# Human hearing at low frequencies
## with focus on noise complaints

Ph. D. thesis by
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# Preface

This thesis was submitted to the Faculty of Engineering and Science at Aalborg University, Denmark, in partial fulfilment of the Ph.D. study programme. The work reported here was done at the Acoustics, Department of Electronic Systems, Aalborg University between June 2003 and December 2007. The first edition of the thesis was submitted in May 2007, but at that time the extensive measurements for Manuscript B had to be remade and the test facility was not available at that time. Since then the measurements have been made and Manuscript B and C have been revised with the suggestions from the assessment committee. Although good suggestions for corrections of Manuscript A were given, this manuscript was not revised as it appears in the form that it was published in Noise and Health.

The thesis was defended the 25th of February 2008 and this final version of the thesis has been revised with corrections suggested from the assessment committee. Furthermore, Manuscript C was published in *Journal of Low-Frequency Noise, Vibration and Active Control* and this version have been included.

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I would like to thank all my colleagues for many fruitful discussions and for a good scientific and social atmosphere. I would especially like to thank my supervisors Henrik Møller, and Kerstin Persson Waye who have contributed extensively in the presented work, and who always have good questions and answers. I would like to thank our technicians Claus Vestergaard Skipper and Peter Dissing who did most of the dirty work to seal leakages in the ventilation system of the low-frequency test facility including repair and modification of equipment etc.

I would like to thank all the test subjects who participated in the investigation. Not only did they open their home for us for making sound recordings. They also spend a day of their spare time to travel to Aalborg and participate in the laboratory experiments.

Finally I would like to thank the assessment committee: Dorte Hammershøi, Geoff Leventhall and Yôiti Suzuki for their good and constructive suggestions for corrections of the thesis and for a pleasant atmosphere and clever questions at the defence.

# Table of contents

# Summary

The human hearing is generally not sensitive at low-frequencies and relatively high sound pressure levels are needed before the sound is audible. However, if the sound is audible then slight changes in the level gives relative large changes in the perception of the sound which is reflected in the compression of the equal-loudness-level contours at low-frequencies. Combined with individual differences in the hearing function with possible extraordinary low-frequency hearing this could explain cases where only one person in the household complain about a low-frequency sound which is not audible to the rest of the household. However, there are cases where no apparent sound source is found and noise measurements are not able to show any sound that could be causing annoying. This raises the fundamental question if it is a physical sound that causes the annoyance. To answer this question a selection of twenty-one cases of low-frequency noise complaints were investigated with sound recordings in the home and laboratory experiments in a new low-frequency test facility which allows for great control of the sound exposure with low background noise and low distortion. The facility uses digital signal processing in order to create a homogeneous sound field for the entire low-frequency region. The low-frequency hearing threshold and an equal-loudness contour were measured for each complainant. The sound recordings were played back to the complainant in blind tests in order to reveal if the physical sound in the home is audible to the complainant. In cases of audible sound recognition tests provided information whether the sound was similar to the annoying sound. The audible sounds were filtered into four different frequency ranges which were presented to the complainant in another series of blind tests and recognition tests in order to find the audible and annoying frequency components. Finally a matching experiment was used to approximate the frequency and level of the annoying sound.

No cases of extraordinary hearing were found among the complainants. The results shows that in seven cases the complainant is annoyed by a physical sound in the home, while in six cases low-frequency tinnitus is responsible. In the remaining eight cases the complainants could hear the recorded sound but it is not clear whether it is physical sound or low-frequency tinnitus that is responsible for the annoyance. In none of the cases is infrasound responsible for the annoyance. It is not audible even at 10 dB above the recorded level. Comparisons between results obtained by the Danish, Swedish and a three-dimensional corner measurement procedure show that especially the Danish method gives much variation and both the Swedish and the Danish method gives lower values than the three-dimensional corner method. For the seven cases clear cases with annoyance from a physical sound only three of the cases had levels exceeding the Danish limits for low-frequency noise even if the three-dimensional corner method is used. This shows that further research is needed on finding acceptable limits for low-frequency noise.

# Resumé (summary in Danish)

Mennesket hørelse er generelt ikke følsom ved lave frekvenser, og der skal være relativt høje lydtryk før lyden er hørbar. Hvis lyden er hørbar, så giver små ændringer i niveau dog relativt store ændringer i opfattelsen af lyden, hvilket er afspejlet i kompressionen af hørestyrker kurverne ved lave frekvenser. Kombineret med individuelle forskellige i hørelsen muligvis med særlig følsom hørelse ved lave frekvenser kan dette for klare tilfælde, hvor kun én person i hjemmet klager over lavfrekvent støj, som ikke er hørbar for andre i hjemmet. Der er dog tilfælde, hvor ingen umiddelbar lydkilde er fundet, og støjmålinger kan som regel ikke vise nogen lyd, som kan være generende.. Dette frembringer det fundamentale spørgsmål om det er en fysisk lyd, som er skyld i generne. For at besvare dette spørgsmål blev 21 tilfælde at klager over lavfrekvent støj undersøgt ved hjælp af. lydoptagelser i hjemmene og laboratorieundersøgelser i en ny lavfrekvens testfacilitet, som tillader god kontrol over lydeksponeringen med lav baggrundsstøj og lav forvrængning. Faciliteten bruger digital signalprocessering til at generere et homogent lydfelt for hele det lavfrekvente område. Den lavfrekvente høretærskel og en hørestyrke kurve blev målt for hver klager. Lydoptagelserne blev afspillet for klageren under blindtests for at undersøge, om klageren kan høre den fysiske lyd i hjemmet. I de tilfælde, hvor der var hørbar lyd gav genkendelses tests svar på om lyden mindede om den generende lyd. De hørbare lyde blev filtreret i fire forskellige frekvensområder, som blev afspillet for klageren i en ny række blindtests og genkendelsestests for at finde de hørbare og generende frekvens komponenter. Endelig blev et match eksperiment brug til at indkredse frekvens og lydtryk for den generende lyd.

Ingen tilfælde af særlig hørelse blev fundet blandt klagerne. Resultaterne viser, at i syv tilfælde er klageren generet af en fysisk lyd i hjemmet, mens det i seks tilfælde er lavfrekvens tinnitus. I de resterende otte tilfælde kunne klagerne høre lydoptagelserne, men det er ikke klart om det er fysisk lyd eller lavfrekvens tinnitus, som giver generne. I ingen af tilfældene er infralyd skyld i generne. Den er ikke engang hørbar 10 dB over det naturlige niveau. Sammenligninger mellem resultater opnået med den danske, svenske og en tredimensionel hjørne målemetode viser, at især den danske metode giver stor variation og både den svenske og danske metode giver lavere værdier end den tredimensionelle hjørnemetode. I de syv klare tilfælde af gener fra fysisk lyd er der kun overskridelse af de danske grænser for tre, selv hvis den tredimensionelle hjørnemetode bliver anvendt. Dette viser, at yderligere forskning er nødvendig for at finde acceptable grænser for lavfrekvent støj.

# Introduction and overview of the thesis

### 1. INTRODUCTION

The human hearing at low-frequencies (<200 Hz) is a research area, where the knowledge is still quite limited. The work presented in this thesis is an attempt to broaden the knowledge especially by investigating cases, where people are annoyed by low-frequency noise in their home, and often no apparent noise source can be found. The fundamental question is if these people are annoyed by a physical sound or not?

The thesis consists of three manuscripts:
**[Manuscript A]**[1]**:** Henrik Møller and Christian S. Pedersen, "Hearing at Low and Infrasonic Frequencies", *Noise & Health*, 2004, **6** (23), 37-57
**[Manuscript B]:** Christian S. Pedersen and Henrik Møller, "A new low-frequency test facility", to be submitted to Journal of Low Frequency Noise, Vibration and Active Control
**[Manuscript C]**[2]**:** Christian S. Pedersen, Henrik Møller and Kerstin Persson Waye, "A detailed study of low-frequency noise complaints", *Journal of Low Frequency Noise, Vibration and Active Control*, 2008, **27** (1), 1-33

In Manuscript A the human hearing at low and infrasonic frequencies is reviewed. In Manuscript B, the design and implementation of a new low-frequency test facility is described. This test facility allows great control of the sound field which is essential for making the psychoacoustic experiments described Manuscript C, where twenty-one cases of low-frequency complaints are investigated.

### 2. LOW-FREQUENCY NOISE PROBLEMS

Many cases of noise annoyance deal with noise that has a significant content of low frequencies. The complainant typically describes the noise as "rumbling". Among the sources are compressors, ventilation systems, and slow-running or idling engines. The cases are often solved by identifying the noise source and attenuating the sound emission.

However, there seems to be a group of cases, where persons claim to be annoyed by rumbling noise, but where they are not helped in a way that they find satisfactory. This often leads to repeated complaints, anger at authorities, feeling of helplessness, and reports in the daily press. To a certain extent, these cases have some common characteristics. There is often no obvious noise source, and often only a single or few persons are annoyed. Many of the cases are in areas that are generally quiet, and, if measurements are made, they often show low levels. This raises the fundamental question if it is a physical sound that is the cause of the annoyance.

One explanation could be that the annoyed persons suffer from an internal sound – a tinnitus with low frequency character – which could be called *low-frequency tinnitus* (see e.g. [1]) If the annoyance is caused by a real, physical sound, an explanation could be an unusually low hearing threshold of the annoyed person. Also the individual growth of loudness above threshold and/or the individual sensitivity to noise may play a role.

In the following the human hearing at low-frequencies is reviewed with special focus on individual differences that might explain these cases.

[1] Although good suggestions for changes in this manuscript was provided by the assessment committe, no changes has been made as the manuscript appears as it was published in "Noise and Health".
[2] The title have been changed from: "A study of twenty-one cases of low-frequency noise complaints".

