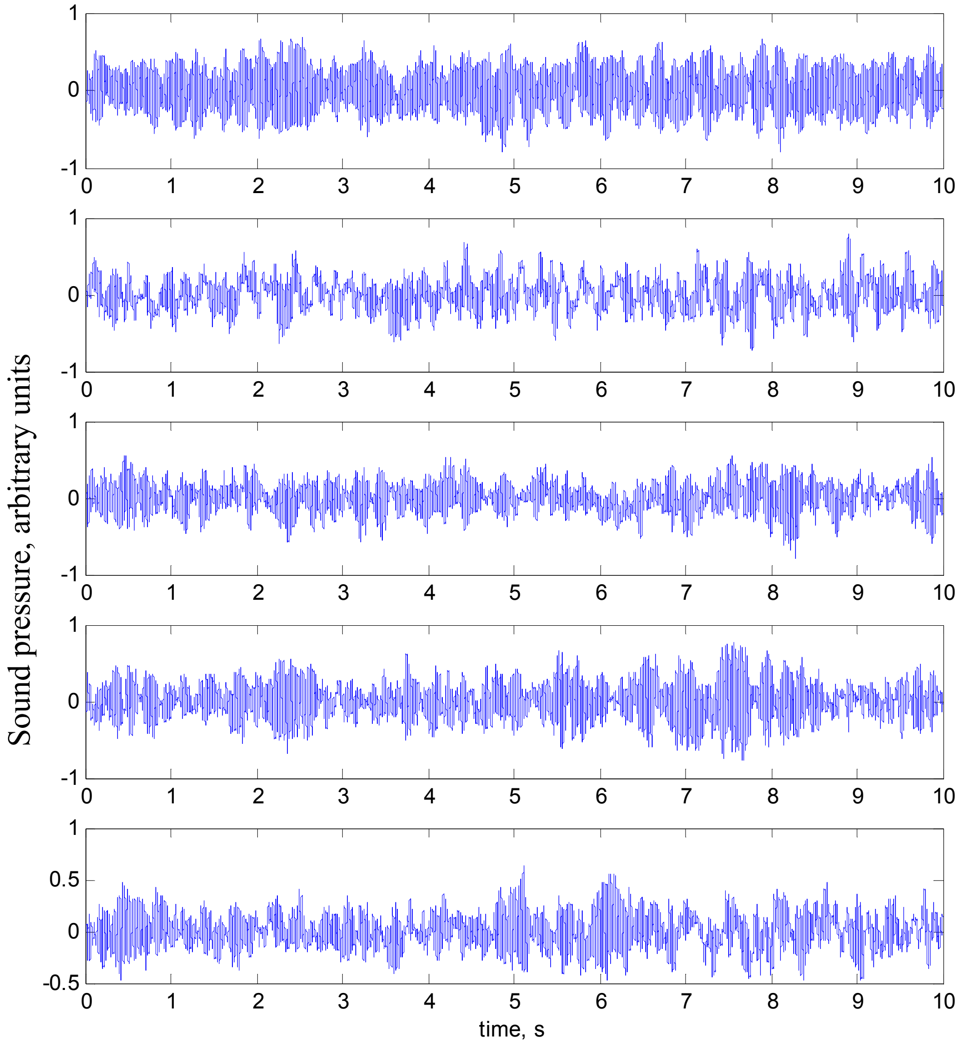

Figure 15: Waveforms of the real sounds Tracks 1-5 used in the laboratory tests

These real sounds did not fully answer all our needs, because it would provide results only at a single frequency. In order to test the threshold of acceptability tests were needed at controlled frequencies over the whole of the low frequency range. Field recordings could not be used for this purpose because the 'problem' frequencies recorded on site lay in a narrow range. Also, it would not have been possible to produce a set of sounds in which only the frequency varied in a controlled way. Hence, the real sounds above were supplemented by synthesised sounds.

Ideally, we would have produced sounds over a range of frequencies and with a range of fluctuation. However, this would have required too many sounds for subjects to evaluate in the time available. Hence, two sets of synthesised sounds were used:

- a set of pure tones at third octave band centre frequencies between 25Hz and 160Hz so as to cover the entire frequency range for testing the shape of the reference curve

- two pairs of sounds, one fluctuating at one and a half beats per second (a beating tone) and one steady (a pure tone) so as to evaluate fluctuations at 40 and 60Hz

The 'beating tones' were synthesised by combining two steady tones of similar frequencies as shown in Table 5. The result was the waveforms as shown in Figure 16: Waveforms for beating tones at 40 and 50Hz used in the laboratory tests. The frequencies of 40Hz and 60Hz were chosen because these were frequencies at which problems occurred most often in the field studies.

40Hz beating tone	60Hz beating tone
Formed from two tones: 40Hz at 0dB 41.5Hz at –8dB	Formed from two tones: 60Hz at 0dB 61.5Hz at –8dB

Table 5: Details of how the beating tones were synthesised

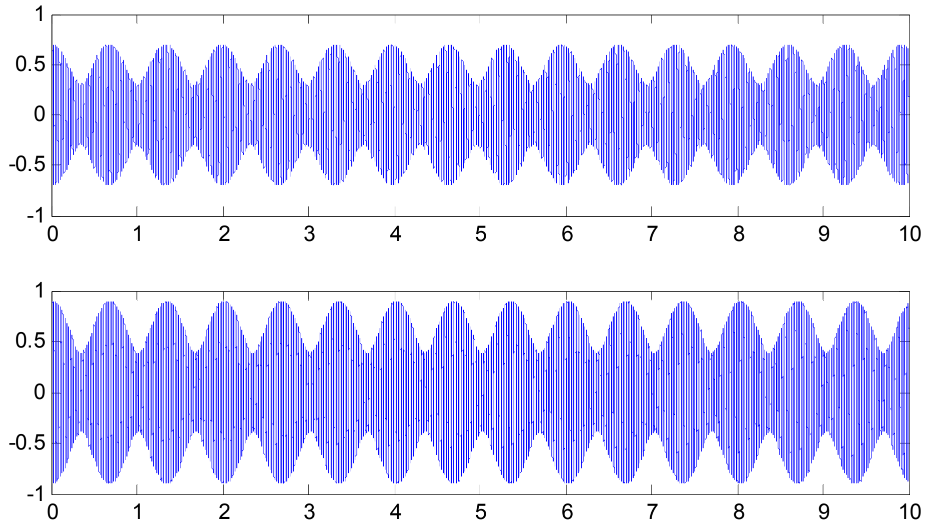

Figure 16: Waveforms for beating tones at 40 and 50Hz used in the laboratory tests

To summarise, three sets of sounds were used:

a. Real sounds
b. Steady tones
c. Beating tones.

Choice of subjects

The choice of both the number and make up of subjects is an important consideration. The total number of subjects was set at 18. A slightly higher number (22 subjects) was used in a similar test in Denmark [Po03]. However, these were mostly young subjects, and by selecting subjects with age and sex profile of sufferers the significance of the results could be increased.

Regarding the profile of subjects, low frequency noise sufferers tend to be middle aged or elderly, and the majority are women. Also, there is evidence that people known to be disturbed by low frequency noise will judge sounds differently to a cross section of non-sufferers [Pe03]. Consequently the following profile was proposed:

Group 0 3 subjects known to be disturbed by low frequency sounds
Group 1 8 subjects with the age profile of typical sufferers (55-70 year old) but without a history of disturbance by low frequency noise
Group 2 7 subjects from a younger age group chosen at random.

Subject	Age	Sex	Group
1	75	F	0
2	20	F	2
3	63	M	1
4	47	F	0
5	57	M	1
6	40	F	2
7	23	M	2
8	65	M	1
9	59	F	1
10	60	F	1
11	34	F	2
12	44	F	2
13	25	M	2
14	58	M	1
15	63	F	0
16	60	M	1
17	60	F	1
18	39	F	2

Table 6: Make up of subjects for laboratory test

Group	Average age	Sex	Total
Group 0	62	3F	3
Group 1	60	5M, 3F	8
Group 2	32	2M, 5F	7
All	50	7M, 11F	18

Table 7: Make up of subject for laboratory tests by group

Length of the tests

The length of the tests was determined by the following argument. From experience of similar tests the maximum test period over which subjects can maintain concentration is 20 minutes after which a break is required. Also, it was considered that a three-hour session was the maximum over which reasonable results could be obtained from the point of view of subject fatigue. A period of training was required of about 20 minutes, and two audiometric tests taking about half an hour in total. Taking these constraints into account the maximum number of test session was three with a total listening time of 1 hour. This placed a limit on the number of sounds that could be played.

Listening room test setup

Tests were carried out in the listening room at Salford University, which conforms to the stringent requirements of ITU-RBS1116 (standard for listening rooms). The room is designed for comfortable listening conditions. Subjects were asked to sit on a reclining chair, which was selected both to minimise its effect on the sound field, and to provide a relaxing, reclined position for the night time tests.

The sound was produced through a single REL Strata V subwoofer, combined with Genelec speakers mounted so as to give the subject the impression of being surrounded by sound as in a real situation. Speakers were hidden from the subject by cloth screens. Experience showed that the source could not be located by ear. The test arrangement is shown in Figure 17.

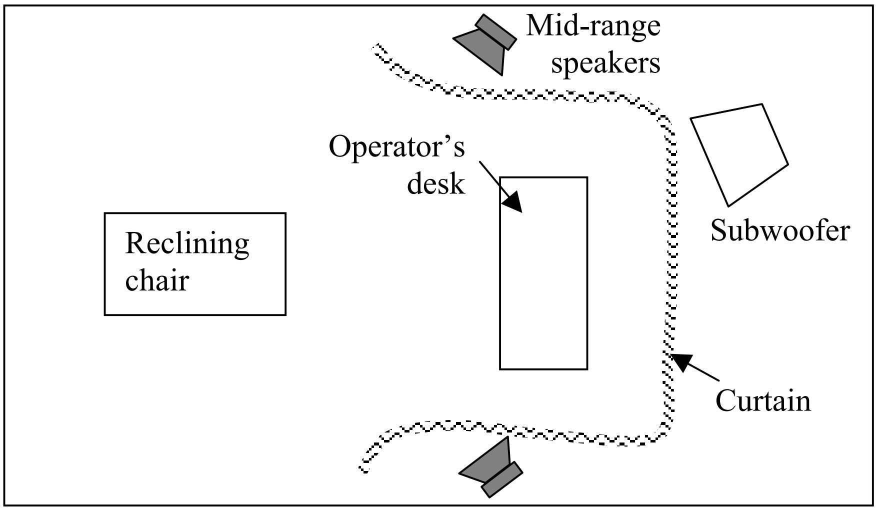

Figure 17: Listening room setup

Once subjects were seated in the reclining chair they were read the following instructions for the 'day time' tests:

"Imagine you are at home during the day. Press the button whenever you consider the sound is not acceptable to live with and keep it pressed. Whenever you consider the sound is acceptable to live with, release the button."

or alternatively, for the 'night time' tests:

"Imagine you are at home at night and trying to get to sleep. Press the button whenever you consider the sound is not acceptable to live with and keep it pressed. Whenever you consider the sound is acceptable to live with, release the button."

For the 'day time' tests the main lights were on in the room, and for the 'night time' tests the main lights were switched off leaving a low level lamp.

An operator adjusted levels using similar techniques to those used in audiometry, i.e. by reducing the level when the button was pressed until it was released. A coarse adjustment was made up and down to find an approximate threshold during the first few seconds followed by finer adjustments. The operator was experienced in audiometric testing, which helped to improve the quality of the results. The bus level on the mixing desk was noted after each sound, and this was later calibrated to give the sound pressure present at the ear of each subject. Each sample lasted 90 seconds, which had been found during preliminary tests to be sufficient time to obtain a reliable threshold. It was found by experience that, after an initial training period, the threshold levels were repeatedly set to within 1dB, which is extremely close for this type of test. This gave considerable confidence in the technique.

Calibration of the listening room

The listening room is specially designed to have a 'flat' frequency response, meaning that it is has no acoustic character that would 'colour' the sound, for example by room resonances. However, the usual frequency range for listening tests is down to about 40Hz, whereas in this case low frequency measurements were needed down to 25Hz (the lowest 'problem' frequency from field tests was 34Hz). At such low frequencies there is no such thing as a flat response for any normal sized room. To compensate for any colouration effects, a third octave band graphic equaliser was used and adjusted so that the frequency response of the combined sound system and room was flat. In fact, the sounds presented were predominantly single frequency sounds, so that colouration effects are unlikely to play any role.

The room is also designed for low background noise. The only audible sound, apart from the test sound was a faint buzz from amplifiers. This could have been removed, but preliminary testing showed it to have no effect.

It was necessary to relate the bus levels, as recorded by the operator, to the actual sound level as perceived by the subject. This was done in a calibration test before the main block of tests in which each sound was recorded on a microphone at the position of the subject's head. The sound pressure levels (Leq) recorded were used to calibrate the bus levels.

Additionally, an overall calibration was carried out at the beginning and end of each day, using pink noise. The variation in sound pressure level at the subject's head position was never more than about ±0.2dB over the entire test run, which is within the tolerance allowed for precision sound level meters.

Audiometric tests

There were two parts to the audiometric testing, a conventional test and a low frequency test.

The conventional test was conducted using a Bekesy automated audiometer over the frequency range 250Hz-6kHz. These frequencies are all above those of the sounds presented in the listening tests, but it was considered wise to carry out the test so as to show up any hearing defects that could affect the results. The results of these tests are not reported here.

The low frequency audiometric tests were carried out in the anechoic chamber at Salford University. This facility is calibrated and accredited by UKAS for testing according to British and European standard number BSEN24869. The standard test procedures had to be extended and modified for the purposes of this study. Firstly, the frequency range was extended down to 31.5Hz. Secondly, pure tones were used as a test signal rather than filtered pink noise because this is more representative of how low frequency noise typically occurs in the field. Test frequencies were the third octave band centre frequencies between 31.5 and 160Hz. These low frequency hearing thresholds were needed for interpretation of subjective responses, because individual sensitivity will affect perception.

Test procedure

All subjects participated in five separate tests

1. training period
2. audiometric testing
3. steady tones night time
4. real sounds/ beating tones day time
5. real sounds/ beating tones night time

The order of the first two sessions was reversed for half the subjects to allow access to the audiometric facility. The order of the day and night sessions was varied randomly in order to prevent any bias in the results.

During the training period subjects were introduced to the listening room and the sequence of testing was explained. They were played a selection of sounds and given some practice in adjustment of the levels. Such training periods are a widely accepted as a necessary practice in this type of testing. In preliminary tests a training effect was noted in which subjects tended to indicate lower thresholds the second time they were played a sound. This was attributed to them ‘learning’ to recognise the sound. Further preliminary tests showed that a single period of training was sufficient to overcome this effect.

Laboratory test results

Low frequency hearing thresholds

Figure 18 shows the hearing thresholds of all subjects. There is a spread of between 25 and 40dB between the most and least sensitive subjects. Figure 19 shows the results averaged over each group. It shows that the younger age group (group 2) has more sensitive hearing than the 55-70 year old group (group 1) by about 5dB. This would be expected as hearing sensitivity tends to reduce with age. The shapes of the spectra follow the published ISO values fairly faithfully, and the levels are in agreement given that the ISO curve applies to 18-25 year olds whereas the average

age of the subjects was 60 and 32 years for group 1 and 2 respectively. (Note that the ISO thresholds were increased by between 1 and 4 dB in 2003.)

Figure 18 also shows that the least sensitive group in terms of hearing threshold is group 0 (sufferers). This contradicts the view sometimes expressed that those who suffer from low frequency noise have especially acute hearing at low frequency, although the number of subjects is too small to draw a general conclusion on this.

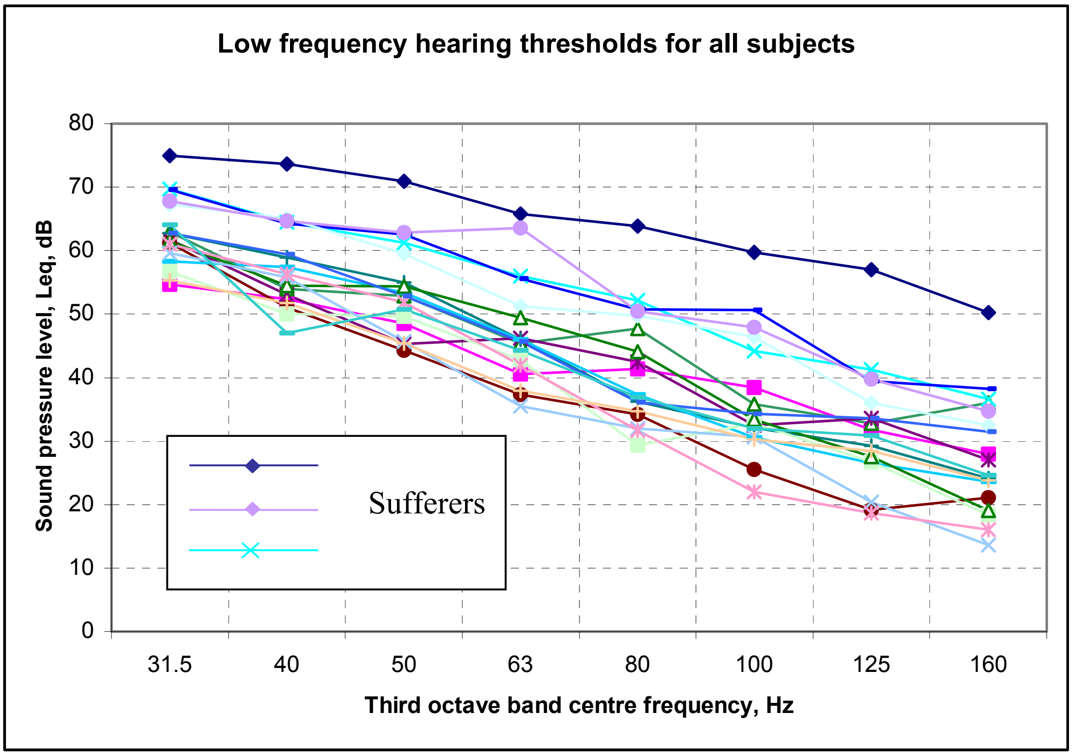

Figure 18

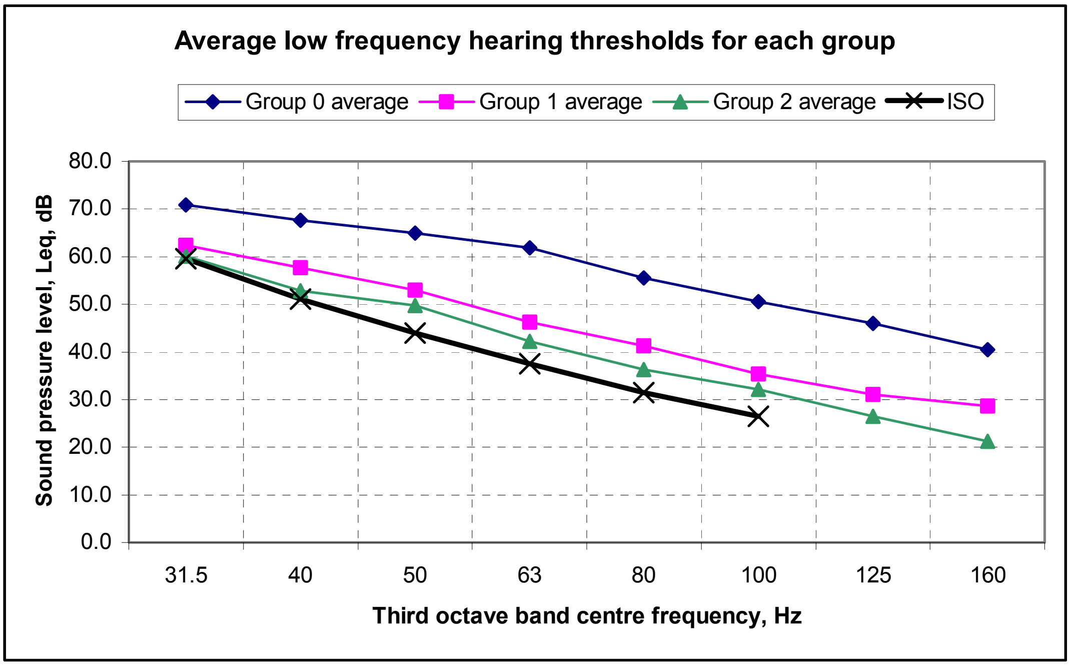

Figure 19

Threshold of acceptability for pure tones

Figure 20 shows the thresholds of acceptability set by all subjects to tones plotted against the frequency of the tone. There is a range of about 30dB between the most and least sensitive subject. This is not surprising given that the thresholds of hearing have a similar spread. Figure 21 shows the values averaged out over each group. It shows that in absolute terms the sufferers are the least sensitive group, followed by the older and then the younger group. As mentioned above, this contradicts the often-held view that sufferers tend to be particularly sensitive.

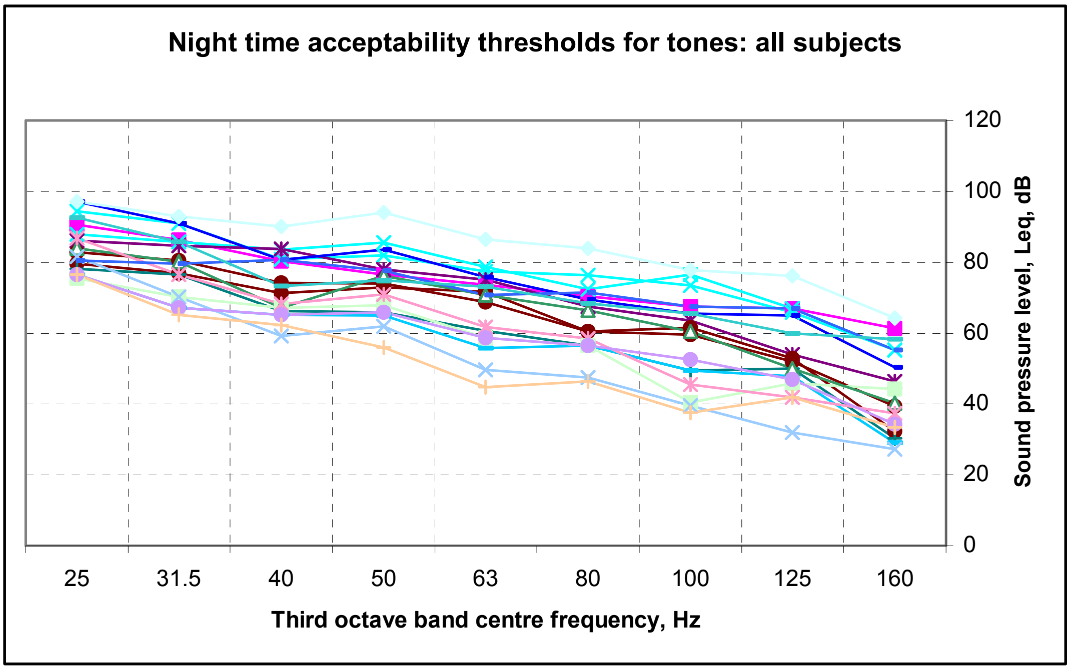

Figure 20

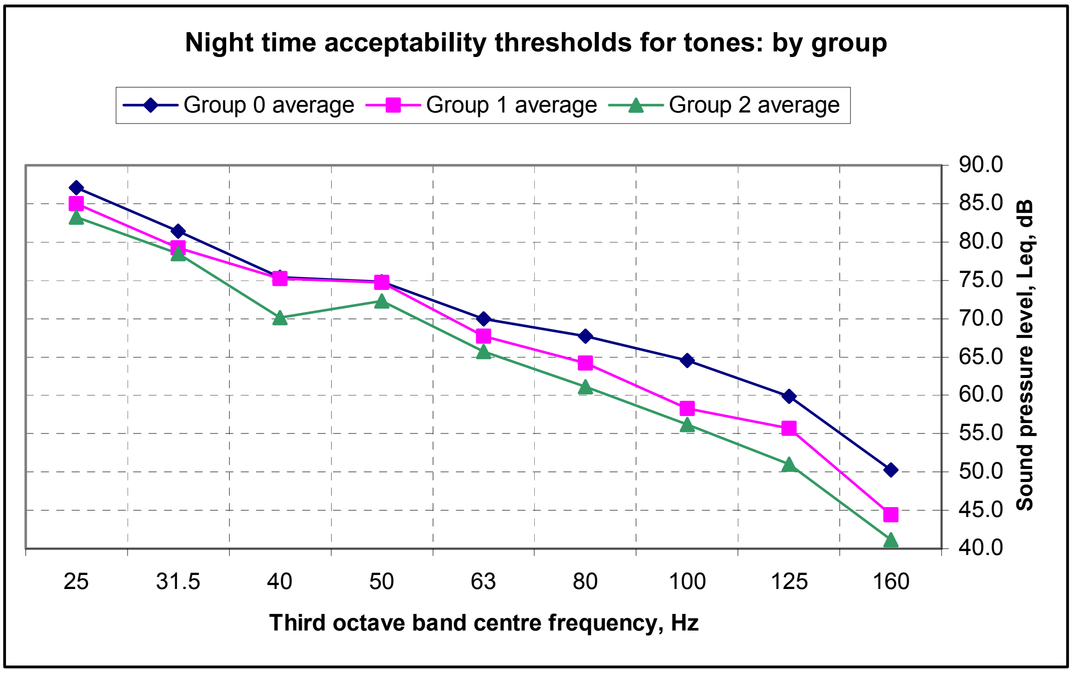

Figure 21

We would expect each individual's threshold of hearing to have a strong effect on where they set the threshold of acceptability. Therefore it is interesting to see how far above the hearing thresholds subjects set their threshold of tolerance. Shown in Figure 22 are the 'relative' thresholds, i.e. the difference between the threshold of acceptability and of hearing for each individual. There is about a 35dB spread in the results. Some subjects set the threshold of acceptability only a few dB above their hearing threshold, in other words they judged a sound that was only just audible to be unacceptable. (In one case the threshold of acceptability is set slightly below the threshold of hearing, which can be attributed to subject variability). Others set the difference very much higher, so that the sound would be clearly audible before they judged it unacceptable.

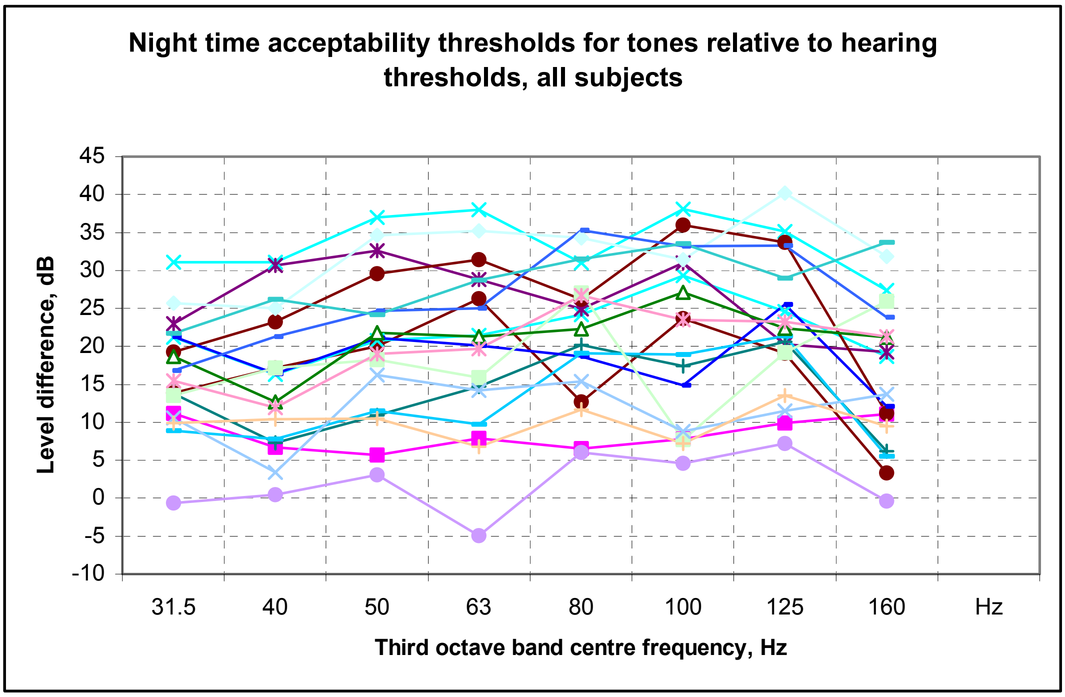

Figure 22

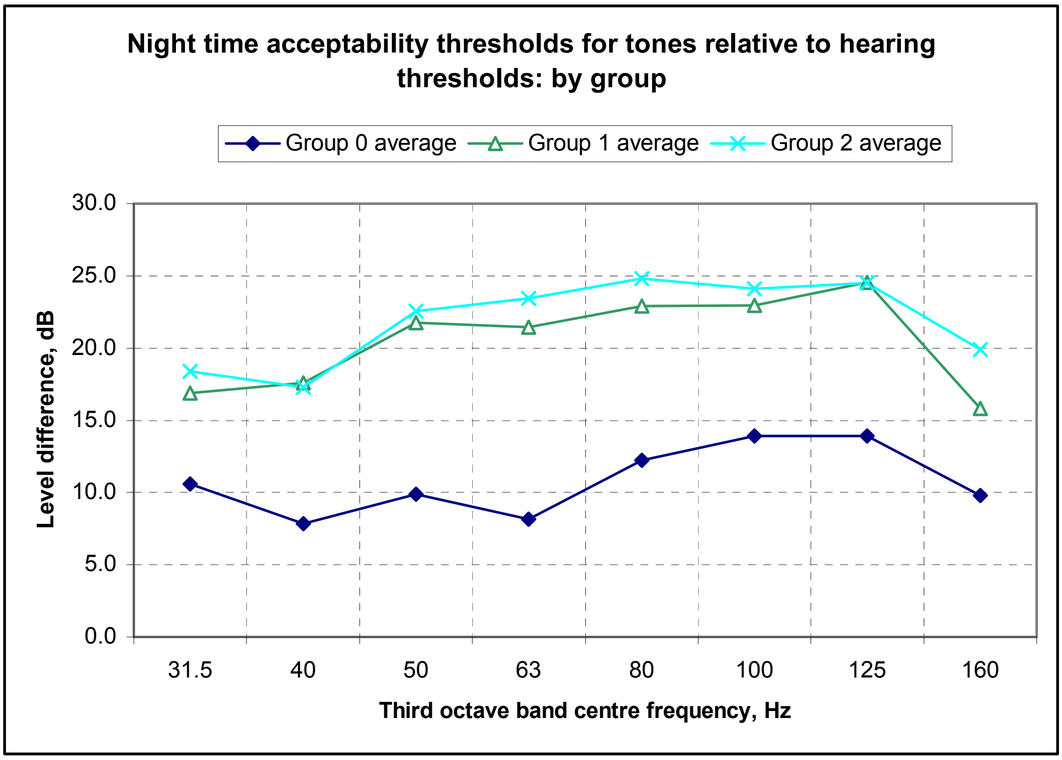

Figure 23

Figure 23 shows the values averaged by group. Two points of interest come out of this. Firstly, there is a marked difference in the average response of sufferers compared with the other two groups. They set the acceptable level about 10dB higher than hearing threshold on average, whereas for non-sufferers, the difference was about 20dB. Thus, we can say that the sufferers are more sensitive in relative terms than others (meaning relative to their hearing threshold), although as stated above in absolute terms they were less sensitive. (Again, we should be cautious about drawing general conclusions based on three subjects.)

The second point from Figure 23 is that the threshold of acceptability reduces, i.e gets closer to the threshold of hearing for the lower frequency bands. For groups 1 and 2 the relative threshold in the 31.5 and 40Hz bands are lower by about 10dB than those for higher bands. For group 0, they are lower by about 10dB between the 31.5 and 63Hz bands. (The 160Hz band is also lower, but we believe this may be an artefact of the crossover to mid-range speakers from the subwoofer at this frequency rather than a real effect). This is significant because it suggests that the optimum shape of a reference curve does not follow the threshold of audibility over the whole of the low frequency range. Rather, it will tend to follow the hearing threshold for the lower bands but then move away from it above around 50Hz.

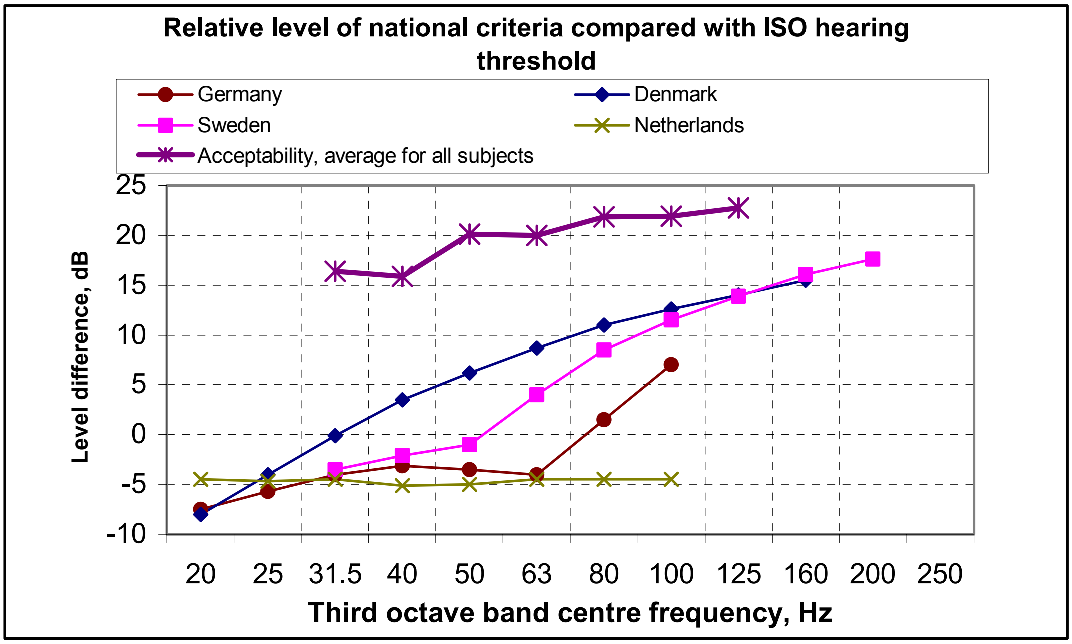

Figure 24

The thick line in Figure 24 is the threshold of acceptability relative to hearing threshold averaged over all subjects. Shown on the same plot, are the national criteria referenced to the ISO hearing threshold [IS03]. (Note that the ISO thresholds were republished in 2003, with values between 1 and 4dB higher than the previous values.) In other words all curves give the amount above or below a relevant hearing threshold. The purpose of the plot is to compare the shapes of the curves. It can be argued that the acceptability threshold is most similar to the Swedish curve, in that it is flat for the lower bands and then rises, although the Swedish curve rises faster.

Threshold of acceptability for real sounds

The thresholds of acceptability for the real sounds are shown in Figure 25 for all subjects in the 'night time' situation. (Waveforms of these sounds are plotted in Figure 15). There is a wide spread of results as was found for tones. This might be expected given the wide range of hearing thresholds. However, the lines are surprisingly parallel, which shows that all subjects responded in a similar way to the various sounds, but at a different overall level.

Figure 26 shows the same data as Figure 25, but averaged by group. We see that, as for the tones, group 0 is less sensitive in absolute terms than the other two groups, by about 2dB. There is no significant difference in the responses of the other two groups.

Subjects were generally more tolerant of track 1 (which displayed the smallest fluctuations) by about 5dB, and judged the other four sounds to be similar in terms of their acceptability.

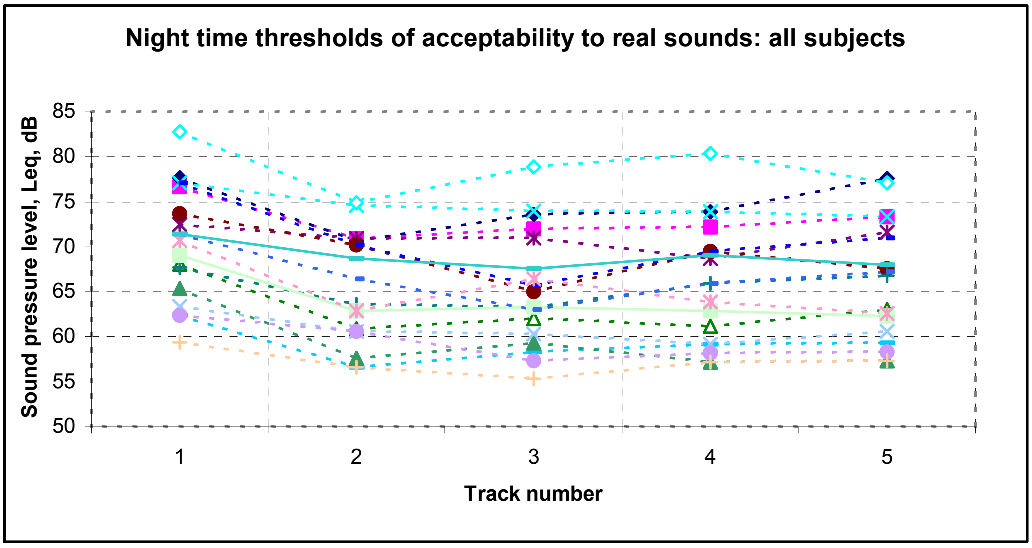

Figure 25

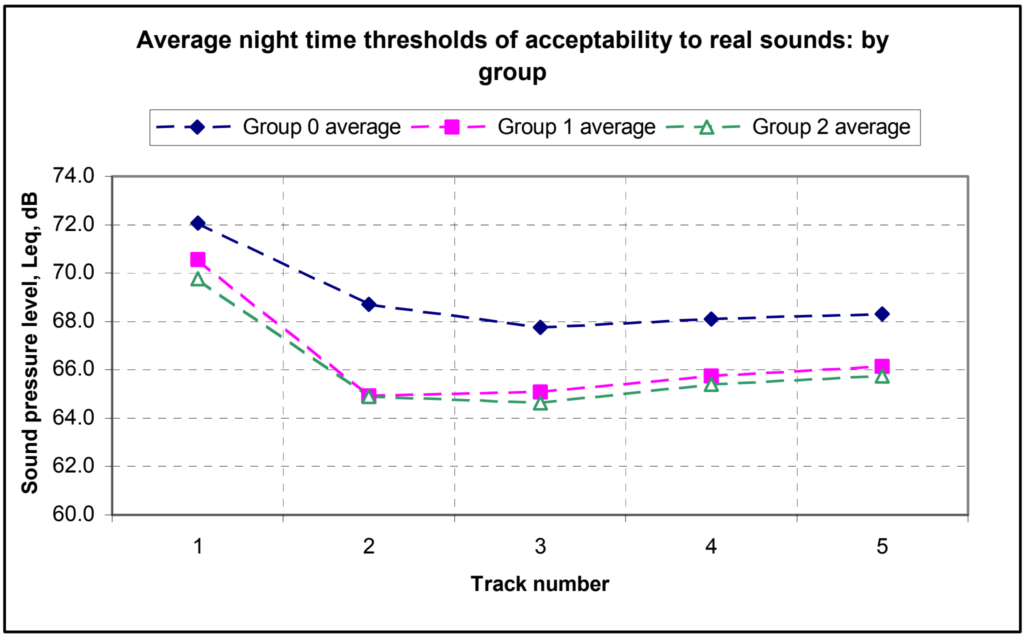

Figure 26

Figure 27 and Figure 28 show the same data as Figure 25 and Figure 26, but for 'day' rather than 'night', and show similar trends. The average day and night curves are shown together in Figure 29 which shows that on average respondents set the night time thresholds 2dB lower than for the day. More importantly for this study is the fact that the difference between day and night was almost identical for each sound, which gives some confidence that there is not a qualitative difference in the sounds, with some being relatively more disturbing at night.

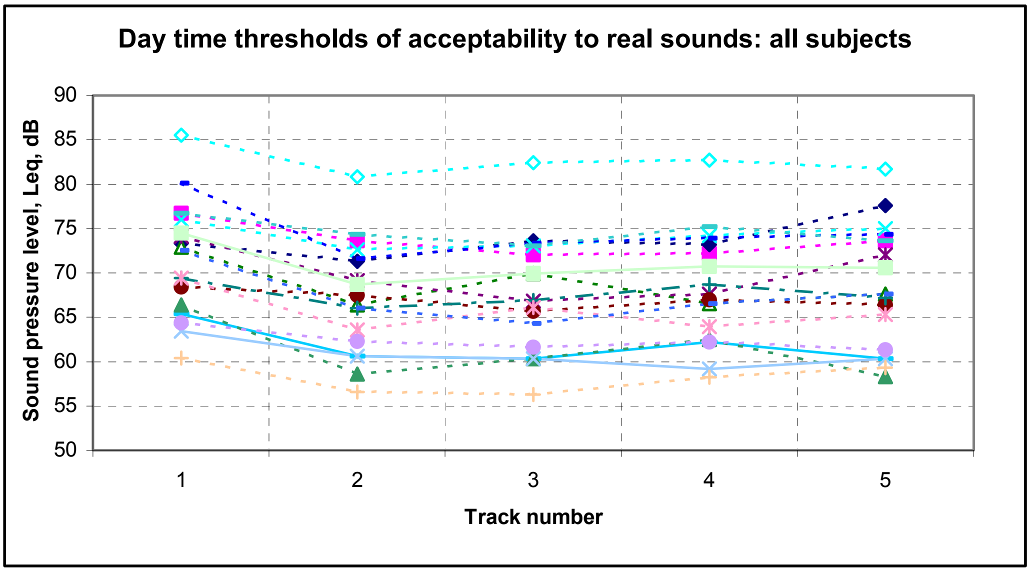

Figure 27

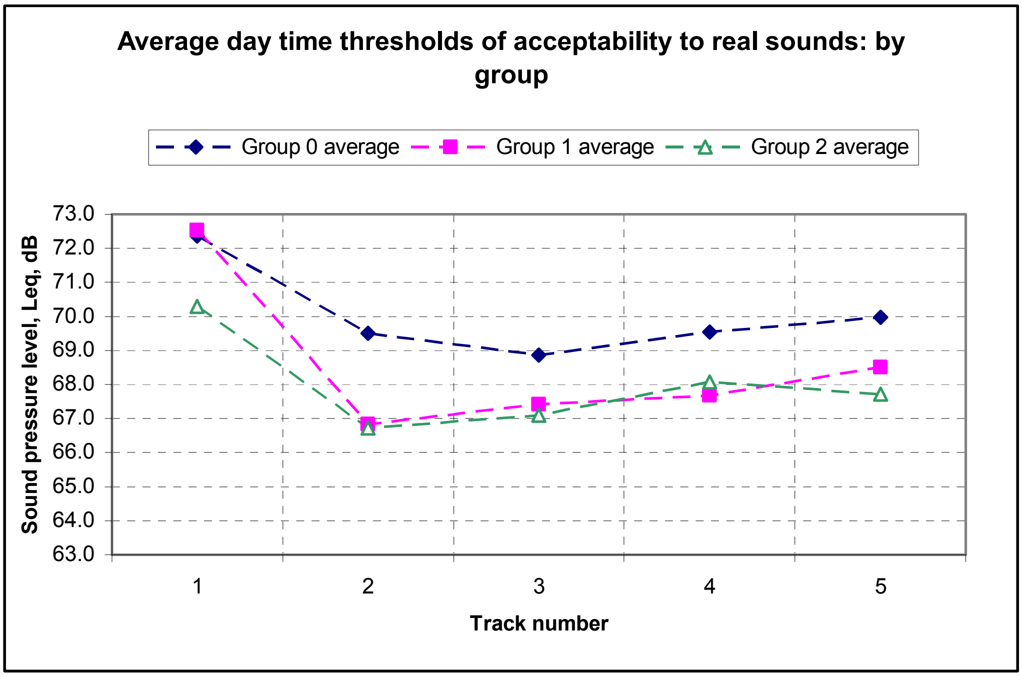

Figure 28

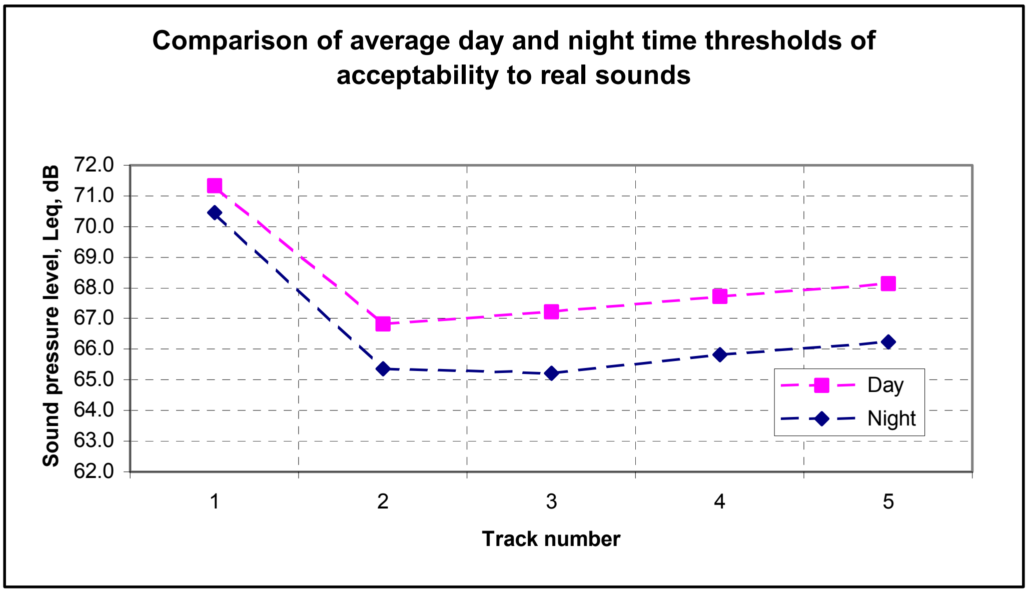

Figure 29

We would expect the acceptability thresholds set to depend on the hearing thresholds. Therefore, as for the tones, it is useful to look at the difference between these two thresholds for each subject. These figures are given in Figure 30 for night time and Figure 31 for day time. Two interesting points come out of these figures:

- sufferers tend to set acceptable levels very close to their threshold of hearing, both day and night
- the youngest group was most tolerant, and the older group less so to these sounds.

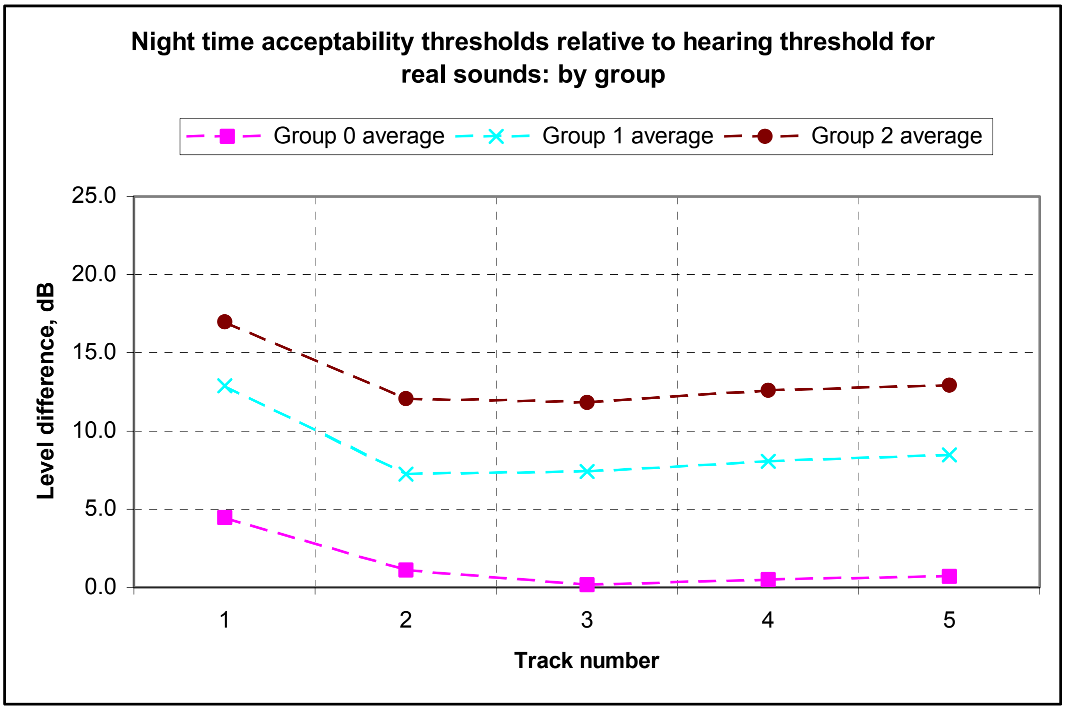

Figure 30

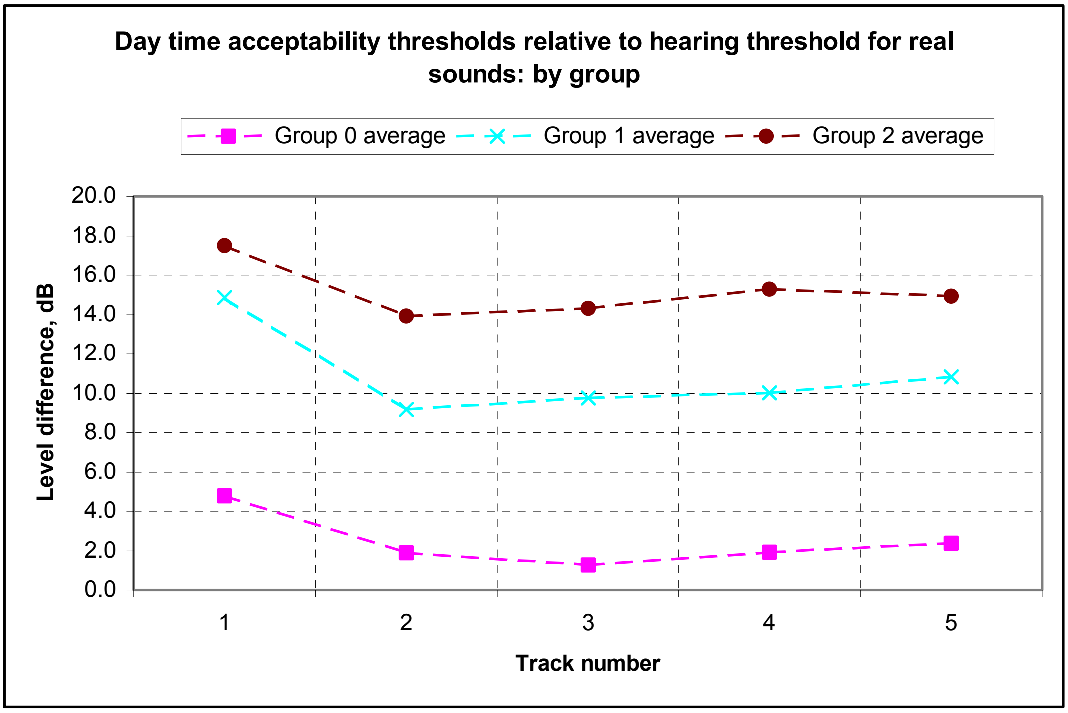

Figure 31

Threshold of acceptability for 'beating' tones

For the beating tones, only the relative thresholds are shown for simplicity. In Figure 32 and Figure 33 are shown the night and daytime thresholds respectively, averaged by group. There are several clear trends.

Firstly, as before, Group 0 (sufferers) is the most sensitive group in relative terms, setting the acceptability threshold only 2-3dB above audibility threshold for night time beating tones. Secondly, subjects were more tolerant of the steady tones than of the corresponding beating tone by 3-5dB. Thirdly, daytime levels were set an average of 3-4dB higher than the corresponding night time levels. Lastly, the effect of the beating on the response was essentially the same for day and night. These last two points are emphasised further in Figure 34.

The question arises, does Group 0 set lower levels because they were more sensitive in the first place, or is it because they have already suffered prolonged exposure to low frequency noise and have become sensitised (of course many other factors may also be involved such as personality and expectations etc.)? This is an important question when it comes to setting limits. If the latter is the case, then all subjects might be expected to respond in a similar way after prolonged exposure. This would give strong support to the idea that levels need to be set at or below the audible thresholds in order to protect the majority of the population. However, as it is not possible to envisage an ethical way to test this, it is unlikely that we will ever be able to answer this question. One young sufferer (whose case was eventually not used) reported that he thought he would be able to get used to the sound, but was surprised and dismayed to find out that he couldn't. This tends to suggest that sensitisation may be an issue in some cases at least, although no general conclusions can be drawn from only one case.

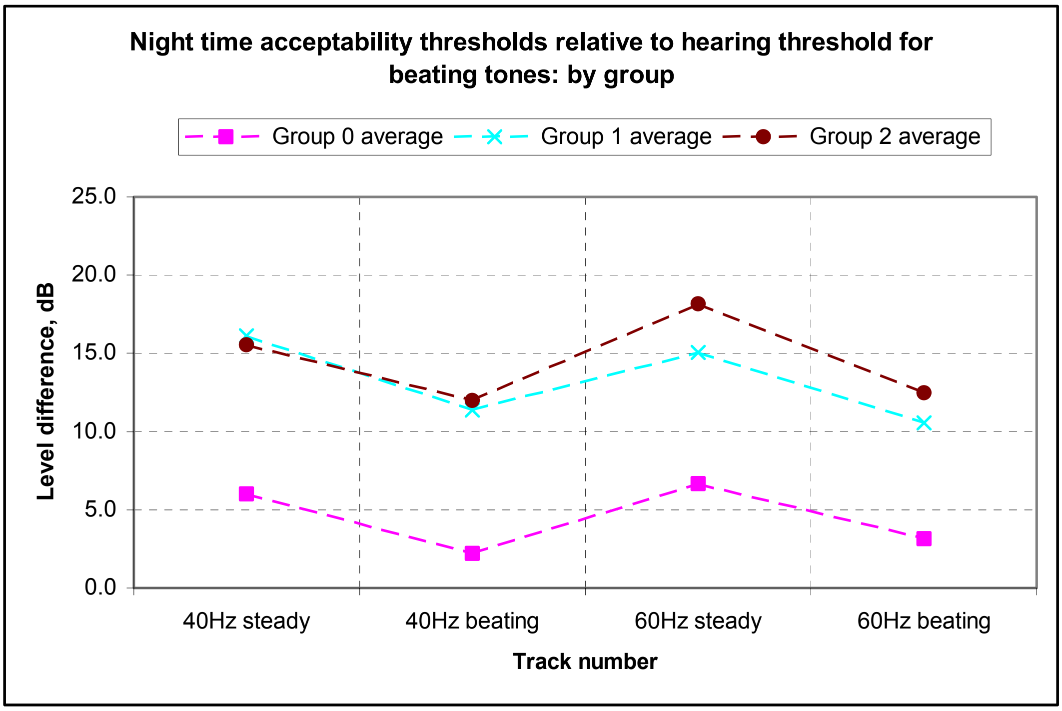

Figure 32

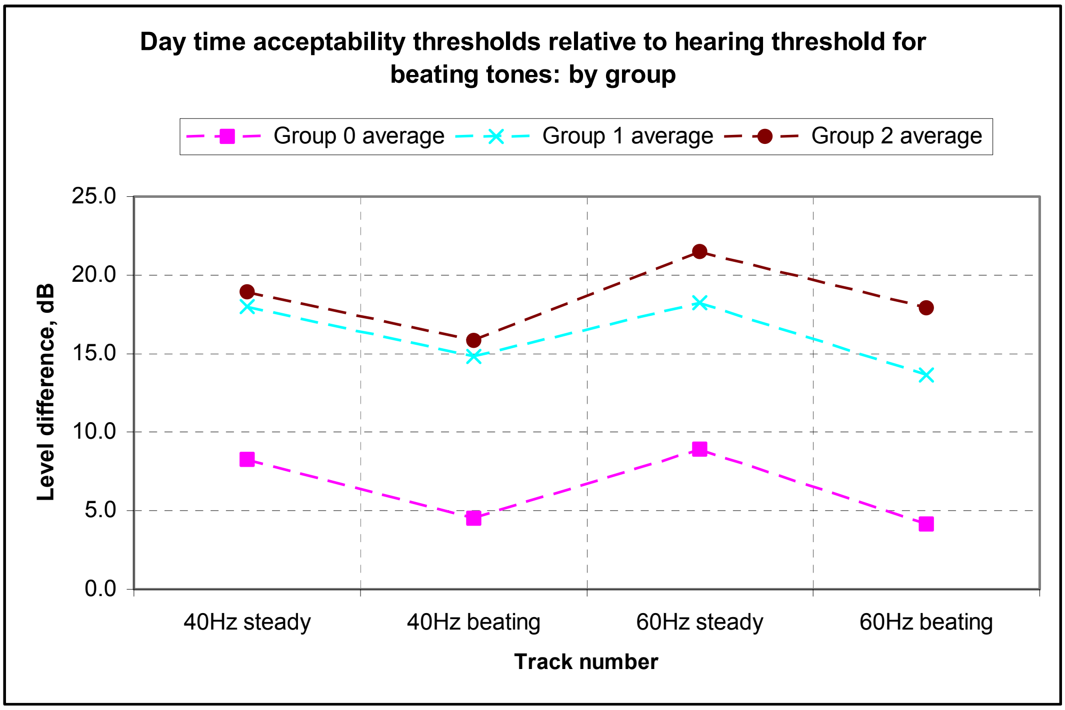

Figure 33

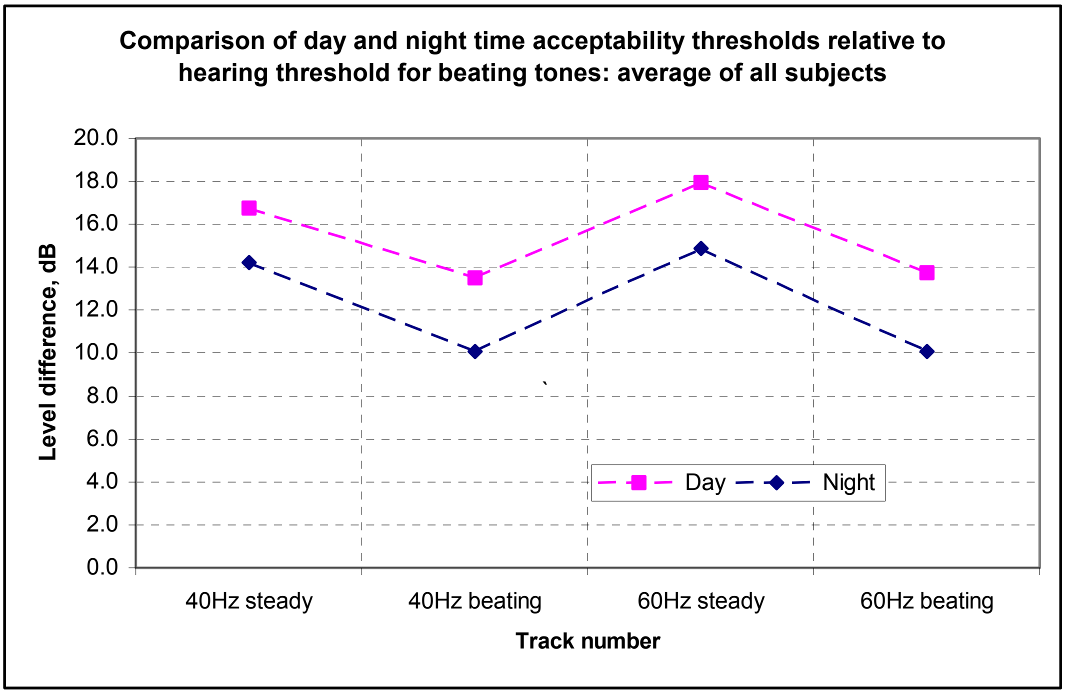

Figure 34

Evaluation of fluctuations

Having quantified subjective response to fluctuating sound, in this section an objective parameter is sought that reflects the responses.

Fluctuation strength

The first parameter investigated was the 'fluctuation strength' [Te68]. This is a relatively sophisticated parameter developed to provide a measure of sound fluctuations for the vehicle industry. It is relatively difficult to evaluate, requiring an appropriate computer programme which is only available on specialist equipment. The parameter was evaluated for sounds from the field studies, but was found to give no correlation with a subjective sense of fluctuation. It was concluded that although it sounds promising, this parameter is not suitable for evaluation of fluctuations in LFN.

Standard deviation of sound pressure level

An alternative measure of the fluctuations is to look at the statistical distribution of the sound pressure level sampled at set intervals. Figure 35 shows the probability distribution plots from a 30 second sample of the 5 real sounds normalised to a mean level (Leq) of 60dB. The height of each bar represents the length of time spent at a particular sound level. The width of the distribution is a measure of the variation in the sound. For example, Track 1 shows the least variation, the sound level varying only by ±3dB from the mean, apart from a small 'tail' of lower levels, whereas track 4 has a wider spread[*]. The spread of the results can most conveniently be described by

[*] Sounds can be heard on http://www.acoustics.salford.ac.uk/lfn.htm

the difference between the statistical parameters L_{10}-L_{90} (sometimes called the noise climate). These parameters are available on most modern sound level meters. The values for the five real sounds are shown in Table 8. Comparing with Figure 30 and Figure 31 there seems to be some correlation with the thresholds of acceptability. In particular, track 1 has the highest threshold of acceptability, typically 5dB higher than the others and also the lowest value of L_{10}-L_{90}.

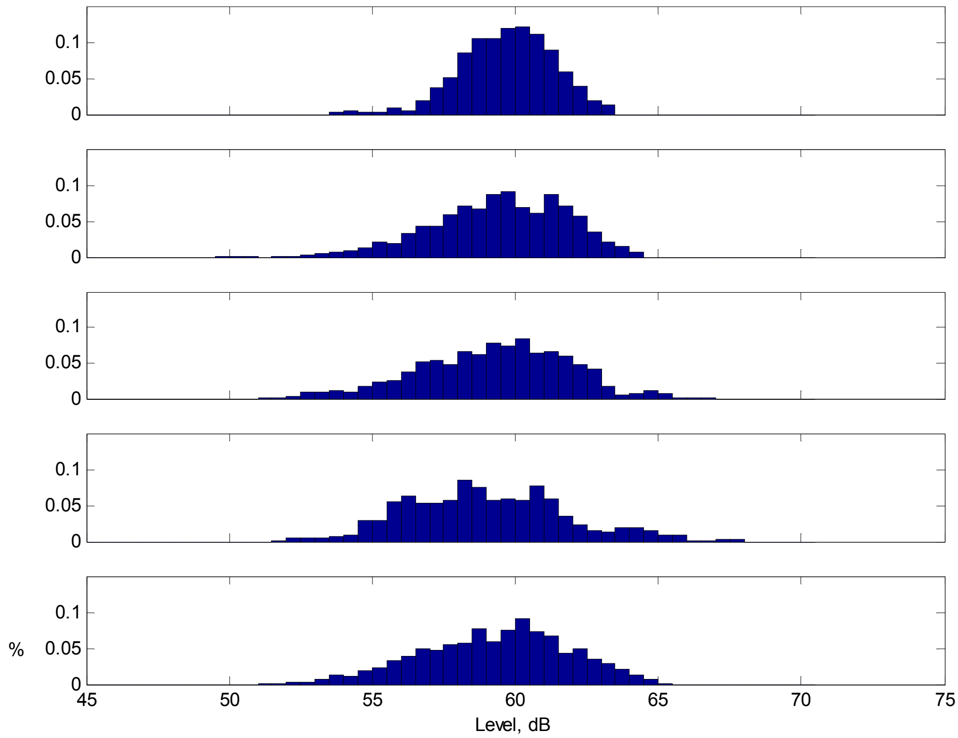

Figure 35: Distribution plots for sound levels for real sounds, Tracks 1-5

	Track 1	Track 2	Track 3	Track 4	Track 5
L10,dB	61.6	62.2	62.4	62.8	62.5
L90,dB	57.7	56.2	55.7	55.6	55.8
L10-L90, dB	3.9	6.0	6.7	7.2	6.7
Average magnitude of rate of change of level, dB/s (defined in the next section)	15.6	23.6	24.4	22.4	22.7

Table 8: L10, L90 and rate of change of level for a 30 second sample of the real sounds used in the laboratory tests

The relative thresholds of acceptability are plotted in Figure 36 against the value of L_{10}-L_{90} for the each sound. The points are the average for all subjects. Included on the plot are the values for the five real sounds (diamonds), pure tones at 40 and 60Hz (circles) and beating tones (squares – there are two points for beating tones at 40 and 60Hz, but they are so close together they cannot be distinguished).

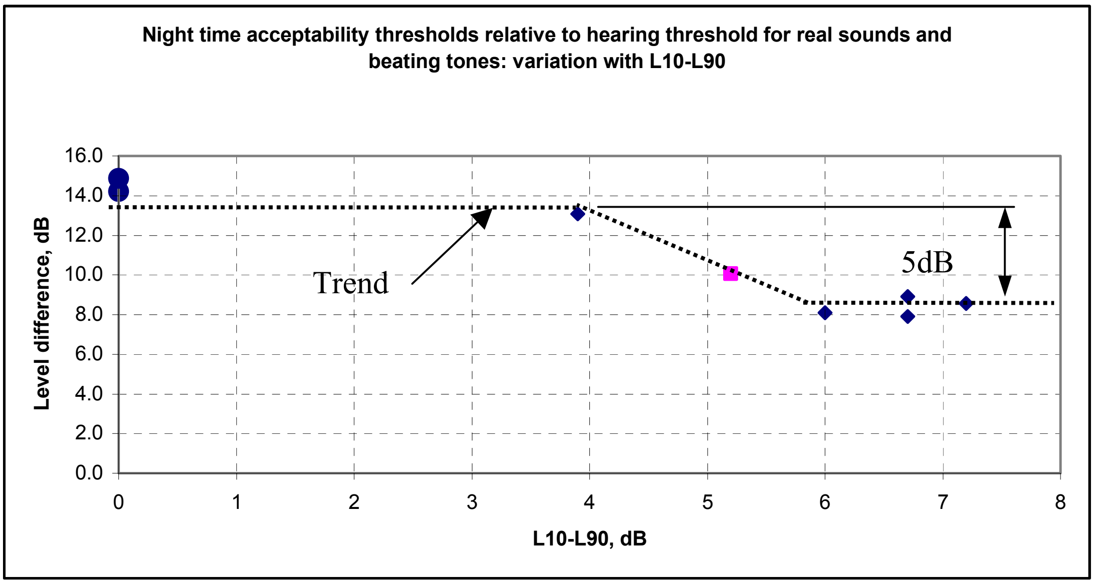

Figure 36

In interpreting Figure 36 it is helpful to describe some findings from one of the preliminary tests. Here subjects were played a sequence of beating tones with varying degrees of fluctuation. We found that the thresholds of acceptability were set at about the same level for the various beating tones, but that there was a clear difference of about 5dB from those for the steady tones. Arguably, Figure 36 also displays this trend: the most fluctuating sounds, represented by points to the right, were given a 'penalty' of about 5dB compared with steady sounds on the left. This penalty does not go on increasing as the L_{10}-L_{90} increases, but 'bottoms out' above L_{10}-L_{90} greater than about 6dB. There is a transition region for L_{10}-L_{90} of between 4 and 6dB where the penalty varies on a sliding scale between 0 and 5dB (as marked in dotted lines). The overall trend can be simplified without much loss of accuracy by ignoring this short transition range. The simplified trend can then be described as follows:

- L_{10}-L_{90}<5: no penalty
- L_{10}-L_{90}≥5: penalty of 5dB.

This is in a form that could be used by EHOs to decide whether to apply the 5dB penalty.

'Prominence'

Although the above looks promising, the difference L_{10}-L_{90} is not a foolproof parameter because it does not include any effect of the rate of fluctuations. The same value of L_{10}-L_{90} can be obtained for a slowly varying and a rapidly varying sound, whereas experience suggests that they would be judged differently in terms of a threshold of acceptability. The main purpose of this section is therefore to find a way to distinguish between rapidly varying sounds (which should be given a penalty) and sounds that vary sufficiently slowly that they are to all intents and purposes steady, and which therefore should not be given a penalty.

A parameter has been investigated known as 'prominence' [Pe01] (not to be confused with the sound quality parameter of the same name). This has been suggested for evaluation of impulsive sounds using the overall A weighted sound level. In its original form it is not therefore suitable for low frequency sound. However, we can take part of the concept and adapt it for the current problem, namely the idea of assessing the rate of change of the rms Fast* sound pressure level. (In fact the idea of using the rate of change of level has been around since at least the 1970s [Ja78].) In the method the start of an impulse is defined when the sound pressure level starts to vary by more than 10dB per second. We would like to establish whether this is an appropriate figure for our purposes.

Figure 37 shows the rate of change of level for a 30 second sample of the real sounds used in the laboratory plotted instant by instant. The time-averaged magnitude is also given in Table 8. The sound level varies by considerably more than 10dB per second. This was true also for the beating tones, where the maximum slope was about 30dB/s, and the mean value 17dB/s. Thus, all the sounds used in the laboratory tests, except for the steady tones exceeded the 10dB/s value and would be classed as containing impulses according to the prominence method. However, for slowly varying sounds the 10dB/s value would not be exceeded. On the basis of these results then, the figure of 10dB/s seems suitable for the current purposes. Consequently, it is suggested that a sound only be considered to be fluctuating if the slope of the sound level (rms fast) curve exceeds 10dB/s. Therefore, fluctuating sounds would attract a 5dB penalty if the value of L_{10}-L_{90} exceeds 5dB and the slope exceeds 10dB/s.

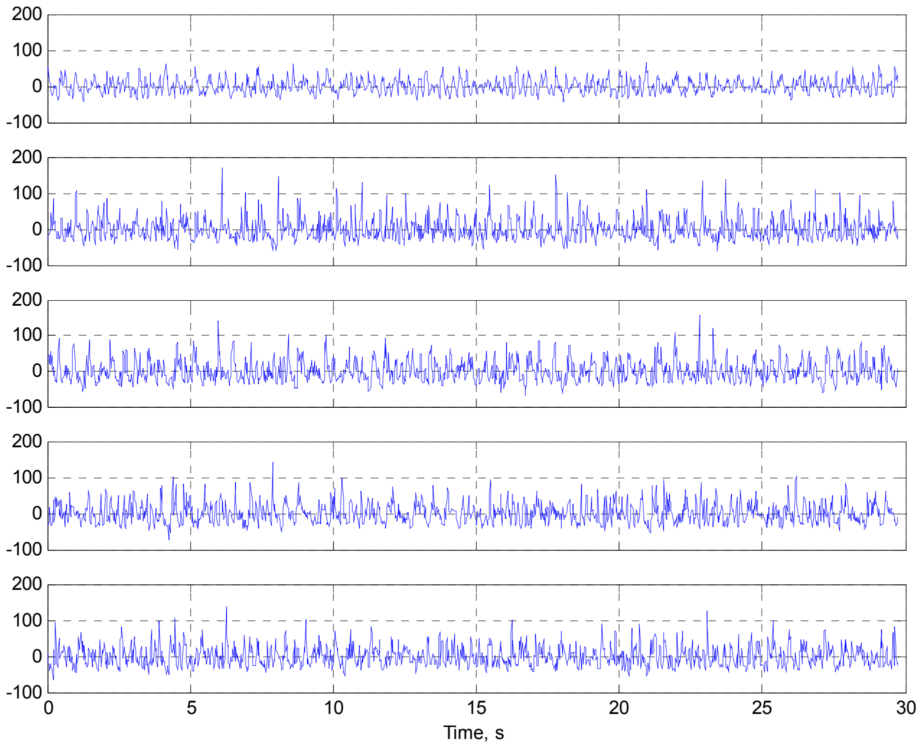

Figure 37: Rate of change of rms Fast sound level in dB/s for a 30 second sample of real sounds

* rms Fast: is the usual setting on a sound level meter for environmental noise measurement. Rms stands for 'root mean square', and 'Fast', as opposed to 'Slow' refers to the averaging time.