### 3. THE HUMAN HEARING AT LOW FREQUENCIES

The human hearing is generally not sensitive at low frequencies and as the frequency becomes lower, the hearing threshold becomes gradually higher as shown in the normal hearing threshold [2]. However, if a low frequency sound is audible then only slight changes in the level results in relatively large changes in the perceived sound which is reflected in the compression of the normal equal-loudness-level contours [3], [4] (unfortunately no references could be made to [4] in Manuscript A as it was published around the same time) at low frequencies.

The hearing threshold and equal-loudness-level contours are standardized down to 20 Hz and earlier it was believed that humans could not hear frequencies below 20 Hz - hence the term *infrasound* was introduced. Today we know that infrasound is audible at sufficient high levels and at even higher levels it can be felt by other parts of the body [5]. Békésy [6] was one of the first workers to attempt to establish the hearing threshold for these low frequencies, and since then a number of workers have been experimenting in this frequency region. A second order regression of the most reliable data (reported in [7] with additional data from [8], [9] and [10]) is shown in Figure 1. Unfortunately there are quite high deviations between data from different studies which might be explained by the significant problems that are associated with creating sufficient high level low-frequency sound without audible distortion in a controlled sound field (see section 4).

If one person is annoyed by a sound that other persons cannot hear the simple explanation could be that this person has a more sensitive hearing. Data from threshold determination experiments with "normal" hearing persons show a standard deviation between subjects in the order of 5 dB regardless of frequency. Assuming that the hearing is normally distributed then approx. 2% of the population can be expected to have a hearing threshold 10 dB below the standard. Some evidence of extraordinary hearing thresholds do exist in the literature (e.g.[11], [12] and Lydolf unpublished (1997)) as shown in Figure 1.

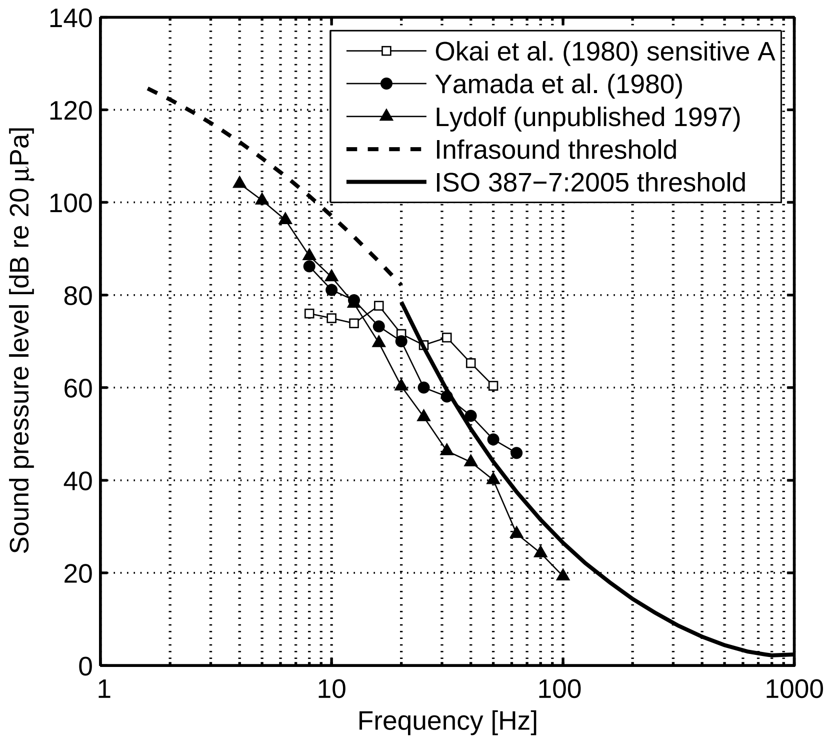


**Figure 1: Examples of threshold data from three especially sensitive persons plotted with the normal hearing threshold and an infrasound threshold based on [7] with additional data from [8], [9] and [10].**

#### 4. PROBLEMS IN LOW-FREQUENCY PSYCHOACOUSTIC EXPERIMENTS

There are two major problems that need to be addressed when making low-frequency psychoacoustic experiment, namely:

1. Recording and playback of low-frequency sound are affected by the room.
2. Playback of high sound pressure levels at low frequencies often causes high distortion.

Problem 1 is caused by reflections from surfaces that interfere with the direct sound which causes frequency dependent peaks and dips in the sound pressure distribution inside a room.
In recording low-frequency sound indoor problem 1 can be dealt with by measuring in many positions in the room. But a more practical approach is to use three-dimensional corner positions as they usually contain the pressure maximum of standing wave patterns [13].

In playback of low-frequency sound problem 1 must be dealt with either by removing the reflections (anechoic room) or by using a small enclosure (pressure-field chamber) to take advantage of the reflections to amplify the sound, which helps with problem 2. An anechoic room is usually not anechoic below 50 Hz and problem 2 is a major concern. A pressure-field chamber on the other hand can only have a pressure field up to a certain frequency depending on the dimensions of the room, but here problem 2 is not as problematic.

In the following the solution that can take advantage of the pressure field at low frequencies and remove the influence of the room at higher frequencies is described.

#### 5. A NEW TEST FACILITY FOR PSYCHOACOUSTIC EXPERIMENTS AT LOW FREQUENCIES

The test facility consists of a rectangular room with a total of 40 loudspeakers distributed evenly on to opposing walls. If the same signal is sent to all the loudspeakers then pressure-field conditions with a homogeneous sound field can be obtained up to approx 30 Hz. However, by controlling the signal sent to each loudspeaker it is possible to use one loudspeaker wall to generate a plane wave that is actively absorbed when it reaches the other loudspeaker wall. The advantage of this approach is that reflections from the back wall are avoided, while reflections from sidewalls floor and ceiling are minimized as these surfaces are perpendicular to the plane wave propagation. This plane-wave playback gives a homogeneous sound field in a large part of the room for the entire frequency range 2-300 Hz (±1 dB). Examples of improvement of the sound field are shown in Figure 2.

The plane-wave playback is quite inefficient in terms of generating high sound pressure levels at low frequencies compared to the pressure-field conditions as only 20 loudspeakers are used to generate the sound and no advantage of pressure build up in the room is used (as it is in pressure-field playback). Therefore a third sound field is introduced, a hybrid field, where the lowest frequencies are played back in pressure-field conditions while the highest frequencies are played back using the plane-wave playback. This approach gives a homogeneous sound field in the same frequency range as the plane-wave playback alone, but it can create much higher sound pressure levels at frequencies below 20 Hz without significant distortion.

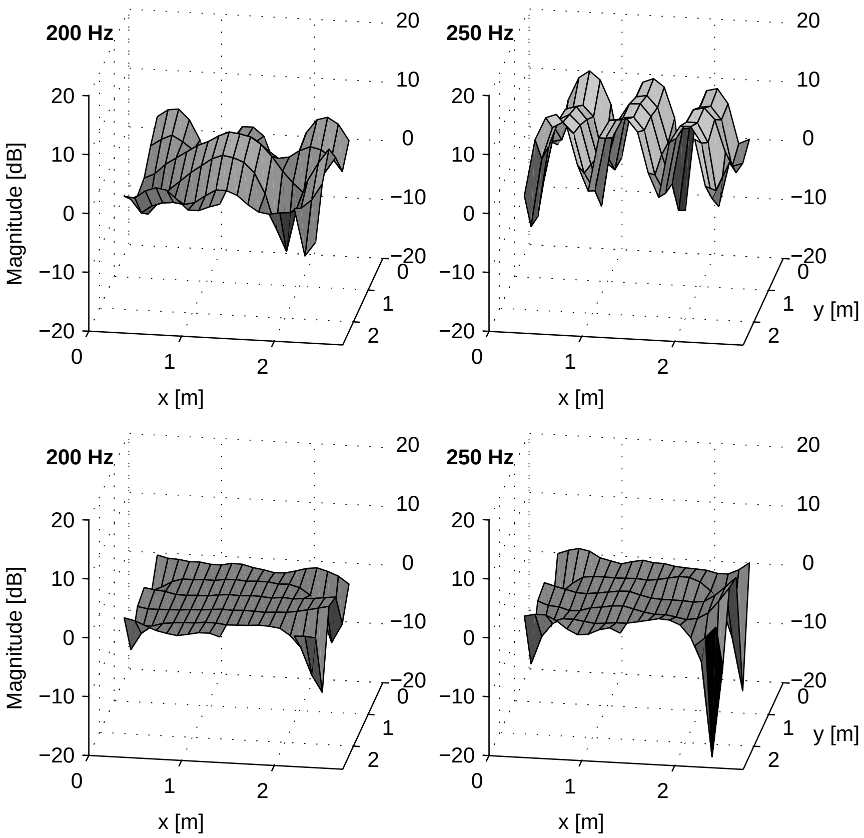


**Figure 2: Sound pressure distribution in the room for pressure-field playback (top) and plane-wave playback (bottom).**

### 6. INVESTIGATION OF CASES OF LOW-FREQUENCY NOISE COMPLAINTS

Thanks to the new low-frequency test facility it is possible to make laboratory experiments where complainants are exposed in a controlled sound field to recordings from their home. This is essential in order to answer the fundamental question if it is physical sound that causes the annoyance.

The twenty-one subjects in this study were chosen from an earlier questionnaire study [14] where 203 low-frequency noise complainants participated. Recordings in 20 different microphone positions (taking the nature of standing waves into account) were made in the home of each subject when they reported that the annoying sound was present. From these recordings stimuli were found that are representative for the highest levels found for the dominating frequency components. Each subject was examined by an otolaryngologist before participating in the laboratory tests where the low-frequency hearing threshold and an equal-loudness contour were measured. In a blind test it was confirmed if the subject could hear the recorded sound and a recognition test revealed if the recorded sound was similar to the annoying sound. Audible sounds were filtered for new blind tests and recognition tests, in order to establish what frequency ranges are audible and similar to the annoying sound. Finally, the frequency and level of annoying sound were approximated in a matching experiment.