Conclusions from laboratory tests

In absolute terms, the sufferers in these tests were the least sensitive group to low frequency sounds. A major factor in this is that their thresholds of hearing were higher than other groups. We should avoid strong general conclusions because only three sufferers were tested, and there was variation between them. Nevertheless, this finding contradicts the view sometimes expressed that LFN problems are a result of exceptional sensitivity.

In relative terms, sufferers tend to set the threshold of acceptability much closer to the threshold of hearing than other groups. Whether this is because they are naturally less tolerant, or have become sensitised by exposure is not known and probably never will be. However, if as we suspect, it is at least in part due to sensitisation, then we would expect all groups to respond similarly were they exposed for an extended period. This supports the setting of levels close to the threshold of audibility.

The shape of the threshold of acceptability follows that of the hearing threshold up to between 50 and 80 Hz and then rises. This is consistent in principle with the various national criteria, and most closely resembles the Swedish curve.

Thresholds of acceptability were set typically 4-5dB higher for sounds with strong fluctuations than for steady sounds. This is consistent with the Danish standard method of adding a 5dB penalty for impulsive noise, as well as existing UK guidelines for other types of noise (not low frequency) where a 5dB penalty is added for noise with noticeable features. It is also consistent with previous published research [Br94]. Therefore, we conclude:

- it is appropriate to penalise fluctuating sounds compared with steady sounds
- 5dB is an appropriate level for any such ‘fluctuation penalty’.

Fluctuation strength is not successful at quantifying low frequency fluctuations. The most successful parameter was found to be the difference L_{10}-L_{90} which has the additional advantage that it is generally available to EHOs. Results suggest that a penalty for fluctuations is appropriate when this value exceeds 5dB. In addition, a sound should only be considered fluctuating when the rate of change of the rms fast sound level in the third octave band of interest exceeds 10dB per second. The rate of change of level is not a standard parameter, but EHOs with a PC-based, logging sound level meter should be able to calculate the value without much difficulty. Those without such a facility should be able to make a reasonable estimate ‘by eye’ (see Proposed Criteria for suggestions as to how this can be done).

Night time thresholds of acceptability were set 2-3dB lower than the corresponding day time limit. This is a slightly lower difference than the 5dB day-time relaxation used in the German standard. However, it is likely that, if anything, this difference is underestimated in the laboratory tests, (see [In00]), so the figure of 5dB is an appropriate amount by which to relax the limits for sounds only present during the day.

There was consistency in the effect of fluctuations for day and night. Therefore, the procedure used to assess fluctuations can be applied equally to night and day.

CONCLUDING REMARKS

Field studies show that the various national criteria were reasonably successful in differentiating between ‘positively identified’ and ‘unidentified’ problems. Furthermore, the former correspond to cases where EHO intervention is likely to be beneficial, and the latter to cases where they will not be able to help. On this basis, some criteria along the lines of the various national guidelines would be of considerable benefit to EHOs in the UK faced with complaints about LFN.

The question then arises as to which of the methods is most suitable. There is not much evidence from the field studies to distinguish one method from another, all worked about equally well. This is probably because the problem frequencies lie in the frequency range where the various national reference curves are in close agreement. However, outside this range there are some differences so the choice of curve is important. From the results of the laboratory test the Swedish curve was identified as being the best overall shape. Poulsen [Po03] also identified the Swedish method as the best after the Danish one, although there was little to separate them except for music noise, which is excluded from the scope of this study. There is an additional advantage of the Swedish method over the Danish one in that it is considerably easier to apply.

Comparing the Swedish curve to the German one, it is less stringent at 63Hz and above. This is seen as a positive thing because these bands often include traffic noise above the audible threshold. This was the case in several of the field studies where the audible threshold was exceeded in the 80 and 100Hz band but no source of LFN was identified. The Swedish method is therefore less likely than the German method to falsely identify traffic noise as LFN. Thus, for several reasons, the Swedish curve is preferred at this stage.

However, the Swedish curve only extends to 31.5Hz, whereas other methods include frequencies down to 10Hz. There is no particular evidence from the field studies to suggest the range should be extended below 31.5Hz. However, other experience from the literature suggests that, although rare, problems do occasionally occur below 31.5Hz and are no less serious than above 31.5Hz. Therefore, we propose that the Swedish curve is extended down to 10Hz. The Swedish and German curves are just under 5dB below the ISO 226 (2003) threshold at 31.5Hz, and it is proposed to continue this trend down to lower frequencies. ISO 226 does not give values below 20Hz, but the thresholds published by Watanbe and Moller [Wa90] can be used.

Regarding the maximum frequency, there is little evidence from the case studies to suggest up to what frequencies should be included. On the basis of experience, the upper frequency limit will be set at 160Hz, consistent with the Danish method.

This proposed reference curve turns out to be similar to one proposed in the Netherlands for setting low frequency noise limits in planning applications [Sl01]. It appears that this method is already in use on a trial basis, and is thought to work well by those who use it. The fact that similar limits have been derived independently here gives some measure of confidence.

Regarding fluctuations, there is evidence from the laboratory tests that a penalty for fluctuating sounds of 5dB is appropriate. There is also evidence that such a penalty should be applied when the difference L_{10}-L_{90} exceeds 5dB, and when the rate of change of the rms Fast sound level in the third octave band under consideration exceeds 10dB per second. What is not clear at present is how this penalty should relate to the absolute level of the reference curve, i.e. whether 5dB should be subtracted from the curves to make them more stringent, or whether the curves should be considered to have the penalty already applied. From experience it seems likely that most problem LFN sounds would attract the penalty, and on this assumption the positive experience from around the world suggests that the national criteria are set at the right level for fluctuating sounds. This being the case, it seems appropriate to allow a relaxation of 5dB for steady sounds rather than to apply a penalty for fluctuating sounds. This also agrees with the laboratory tests where steady sounds were set typically more than 5dB above threshold by the most sensitive group, i.e. sufferers, (although as stated before we should be careful about establishing absolute levels from short exposure tests). Furthermore, one can argue that a fluctuating sound with an average level 5dB below the threshold would be audible, whereas a steady sound would not. Since the curve values at low frequency are set 5dB below threshold this is again consistent with allowing a relaxation for steady sounds.

We do not have much evidence as to how long, or what proportion of the time a sound needs to be present to become a problem. However, for case studies where a problem was positively identified the sounds were clearly not ‘occasional’ but were present on a permanent if not continuous basis. It would have been relatively straightforward for an EHO to decide this on the basis of measurement. Therefore, we do not propose rigid rules but rather to leave it to the judgement of the EHO.

The equipment needed to apply the proposed method is a minimum of a sound level meter with third octave bands down to 10Hz. This would be available to most local authorities. Many are nowadays equipped for unmanned logging, and such equipment would be an advantage. If audio recording is also available, this can improve the confidence in the result. A simple method is proposed in the German method (dBC-dBA>20dB) as an initial indicator that requires less sophisticated equipment. However, there is evidence that although useful, this is not reliable, so it should not form the basis for a decision.

We expect a reasonably high proportion of cases to remain unsolved even if a criterion is adopted. This is indicated in the results of the field studies, half of which were unidentified, and is a common experience in countries where criteria are in use. However, this does not negate the value of a criterion which should provide EHOs with a means of distinguishing cases where they should act from those where they can do nothing to help. However, it does indicate the need for some alternative for those sufferers not satisfied with the outcome. Currently, the only backup is through voluntary organisations such as the Low Frequency Noise Sufferers Association, who do good work but with very limited resources. An ideal complement to the proposed criterion would be develop techniques by which the sufferer may acquire a degree of control over their adverse reactions to the sound (see for example [Ba97]). This is strongly recommended as an important area for further funded research (see also [Le03].

It is suggested that the proposed criterion be used not as a prescriptive indicator of nuisance, but rather in the sense of guidance to help determine whether a sound exists that might be expected to cause disturbance. Some degree of judgement by the EHO is both desirable and necessary in deciding whether to class the situation as a nuisance, and is likely to remain so. One of the main reasons is that, from the control cases, it is clear that problems do not necessarily arise when the criteria are exceeded. Indeed, we can conjecture that genuine LFN complaints occur only in a few such cases. Therefore, factors like local knowledge and understanding of the broader situation are likely to remain important aspects of the assessment. It is thought that this approach is likely to find acceptance since EHOs in the UK are accustomed to a fairly wide scope in interpreting guidelines on noise nuisance.

Although sufferers often claim there is a vibration element to the noise it is rare to find vibration levels above the perceptible limits ([Sl01, [Ru00]).

Proposed criteria and procedure for assessing low frequency noise

Measurement should be taken with the microphone in an unoccupied room where the complainant says the noise is present. (Note that the person taking the measurements may not be able to hear the sound).

Record L_{eq}, L_{10} and L_{90} in the third octave bands between 10Hz and 160Hz.

If the L_{eq}, taken over a time when the noise is said to be present, exceeds the values in Table 9 it may indicate a source of LFN that could cause disturbance. The character of the sound should be checked if possible by playing back an audio recording at amplified level.

If the noise occurs only during the day then 5dB relaxation may be applied to all third octave bands.

If the noise is steady then a 5dB relaxation may be applied to all third octave bands. A noise is considered steady if either of the conditions a. or b. below is met:

a. L_{10}-L_{90} < 5dB
b. the rate of change of sound pressure level (Fast time weighting) is less than 10dB per second*

where the parameters are evaluated in the third octave band which exceeds the reference curve values (Table 9) by the greatest margin.

Table 9 Proposed reference curve

Hz	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
dB, Leq	92	87	83	74	64	56	49	43	42	40	38	36	34

* For a meter capable of storing short term L_{eq} the rate of change is $(L_2 - L_1)/t_s$ where L_1 and L_2 are subsequent values of the level and t_s is the time for each sample (should be less than 0.1s). For simpler instruments it should be possible to estimate the rate of change from the depth and speed of fluctuations judged by eye. For example, if there are 2 fluctuations per second with a difference of 6dB from peak to trough then the total change in a second is 24dB (two up, two down, each 6dB). The rate of change would therefore be at least 24dB if the level changes smoothly, and more than this if it changes irregularly or suddenly.

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ACKNOWLEDGEMENTS

This project was funded by Defra, whose support is gratefully acknowledged.
We would like to thank all participants of field and lab studies, as well the EHOs who helped to set up the field studies. These people cannot be named for confidentiality reasons.
The laboratory tests were set up by Dr Bill Davies and were conducted by Paul Kendrick.
We would like to acknowledge the contribution Geoff Leventhall in making helpful suggestions for revision of the text.
We would also like to thank Hazel Guest, David Manley and Rosemary Mann for their support.

APPENDIX: SUMMARY OF RESULTS FROM FIELD STUDIES

Results for case studies not presented in the main text are given here. The experimental details were the same as for cases 20 and 2 discussed in the main text except that a 10Hz high pass filter has been applied in Cases 13, 16, 19 and 19A.

Case 5

Measurement filename	**Times identified by respondent**
Case5_4421_210000.cmg	04h40
Case5_4423_210000.cmg	23h20
Location	Urban
Source	Suspected industrial
Microphone position	Corner of bedroom

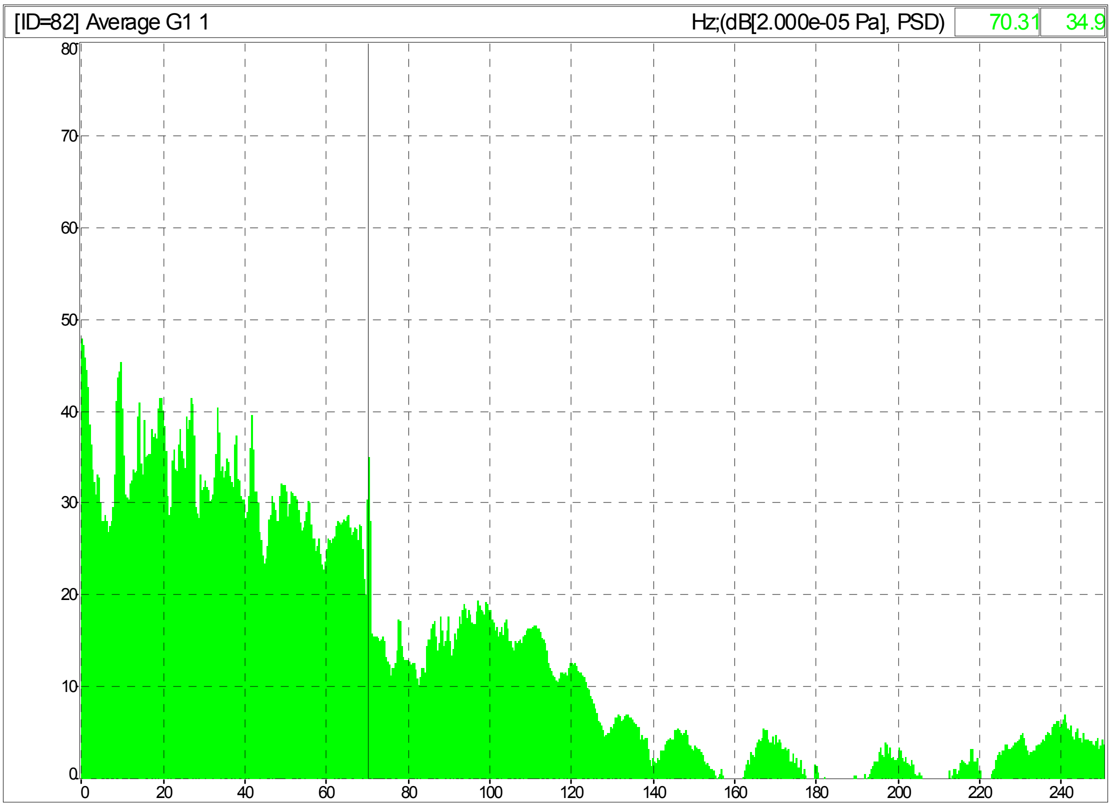


Figure 38: FFT of 9m30s audio record starting 04h40m from measurement Case5_040421_210000.cmg

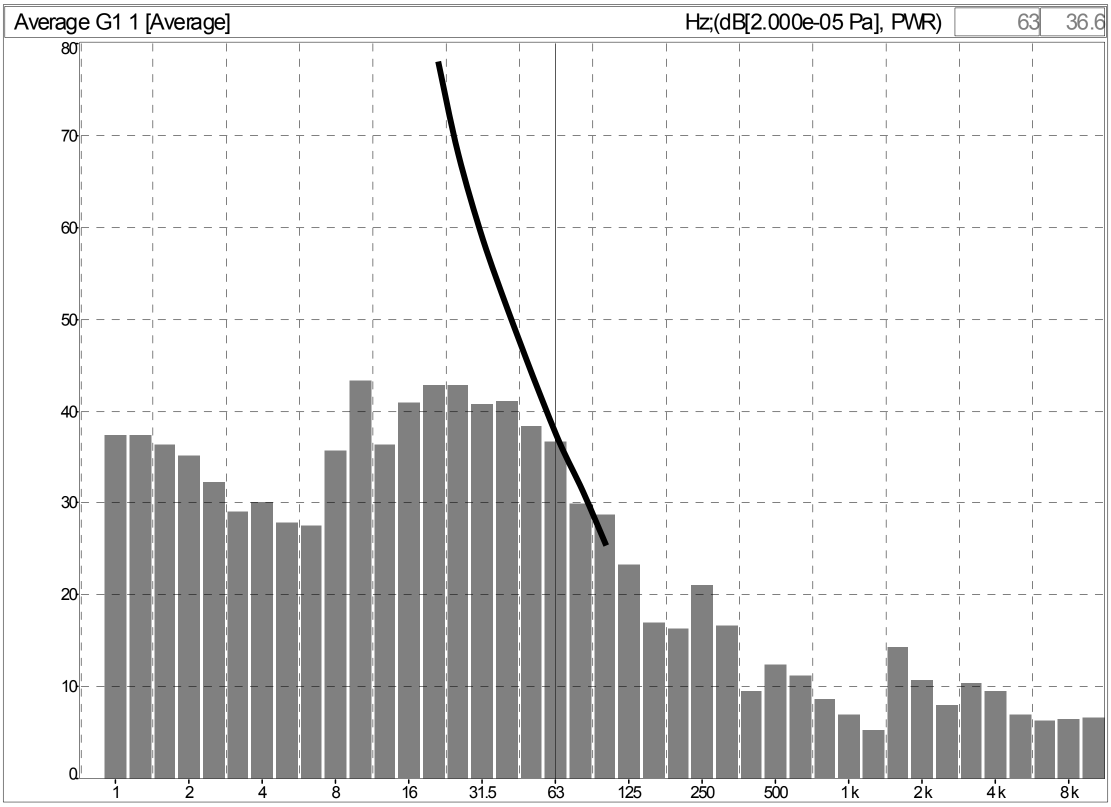


Figure 39: Mean 1/3 octave band spectrum 9m30s starting 04h40m from measurement Case5_040421_210000.cmg

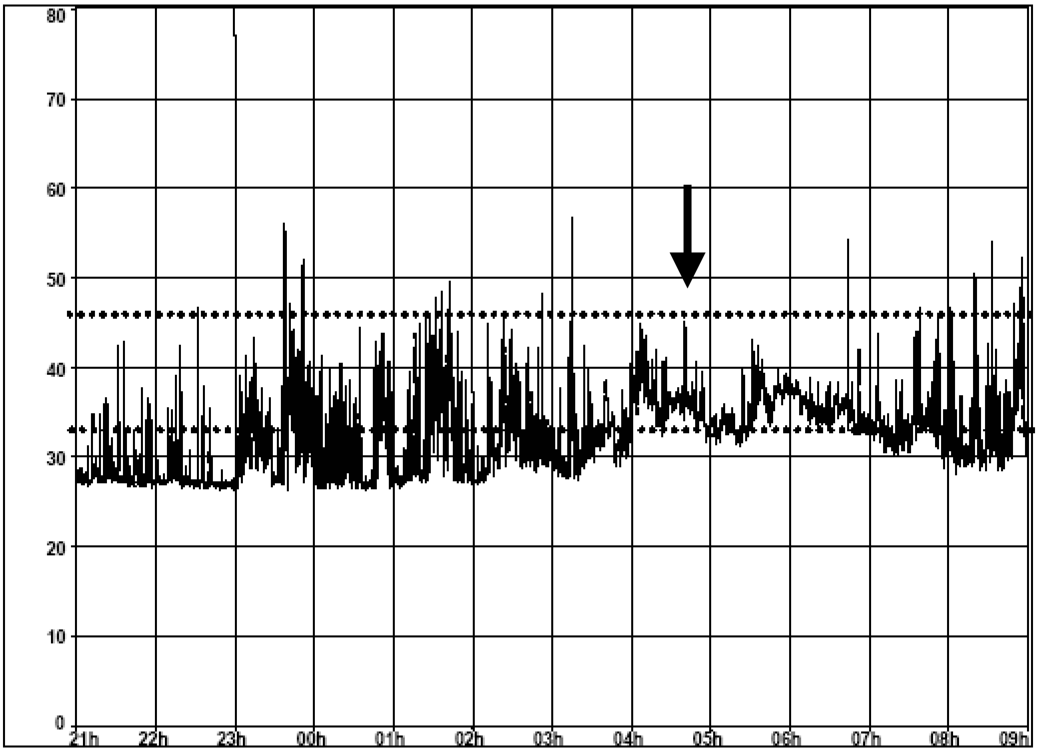


Figure 40: Time history showing 63Hz 1/3 octave spectrum band from measurement Case5_040421_210000.cmg together with lower Dutch (audibility) 33dB and Danish 46.2dB limits

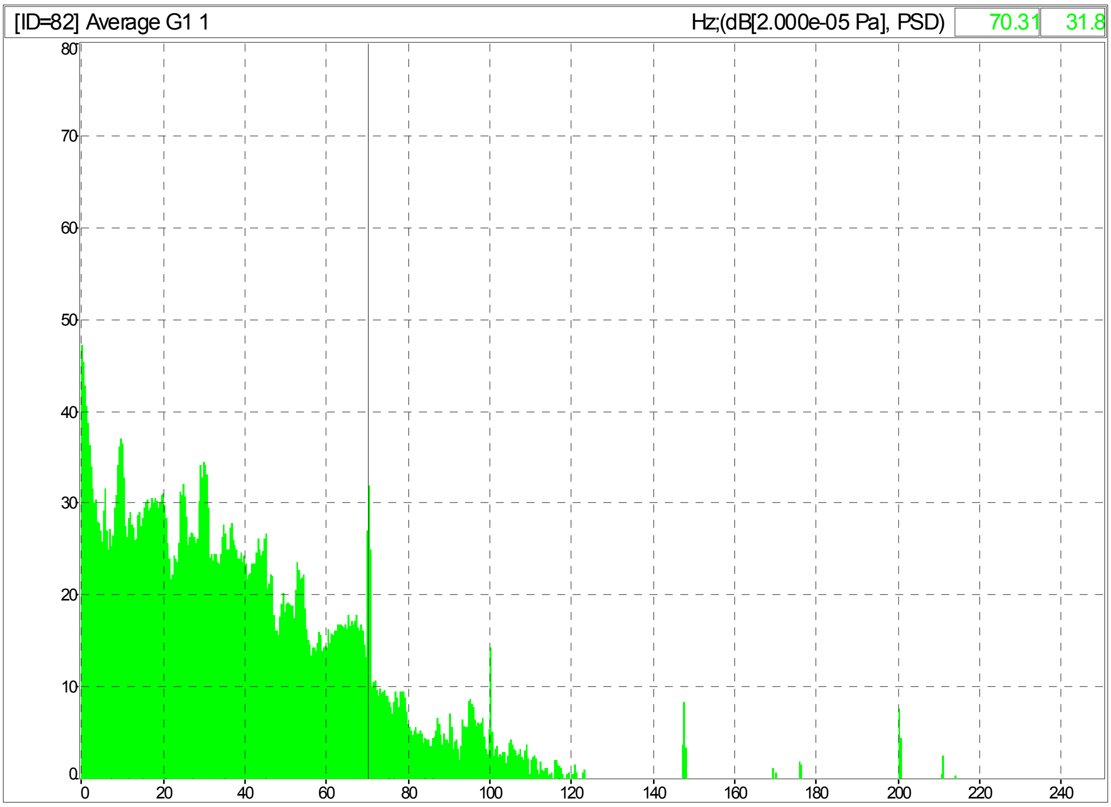


Figure 41: FFT of 9m30s audio record starting 23h20m from measurement Case5_040423_090000.cmg

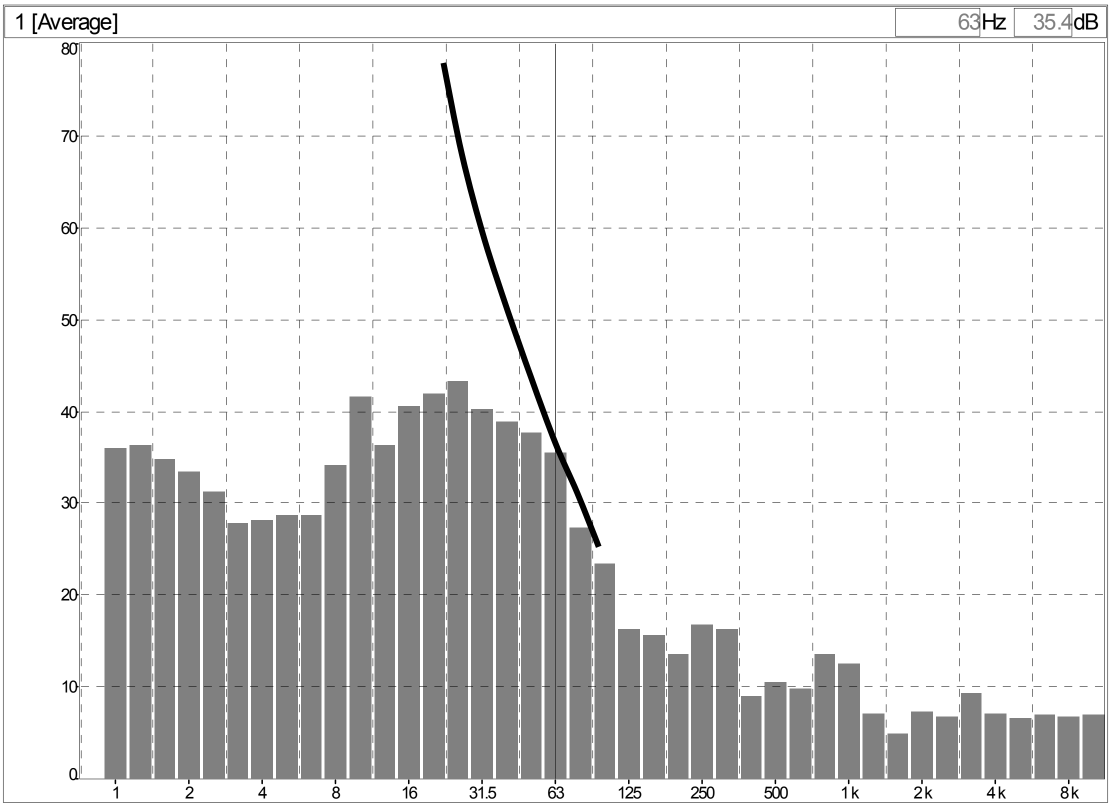


Figure 42: Mean 1/3 octave band spectrum 9m30s starting 23h20m from measurement Case5_040423_090000.cmg

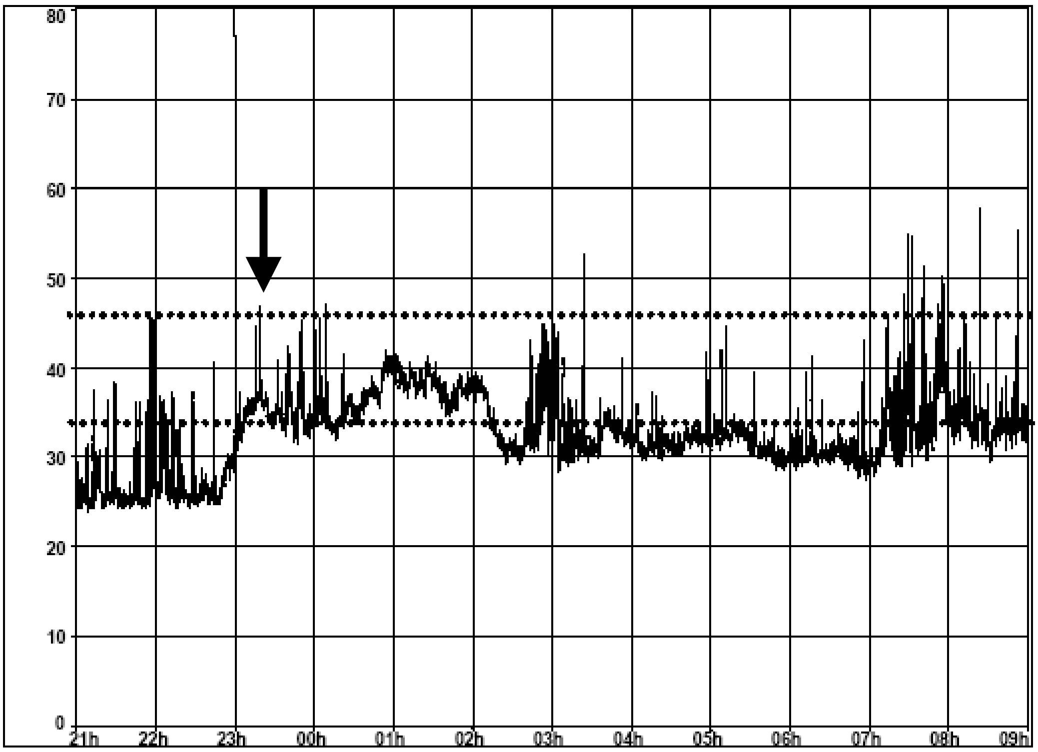


Figure 43: Time history showing 63Hz 1/3 octave spectrum band from measurement Case5_040423_090000.cmg together with lower Dutch (audibility) 33dB and Danish 46.2dB limits

Case 6

Measurement filename	Times identified by respondent
Case6_4325_210000.cmg	08h50
Case6_4328_210000.cmg	03h50
Location	Suburban
Source	Suspected industrial
Microphone position	Corner of bedroom

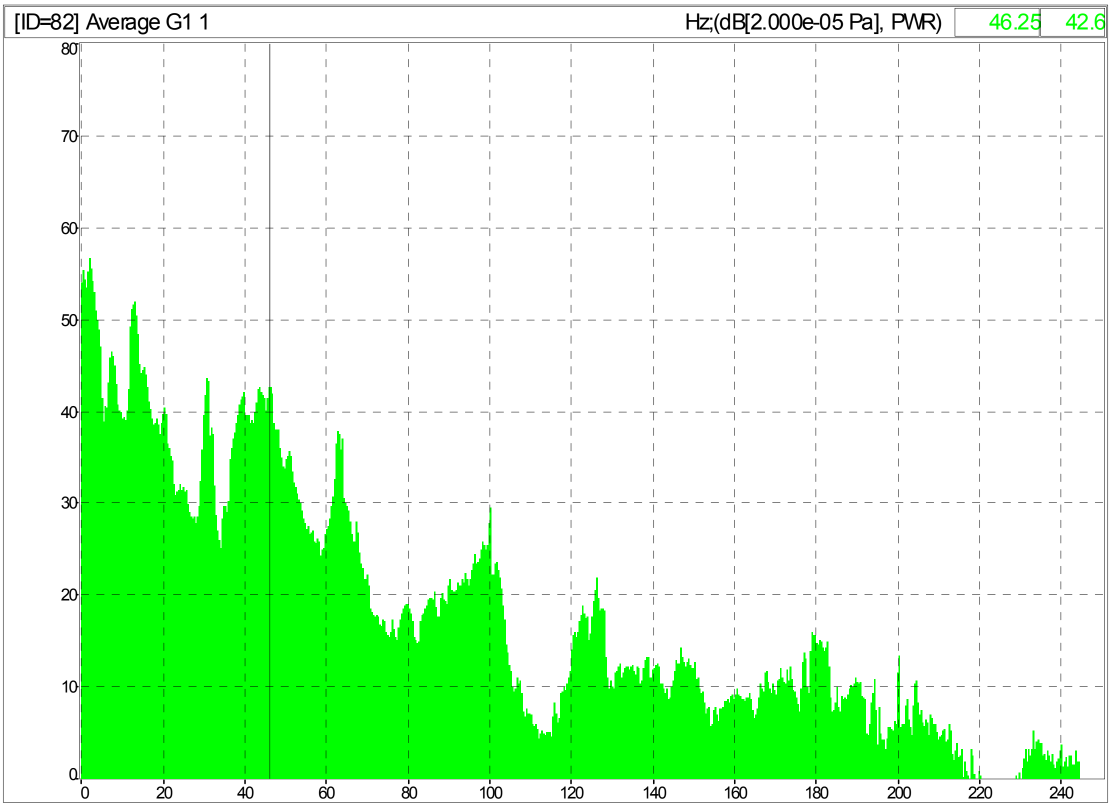


Figure 44: FFT of 9m30s audio record starting 08h50m from measurement Case6_040325_210000.cmg

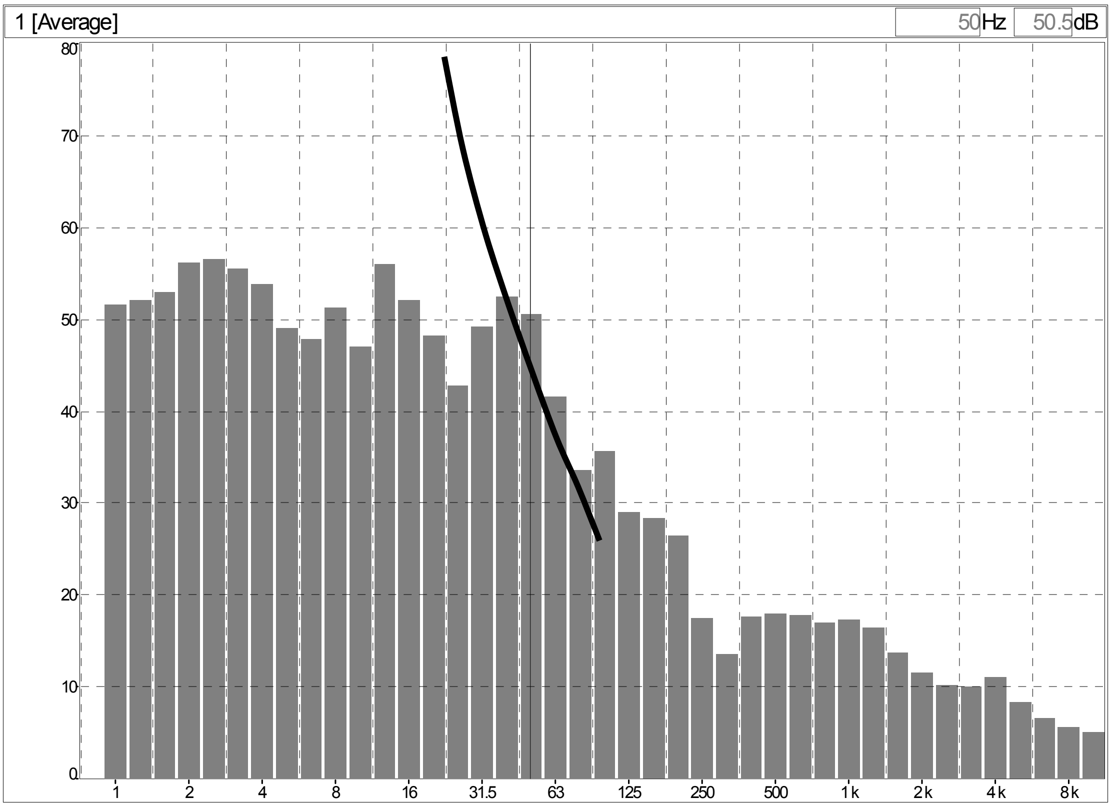


Figure 45: Mean 1/3 octave band spectrum 9m30s starting 08h50m from measurement Case6_040325_210000.cmg

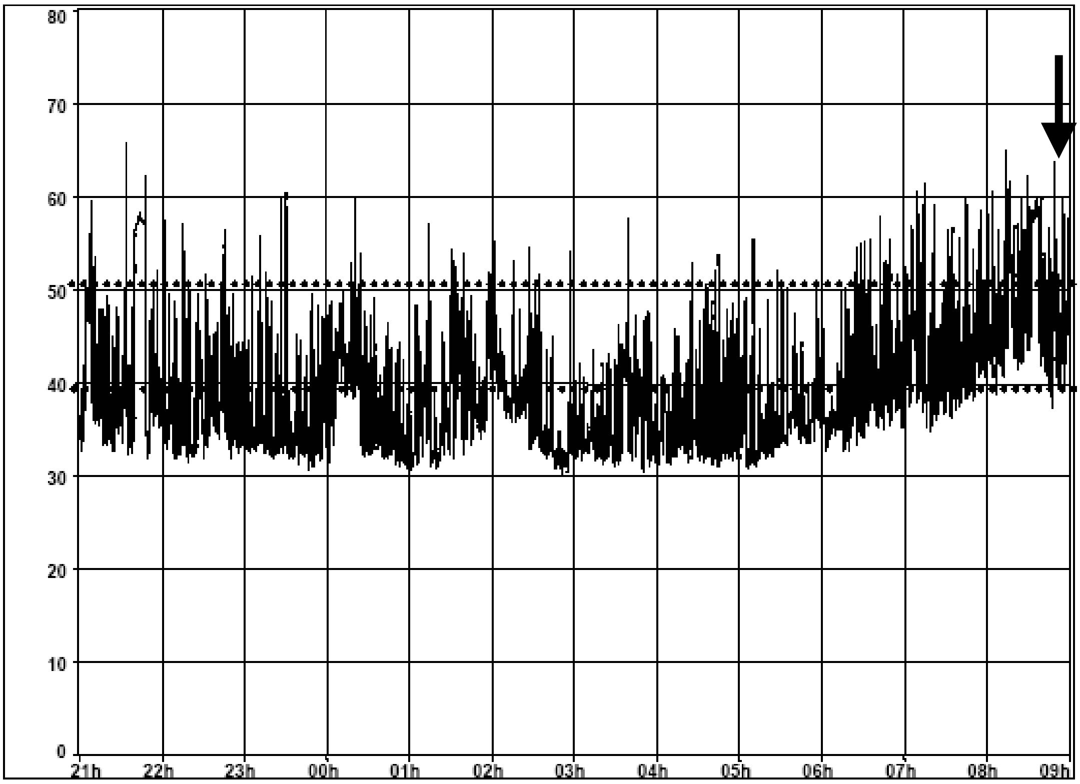


Figure 46: Time history showing 50Hz 1/3 octave spectrum band from measurement Case6_040325_210000.cmg together with Dutch (audibility) 39dB and Danish 50.2dB limits

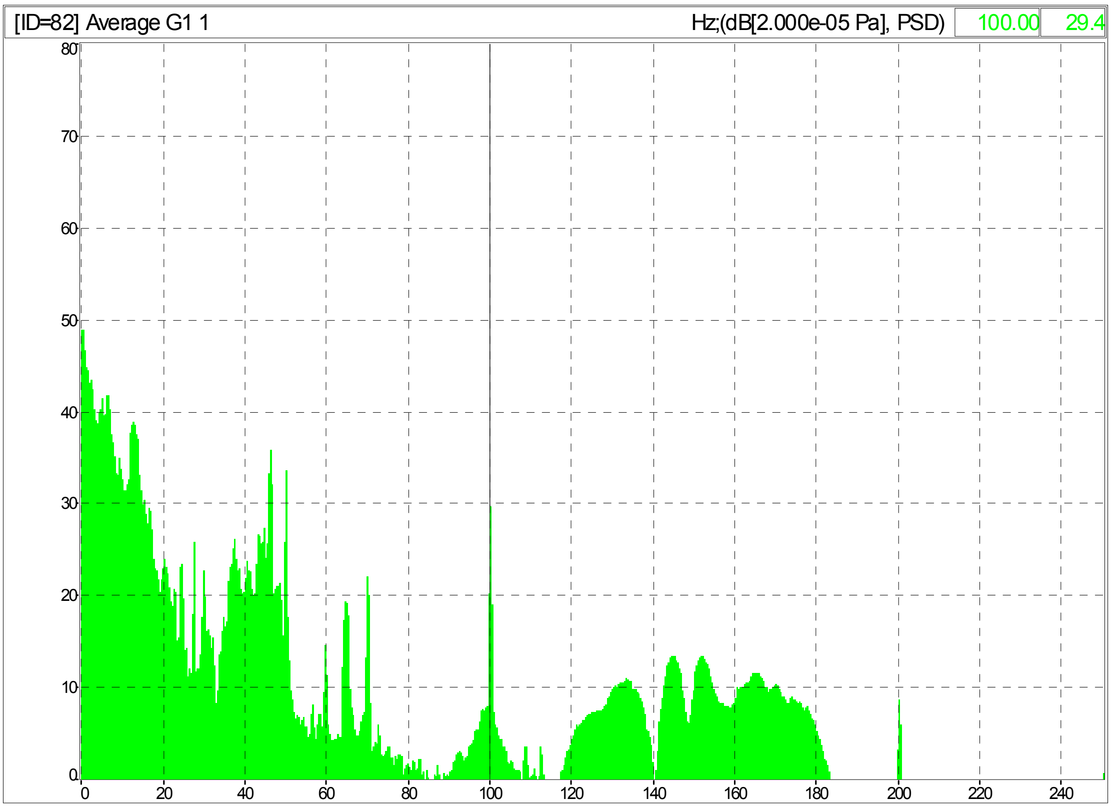


Figure 47: FFT of 9m30s audio record starting 03h50m on 29/03/04 from measurement Case6_040328_210000.cmg

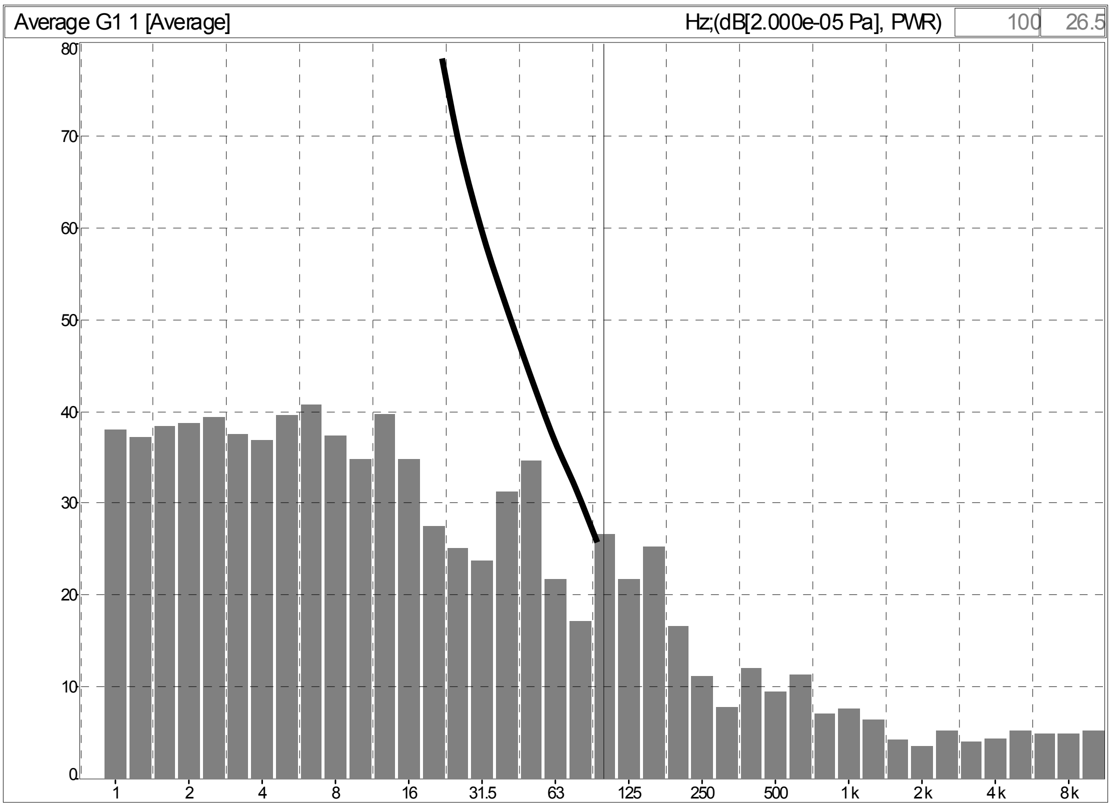


Figure 48: Mean 1/3 octave band spectrum 9m30s starting 03h50m on 29/03/04 from measurement Case6_040328_210000.cmg

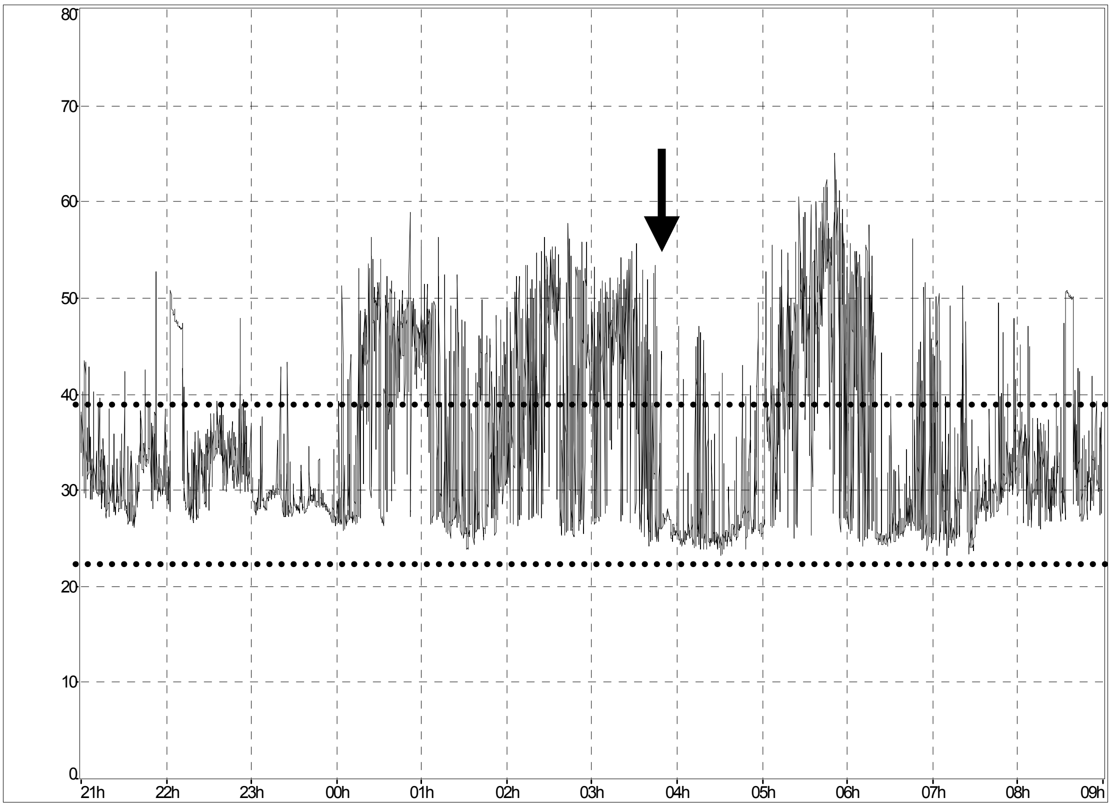


Figure 49: Time history showing 100Hz 1/3 octave spectrum band from measurement Case6_040513_210000.cmg together with Dutch (audibility) 22dB and Danish 39.1dB limits

Case 7

Measurement filename	Times identified by respondent
Case7_4514_134035.cmg	19h30
Case7_4514_134035.cmg	13h30
Location	Suburban
Source	Suspected industrial/ commercial
Microphone position	Corner of downstairs back room

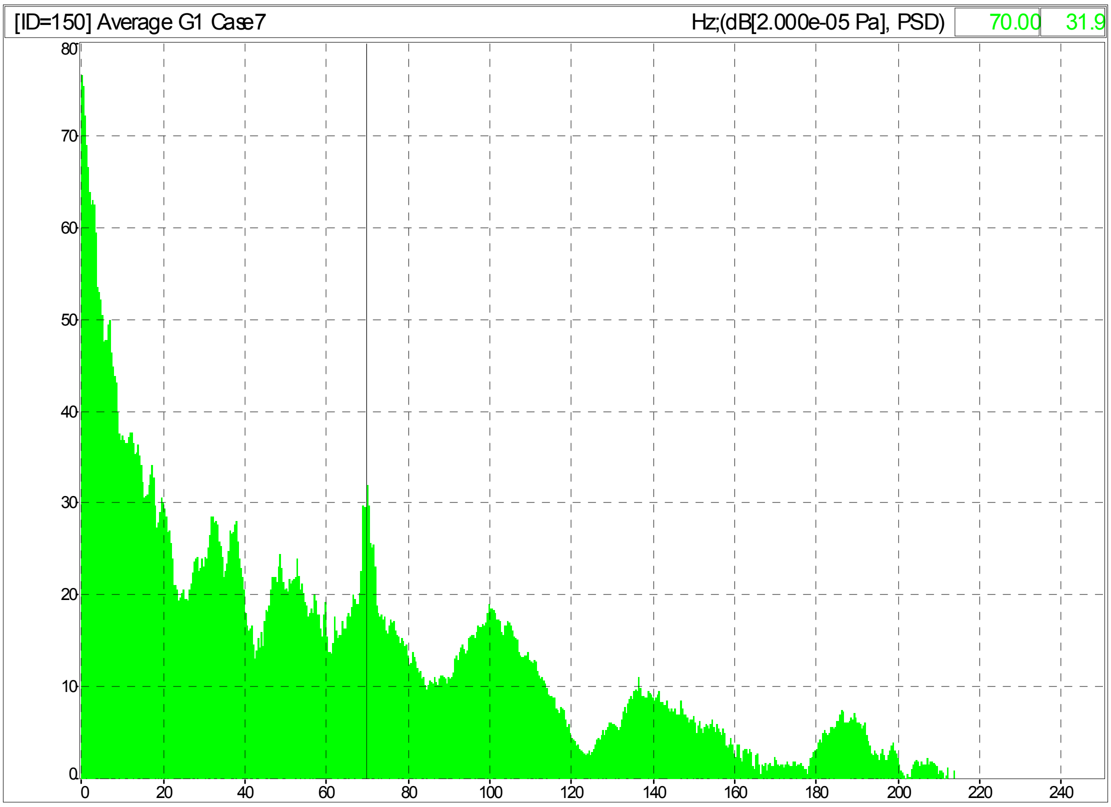


Figure 50: FFT of 9m30s audio record starting 19h30m from measurement Case7_040514_134035.cmg

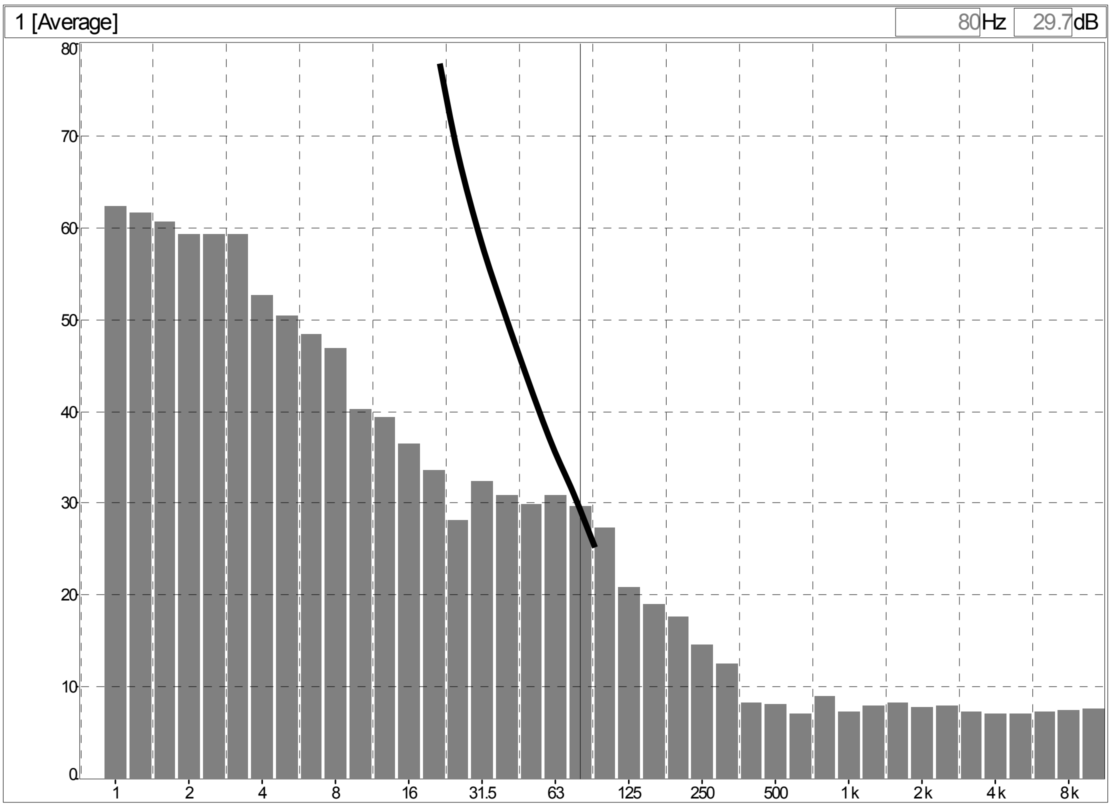


Figure 51: Mean 1/3 octave band spectrum 9m30s starting 19h30m from measurement Case7_040514_134035.cmg

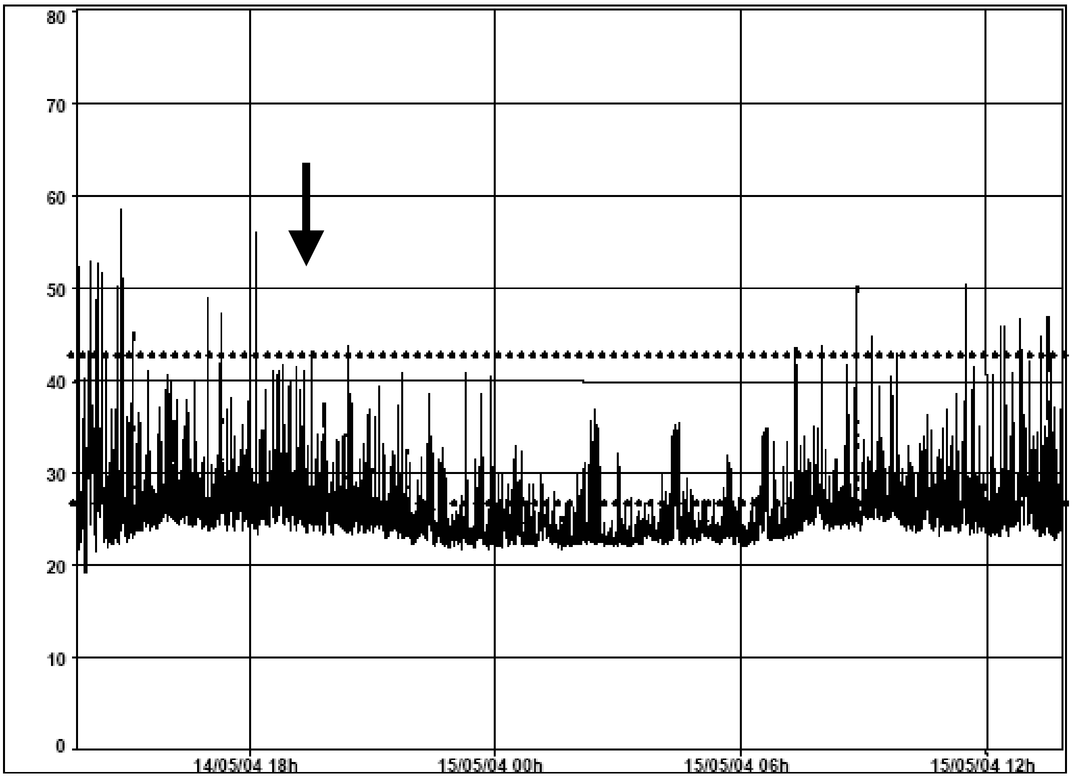


Figure 52: Time history showing 80Hz 1/3 octave spectrum band from measurement Case7_040514_134035.cmg together with lower Dutch (audibility) 27dB and Danish 42.5dB limits

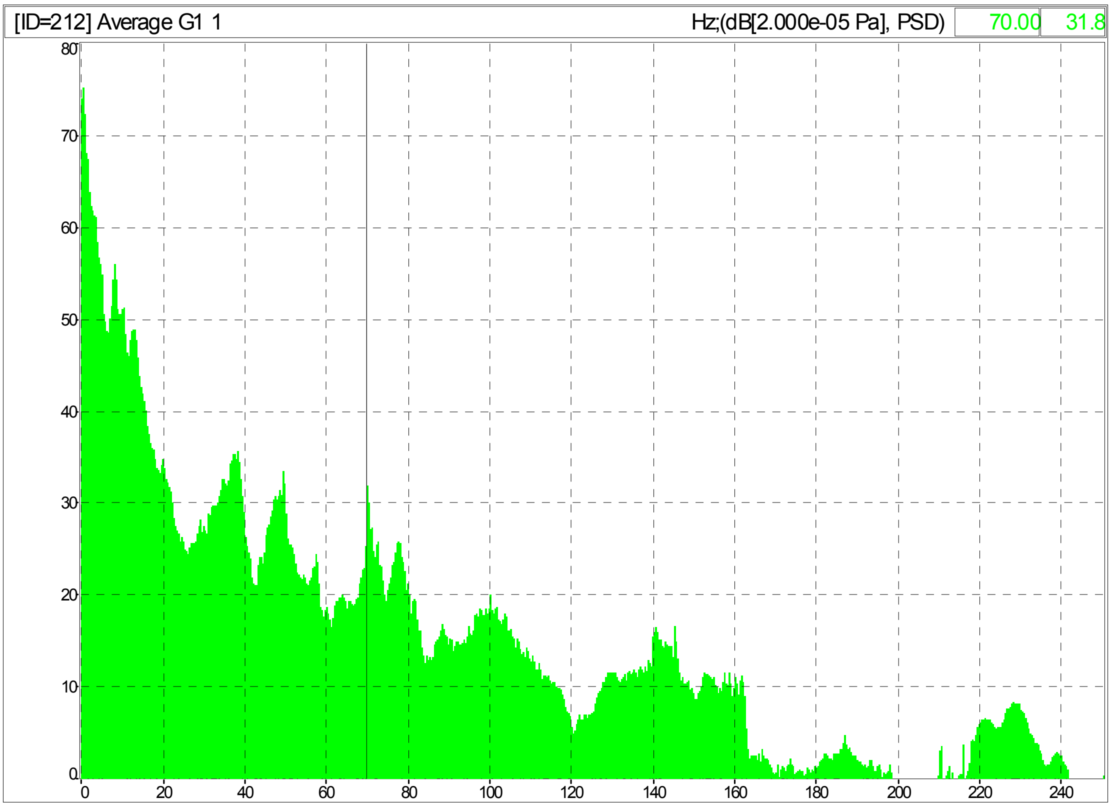


Figure 53: FFT of 9m30s audio record starting 13h30m on 15/05/04 from measurement Case7_040514_134035.cmg

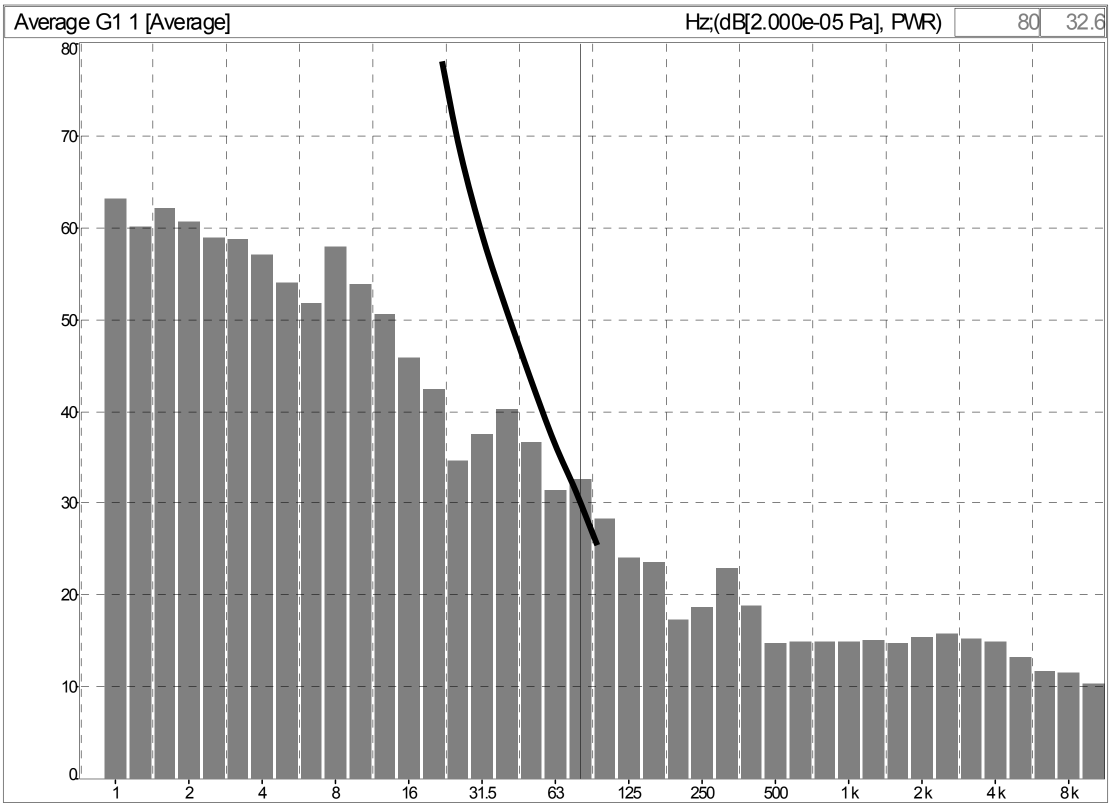


Figure 54: Mean 1/3 octave band spectrum 9m30s starting 13h30m on 15/05/04 from measurement Case7_040514_134035.cmg

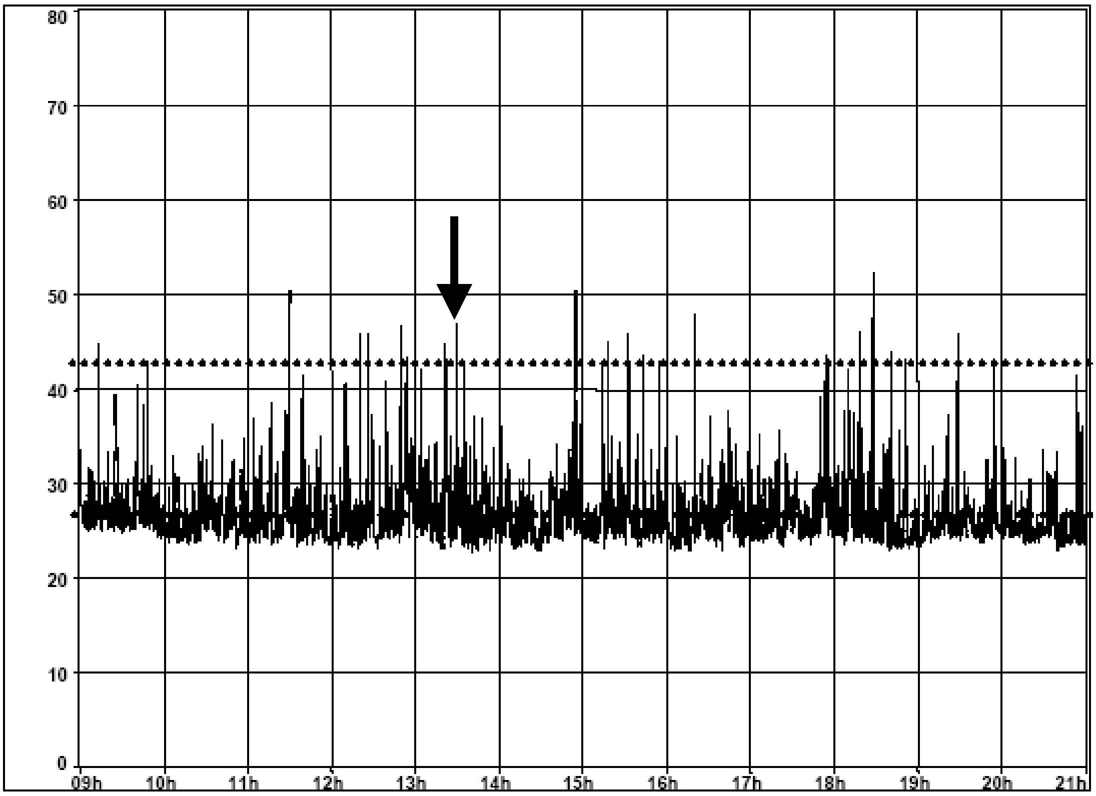


Figure 55: Time history on 15/05/04 showing 80Hz 1/3 octave spectrum band from measurement Case7_040514_134035.cmg together with lower Dutch (audibility) 27dB and Danish 42.5dB limits

Case 8

Measurement filename	Times identified by respondent
Case8_4512_210000.cmg	03h30
Case8_4513_210000.cmg	04h00
Location	Suburban
Source	Suspected industrial
Microphone position	Upstairs bedroom

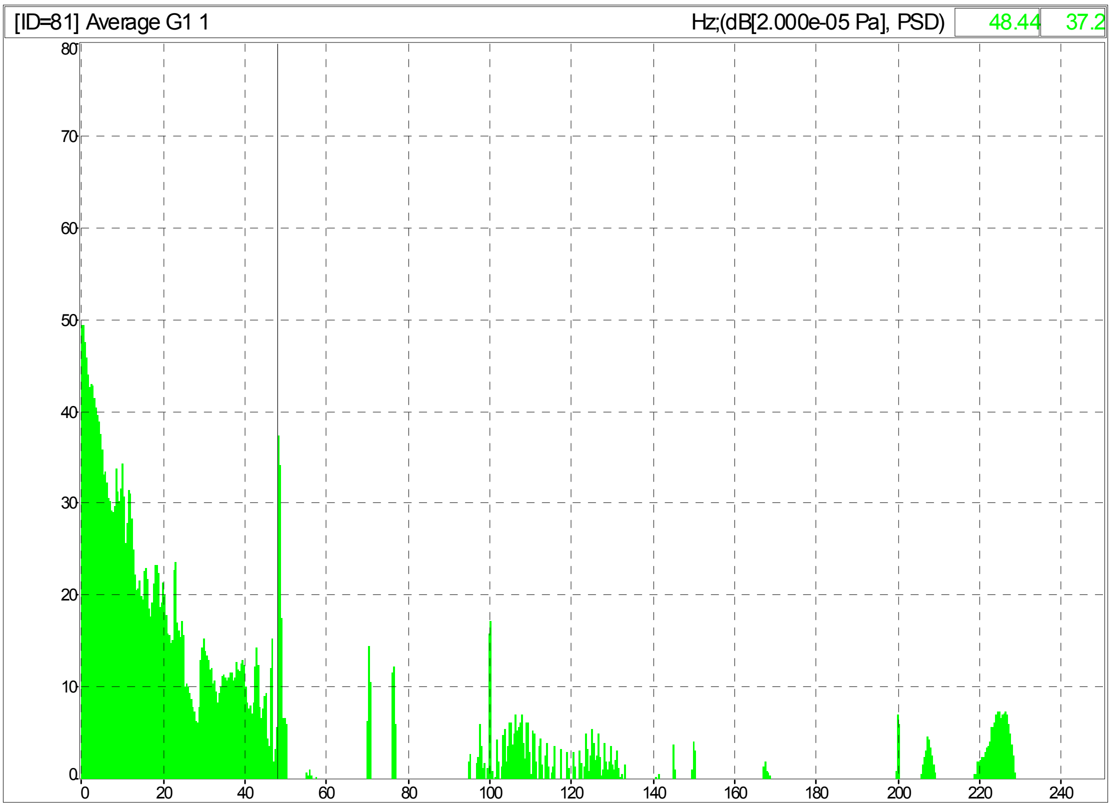


Figure 56: FFT of 9m30s audio record starting 03h30m from measurement Case8_040512_210000.cmg

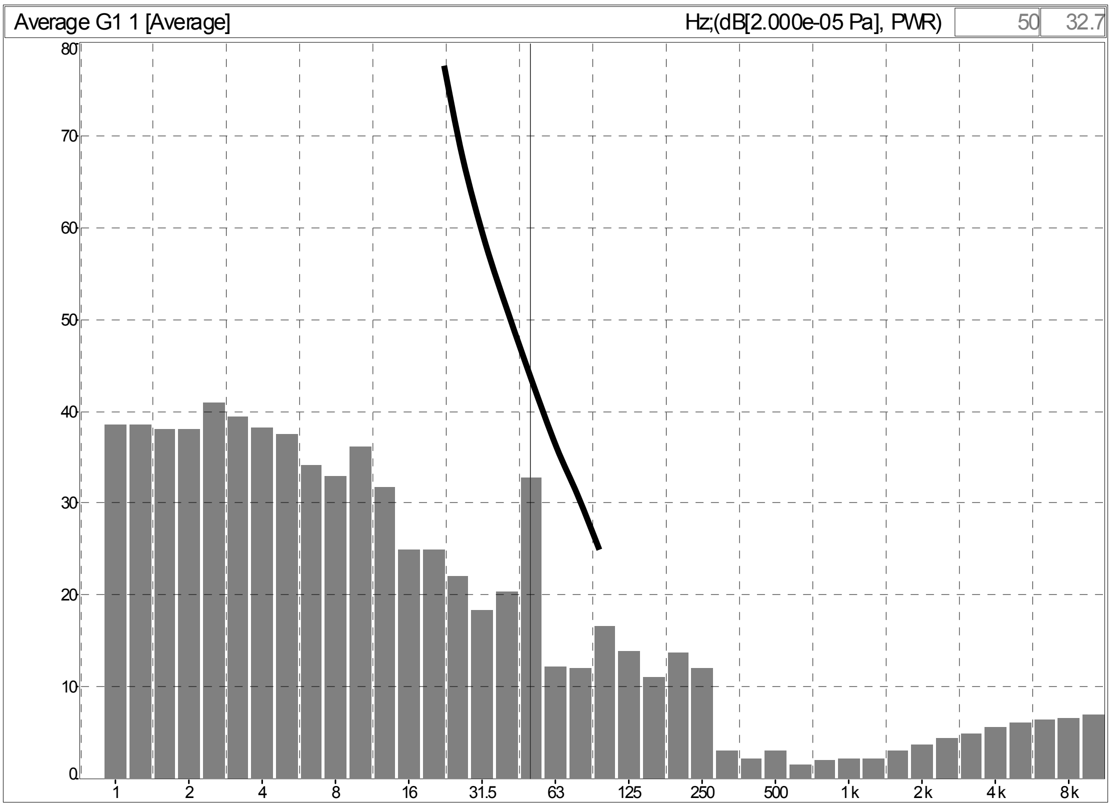


Figure 57: Mean 1/3 octave band spectrum 9m30s starting 03h30m from measurement Case8_040512_210000.cmg

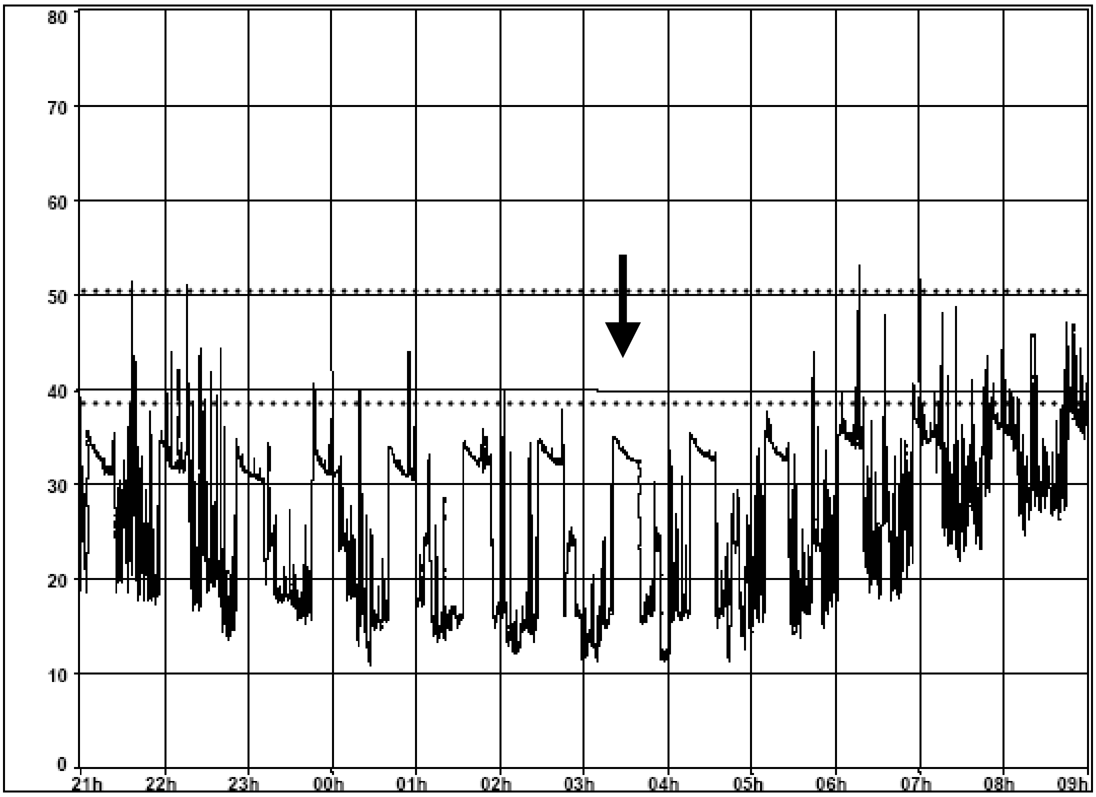


Figure 58: Time history showing 50Hz 1/3 octave spectrum band from measurement Case8_040512_210000.cmg together with Dutch (audibility) 39dB and Danish 50.2dB limits