In general the complainants could be classified in three groups. One group who are annoyed by a real physical low-frequency sound. Another group who suffer from a tinnitus perceived as a low-frequency sound and a third group who could hear the sound recorded in the home, but could not recognize it as being the annoying sound. For this group a more interactive procedure might explain these cases as well. The individual results for each group are summarized in Figure 3, where the first seven belong to the physical sound group (subject B, E, H, I, P, Q and R), the next six belong to the tinnitus group (subject A, C, J, T, U and D) and the remaining eight belong to the uncertain group (Subject F, G, K, L, M, N, O and S).

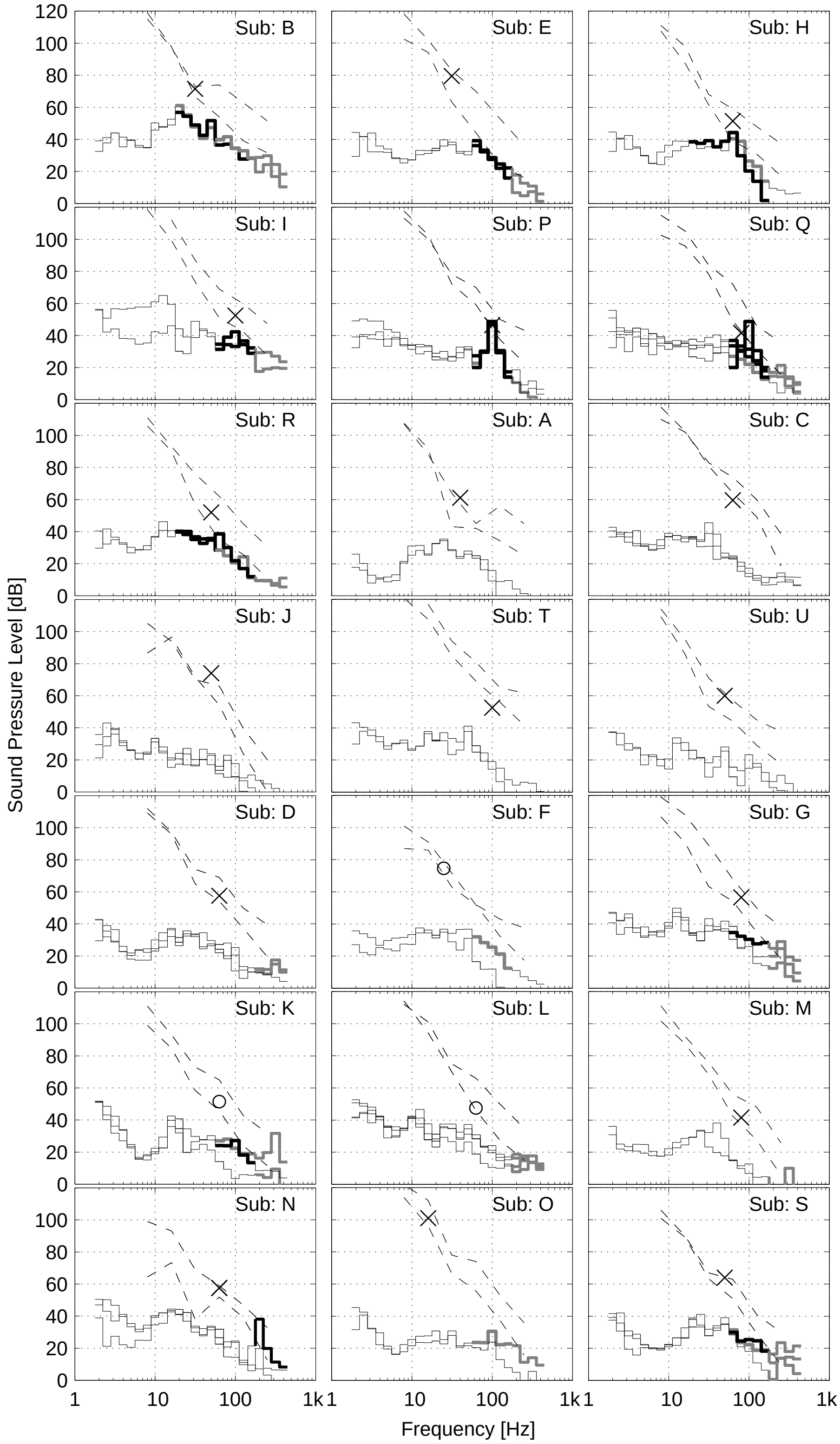


**Figure 3: Individual data for each subject: Third-octave analysis of the stimuli, where the thick lines in grey and black represent a frequency range audible to the subject at natural level (from blind tests with filtered sounds) and black is the most resembling frequency range (from recognition tests with filtered sounds). Dashed lines show individual hearing thresholds and equal-loudness contours. Results from the matching experiment are shown as x for tones and circles for third-octave noise.**

#### 7. CONCLUSIONS

The human hearing at low-frequencies has been reviewed and generally the human hearing is not sensitive at low frequencies. However, individual differences can potentially explain cases where some people are annoyed by a sound that is inaudible to others. There is even evidence of cases where the threshold is more than 20 dB below the normal hearing threshold.

A new low-frequency test facility has been designed and implemented in the laboratory of Aalborg University. This facility has a low background noise and is capable of generating high sound pressure levels with low distortion. Furthermore the test facility can generate a homogeneous sound field over a considerably frequency range (2-300 Hz), which allows for controlled reproduction of broad band low-frequency noise recordings.

This test facility has been used in laboratory experiments where the hearing function of twenty-one low-frequency noise complainants has been measured. Furthermore, recordings made at each complainant's home has been used in a blind test in order to investigate if the recorded sound is audible, while recognition tests revealed if the recorded sound is similar to the annoying sound.
The important conclusions from this study are:

1. None of the complainants have an extraordinary hearing threshold.
2. Infrasound is not found to be the cause of annoyance in any of the cases. It was not even audible at 10 dB above the recorded levels.
3. In seven cases the annoyance is caused by physical sound.
4. In six cases the annoyance is cause by low-frequency tinnitus.
5. In the remaining eight cases the complainants could hear the recorded sound, but it is not clear whether it is this sound that causes the annoyance.
6. The microphone position is very important in indoor low-frequency measurement. Large variation is seen within and between measurement methods and especially the Danish method gives much variation and lower levels compared to what is found in the room.
7. In the seven cases with a physical low-frequency noise problem only three had noise levels exceeding the Danish limits for low-frequency noise.

#### 8. FUTURE WORK

In the light of the finding that only three of seven cases of physical low-frequency had levels exceeding the Danish limits for low-frequency noise it would be appropriate to find better assessment criteria based on laboratory experiment. In this connection measurement of the critical bandwidth at low frequencies would provide valuable information. Furthermore, different physical parameters and their correlation with annoyance must be found. Finally, it would be very helpful if a simple procedure for distinguishing between case of real noise and tinnitus is developed.

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# Hearing at Low and Infrasonic Frequencies

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**The human perception of sound at frequencies below 200 Hz is reviewed. Knowledge about our perception of this frequency range is important, since much of the sound we are exposed to in our everyday environment contains significant energy in this range. Sound at 20-200 Hz is called low-frequency sound, while for sound below 20 Hz the term infrasound is used. The hearing becomes gradually less sensitive for decreasing frequency, but despite the general understanding that infrasound is inaudible, humans can perceive infrasound, if the level is sufficiently high. The ear is the primary organ for sensing infrasound, but at levels somewhat above the hearing threshold it is possible to feel vibrations in various parts of the body. The threshold of hearing is standardized for frequencies down to 20 Hz, but there is a reasonably good agreement between investigations below this frequency. It is not only the sensitivity but also the perceived character of a sound that changes with decreasing frequency. Pure tones become gradually less continuous, the tonal sensation ceases around 20 Hz, and below 10 Hz it is possible to perceive the single cycles of the sound. A sensation of pressure at the eardrums also occurs. The dynamic range of the auditory system decreases with decreasing frequency. This compression can be seen in the equal-loudness-level contours, and it implies that a slight increase in level can change the perceived loudness from barely audible to loud. Combined with the natural spread in thresholds, it may have the effect that a sound, which is inaudible to some people, may be loud to others. Some investigations give evidence of persons with an extraordinary sensitivity in the low and infrasonic frequency range, but further research is needed in order to confirm and explain this phenomenon.**

*Keywords: low-frequency sound, infrasound, hearing thresholds, equal-loudness-level contours, binaural advantage, sensitive persons*

## Introduction

It is traditionally said that the human hearing covers a certain frequency range, called the *audible range* or the *audio frequency range*. The lower limit of this range is usually given as 16 or 20 Hz, and the upper limit is typically said to be 16 or 20 kHz.

The upper limit is fairly sharp in the sense that the hearing threshold rises rather steeply above the upper limit - meaning that the hearing almost “stops” at this frequency. The lower limit is more smooth, and the hearing threshold follows a curve that gradually goes to higher levels for decreasing frequency. As a surprise to most people (even to many acousticians), the threshold curve continues below 20 and even 16 Hz, and - as it will be seen in the following sections - humans can perceive sound at least down to a few Hertz. This applies to all humans with a normal hearing organ, and not just to a few persons.

Since the threshold curve goes up for decreasing frequency, it reaches quite high sound pressure levels at the lowest frequencies. Even when rather high sound pressure levels are needed to cause a perception, there are many sources in our everyday environment that do produce audible sound in this frequency range. Engines, compressors, ventilation systems, traffic and musical instruments are examples of man-made sources, but also natural sources exist like thunder, ocean waves and earthquakes. Driving a car at highway-speed with an open window is a situation, where many people expose themselves to perceivable levels of 10-20 Hz sound.

The ear is most sensitive in the frequency range from 200-300 Hz to around 10 kHz, and this is the frequency range we mainly use in communication. As a natural consequence it is also the frequency range, where most hearing research has been made. However, it is important to have insight in the hearing function also outside this frequency range, in particular at frequencies below, since much of the sound that we are exposed to in our everyday environment contains significant energy in this range. The present article gives a review of studies of the hearing function below 200 Hz, focussing on the hearing threshold and the loudness function.