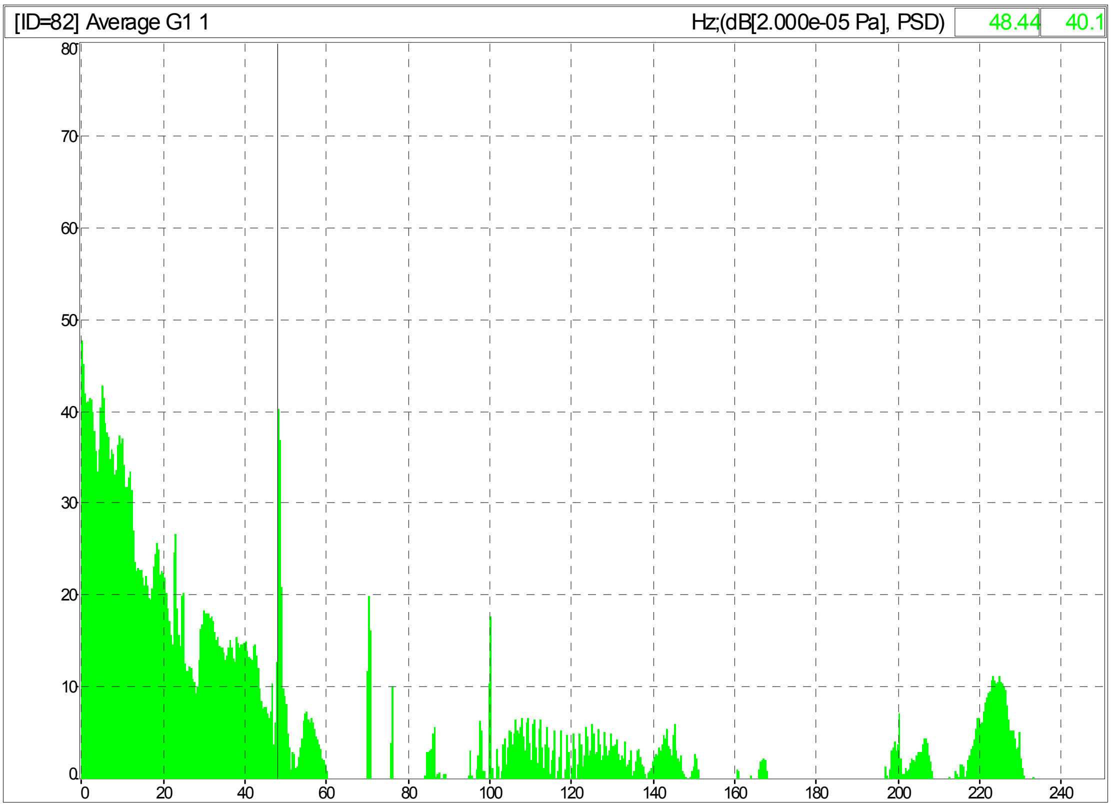


Figure 59: FFT of 9m30s audio record starting 04h00m on 14/05/04 from measurement Case8_040513_210000.cmg

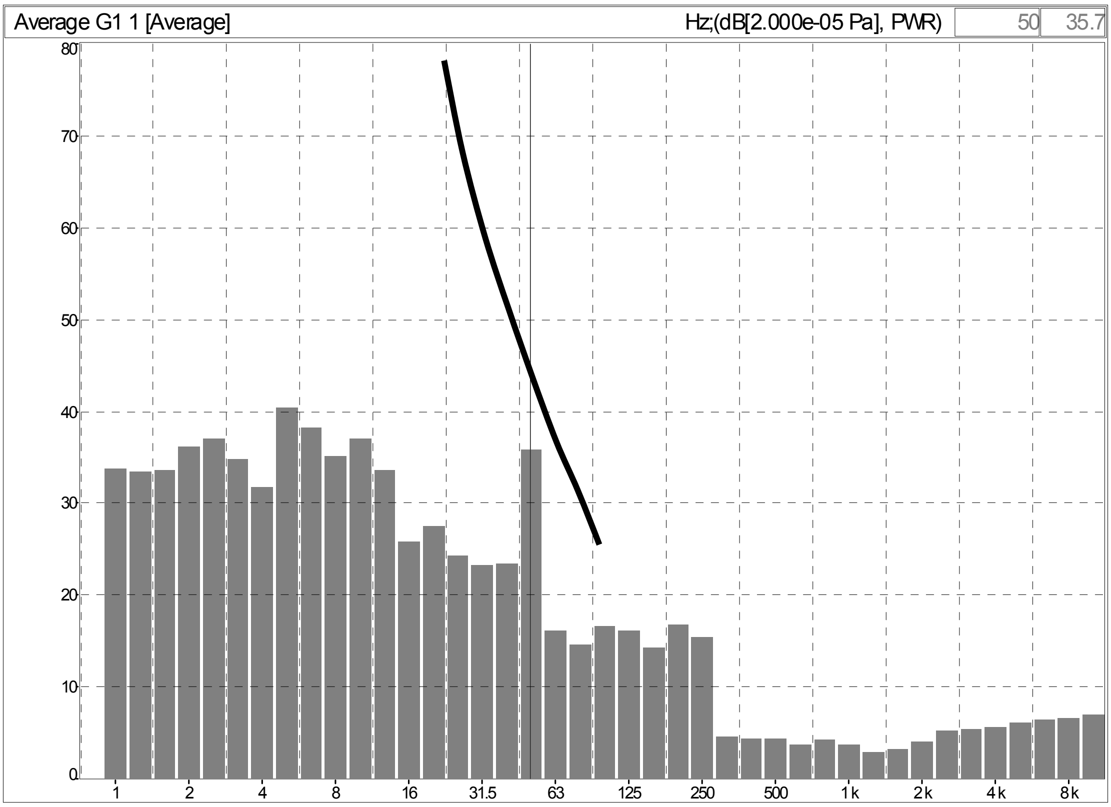


Figure 60: Mean 1/3 octave band spectrum 9m30s starting 04h00m on 14/05/04 from measurement Case8_040513_210000.cmg

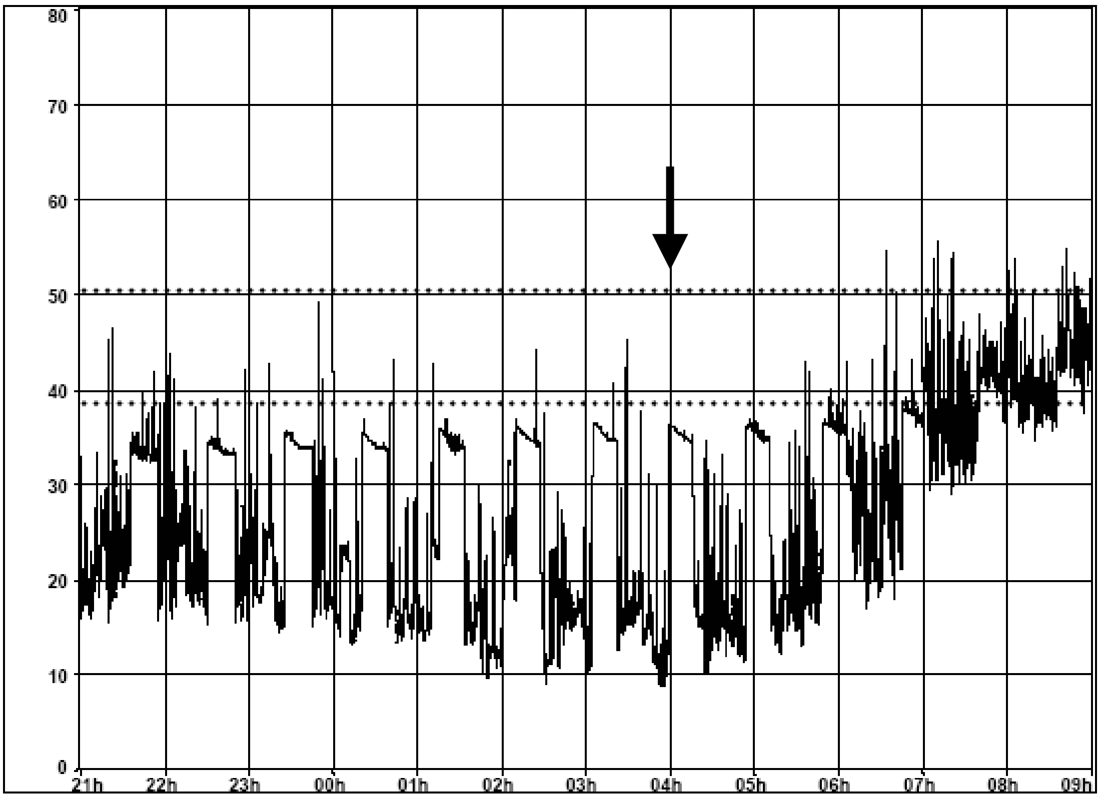


Figure 61: Time history showing 50Hz 1/3 octave spectrum band from measurement Case8_040513_210000.cmg together with lower Dutch (audibility) 39dB and Danish 50.2dB limits

Case 13

Measurement filename	Times identified by respondent
Case13_4405_210000.cmg	04h00
Case13_4406_210000.cmg	05h00
Location	Suburban
Source	Not known
Microphone position	Corner of living room

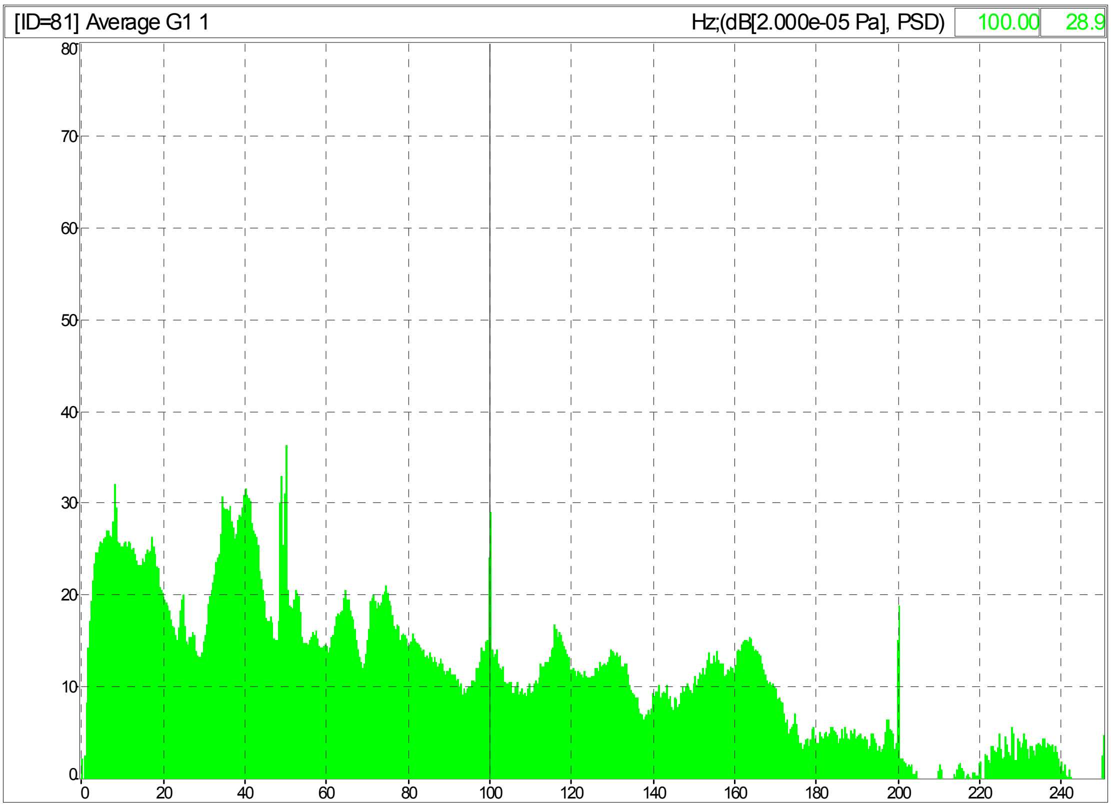


Figure 62: FFT of 9m30s audio record starting 04h00m from measurement Case13_040406_210000.cmg

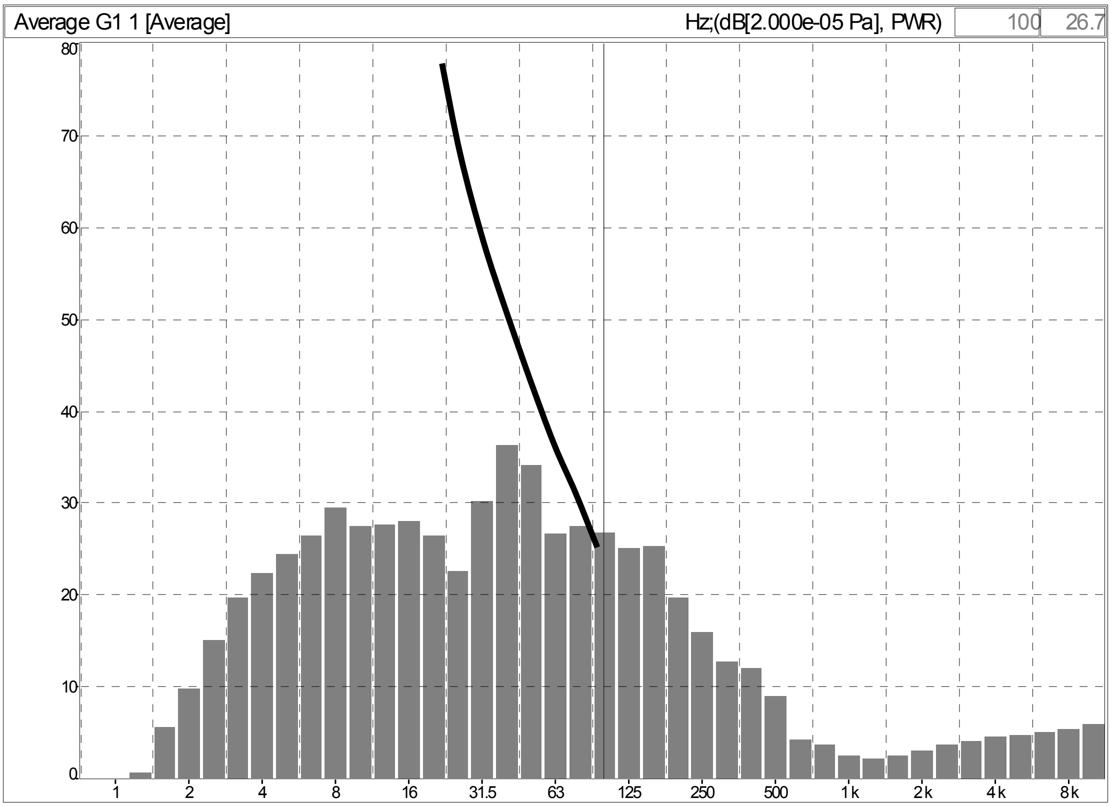


Figure 63: Mean 1/3 octave band spectrum 9m30s starting 04h00m from measurement Case13_040406_210000.cmg

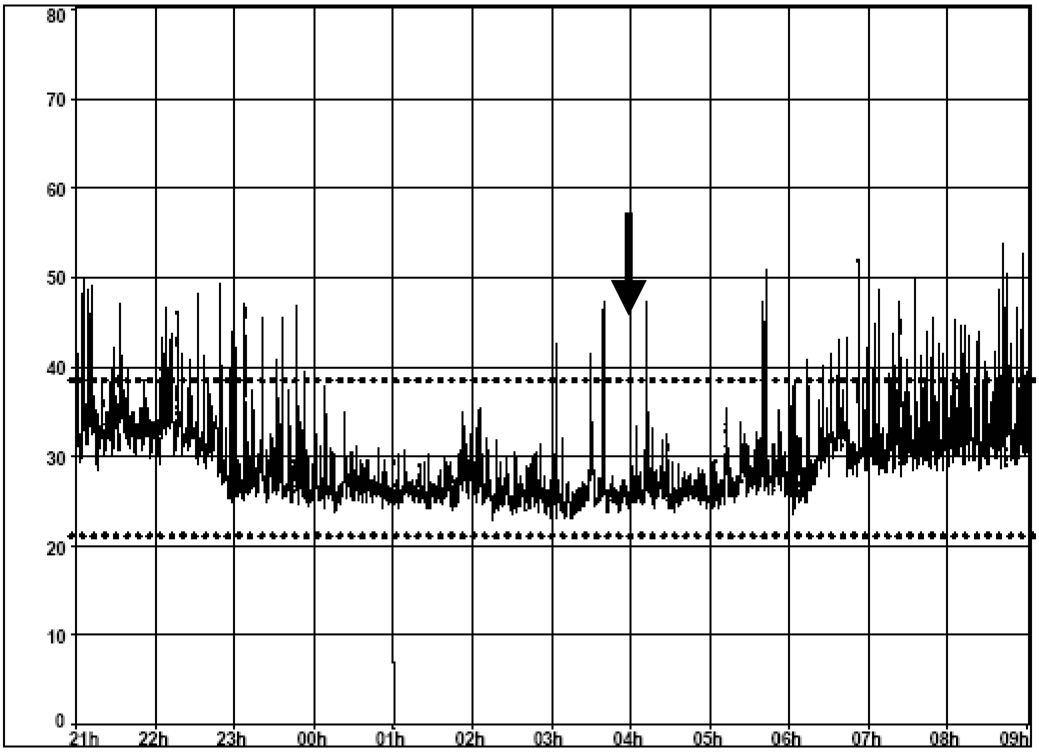


Figure 64: Time history showing 100Hz 1/3 octave spectrum band from measurement Case13_040406_210000.cmg together with Dutch (audibility) 22dB and Danish 39.1dB limits

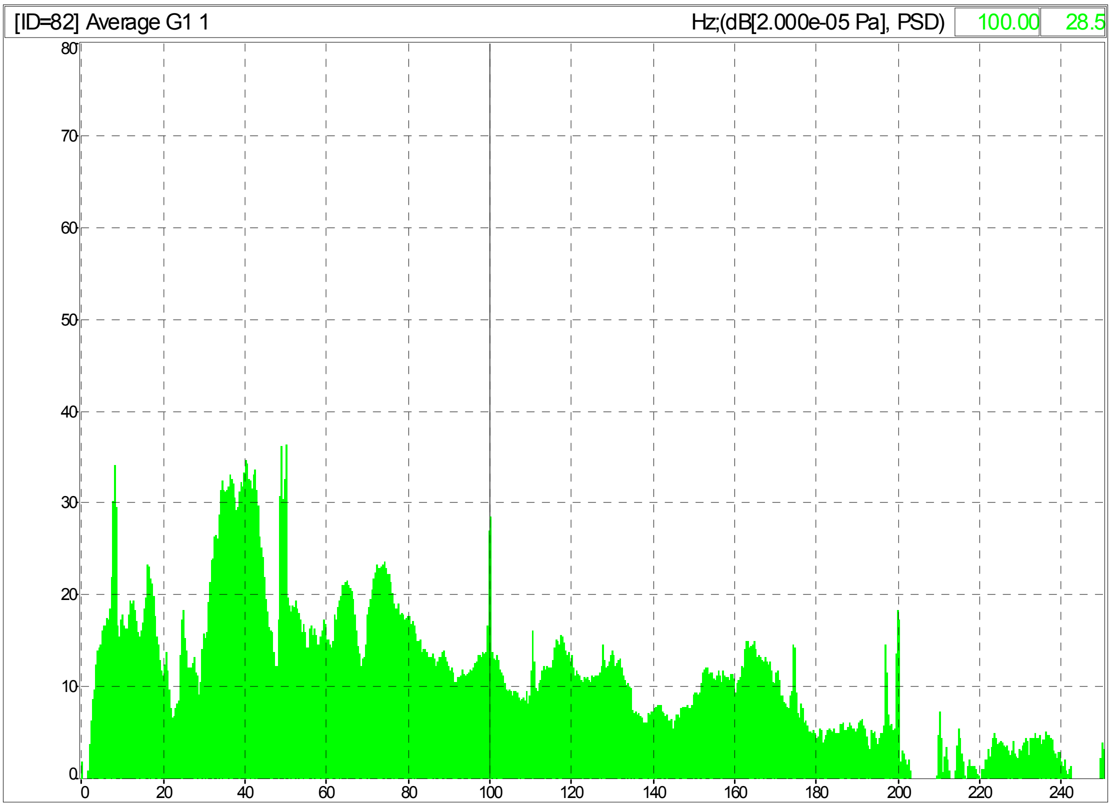


Figure 65: FFT of 9m30s audio record starting 05h00m on 07/04/04 from measurement Case13_040406_210000.cmg

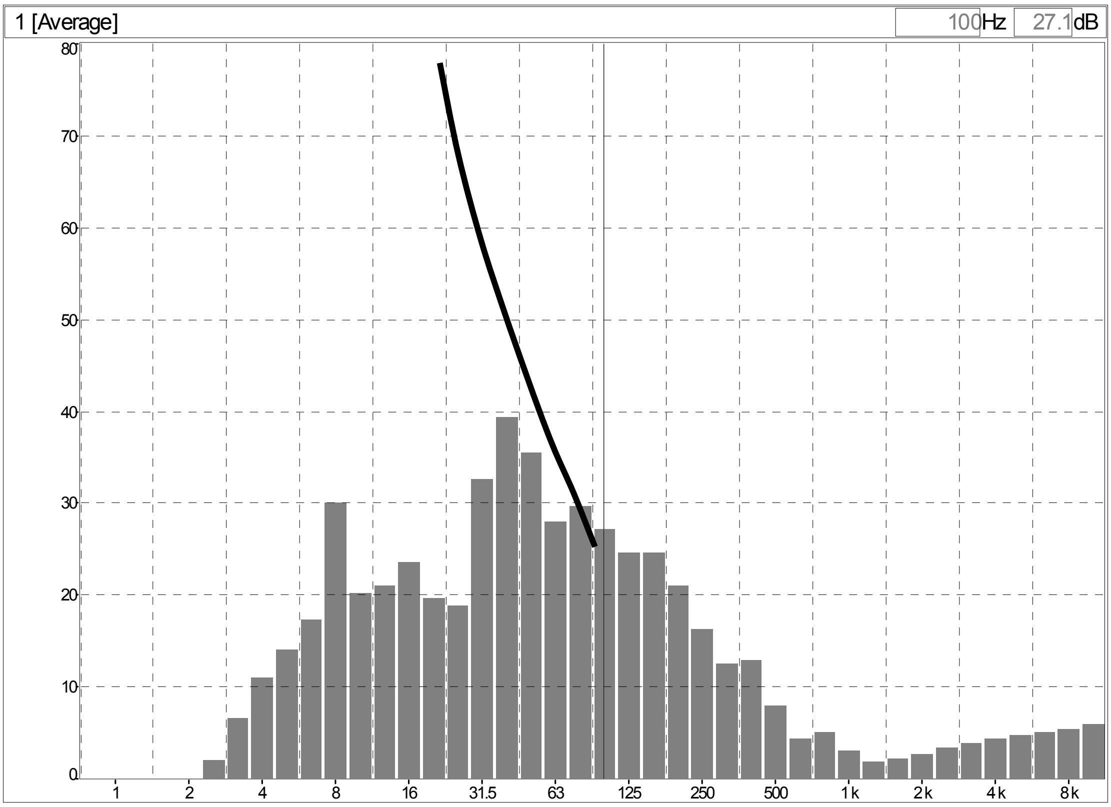


Figure 66: Mean 1/3 octave band spectrum 9m30s starting 05h00m on 07/04/04from measurement Case13_040406_210000.cmg

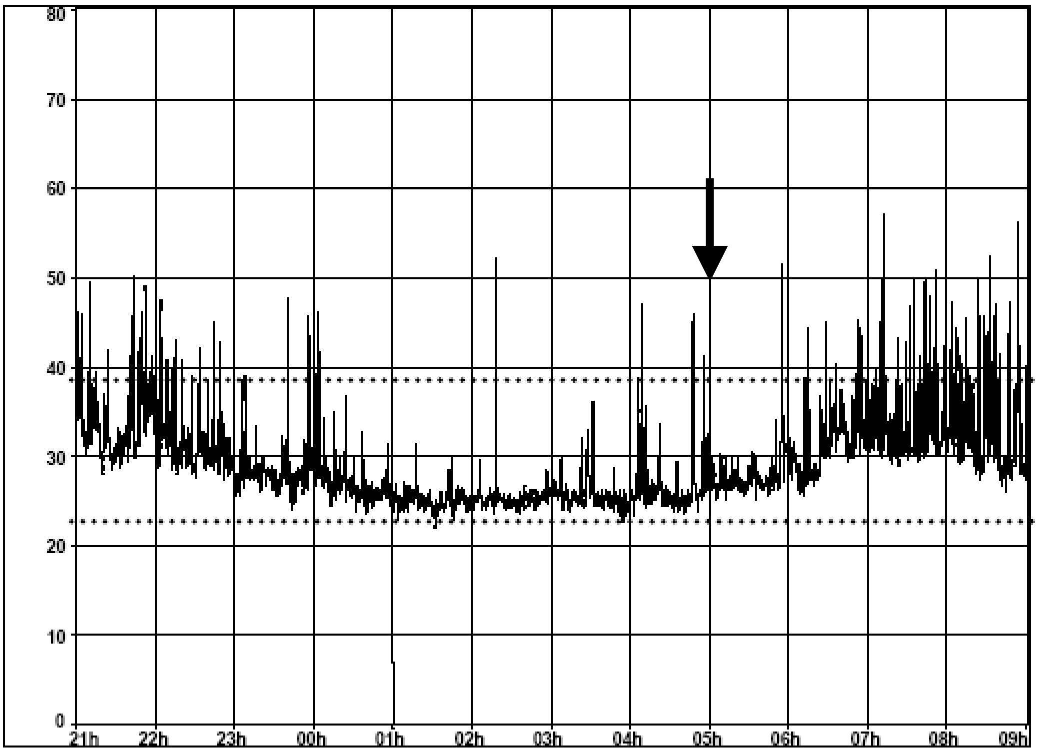


Figure 67: Time history showing 100Hz 1/3 octave spectrum band from measurement Case13_040406_210000.cmg together with lower Dutch (audibility) 22dB and Danish 39.1dB limits

Case 16

Measurement filename	Times identified by respondent
Case16_4402_210000.cmg	02h30
Case16_4402_210000.cmg	04h10
Case16_4405_210000.cmg	02h33
Location	Suburban
Source	Not known.
Microphone position	Corner of downstairs room
Notes	Fridge/ aircraft

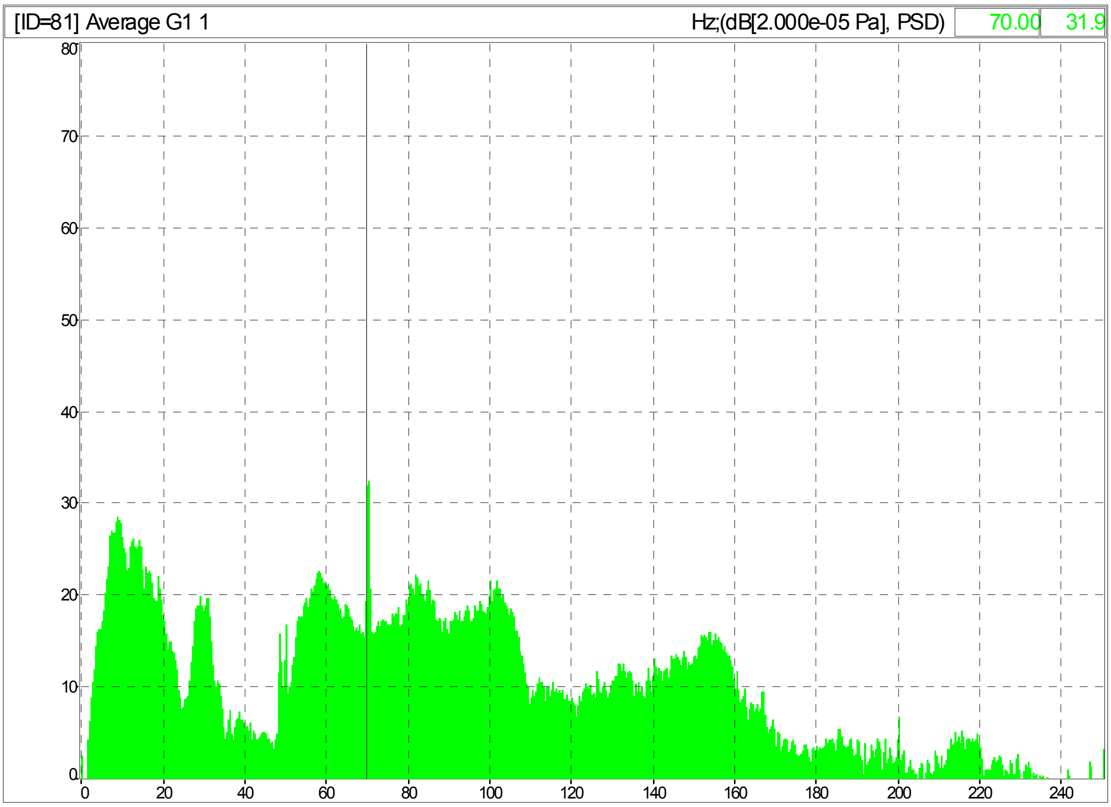


Figure 68: FFT of 9m30s audio record starting 02h30m on 03/04/04from measurement Case16_040402_210000.cmg

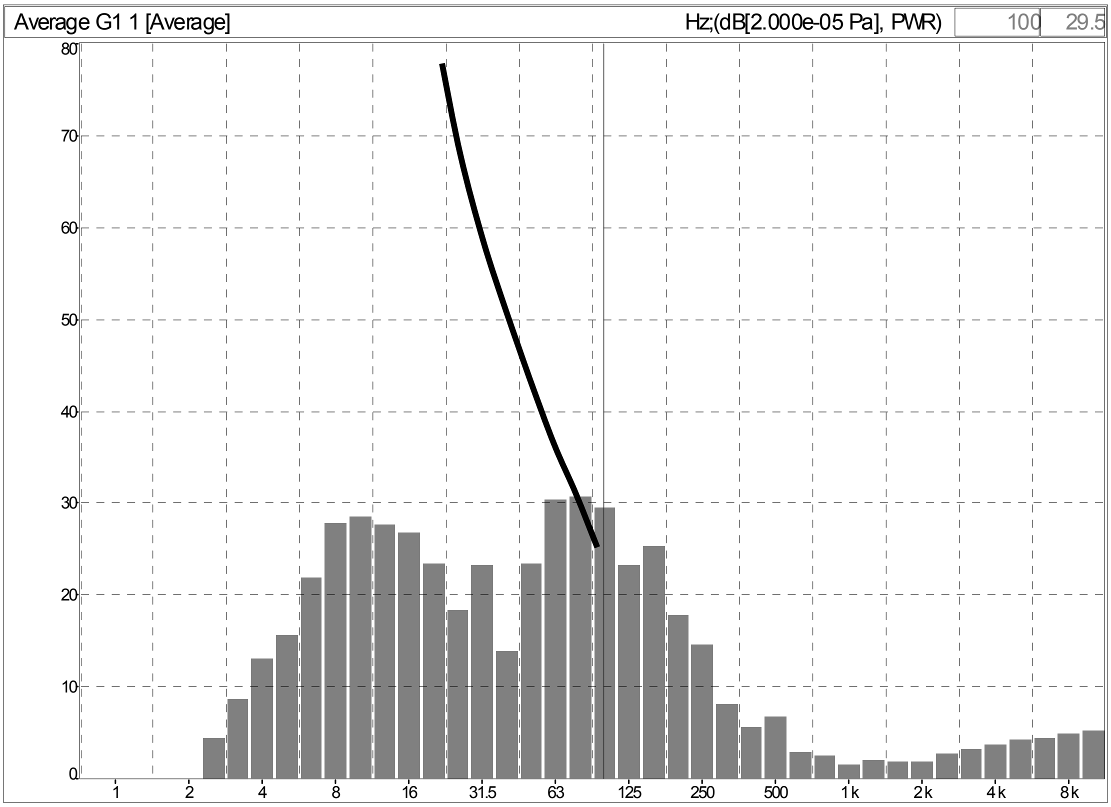


Figure 69: Mean 1/3 octave band spectrum 9m30s starting starting 02h30m on 03/04/04from measurement Case16_040402_210000.cmg

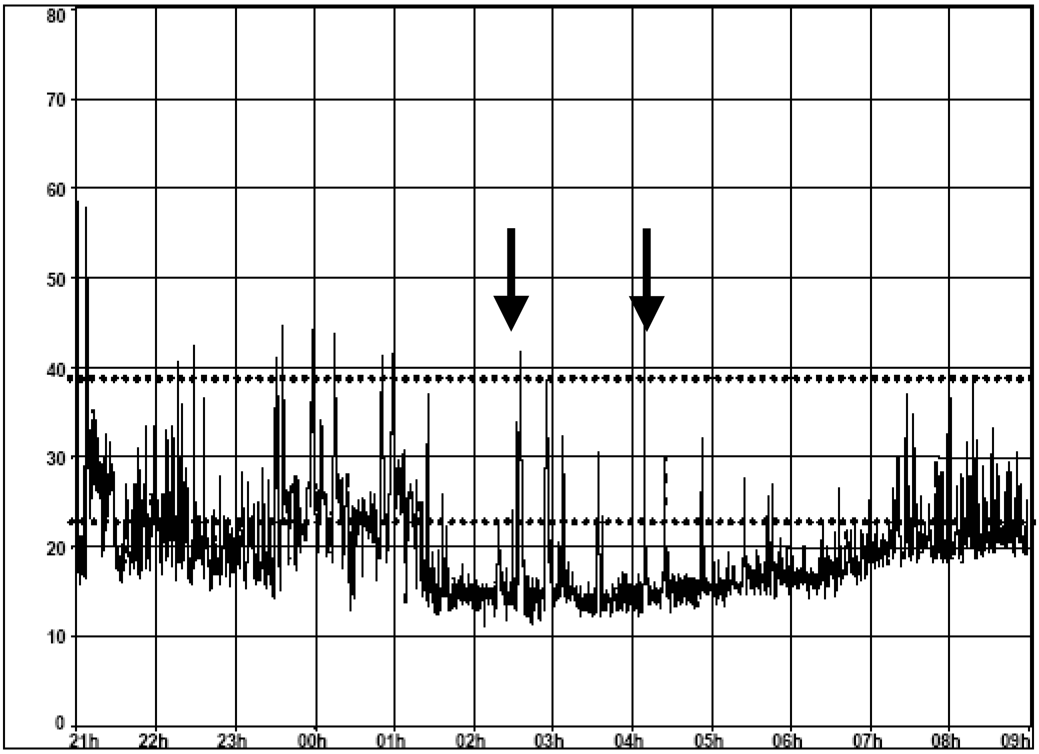


Figure 70: Time history showing 100Hz 1/3 octave spectrum band from measurement Case16_040402_210000.cmg together with Dutch (audibility) 22dB and Danish 39.1dB limits

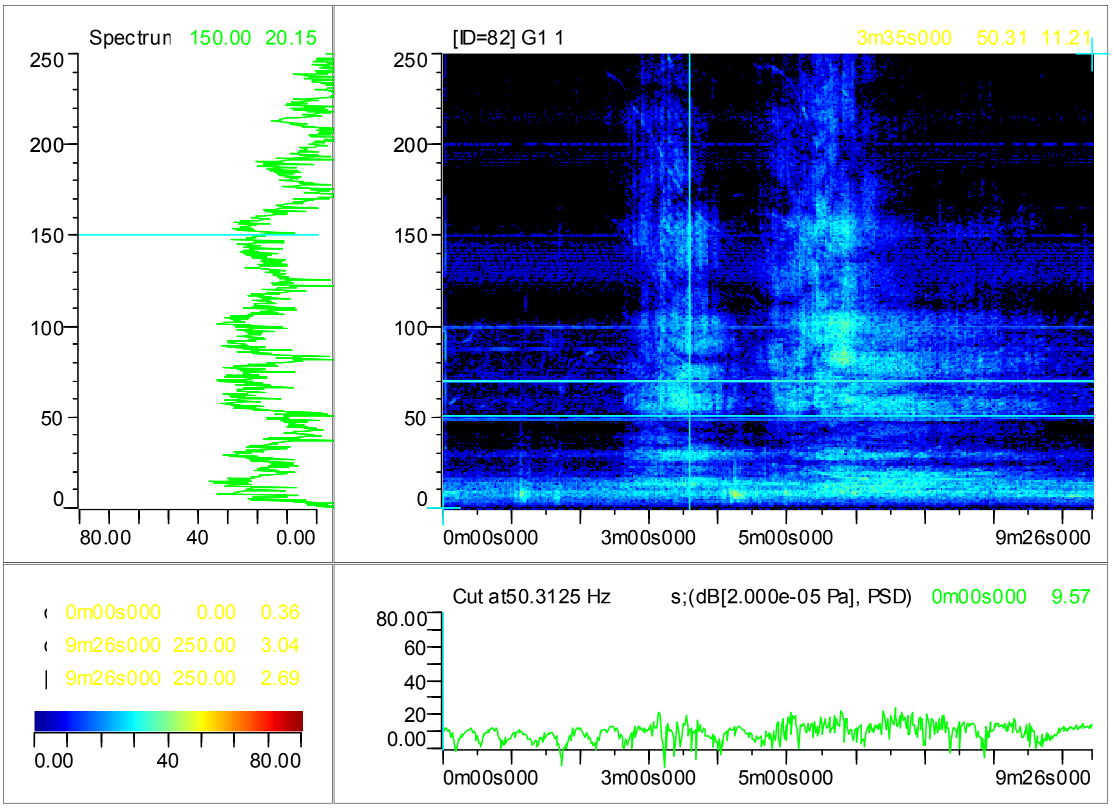


Figure 71: Sonogram of 9m30s audio record starting 02h30m on 03/04/04from measurement Case16_040402_210000.cmg. Illustrating suspected aircraft flyover with tones varying in frequency for example from 240 to 150Hz. Constant tone at 70Hz is possibly a pc fan, while tone at 50Hz is possibly due to the fridge with harmonics at 100, 150 and 200Hz.