**Terminology**

Sound with frequencies below 20 Hz is called *infrasound*, infra being Latin and meaning below. Thus the term refers to the widespread understanding that these frequencies are below the range of (audible) "sound". As mentioned, this understanding is wrong, and the use of the term infrasound for these frequencies has resulted in many misunderstandings. Nevertheless, the term is widely used, and it will also be used in this article. For sound in the frequency range 20-200 Hz, the term *low-frequency sound* is used. Since there is no sharp change in hearing at 20 Hz, the dividing into infrasound and low-frequency sound should only be considered as practical and conventional.

**Sensation of sound at low and infrasonic frequencies**

Everyone knows from his everyday environment the feeling of hearing sound at low and infrasonic frequencies. The following are examples of typical low-frequency sound sources: ventilation systems, compressors, idling trucks and the neighbour's stereo. Infrasound at an audible level is usually found on the car deck of a ferry and when driving a car with an open window. However, infrasound is most often accompanied by sound at other frequencies, so the experience of listening to pure infrasound is not common.

The subjective quality of the sound varies with frequency. In the low-frequency range pure tones still result in a tonal sensation, and - like at higher frequencies - a sensation of pitch is connected to the sensation. If the frequency is gradually lowered from 20 Hz, the tonal sensation disappears, the sound becomes discontinuous in character and it changes into a sensation of pressure at the eardrums. At even lower frequencies it turns into a sensation of discontinuous, separate puffs, and it is possible to follow and count the single cycles of the tone. Some early descriptions of these phenomena were given by Brecher (1934) and by Wever and Bray (1936). However, the lower limit of tonality has been known much longer, e.g. it has influenced the building of musical instruments, where the largest organ pipes are tuned to a frequency around 17 Hz.

Yeowart et al. (1967) described pure tones above 20 Hz as smooth and tonal, at 5-15 Hz a rough sound with a popping effect was reported, and tones below 5 Hz were described as chugging and whooshing. Below 5 Hz a sensation like "motion of tympanic membrane itself" was reported. The perception of noise bands was investigated by Yeowart et al. (1969). For an octave band around 125 Hz the random noise was perceived as banded noise, while at 63 Hz the character changed into a sensation of a fluctuating tone. The octave bands around 32 Hz and 16 Hz were described as traffic rumble, at 16 Hz with a fluctuating flutter, while the band at 8 Hz was described as a rough peaky tone. For the octave-band noise around 4 Hz separate random peaks were perceived.

The early qualitative descriptions are well in line with later descriptions in the literature as well as with reports from numerous experimental subjects in the authors' laboratory and with the authors' experience from exposure of themselves.

It is mentioned by many authors and easily verified in a laboratory with suitable equipment that the loudness of low-frequency and infrasonic sound grows considerably faster above threshold than sound at higher frequencies. Yeowart et al. (1967) mentioned that at 4 Hz a 1 dB change in level was sufficient to cover the whole range from inaudible to definitely detectable. The faster growth of loudness is reflected in the equal-loudness-level contours, where the distance between the curves decreases with decreasing frequency (see separate section 'Studies of equal-loudness-level contours'). An implication of this compression is that if a low-frequency sound is just audible, then a relatively small increase in level will result in a much louder sound.

**The sensation mechanism**

It has been a matter of interest, how we sense the lowest frequencies, and the key question is, if we sense them with our ears and in the same way as we sense higher frequencies.

There is no doubt that the ear is the organ that is most sensitive to sound at these frequencies. This is seen from the fact that hearing thresholds are the same, whether the whole body or only the ears are exposed (see the section 'Do we sense with our ears'). It is more difficult to determine whether the sensory pathway belongs to the auditory system or not. Békésy (1936) noted that it is difficult to distinguish whether the sensation is of a pressure or tactile nature, or of an auditory nature. He argued, though, that touching two symmetrical places on for example the entrance to the external meatus results in two separate sensations, while binaural exposure to infrasound fuses into a single impression localized in the middle of the head. Therefore he concluded that it is in fact an auditory sensation. However, he also observed that at higher sound pressure levels the auditory sensation is accompanied by a "true" sensation of touch at each of the ears. If the level of the sound is increased even further, a sense of tickling or prickling is observed. That the sensation at low levels is auditory is further supported by the fact that perception thresholds for deaf people are much higher than for people with normal hearing (see section 'Non-auditory perception').

It seems fair to conclude that the sense of hearing is the primary sense for detecting sound at low and infrasonic frequencies. However, it has often been proposed that we do not sense infrasound directly, but that we simply hear higher harmonics produced by distortion in the middle and the inner ear (see e.g. Johnson (1980)). If this were true, it would then be reasonable to assume that the subjective quality of a 15-Hz tone would be comparable to that of a tone or a combination of tones at higher harmonics like 30 and 45 Hz. However, to the authors' knowledge such similarity has not been reported, and in an informal listening test with the authors and colleagues as listeners, such sounds were perceived as clearly different in timbre, pitch and general quality. Thus, the theory is not supported.

**Modulation of hearing**

One way in which the presence of infrasonic sound can be detected at levels around or possibly below the hearing threshold is by modulation of higher frequencies. The infrasound moves the eardrum and the middle ear bones, and the displacement may be so large that their mechanical properties and the transmission change. As a consequence, sounds at higher frequencies are amplitude-modulated with the infrasound. This effect is easily demonstrated in a suitable laboratory, and it emphasises the need of very quiet conditions, when perception of infrasound is studied.

**Speech modulation**

Another modulation effect is sometimes mentioned in connection with infrasound, namely modulation of speech. Whereas the effect mentioned in the previous paragraph relates to a person as a sound detector, this effect relates to a person's generation of sound. When a person speaks in the presence of infrasound, the pressure from the infrasound may create a small pulsating airflow in the throat. This flow adds to the natural flow from breathing and speaking, and it modulates the speech. The effect is only noticed at high levels of infrasound.

**Studies of hearing threshold**

The threshold is most likely the single characteristic of the hearing that is investigated most and best known. However, it is not trivial to produce a well-controlled exposure at low frequencies, and many original investigations have a bad coverage of this frequency region. The number of investigations in the infrasonic region is even more limited.

Thresholds are usually given in terms of the pressure of a free plane wave, in which the listener is exposed horizontally and from the front. The pressure is measured without the listener being present in the sound field. A threshold given this way is called the *minimum audible field*, or the MAF. Another possibility is to specify the threshold in terms of the actual pressure at the eardrum during exposure - in principle without specific requirements to the nature of the sound field. This is called the *minimum audible pressure*, or the MAP.

At high frequencies the presence or absence of a person has a substantial impact on the sound field, and there is a significant difference between the MAF and the MAP. Furthermore, the difference depends on the nature of the sound field (e.g. free or diffuse), direction to sound source(s) etc. At low frequencies, however, the listener's head and body have little or no impact on a free plane wave, and it is expected that MAP and MAF will have the same value.

Measurements of MAP may in principle be carried out in any sound field. However, they are usually done either in a pressure-field chamber that encloses the entire body of the listener, or with the sound created in a cavity that is coupled to the ear (or to both ears). If, in the latter case, the cavity is very small, e.g. like that of a supra-aural audiometric earphone, physiological activity around the ear seems to result in noise under the earphone that elevates the threshold, in particular at low frequencies (see e.g. Anderson and Whittle (1971)). Therefore MAP measurements with sound applied in very small volumes have not been included in the following.

Sivian and White (1933) gave a review of earlier studies of hearing thresholds. These investigations differ much in means of exposure and calibration as well as experimental method, and they are now mainly of historical interest. Nevertheless it is interesting to see how close the results of at least some of these studies are to threshold data obtained in more recent years. These early studies will not be further reported here.

Common to all studies mentioned in the following is that they have been made with sinusoidal tones, and that the duration of the tones has been so long that the temporal integration of the ear is expected not to have any impact on the result (usually a duration of 0.5-2 s or longer).

Most studies have been made in a free or an approximately free sound field (e.g. an anechoic room) using an electrodynamic transducer (usually a loudspeaker) as sound source. Data obtained under such conditions have been presented by Sivian and White (1933) (100 Hz-15 kHz, 14 subjects monaural, five subjects binaural), Fletcher and Munson (1933) (60 Hz-15 kHz, 11 subjects), Churcher et al. (1934) (100 Hz-6.4 kHz, 48 subjects), Churcher and King (1937) (54 Hz-6.4 kHz, 10 subjects), Robinson and Dadson (1956) (25 Hz-15 kHz, up to 120 subjects depending on frequency, lowest frequencies measured in a duct), Teranishi (1965) (63 Hz-10 kHz, 51 subjects), Anderson and Whittle (1971) (50-1000 Hz, ten subjects), Brinkmann (1973) (63 Hz-8 kHz, up to 58 subjects depending on frequency), Betke and Mellert (1989) (40 Hz-15 kHz, up to 44 subjects depending on frequency) (reported in more detail by Betke (1991)), Fastl et al. (1990) (100-1000 Hz, 12 subjects), Watanabe and Møller (1990a) (25-1000 Hz, 12 subjects), Takeshima et al. (1994) (31.5 Hz-20 kHz, below 1 kHz: 17-69 subjects depending on frequency) (partly reported on earlier occasions, e.g. by Suzuki et al. (1989)), Lydolf and Møller (1997) (50 Hz-8 kHz, 27 subjects), Poulsen and Han (2000) (125 Hz-16 kHz, 31 subjects) and Takeshima et al. (2001) (31.5 Hz-16 kHz, below 1 kHz: seven to eight subjects). Most likely the study by Bellmann et al. (1999) (40-160 Hz, 12 subjects) was also carried out in a free-field, although it was not specifically reported.

Especially at the lowest frequencies it is difficult to produce sufficiently high sound pressure levels in a free field, and the walls of even the best anechoic room become reflective. As a consequence no free-field data were reported below 25 Hz, and most investigations did not even go down as far as that.

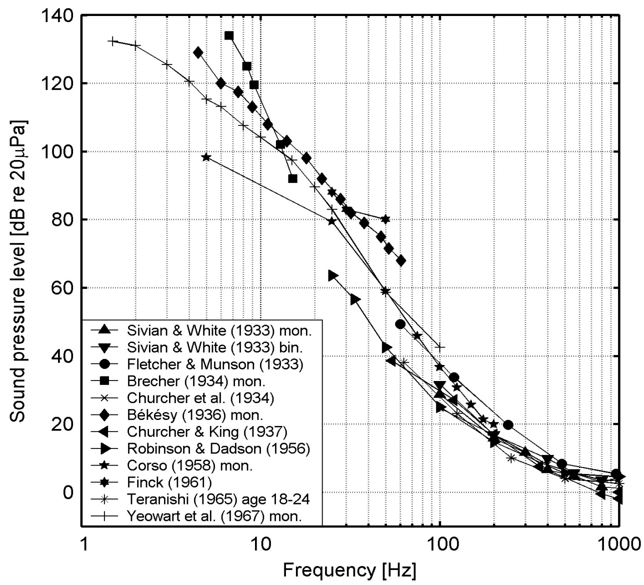


**Figure 1. Low-frequency hearing thresholds measured in the period from 1933 to 1967.**

Some investigators have produced the sound in a pressure chamber connected to the outer ear(s) either directly or by means of tubes. Data obtained under such conditions have been reported by Brecher (1934) (6.7-15.1 Hz, one subject, monaural), Békésy (1936) (4.5-61 Hz, one subject, monaural), Corso (1958) (5-200 Hz, 15 subjects), Finck (1961) (25-50 Hz, five subjects, binaural), Yeowart et al. (1967) (1.5-100 Hz, six to ten subjects depending on frequency, monaural) and Yeowart and Evans (1974) (5-100 Hz, five subjects, binaural). In the study by Brecher (1934) the sound was generated by a membrane driven by an eccentric wheel. Unlike other investigators, Brecher kept the level constant and varied the frequency to obtain the threshold. Békésy (1936) excited the pressure chamber by either a thermophone or a pistonphone. (A thermophone uses an amplitude-modulated alternating current to produce temperature variations in a conducting wire or foil. The surrounding air expands and contracts with the modulation, thereby creating pressure variations at the modulation frequency). The later studies used electrodynamic transducers to generate the sound.

Another group of studies used a larger pressure-field chamber that covered the entire body of the subjects. This applies to studies by Whittle et al. (1972) (3.15-50 Hz, up to 58 subjects depending on frequency), Yeowart and Evans (1974) (2-20 Hz, 12 subjects), Okai et al. (1980) (8-50 Hz, 28 subjects), Yamada et al. (1980) (8-63 Hz, 24 subjects), Nagai et al. (1982) (2-40 Hz, 62 subjects), Landström et al. (1983) (4-25 Hz, ten subjects), Watanabe and Møller (1990b) (4-125 Hz, 12 subjects), Watanabe et al. (1993) (5-40 Hz, 20 subjects) and Lydolf and Møller (1997) (20-100 Hz, 14 subjects plus nine added after publication). All studies made in whole-body pressure-field chambers used electrodynamic loudspeakers to generate the sound. Most studies had the loudspeakers mounted directly in the chamber, while in two (Whittle et al. (1972) and Yamada et al. (1980)) the sound was generated in one box that was connected to the exposure chamber by a tube. The two-box construction was used to reduce high-frequency noise from the amplifier by acoustic filtering. The exposure chamber used by Landström et al. (1983) had an opening to the outside, thereby forming a Helmholtz resonator that was tuned to the exposure frequency.

Figures 1-3 show all the thresholds that have been reported above. Although mainly frequencies below 200 Hz are considered in the present article, data up to 1 kHz are shown. Monaural and binaural data are shown as observed (i.e. with no correction), no distinction is made between data for men and women, and no distinction is made between MAF and MAP. For studies that have reported data for different

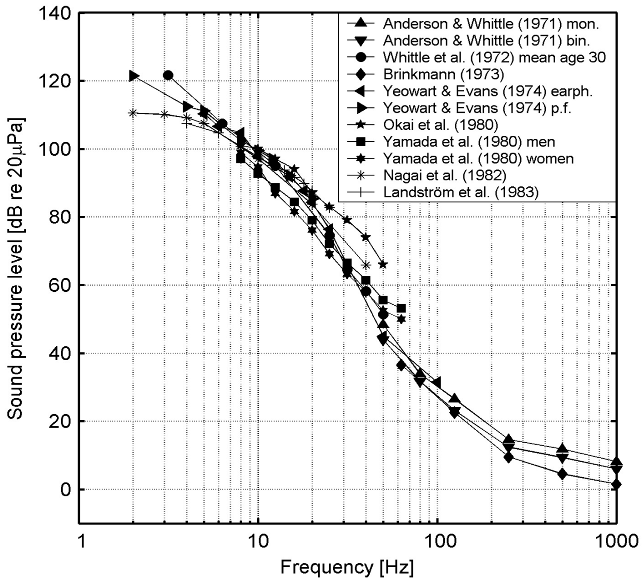


**Figure 2. Low-frequency hearing thresholds measured in the period from 1971 to 1983.**

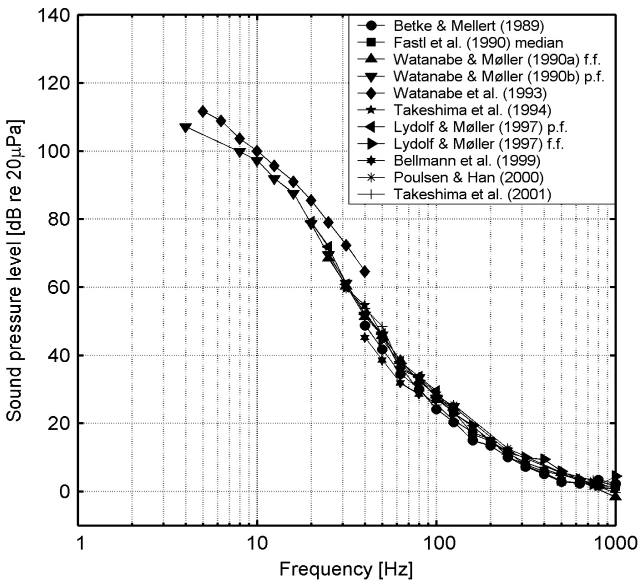


**Figure 3. Low-frequency hearing thresholds measured in the period from 1989 to 2001.**

age groups, the youngest group is shown (Teranishi et al. (1965), Whittle et al. (1972)).

It is obvious from Figures 1-3 that differences between investigations exist. However, one should have in mind that the data are obtained in a period of 70 years with very different techniques. Not surprisingly the largest discrepancies are found in the low and infrasonic frequency region, because it is much more difficult to produce the stimuli needed for this region. The demand on higher sound pressure levels with less harmonic distortion (due to the steep slope of the threshold curve) are difficult to meet as the production of higher sound pressure levels usually causes more harmonic distortion. Other differences between investigations can be found, e.g. in background noise level, sound field, subjects (number, age, selection process), psychometric method, instruction of the subjects, whether mean or median threshold is reported, and number of repetitions.

The differences between the investigations are so large that comparisons across investigations of the results cannot give answers to questions like

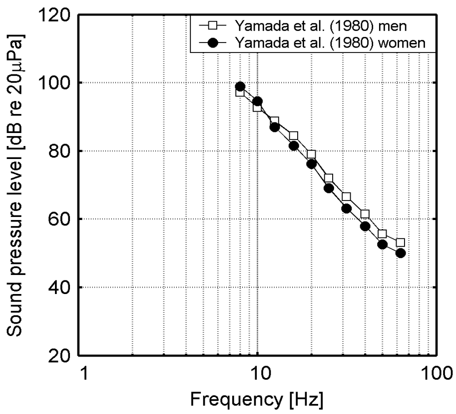


**Figure 4. Low-frequency hearing thresholds for men and women.**

the effect of gender, effect of age, monaural versus binaural exposure, effect of sound-field, and differences between persons. Therefore the following sections will deal with single investigations that focus on these specific issues.

**Significance of gender**

Most investigations have included both male and female subjects. Robinson and Dadson (1956) noted that there was no systematic difference between thresholds of men and women, but they did not show data separately for the two genders. Only Yamada et al. (1980) reported data separately. Figure 4 shows their data for the two genders. Women seem to be around 3 dB more sensitive than men except at 8 and 10 Hz, where men are around 2dB more sensitive. The standard deviation between subjects is not specified, so a statistical test cannot be performed on these data. However, large differences between persons are mentioned in the study, and when the relatively low number of subjects (16 men and eight women) is recalled, it is most likely that the differences between genders are not statistically significant.

**Significance of age**

Several investigations have studied thresholds for different age groups. Robinson and Dadson (1956) had many subjects in a wide age range (16-63 years), and they concluded that there was no effect of age at frequencies below 1 kHz. Consequently only data above this frequency were reported separately for different age groups. Yamada et al. (1980) mentioned threshold differences of 2-6 dB between people below and above 30 years, but he did not mention details about group sizes and age ranges, and the only original data reported are for subjects around 20 years.