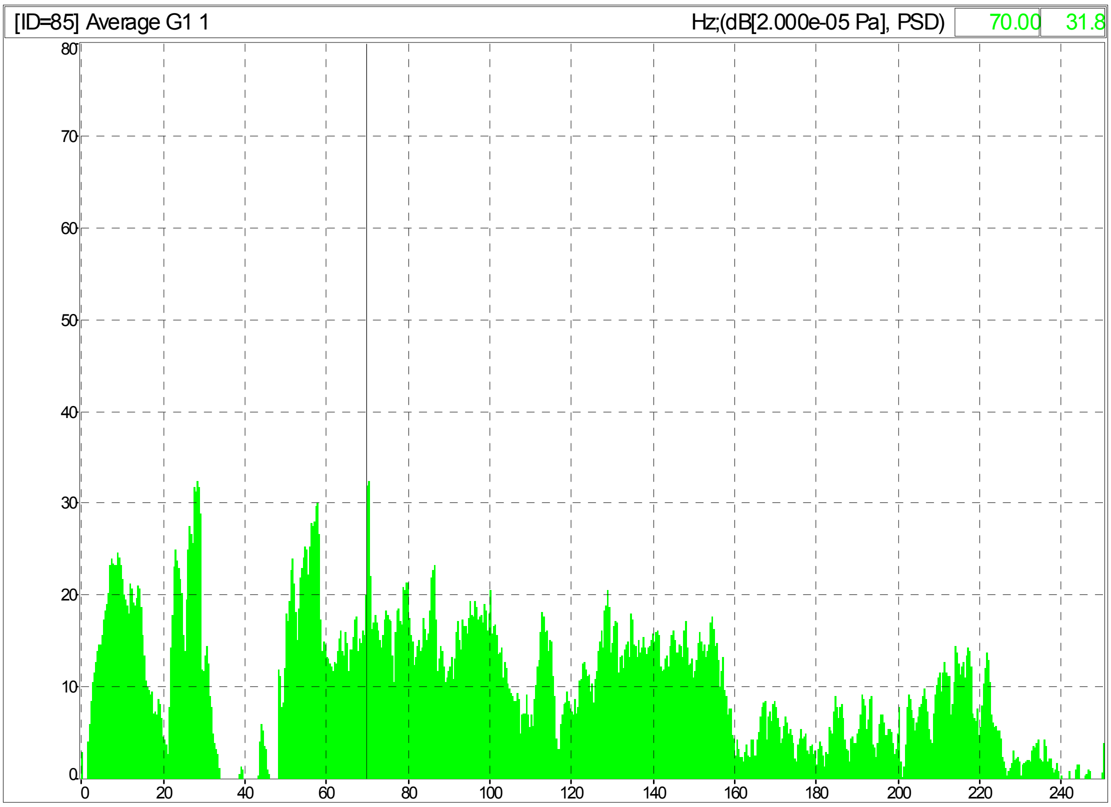


Figure 72: FFT of 3m00s of audio record starting 04h10m on 03/04/04 from measurement Case16_040402_210000.cmg.

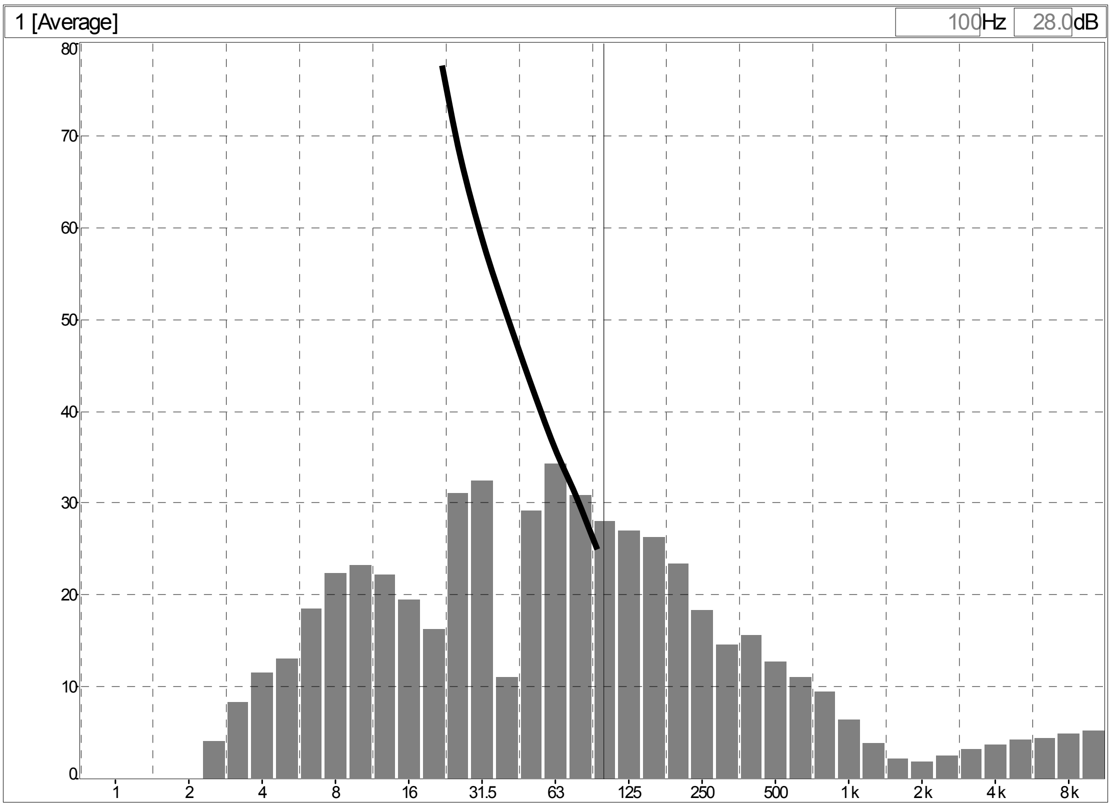


Figure 73: Mean 1/3 octave band spectrum of 3m00s starting starting 04h10m on 03/04/04 from measurement Case16_040402_210000.cmg

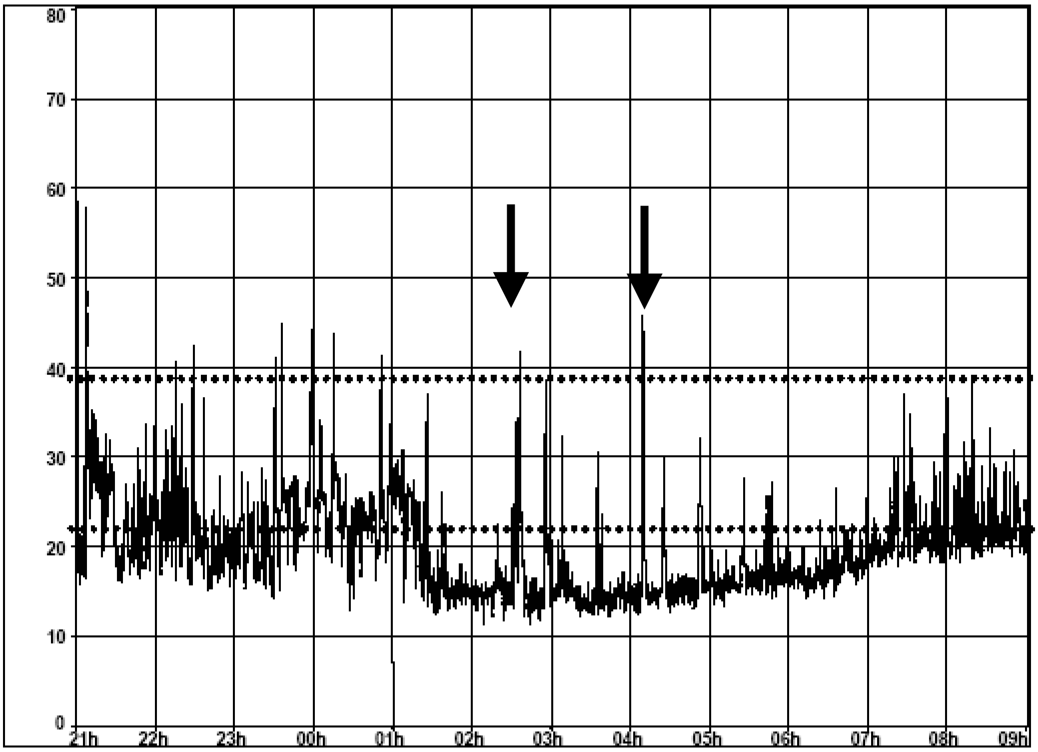


Figure 74: Time history showing 100Hz 1/3 octave spectrum band from measurement Case16_040402_210000.cmg together with Dutch (audibility) 22dB and Danish 39.1dB limits

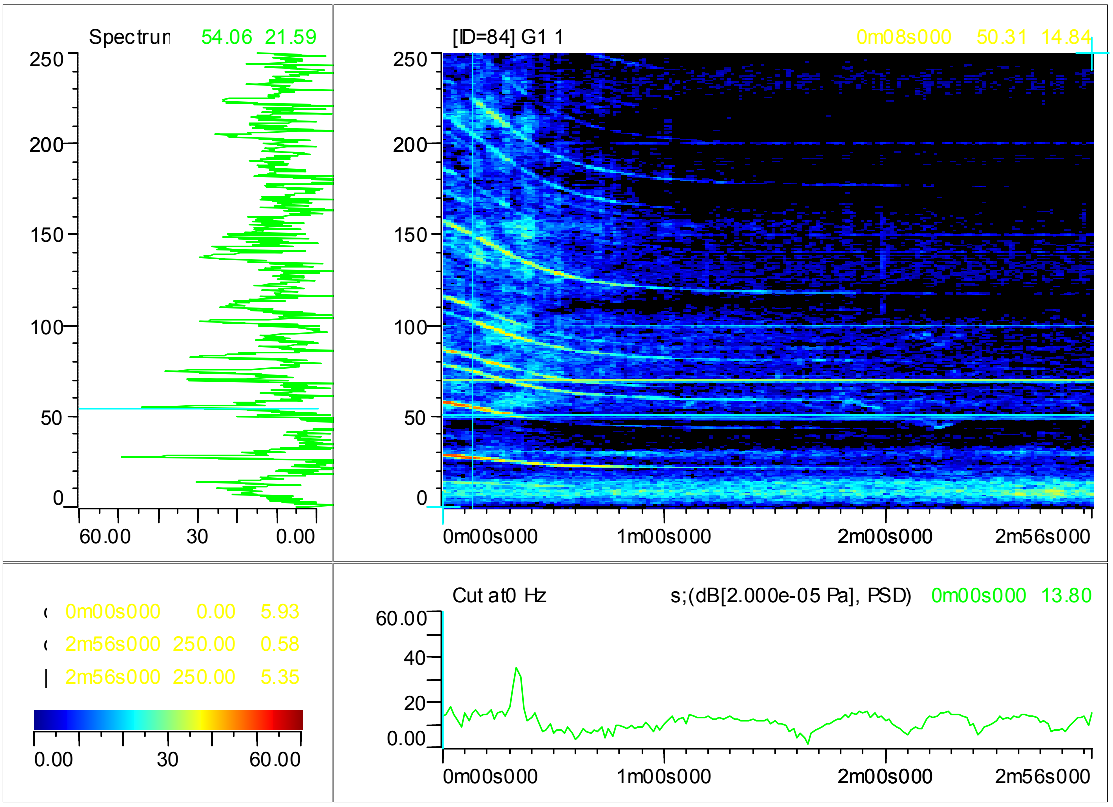


Figure 75: Sonogram of 3m00s of audio record starting 04h10m on 03/04/04from measurement Case16_040402_210000.cmg. Illustrating suspected aircraft flyover with tones varying in frequency for example from 240 to 180Hz. Constant tone at 70Hz is possibly a pc fan, while tone at 50Hz is possibly due to the fridge with harmonics at 100, 150 and 200Hz.

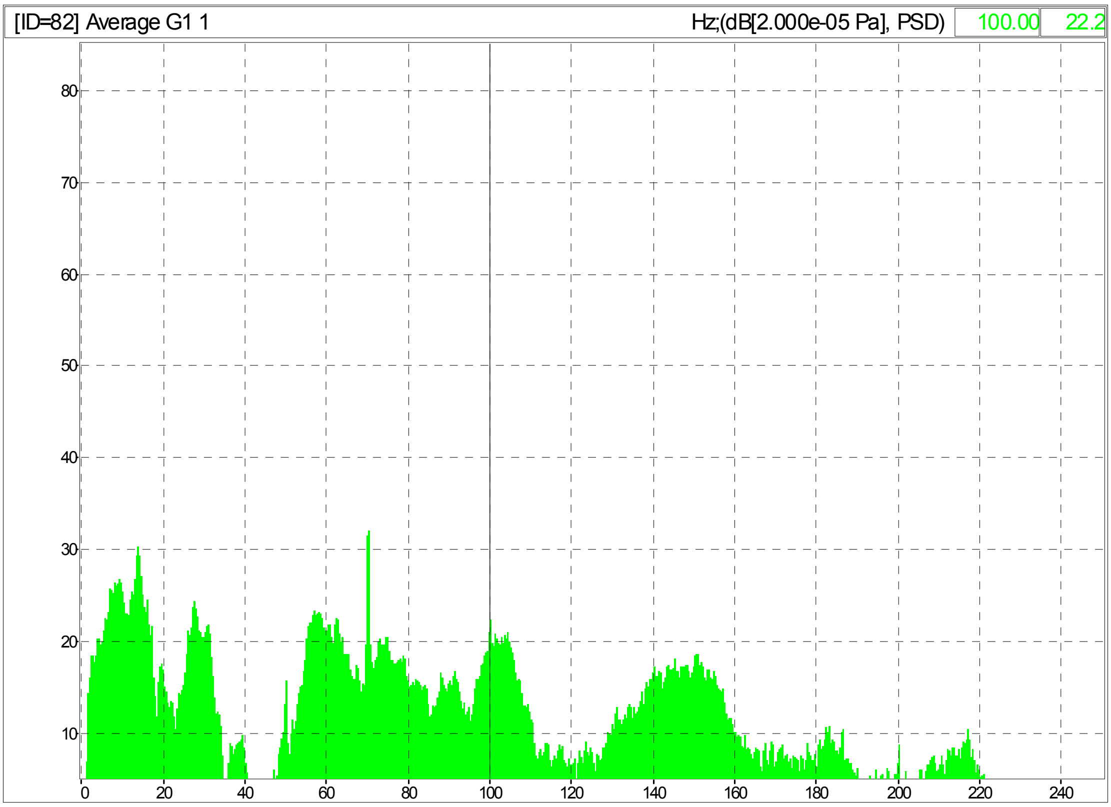


Figure 76: FFT of 2m10s of audio record starting 02h33m from measurement Case16_040405_210000.cmg

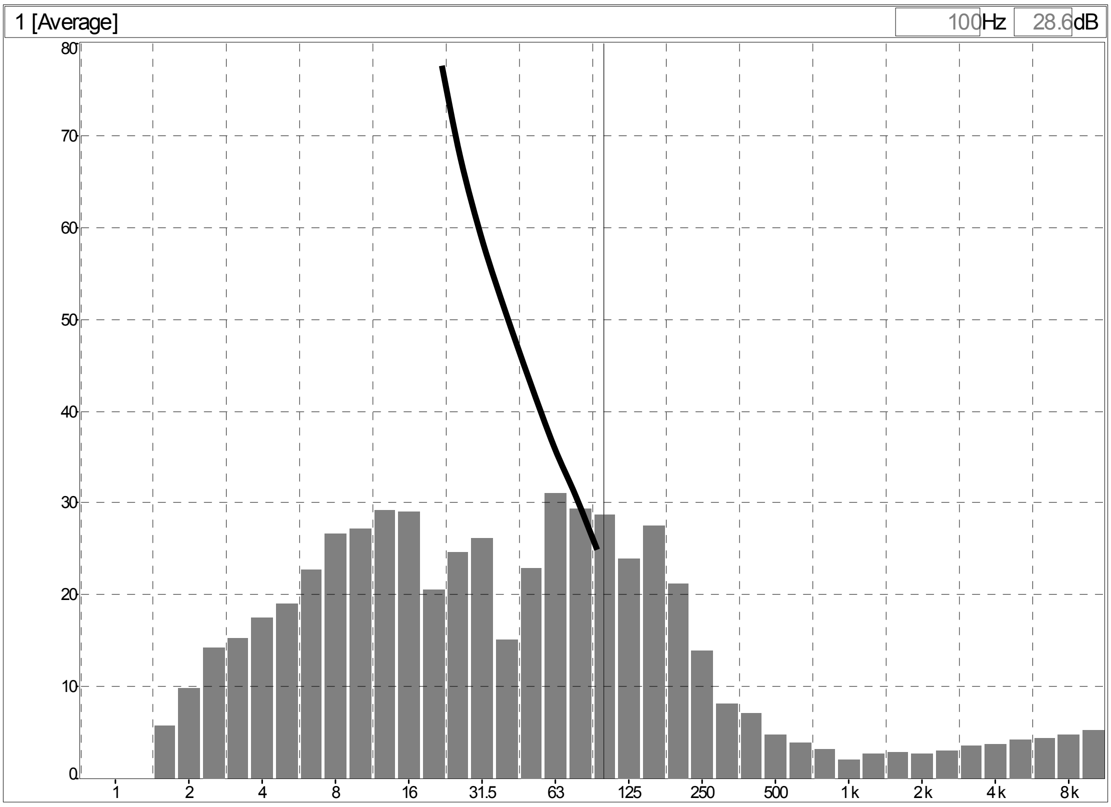


Figure 77: Mean 1/3 octave band spectrum during 2m10s of flyover starting at 02h33 on 06/04/04 from measurement Case16_040405_210000.cmg

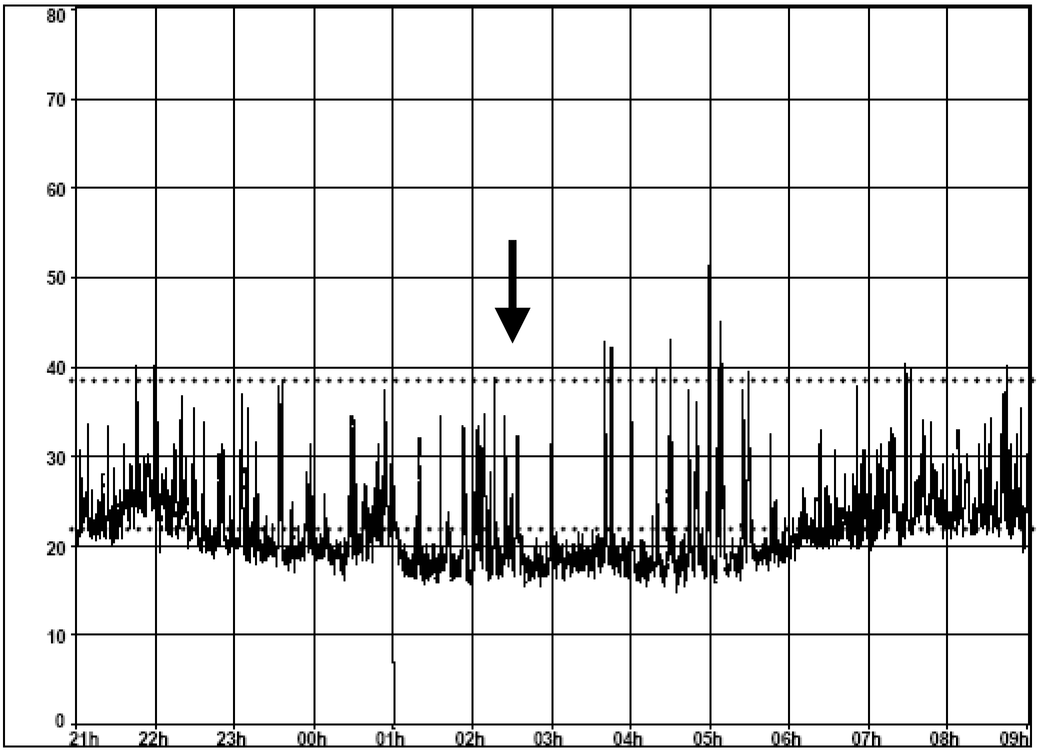


Figure 78: Time history showing 100Hz 1/3 octave spectrum band from measurement Case16_040406_210000.cmg together with Dutch (audibility) 22dB and Danish 39.1dB limits

Case 18

Measurement filename	**Times identified by respondent**
Case18_4423_205000.cmg	22h10
Case18_4424_205000.cmg	05h10
Location	Rural
Source	Suspected industrial
Microphone position	Corner of empty room

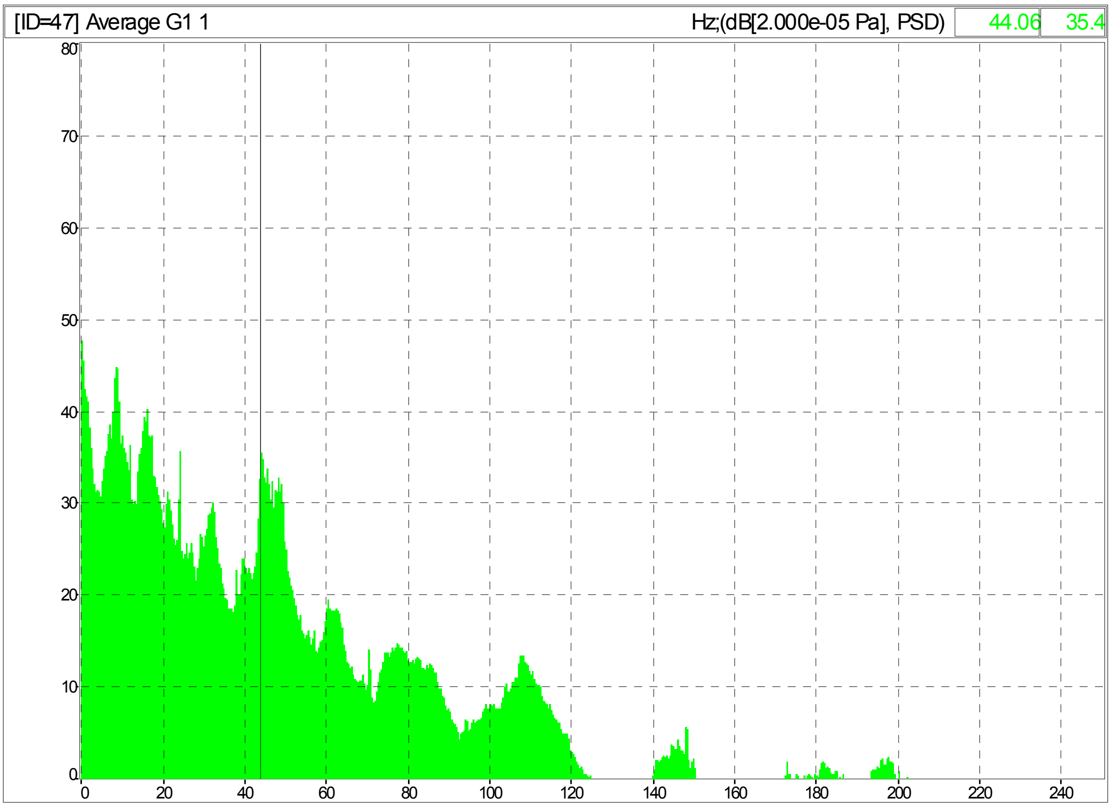


Figure 79: FFT of 9m30s audio record starting 22h10m on 23/04/04 from measurement Case18_040423_205000.cmg

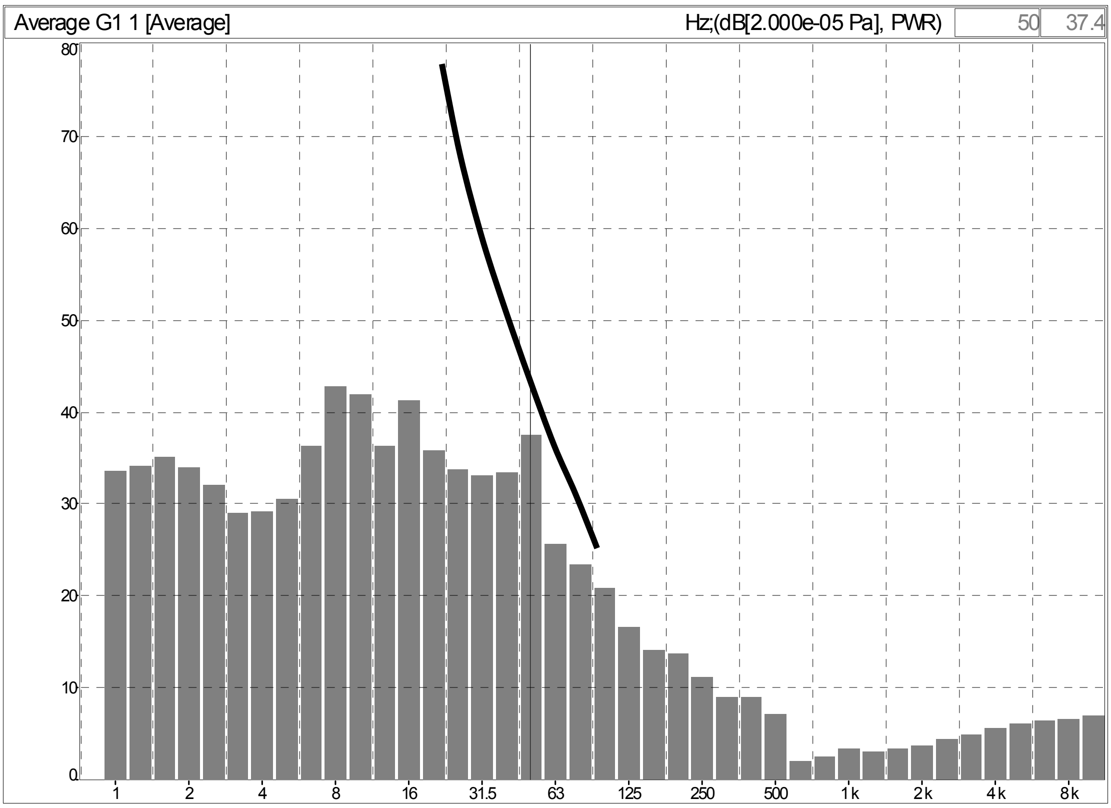


Figure 80: Mean 1/3 octave band spectrum 9m30s starting 22h10m on 23/04/04 from measurement Case18_040423_205000.cmg

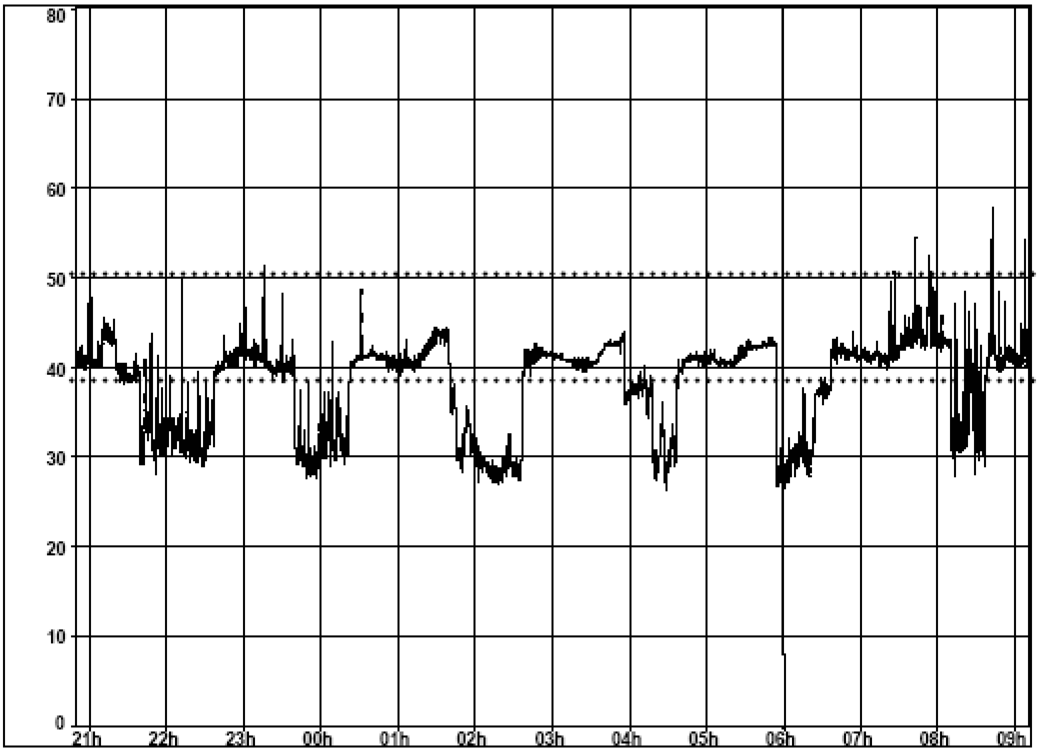


Figure 81: Time history showing 50Hz 1/3 octave spectrum band from measurement Case18_040423_205000.cmg together with Dutch (audibility) 39dB and Danish 50.2dB limits

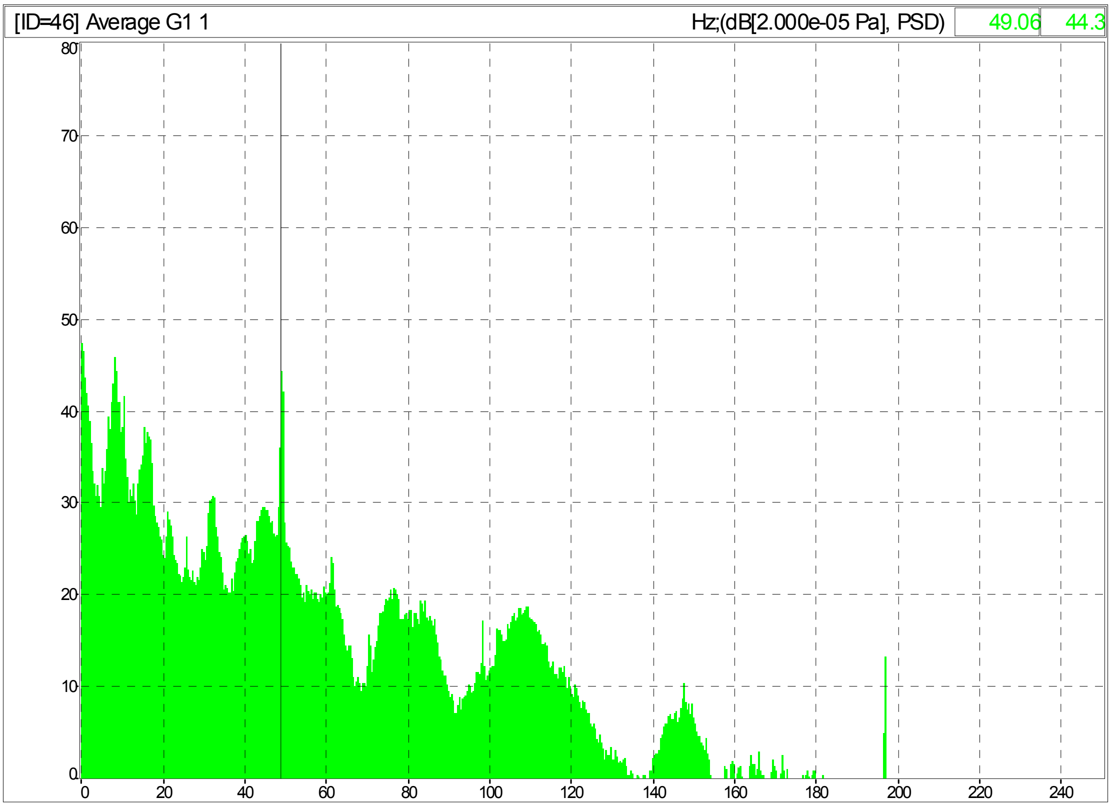


Figure 82: FFT of 9m30s of audio record starting 05h10m on 25/04/04 from measurement Case18_040424_205000.cmg.