Teranishi (1965) reported data separately for five age groups with 10 or 11 subjects in each group. Whittle et al. (1972) reported data for two groups, one with mean age 30 years (23 subjects) and one with mean age 47 years (35 subjects). The data from these two investigations are seen in Figure 5. This data suggests that up to 1000

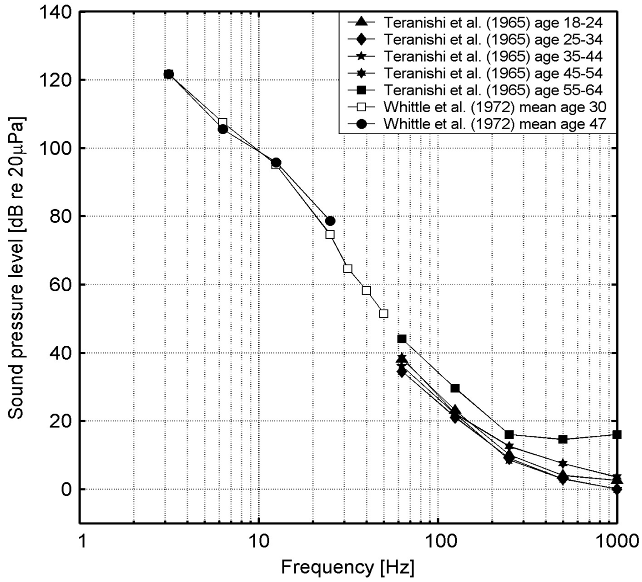


**Figure 5. Low-frequency hearing thresholds for different age groups.**

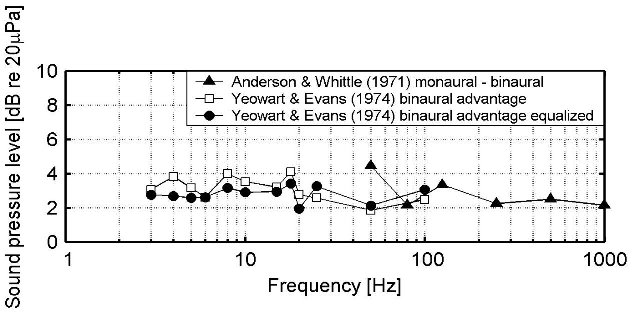


**Figure 6. The difference in thresholds between monaural and binaural exposure. (The data by Yeowart and Evans (1974) marked "equalized" refer to the condition, where signals have been adjusted to obtain equal sensation at the two ears during the binaural exposure).**

Hz there is no effect of age up to about 55 years.

**Monaural versus binaural hearing**

It is well accepted that binaural thresholds are slightly lower than monaural thresholds. The difference is called the binaural advantage, and it is said to be in the order of a few decibels, quite often around 3 dB. Some of the investigations already reported have studied the binaural advantage at low and infrasonic frequencies.

Sivian and White (1933) simply concluded that binaural thresholds were similar to monaural thresholds for the person's best ear. This was observed for only two subjects, and it was most likely too general and inaccurate. Anderson and Whittle (1971) measured for the same 10 subjects both monaural and binaural thresholds. Yeowart and Evans (1974) measured also monaural and binaural thresholds for the same group of subjects (3-4 depending on frequency). The binaural thresholds were measured in two situations, one with equal sound pressure at each of the two ears, and one where a level difference was applied between the two ears corresponding to the difference between ears in the monaural thresholds. The binaural advantage as observed in these two investigations is displayed in Figure 6 (for Anderson and Whittle (1974) calculated by the present authors as the difference between mean monaural and mean binaural thresholds). It is seen that a binaural advantage around 3 dB is probably applicable also at low and infrasonic frequencies.

**Significance of sound field**

Whittle et al. (1972) observed a large difference between their thresholds obtained in a whole-body pressure-field chamber and thresholds for free-field exposure given in ISO R226:1961. In order to see whether this was an effect of the sound field they also measured free-field thresholds for their own subjects. Measurements were made in four series, where the psychometric method and the set of included frequencies varied. A difference of several decibels was seen between thresholds obtained in the two sound fields. However, differences of the same order of magnitude were seen between different series in the same sound field, and no conclusion could be drawn about the effect of sound field.

Watanabe and Møller (1990b) studied for a group of 12 subjects thresholds with exposure in a free field and in a whole-body pressure-field chamber, keeping all other conditions constant. The results are shown in Figure 7. It is seen that there is a very good agreement between the two data sets in the overlapping frequency region. Thus, the data give no reason to suspect any effect of the sound field.

**Do we sense with our ears?**

Connected to the issue of the perception pathway is the question, whether the same thresholds are obtained if the whole body or only the ears are exposed. Yeowart and Evans (1974) measured thresholds in a whole-body chamber and with a binaural earphone. The number of subjects was not the same (12 and five respectively), and it is not stated whether there is overlap between the groups. Nevertheless, psychometric method and conditions in general were probably very similar. The data are seen in Figure 8. It is seen that the agreement between the two data sets is very

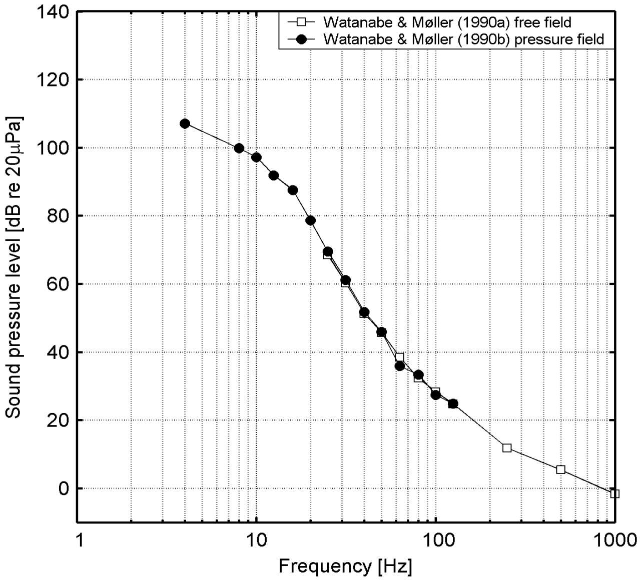


**Figure 7. Low-frequency hearing thresholds measured in free-field and pressure-field conditions.**

good. This supports the assumption that also these low frequencies are actually sensed by the ears.

**Standardization of hearing thresholds**

The first document that expresses an international agreement about the human hearing threshold is ISO R226:1961. The document covered not only the hearing threshold but also equal-loudness-level contours. Like all later standards it does not cover frequencies below 20 Hz. The bibliography of the document includes all relevant studies available at that time (Sivian and White (1933), Fletcher and Munson (1933), Churcher and King (1937), Robinson and Dadson (1956)), but data reflect only the study by Robinson and Dadson (1956).

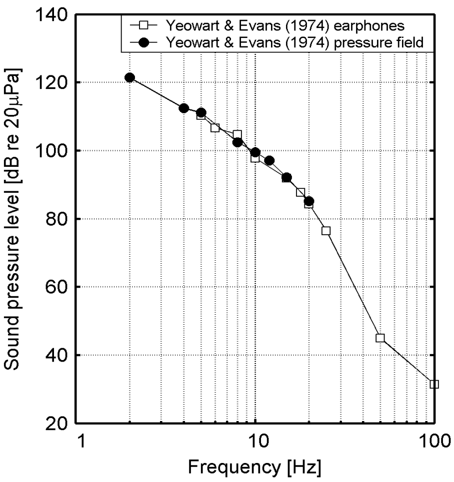


**Figure 8. Low-frequency hearing thresholds measured in ear-only exposure (earphone) and whole-body pressure-field conditions.**

In 1987 ISO R226:1961 was revised and issued as ISO 226:1987. The revision was a major editorial renewal, but the data were unchanged, except that they were specified at slightly different frequencies (the then new standard third-octave frequencies), and the highest frequency had been lowered from 15 kHz to 12.5 kHz. The unused studies had been removed from the bibliography.

In 1996 a standard was issued that covered only the hearing threshold and not the equal-loudness-level contours (ISO 389-7:1996). This was based on data from Robinson and Dadson (1956), Brinkmann (1973), Betke and Mellert (1989), Suzuki et al. (1989), Fastl et al. (1990), Vorländer (1991) (only frequencies above 8 kHz), Watanabe and Møller (1990a) and Watanabe and Møller (1990b). Deviations from previous standards were small (max. 3.9 dB at 20 Hz). An explanatory overview of the aggregation and processing of the data for the standard is given by Brinkmann et al. (1994).

Most recently agreement has been obtained for a complete set of hearing thresholds and equal-loudness-level contours, and a revised ISO 226

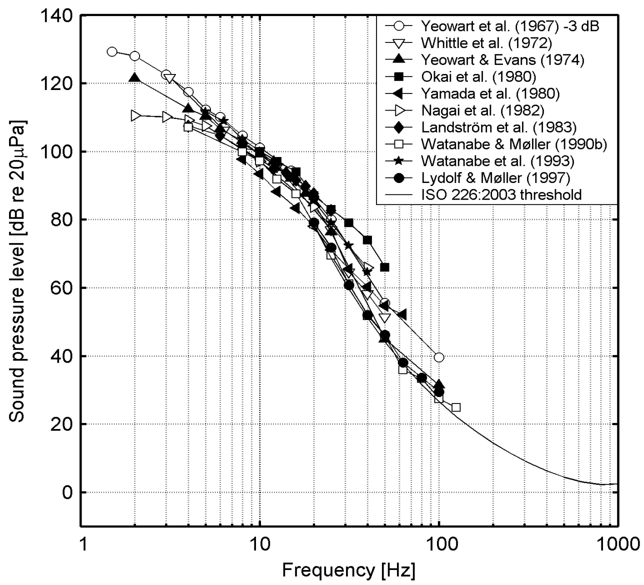


**Figure 9. Standardized hearing threshold above 20 Hz (ISO 226:2003) and results from recent investigations covering frequencies at and below 20 Hz. (Whittle et al. (1972): weighted average of 30- and 43-year groups; Yeowart and Evans (1974): weighted average of ear and full-body exposures; Yamada et al. (1980): weighted average of men and women).**

was issued in 2003 (ISO 226:2003). The hearing threshold is based on the same investigations as ISO 389-7:1996 with the addition of Teranishi (1965), Takeshima (1994), Poulsen and Thøgersen (1994) (only above 1 kHz), Takeshima et al. (2002) (only above 1 kHz), Lydolf and Møller (1997), Poulsen and Han (2000) and Takeshima et al. (2001). There are only small differences (max. 2.1 dB, at low frequencies max. 0.6 dB) between the threshold in this document and in ISO 389-7:1996. In order to avoid two different thresholds being standardized (although they are close), a formal revision has been initiated to make the thresholds of ISO 389-7 identical to those of ISO 226:2003.

The threshold of the most recent standard (ISO 226:2003) is included for reference in the following figures.

**Proposed normal hearing threshold below 20 Hz**

As no standardized hearing threshold exists for frequencies below 20 Hz, it is adequate at this place to propose a normal threshold for the lower frequencies, based on the existing data. Figure 9

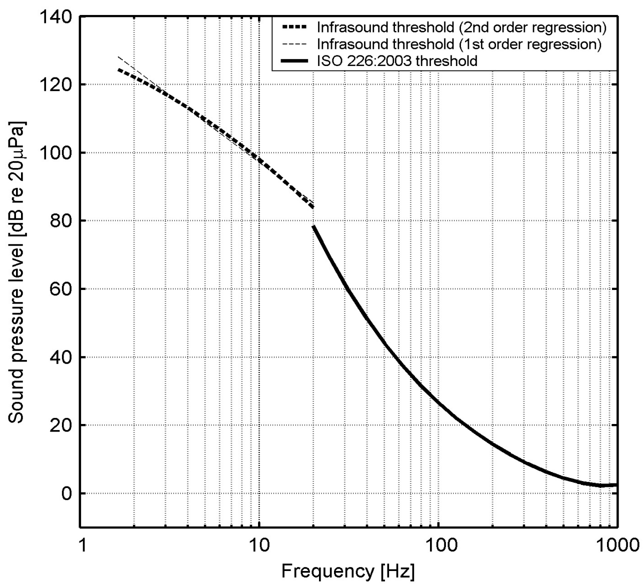


**Figure 10. Standardized hearing threshold above 20 Hz (ISO 226:2003) and proposed normal hearing thresholds for frequencies below 20 Hz.**

shows the most recent investigations of hearing thresholds that have data in the infrasonic frequency range, together with the hearing threshold of ISO 226:2003. (The monaural data from Yeowart et al. (1967) have been adjusted to binaural conditions by subtraction of 3 dB).

Some investigations have obtained values that are clearly too high in the 30-100 Hz range, but there is a remarkably good agreement between investigations in the 5-20 Hz range. Below 5 Hz there are very few investigations, and unfortunately they differ somewhat.

In Figure 10 the bold dashed line shows a second-order polynomial regression curve as an approximation to the data of Figure 9. As seen it does not connect precisely to the curve of ISO 226:2003. There are data that agree well with the standard (Yamada et al. (1980) and Watanabe and Møller (1990)), but other data are higher. It is not possible from the existing data material to give a definitive solution in the area around 20 Hz. The proposed curve is also somewhat uncertain below 5 Hz, where more data would be needed to give more conclusive values. Despite these uncertainties, the curve is probably correct within a few decibels, at least in most of the frequency range.

The thin dashed line gives the more coarse linear regression (approximation of a straight line). The slope of the line is 11.9 dB per octave which is very close to the 12-dB-per-octave slope of the G-weighting filter for infrasound (ISO 7196:1995). The thin dashed line corresponds to a G-weighted sound pressure level of approximately 97 dB.

**Individual differences**

Several hearing threshold studies have reported standard deviations between subjects. A summary of these is given in Figure 11.

In general the standard deviations between subjects are in the order of 5 dB nearly independent of frequency, maybe with a slight increase at 20-50 Hz. Only the study by Sivian and White (1933) shows considerably higher values (in the range 200-1000 Hz), a result that is most likely due to the experimental conditions in this early study.

Nagai et al. (1982) reported that out of 62 subjects 39 had a threshold that followed the general trend with increasing threshold for decreasing frequency, whereas the threshold of the remaining 23 subjects did not increase further below 5 Hz. For the latter group the threshold was claimed to flatten out or even decrease with decreasing frequency. For the same subjects no flattening was observed in

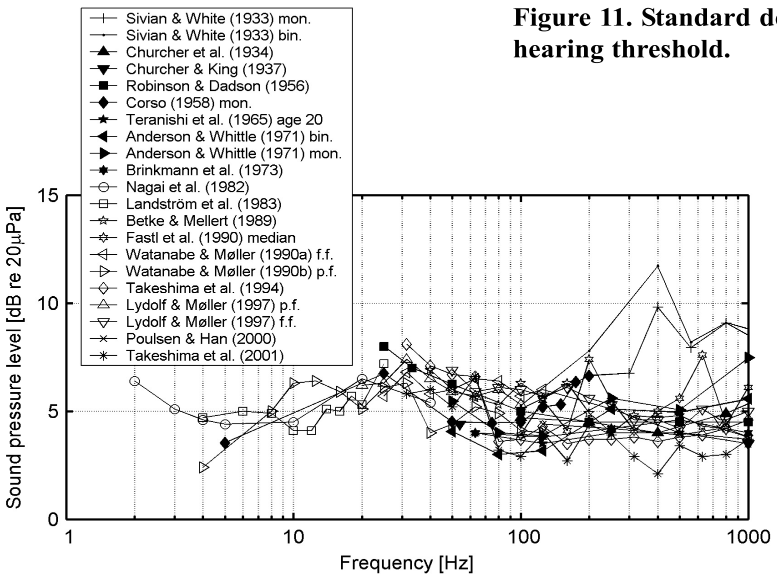


**Figure 11. Standard deviations between subjects of the hearing threshold.**

hearing thresholds for low-pass-filtered white noise, where data were similar to those of the rest of the subjects.

**Especially sensitive persons**

A few studies mention persons with extraordinary high hearing sensitivity at low frequencies. Okai et al. (1980) report of two subjects being especially sensitive to low-frequency sound, and Yamada et al. (1980) report of one subject. In addition, a subject has been observed in our laboratory with a repeatable, very low threshold (Lydolf, unpublished 1997). Figure 12 shows three of these cases compared to the ISO 226:2003 and the proposed normal threshold at infrasonic frequencies from above. (One of Okai's two subjects seems normal when compared to these data and is not shown in the figure). Assuming that the hearing threshold is normal distributed around the mean with a standard deviation of 5 dB, then the probability for a person to have a threshold around 20 dB below the mean - as seen in this figure - is extremely low, and most likely another explanation than the natural spread should be sought.

Extraordinary sensitivity to low-frequency sound might be explained by abnormalities in the person's hearing organs. A theoretical example could be an abnormally small aperture in the helicotrema at the apex of the cochlea. For low-frequency sound the helicotrema acts like a kind of pressure equalization vent for the perilymph in the cochlea, equalizing the pressure between the scala tympani and the scala vestibuli. If the helicotrema is unusually narrow or blocked, it cannot equalize the pressure fast enough, and an unusually high pressure will build up between the scala tympani and the scala vestibuli. The result is a greater mechanical excitation of the basilar membrane, and thus a higher sensitivity to these sounds is expected. For examples of simulations of the effect of the size of helicotrema see e.g. Schick (1994).

**Hearing threshold microstructures**

Another explanation for an apparently high sensitivity to low-frequency sound might be found in so-called microstructures in the individual hearing threshold. Frost (1987) showed that the hearing threshold as a function of frequency is not a smooth continuous line, but has peaks and dips of sometimes several decibels spread over the frequency spectrum. The irregularities were reported to be repeatable and not the result of experimental spread. An example showing microstructures in two persons' hearing thresholds is given in Figure 13. Although these particular persons do not have an especially good hearing, the microstructure is clearly seen. It is evident that for some persons the phenomenon of microstructures may lead to an extreme sensitivity at particular frequencies.

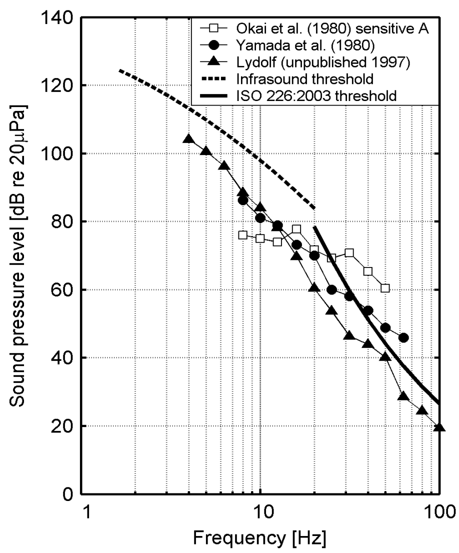


**Figure 12. Hearing thresholds of three especially sensitive persons.**

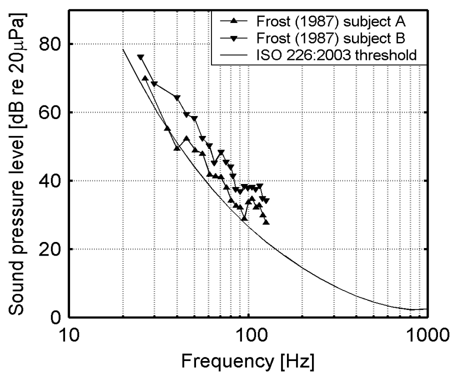


**Figure 13. Example of microstructures in the hearing threshold for two persons.**

### Thresholds for non-sinusoidal sound

Only few threshold measurements exist for low-frequency non-sinusoidal sound. Yeowart et al. (1969) measured thresholds for octave-band-filtered random noise with center frequencies in the range 4-125 Hz and pure-tone thresholds for the same subjects. For center frequencies down to 32 Hz they found no significant difference between pure-tone thresholds and octave-band noise thresholds. In the range 4-16 Hz they found a significantly lower threshold for octave-band noise in the order of 4 dB. An explanation could have been that it is the higher frequency end of an octave band that is most audible, and comparison is then to be made with the threshold at that frequency rather than at the centre frequency of the noise band. With this explanation, the difference will be largest in the frequency range with the highest slope of the hearing threshold, i.e. 20-63 Hz. This was however not the range where the difference was seen, and the theory was thus not supported. This led to the idea, that for frequencies from 16 Hz and down, it might be the individual peaks in the sound pressure that we detect. Yeowart et al. (1969) modelled the hearing with appropriate time constants of the loudness perception and showed that the peak-detection theory could explain the 4 dB lower noise thresholds. The theory is in agreement with the subjective impression of sensing the individual oscillations at the lowest frequencies.