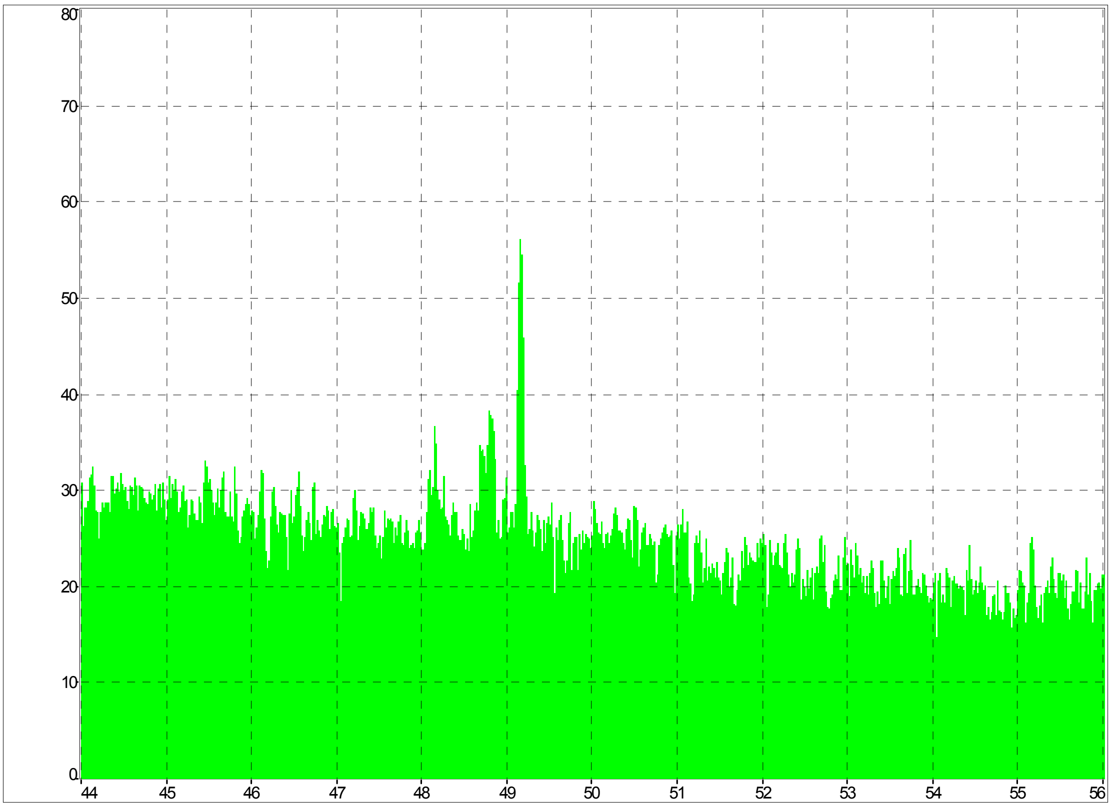


Figure 83: Zoom FFT of 9m30s of audio record starting 05h10m on 25/04/04 from measurement Case18_040424_205000.cmg showing peaks at 48.2, 48.8 and 49.2 Hz.

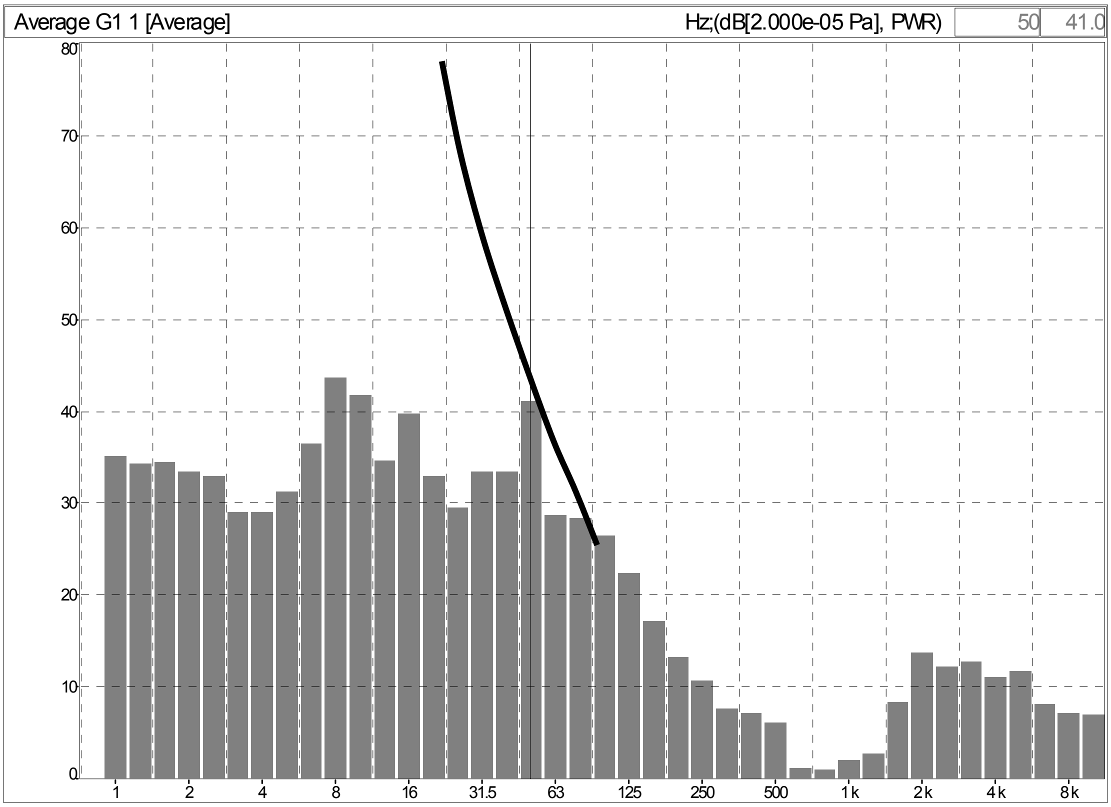
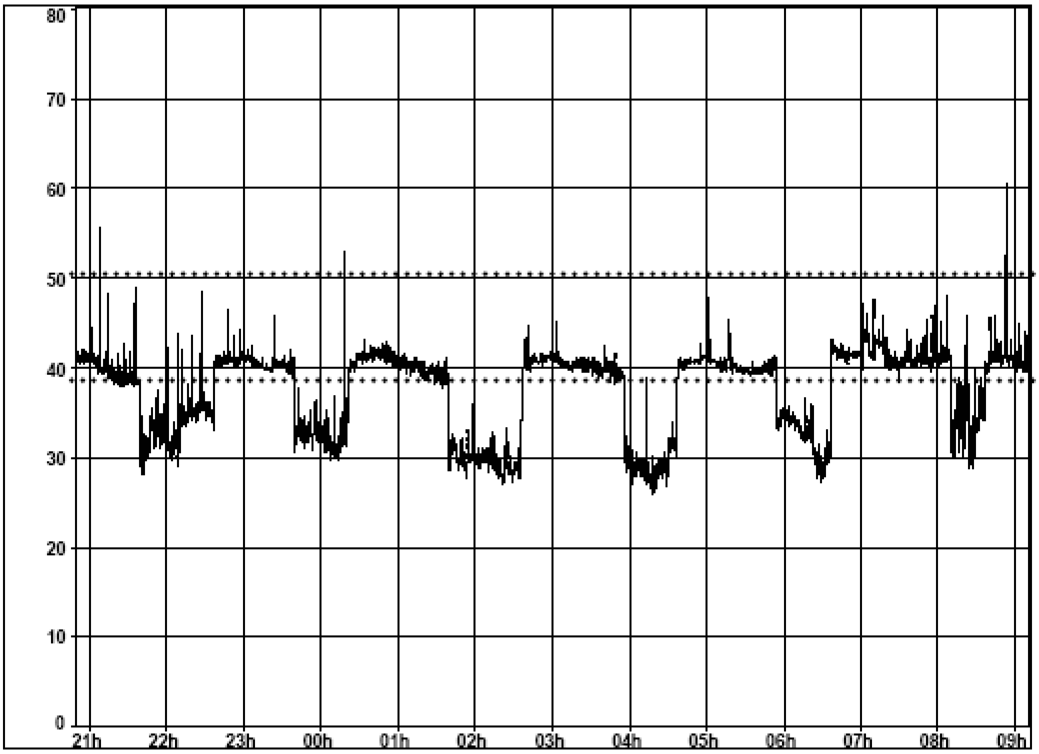


Figure 84: Mean 1/3 octave band spectrum starting 05h10m on 25/04/04 from measurement Case18_040424_205000.cmg

Figure 85: Time history showing 50Hz 1/3 octave spectrum band from measurement Case18_040423_205000.cmg together with Dutch (audibility) 39dB and Danish 50.2dB limits



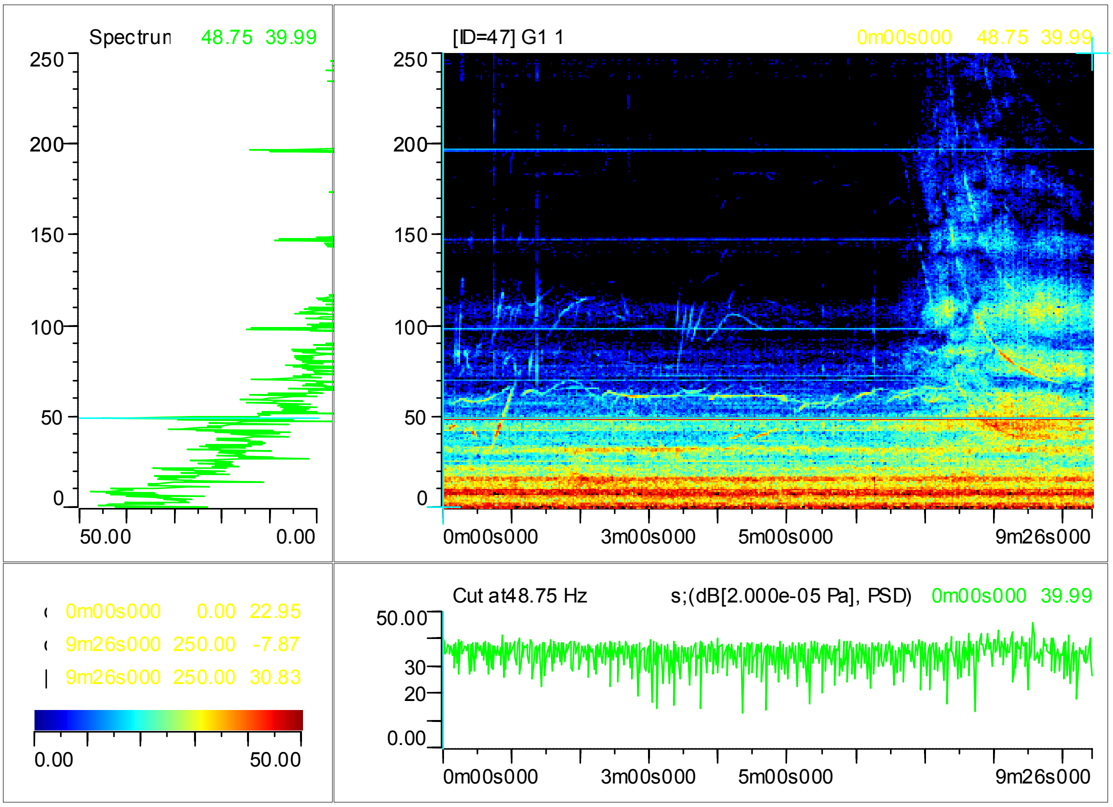


Figure 86: Sonogram of 9m30s of audio record starting 05h10m on 25/04/04 from measurement Case18_040424_205000.cmg. Illustrating falling tones varying in frequency for example from 200 to 40Hz. Constant tone at ~50Hz is due to the fridges with harmonics at 100, 150 and 200Hz.

Case 19

Measurement filename	Times identified by respondent
Case19_4421_09000.cmg	09h20
Case19_4422_09000.cmg	12h20
Location	Urban
Source	Plant
Microphone position	Corner of bedroom

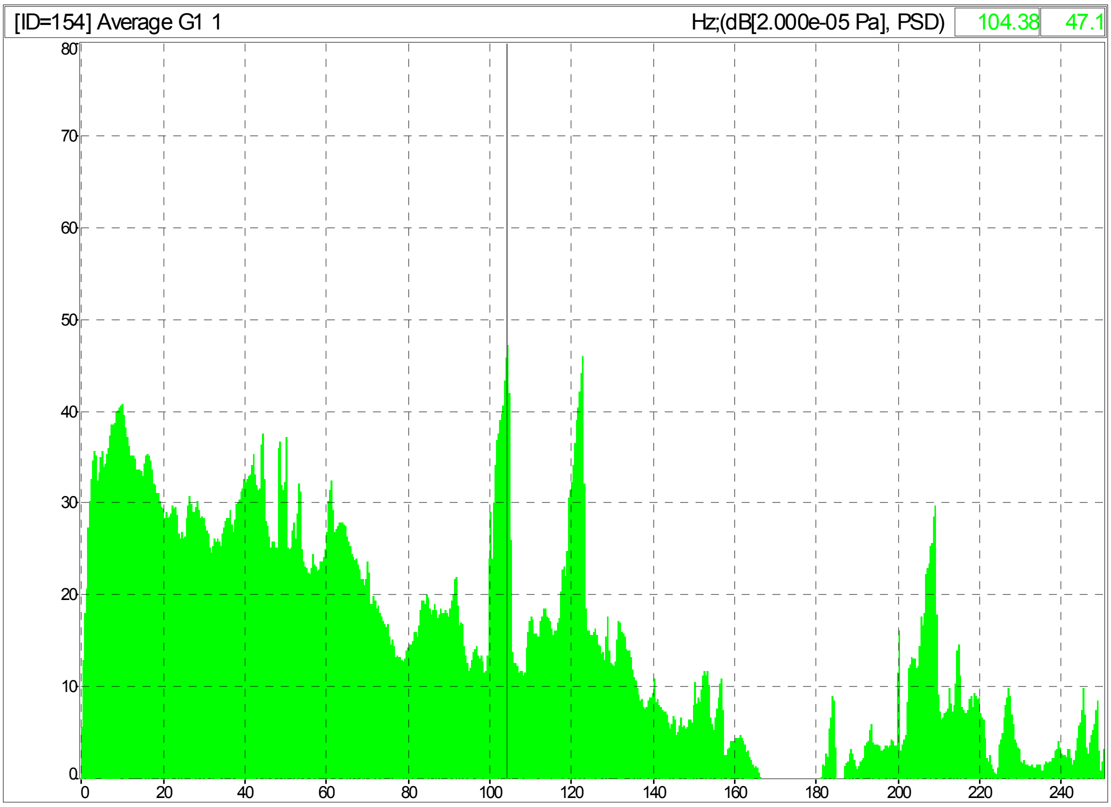


Figure 87: FFT of 9m30s audio record starting 09h20m from measurement Case19_040421_090000.cmg

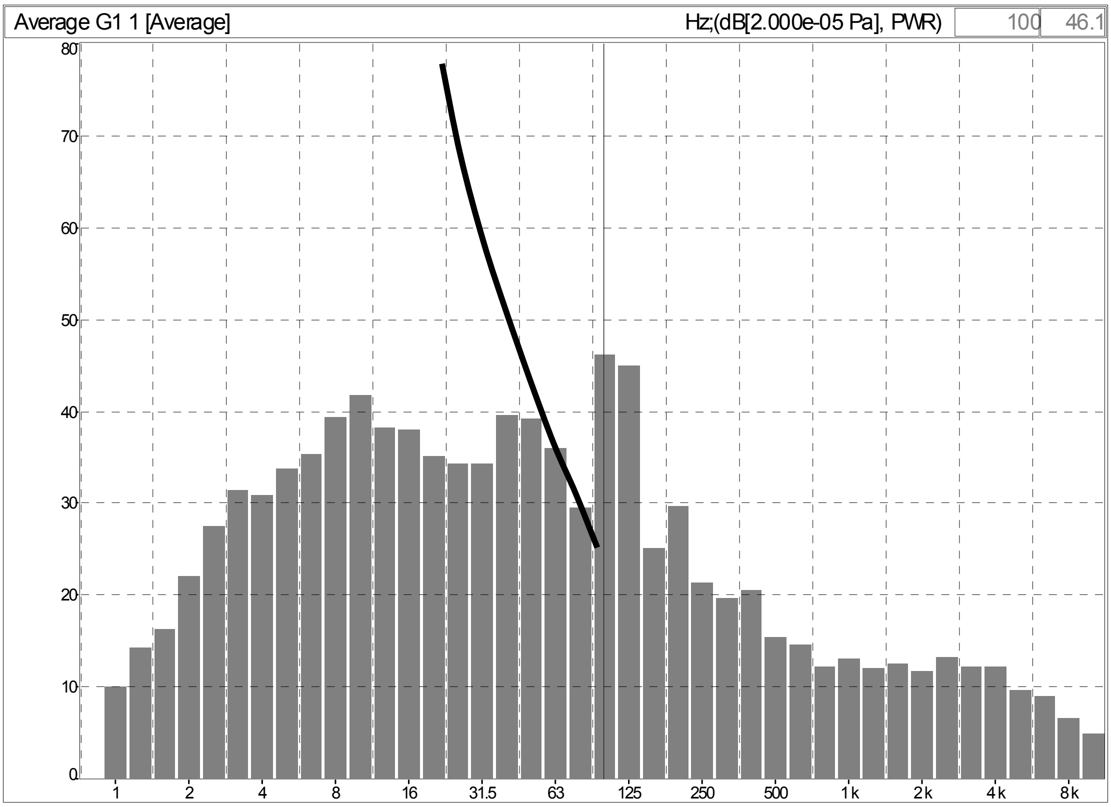


Figure 88: Mean 1/3 octave band spectrum 9m30s starting 09h20m from measurement Case19_040421_090000.cmg

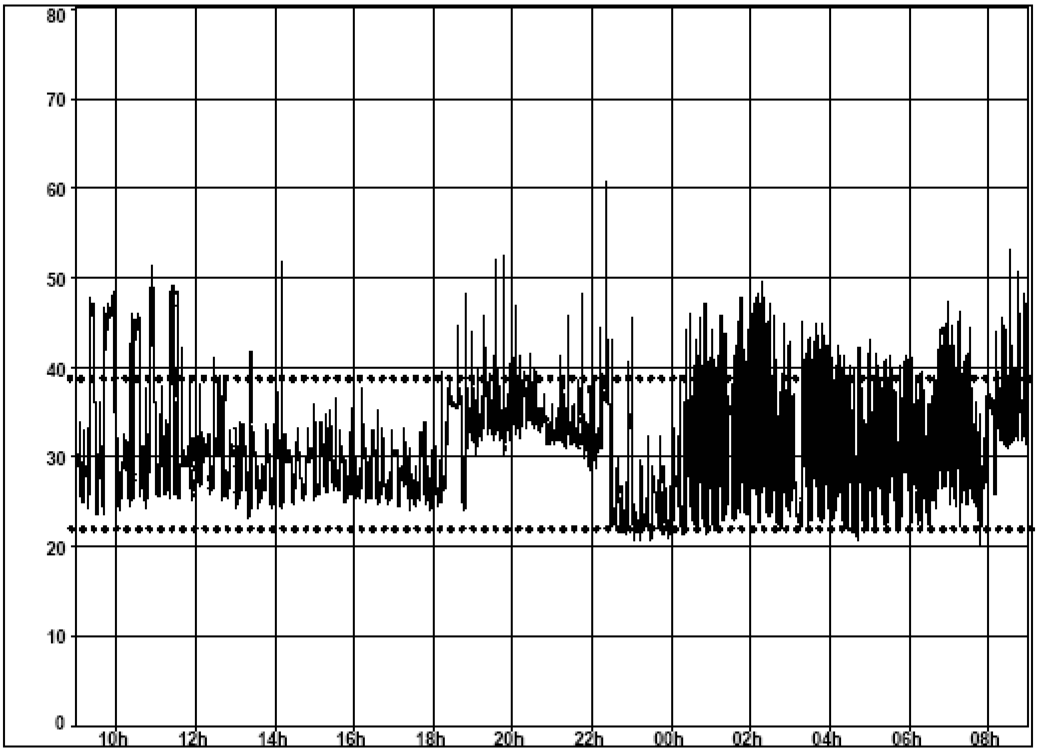


Figure 89: Time history showing 100Hz 1/3 octave spectrum band from measurement Case19_040421_090000.cmg together with lower Dutch (audibility) 22dB and Danish 39.1dB limits

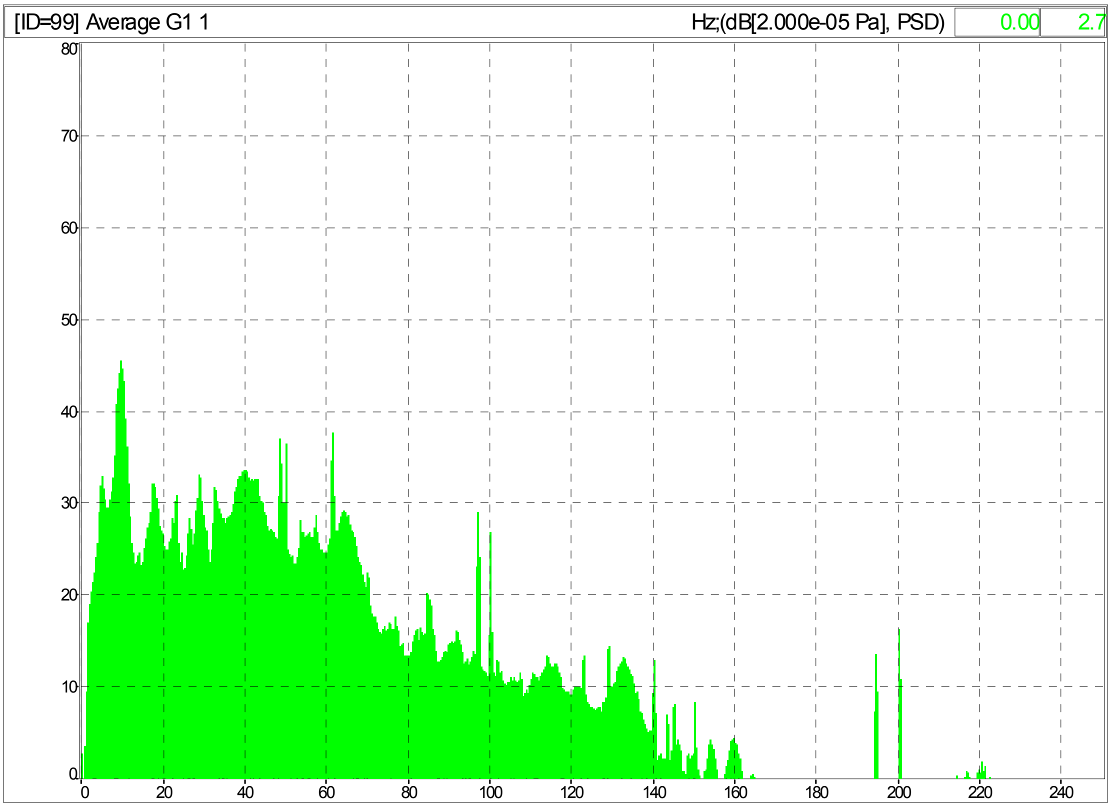


Figure 90: FFT of 9m30s audio record starting 12h20m from measurement Case19_040422_090000.cmg

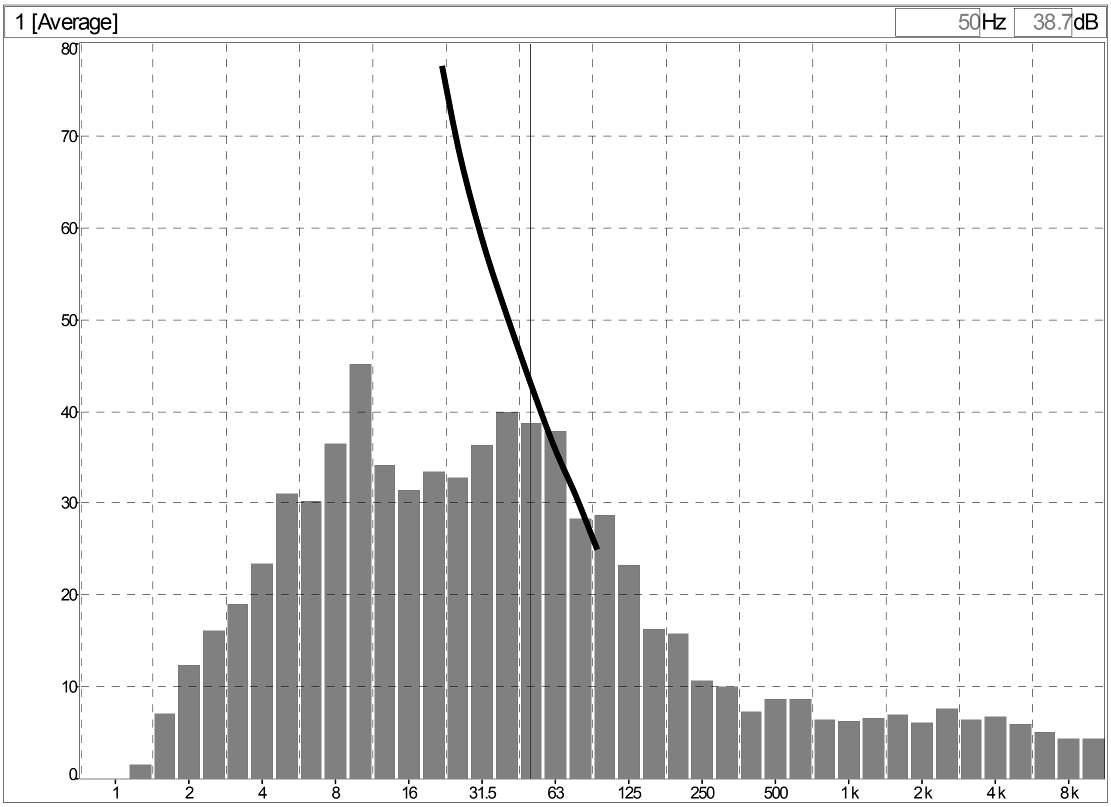


Figure 91: Mean 1/3 octave band spectrum 9m30s starting 12h20m from measurement Case19_040422_090000.cmg

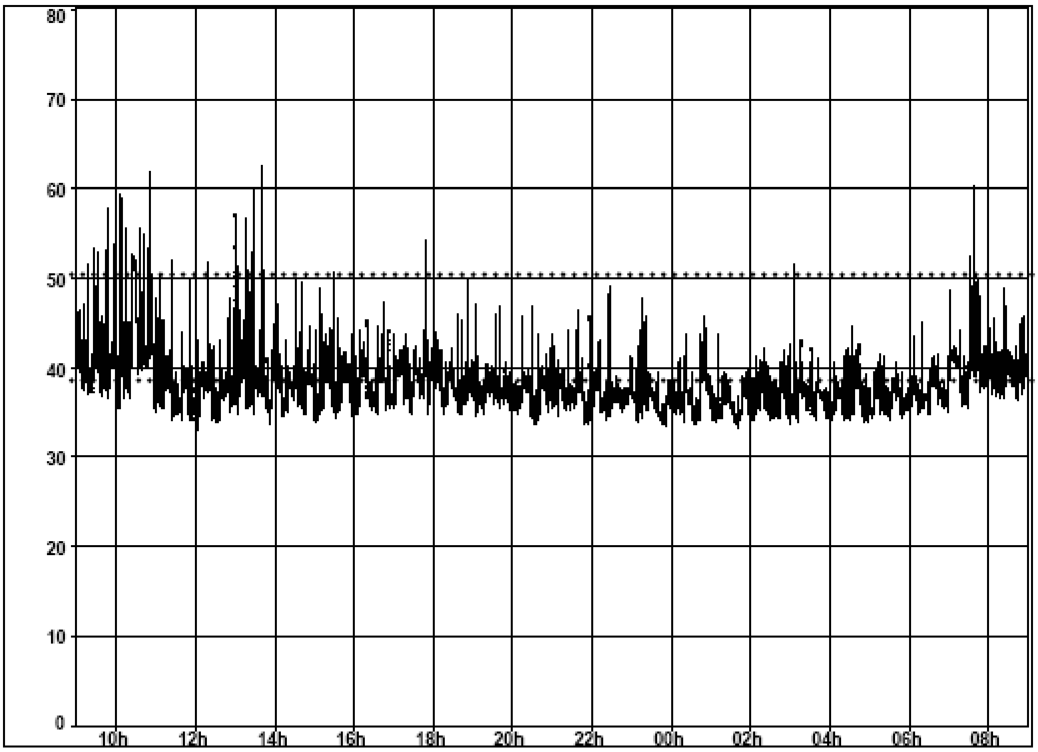


Figure 92: Time history showing 50Hz 1/3 octave spectrum band from measurement Case19_040422_090000.cmg together with lower Dutch (audibility) 39dB and Danish 50.2dB limits

Case 19a

Measurement filename	Times identified by respondent
Case19a_4420_21000.cmg	23h10
Case19a_4422_09000.cmg	12h20
Location	Urban
Source	Plant
Microphone position	Spare bedroom

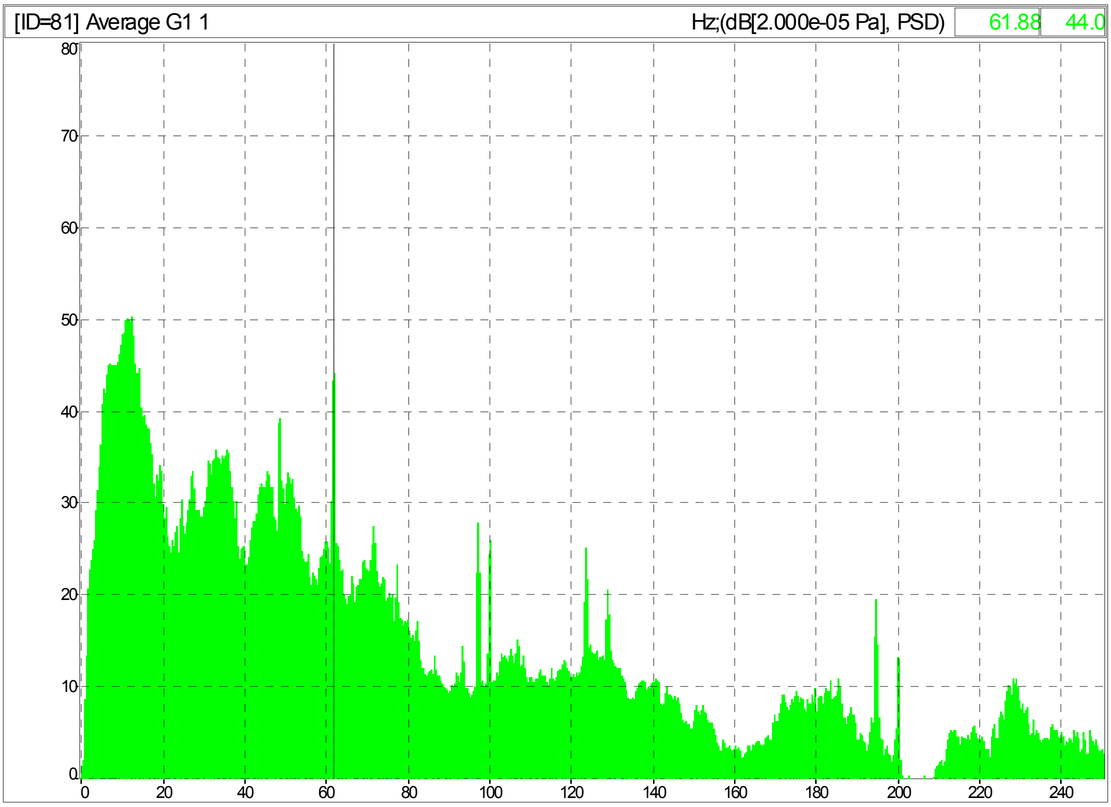


Figure 93: FFT of 9m30s audio record starting 23h10m from measurement Case19a_040420_210000.cmg

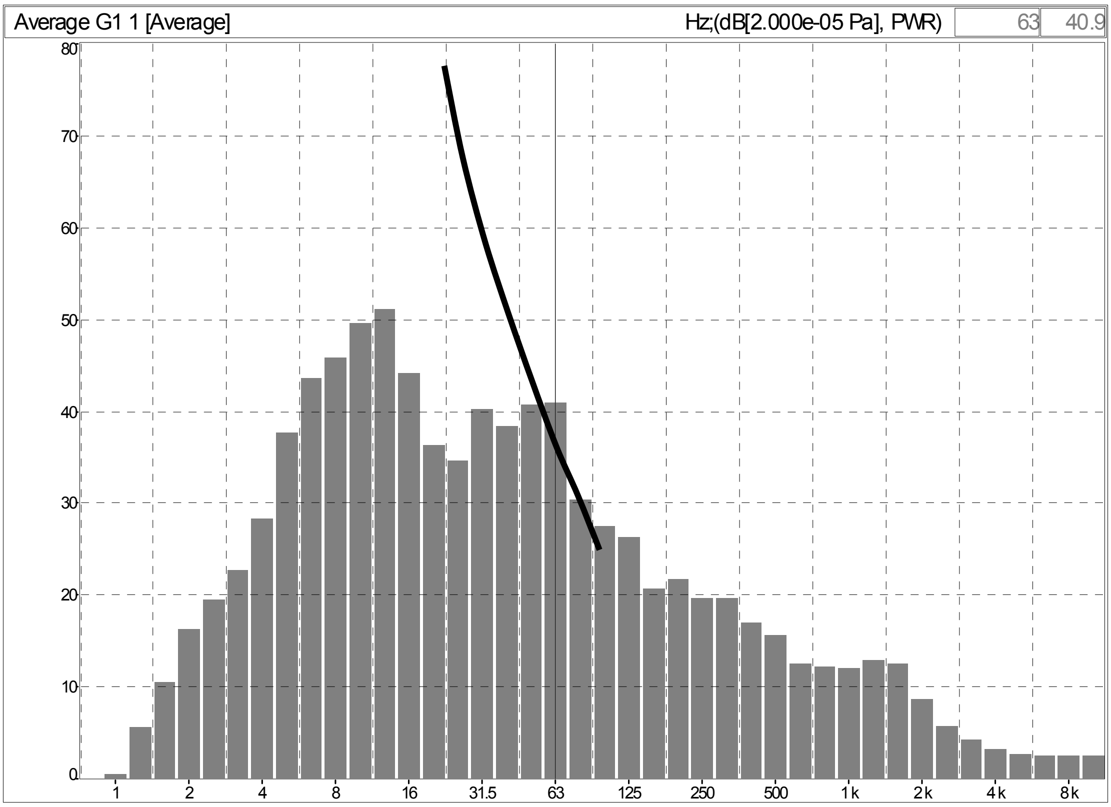


Figure 94: Mean 1/3 octave band spectrum 9m30s starting 23h10m from measurement Case19a_040420_210000.cmg

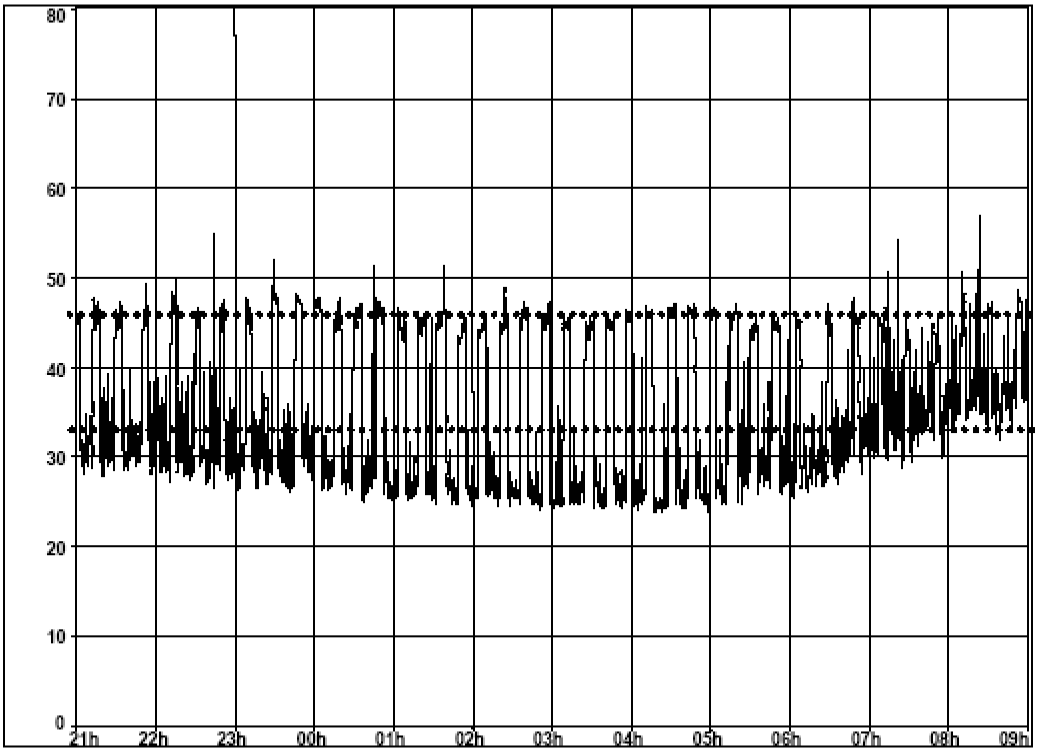


Figure 95: Time history showing 63Hz 1/3 octave spectrum band from measurement Case19a_040420_210000.cmg together with Dutch (audibility) 33dB and Danish 46.2dB limits

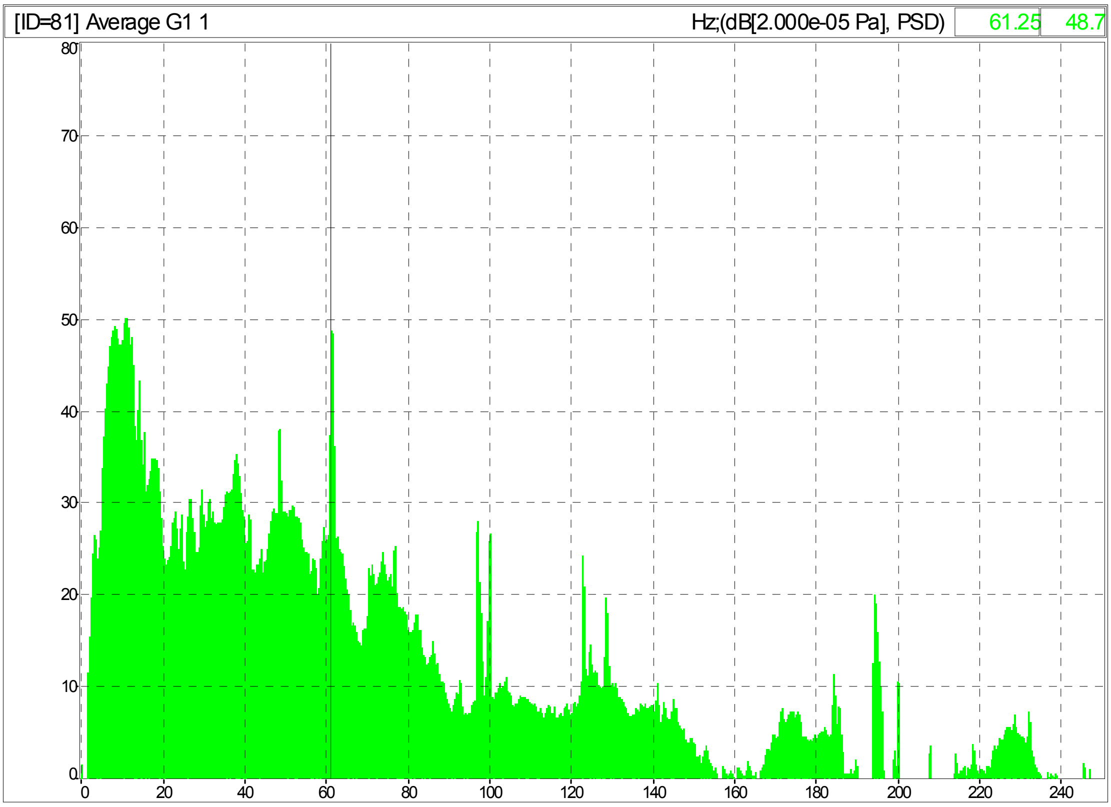


Figure 96: FFT of 9m30s audio record starting 07h00m from measurement Case19a_040424_090000.cmg

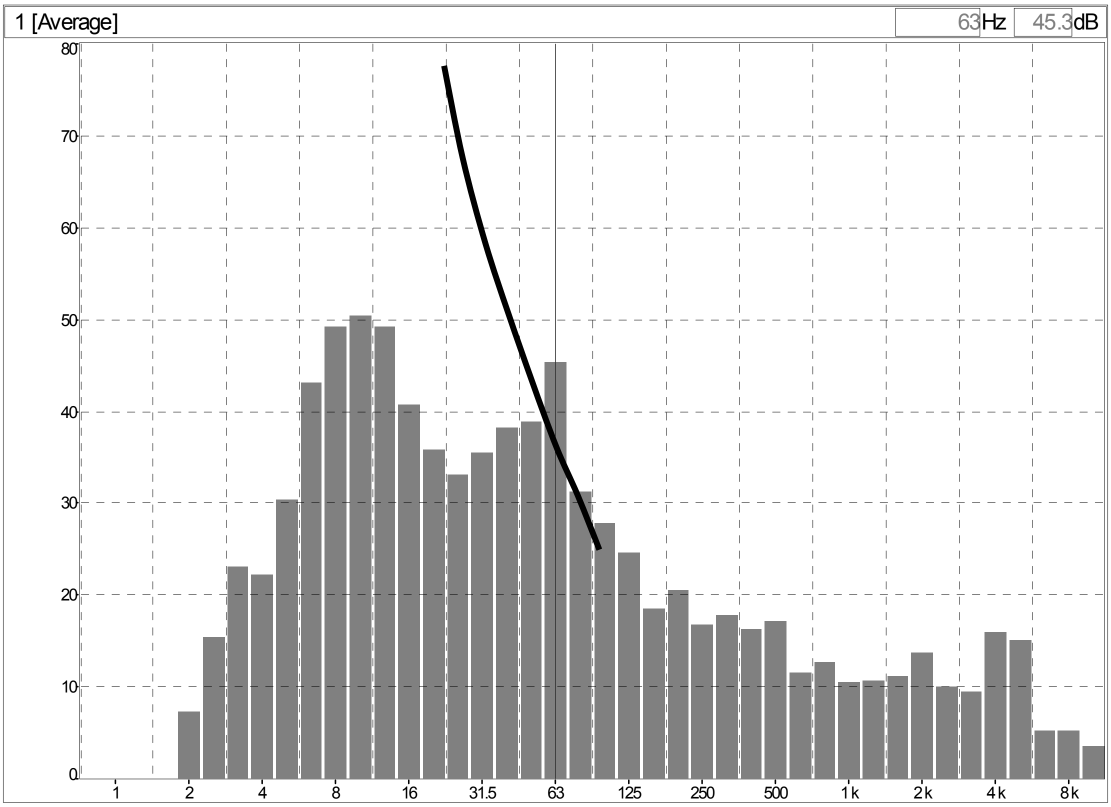


Figure 97: Mean 1/3 octave band spectrum 9m30s starting 07h00m from measurement Case19a_040424_090000.cmg

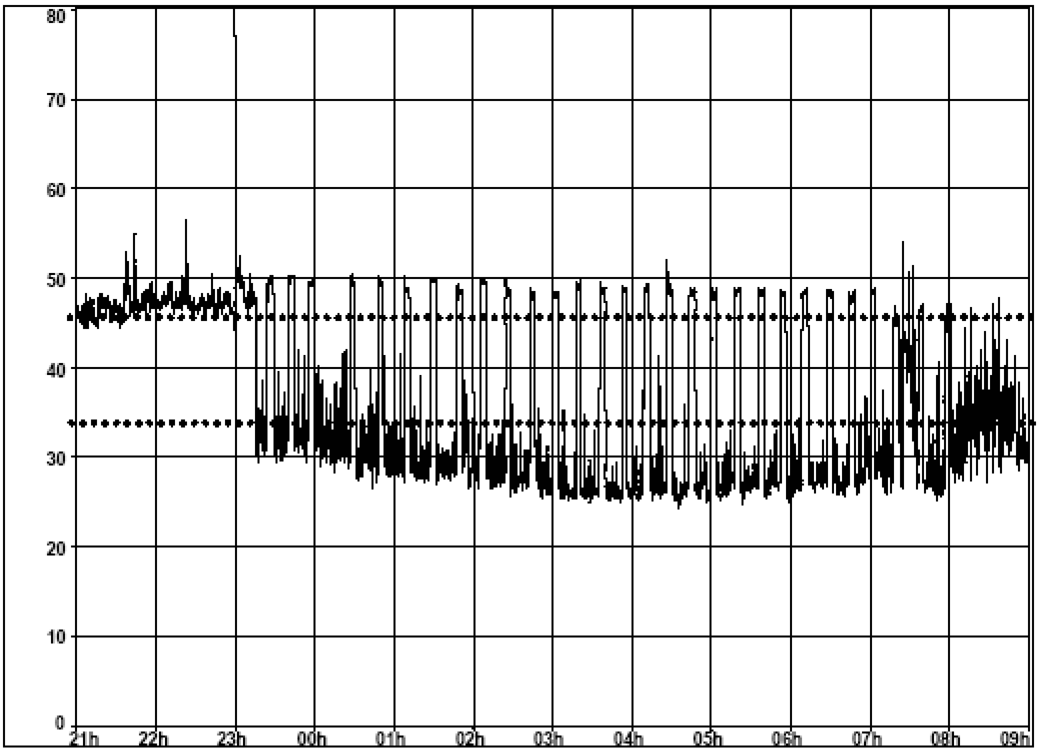


Figure 98: Time history showing 63Hz 1/3 octave spectrum band from measurement Case19a_040424_090000.cmg together with Dutch (audibility) 33dB and Danish 46.2dB limits

Control Case 1

Measurement filename	**Times selected for presentation below**
Control_case_1_4510_193000.cmg	03h00
Control_case_1_4510_193000.cmg	05h10
Location	Suburban
Sources	Motorway ~0.5km Central heating pump
Microphone position	Corner of bedroom

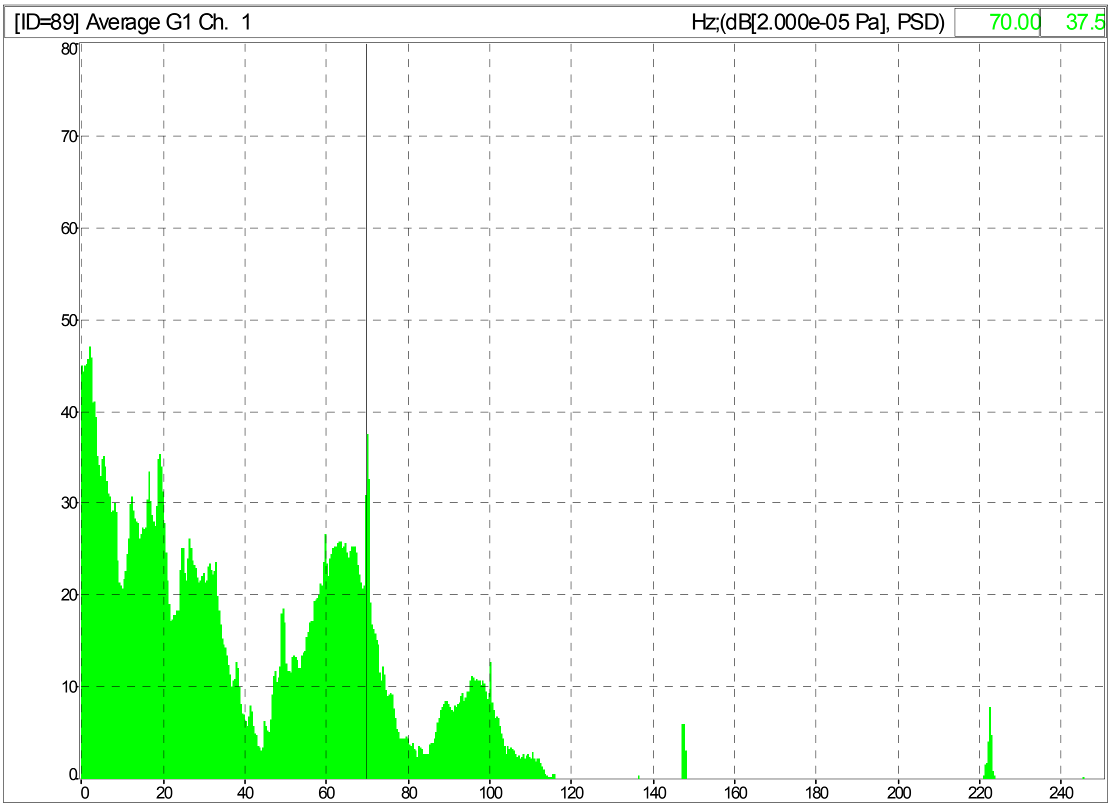


Figure 99: FFT of 9m30s audio record starting 03h00m from measurement Control_case_1_4510_193000.cmg. Background noise is mainly motorway at ~0.5km.

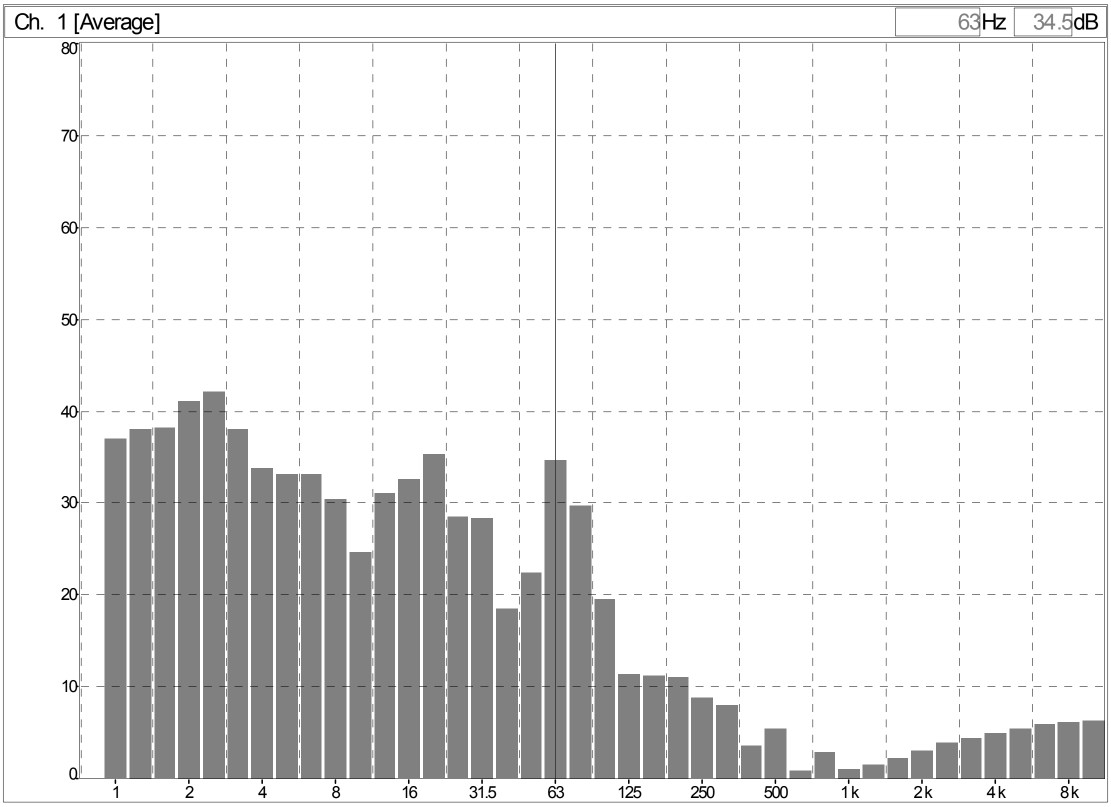


Figure 100: Mean 1/3 octave band spectrum 9m30s starting 03h00m from measurement Control_case_1_4510_193000.cmg

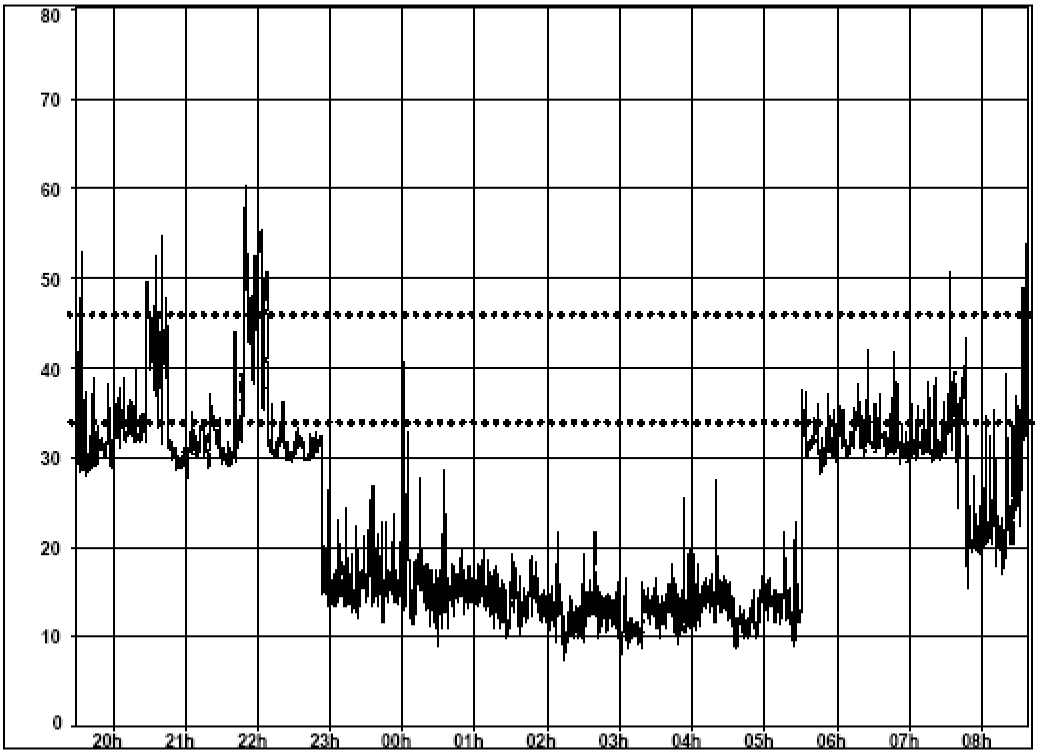


Figure 101: Time history showing 63Hz 1/3 octave spectrum band from measurement Control_case_1_4510_193000.cmg together with Dutch (audibility) 33dB and Danish 46.2dB limits. Noise sources are motorway and central heating.

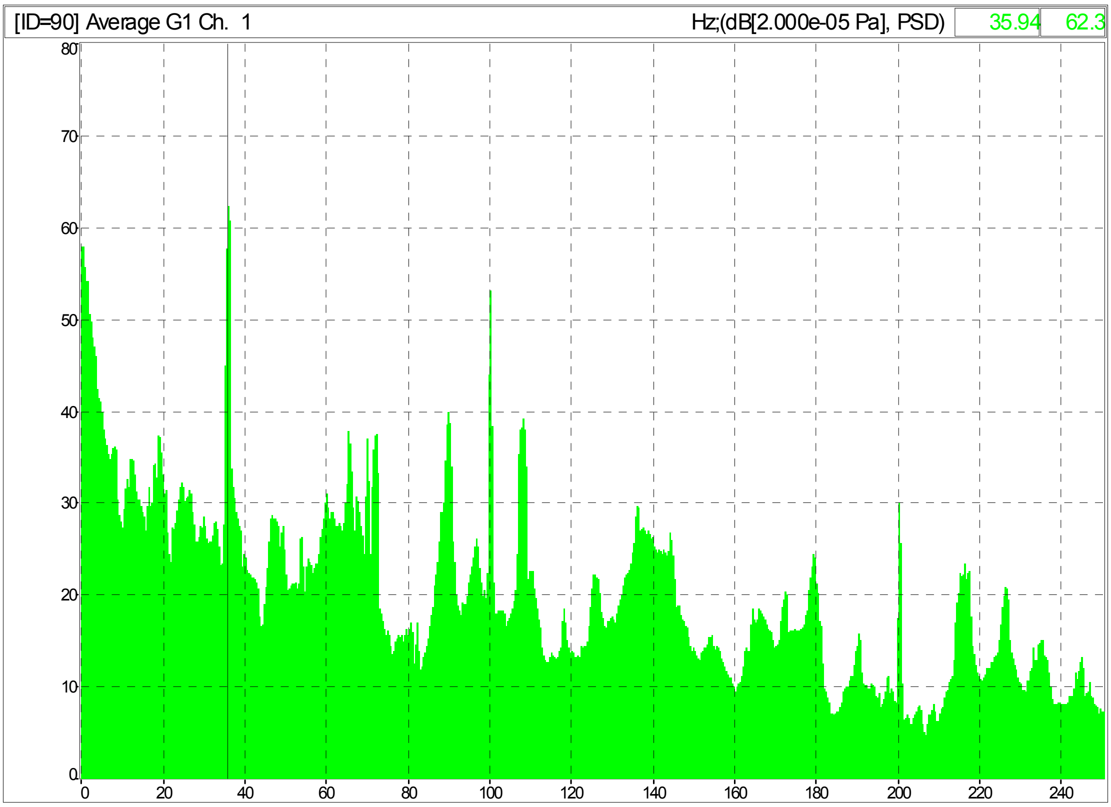


Figure 102: FFT of 9m30s of audio record starting 06h00m from measurement Control_case_1_4510_193000.cmg. Background noise is mainly central heating pump.

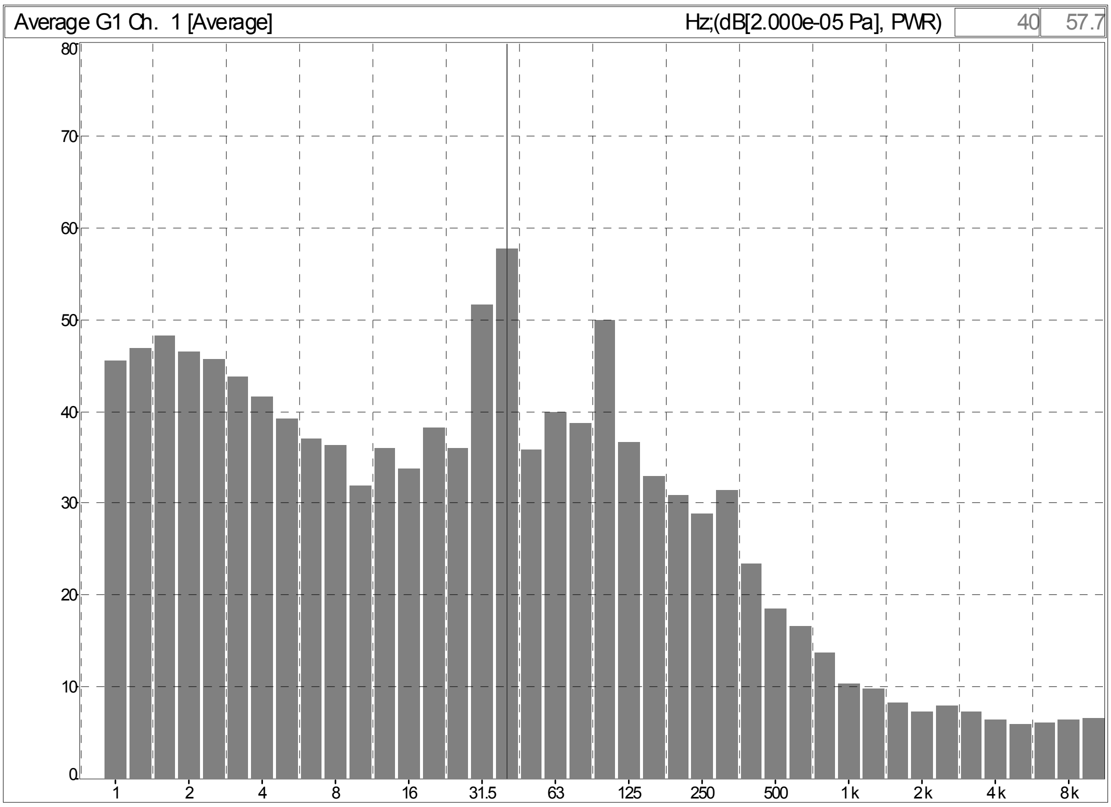


Figure 103: Mean 1/3 octave band spectrum starting 06h00m from measurement Control_case_1_4510_193000.cmg

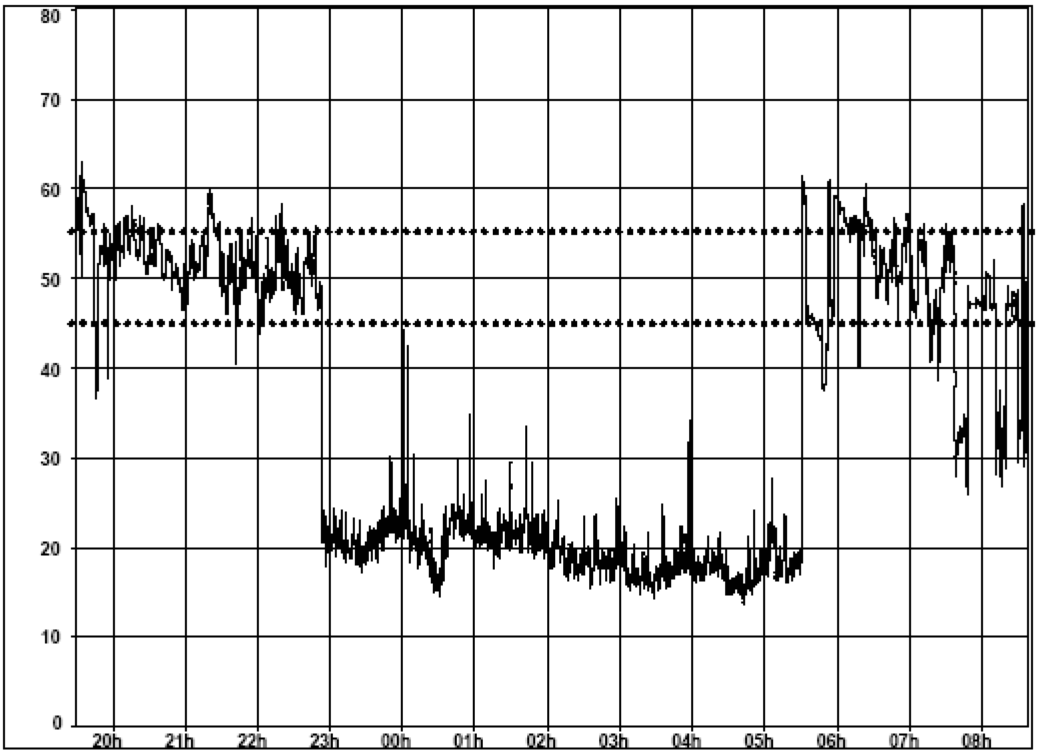


Figure 104: Time history showing 40Hz 1/3 octave spectrum band from measurement Control_case_1_4510_193000.cmg together with Polish (audibility) 44.6dB and Danish 54.6dB limits. Noise sources are motorway and central heating.

Control Case 3

Measurement filename	**Times selected for presentation below**
Control_case3_4511_171944.CMG.cmg	17h19
Location	Ground floor city centre flat
Sources	City centre traffic
Microphone position	Corner of living room

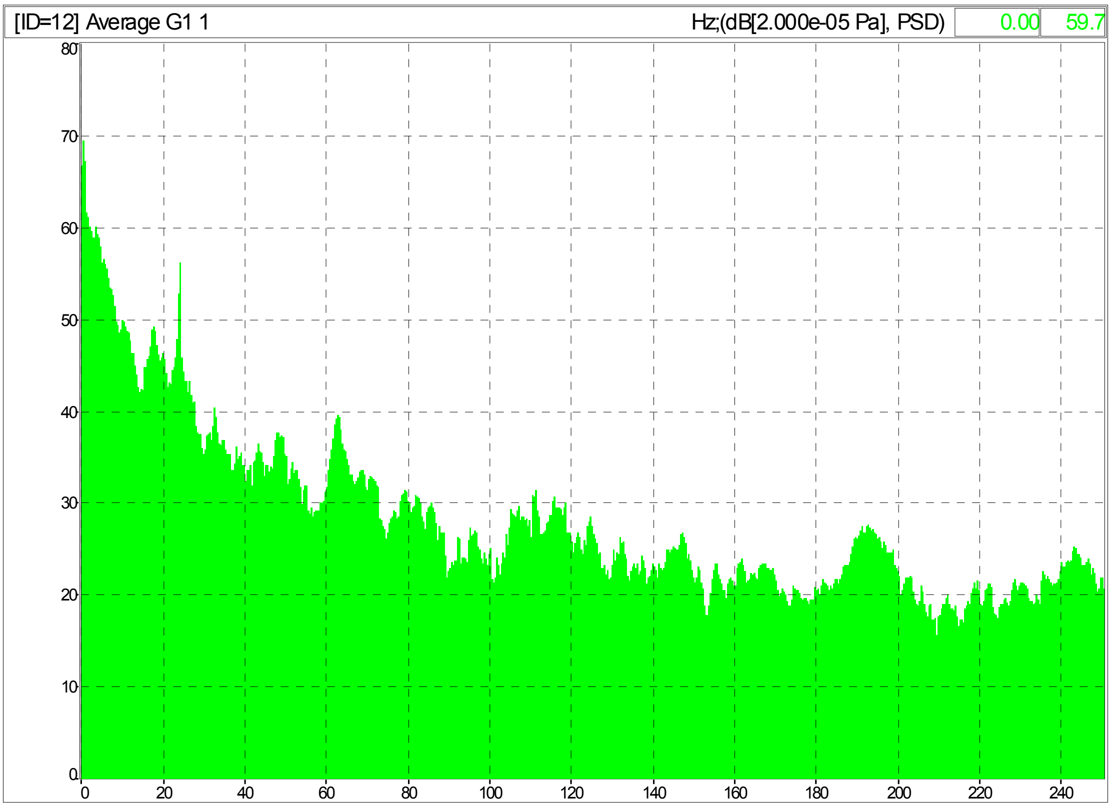


Figure 105: FFT of 9m30s audio record starting 17h19m from measurement Control_case3_4511_171944.CMG.cmg.

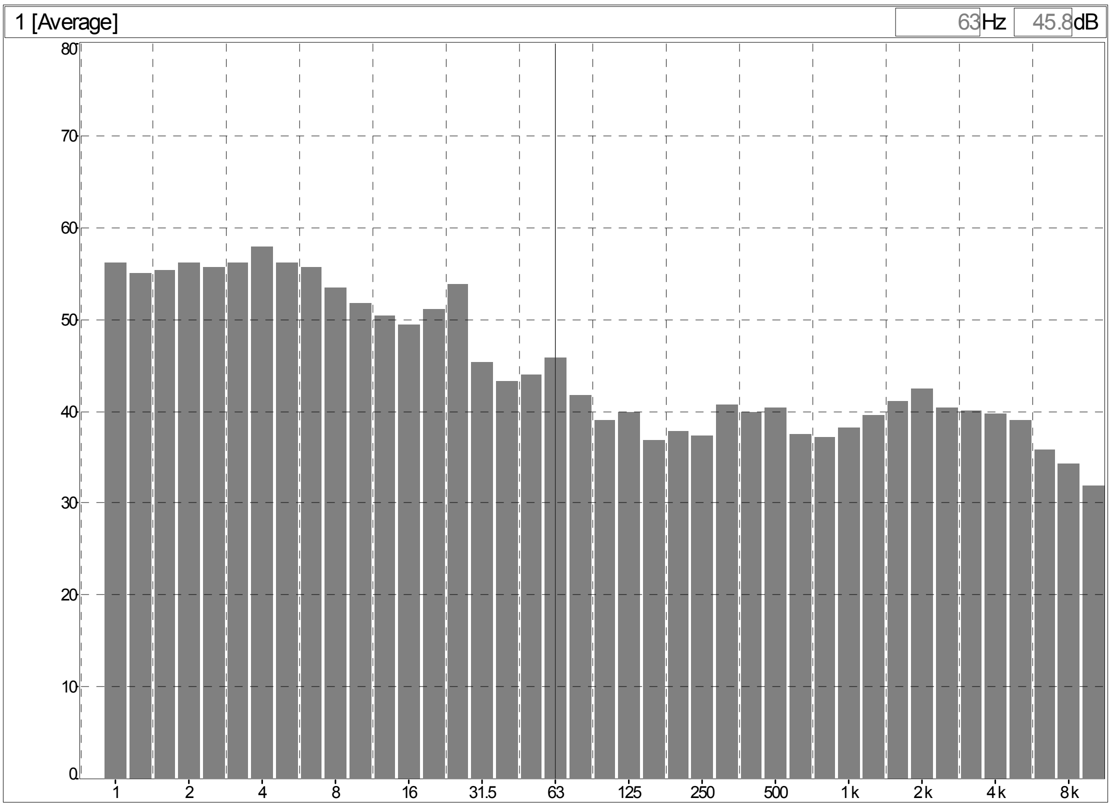


Figure 106: Mean 1/3 octave band spectrum 9m30s starting 17h19m from measurement Control_case3_4511_171944.CMG.cmg

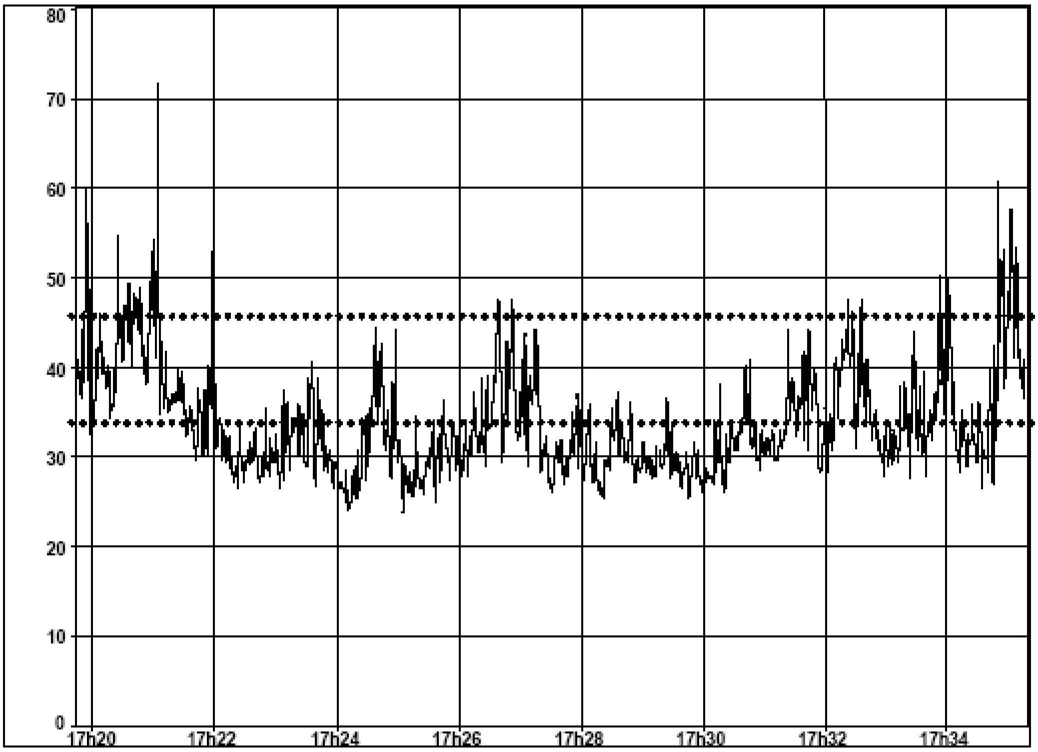


Figure 107: Time history showing 63Hz 1/3 octave spectrum band from measurement Control_case3_4511_171944.CMG.cmg together with Dutch (audibility) 33dB and Danish 46.2dB limits. Main noise source is city centre traffic.