Nagai et al. (1982) made measurements with lowpass-filtered white noise with a lower limit of 2 Hz and upper limits of 5, 10, 20 and 40 Hz. Furthermore pure-tone thresholds were found for the same subjects. These measurements show the opposite pattern as that observed by Yeowart et al. (1969). For the random noise with upper limits of 20 and 40 Hz the threshold was lower than the pure-tone threshold (7-10 dB), but for the 2-5 Hz random noise the threshold was higher than the pure-tone threshold (about 6 dB).

Generally low-frequency and infrasonic sounds from everyday life are not pure tones alone, but rather combinations of different random noises and tonal components. It is however, impossible to make thresholds for all imaginable combinations of sounds that exist, and as seen above there is no final conclusion about possible higher or lower sensitivity to noise bands than to pure tones. Anyway, differences seem to be relatively modest, and the pure-tone threshold can with a reasonable approximation be used as a guideline for the thresholds also for non-sinusoidal sounds.

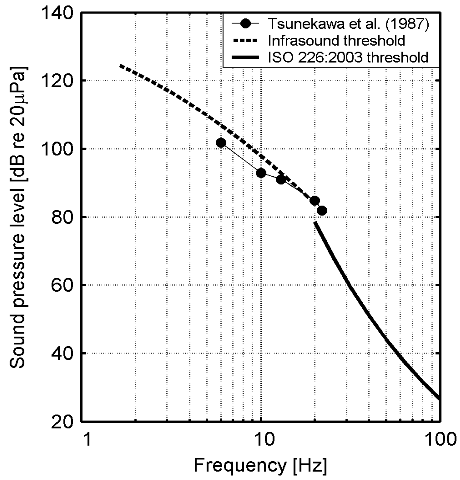


**Figure 14. Hearing thresholds measured in the field by Tsunekawa et al. (1987).**

### Field measurements of hearing thresholds

All the investigations reported in the section 'Studies of hearing threshold' have been carried out in the laboratory. Tsunekawa et al. (1997) carried out an interesting study, where they found hearing thresholds using sound that occurred naturally in the field. They used the sound under two bridges, inside an automobile and beside some cooling towers. Of course, their resolution in frequency was determined by the frequencies that occurred naturally. While they recorded the sound they asked subjects to indicate, when the sound was audible and when it was not. They only used responses, when later analyses showed that the sound was sufficiently pure.

The results are given in Figure 14 together with the standardized threshold for frequencies above 20 Hz and the proposed normal hearing threshold for frequencies below 20 Hz. It is interesting to see how close their results are to the results obtained in the laboratory.

**Non-auditory perception**
As mentioned in the section 'The sensation mechanism', various attempts have been made to determine the way we sense the low and infrasonic frequencies. An investigation by Landström et al. (1983) deserves special attention. Hearing thresholds were measured for 10 normal-hearing subjects (five of each gender). Furthermore vibrotactile thresholds were measured for the same subjects and for 10 subjects with complete perceptive or sensory-neural deafness. The vibrotactile sensation was described as soft vibrations in different parts of the body, mostly in the lumbar, buttock, thigh and calf regions.

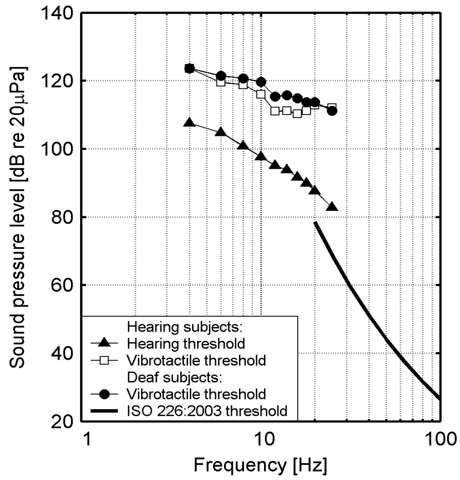


**Figure 15. Hearing and vibrotactile thresholds as measured for hearing and deaf subjects by Landström et al. (1983).**

The results from Landström et al. are given in Figure 15. It is seen that the vibrotactile thresholds are very similar for the hearing and the non-hearing groups. This suggests that the hearing subjects were really able to distinguish between the two sensations. The findings also support the idea that the sense of hearing is the primary sense for detecting the presence of sound at low and infrasonic frequencies. On the other hand, the results suggest that an additional way of sensation connected to vibration occurs at levels that are only 20-25 dB above the hearing threshold.

Spontaneous reactions from subjects and visitors in the authors' laboratory as well as their own experience suggest that vibrotactile sensations and a feeling of pressure may also occur in the upper part of the chest and in the throat region.

**Studies of equal-loudness-level contours**
Loudness is a measure of the subjectively percieved intensity of sound. The unit of *loudness level* is phon, and for a given sound it has the same numerical value as the sound pressure level (in dB relative to 20 μPa) of an equally loud reference sound. The reference sound consists of a frontally incident, sinusoidal plane wave at a frequency of 1 kHz. An equal-loudness-level contour is a curve in the sound pressure level versus frequency plane that represents tones of the same loudness level. Most studies are made with the reference tone held at a constant level, while some psychometric procedure is used to find the level of the test tone that makes the two tones appear equally loud to the subject. A few studies have used fixed levels of the test tone and varied the level of the reference tone, in which case interpolation is needed to obtain equal-loudness-level contours.

Initially, it should be mentioned that Kingsbury (1927) was one of the first to attempt measurements of equal-loudness-level contours. However, he used a monaural earphone, and no attempt was made to calibrate it to free-field conditions, thus his results will not be further reported here. Churcher et al. (1934) also made some early studies of loudness, but they used a reference tone of 800 Hz and a mixture of free-field and earphone exposures, thus their results will also not be reported further.

One of the best known studies of equal-loudness-level contours is the early one by Fletcher and Munson (1933). They reported data for the frequency range 62 Hz-16 kHz and loudness range 10-120 phon, based on measurements with 11 subjects. The measurements were performed using earphones, but since these were calibrated to free-field conditions, their data are considered relevant and will be included in the following. (In the review of hearing thresholds given above, studies that used audiometric earphones were excluded due to the risk of interference from physiological noise. This is not considered a problem for loudness comparisons, which take place at levels somewhat above threshold).

Most studies have determined points of equal-loudness-level directly according to the definition, i.e. through comparisons of the test tone and the reference tone in a free or an approximately free field. This applies to the studies of Churcher and King (1937) (54 Hz-9 kHz, 10-90 phon, up to 30 subjects depending on frequency and level), Betke and Mellert (1989) (100 Hz-1 kHz, 30 phon; 50 Hz-12.5 kHz, 40, 50 and 60 phon, 28 subjects), Suzuki et al. (1989) (125 Hz-8 kHz, 40 and 70 phon, 23 subjects; 63 Hz-12,5 kHz, 20 phon, ten subject), Fastl et al. (1990) (100 Hz-1 kHz, 30, 50 and 70 phon, 12 subjects), Watanabe and Møller (1990a) (25 Hz-1 kHz, 20, 40, 60 and 80 phon, 12 subjects), Lydolf and Møller (1997) (50 Hz-1 kHz, 20, 40, 60, 80, 90 and 100 phon, 27 subjects), Takeshima et al. (1997) (31.5-12.5 kHz, 20, 40, 50, 60, 70 and 90 phon, 9-30 subject depending on frequency and loudness level), Bellmann et al. (1999) (100 Hz-1 kHz, 60 phon, 12 subjects) and Takeshima et al. (2001) (50 Hz-16 kHz, 20, 40 and 70 phon, eight subjects).

For the lowest frequencies it is a practical problem to create sound in the same room as the reference tone (anechoic room) at sufficiently high level without significant harmonic distortion. It will be noted that none of the free-field studies mentioned in the previous paragraph had frequencies below 25 Hz, and most studies did not even go that far down. Furthermore, it is often mentioned that it is difficult for subjects to compare tones that are very distant in frequency. Some investigators have overcome these problems by making indirect loudness matches to the 1 kHz reference tone. Points of equal loudness are determined at a low-frequency anchor point of for example 100 Hz through direct comparisons with 1 kHz in an anechoic room. Then the 100 Hz points are used as new references for loudness matches in a pressure-field chamber, where large sound pressure levels can be produced at the lowest frequencies.

Studies that used exposures in pressure field in combination with individual anchor points determined in free field comprise those of Kirk (1983) (2-63 Hz, 20, 40, 60, 80 and 100 phon, anchor points at 63 Hz, 14 subjects), Møller and Andresen (1984) (2-63 Hz, 20, 40, 60, 80 and 100 phon, anchor points at 63 Hz, 20 subjects), Lydolf and Møller (1997) (20-100 Hz, 20, 40, 60, 80 and 100 phon, anchor points at 100 Hz, 14 subjects plus three added after publication) and Bellmann et al. (1999) (16-160 Hz, 60 phon, anchor points at 100 Hz, 12 subjects).

Two studies used experimental designs equivalent of using non-individual anchor points. Robinson and Dadson (1956) measured equal-loudness relations for the frequency range 25 Hz-15 kHz (up to approximately 130 phon and up to 120 subjects depending on frequency). Free-field conditions were used for the higher frequencies, while a suitably terminated duct was used for the lowest frequencies. At the lowest frequencies they used reference tones of 50 or 200 Hz that were converted into phon by means of interpolation in the data material from the free field. Whittle et al. (1972) used a pressure field for their experiments (3.15-50 Hz, up to 32 subjects depending on frequency). They used a reference tone at 50 Hz at three levels (60, 73 and 86 dB) without measuring the connection to 1 kHz. Subsequently they used ISO 226:1961 to find the standardized loudness levels of their reference tones and labelled the contours accordingly (33.5, 53 and 70.5 phon).

Figures 16-18 show the equal-loudness-level contours measured in the investigations mentioned above. It should be noted that the data from Fletcher and Munson (1933) and Robinson and Dadson (1956) are not original data, but data interpolated between original data points. For the data by Whittle et al. (1972) the authors have taken the liberty of plotting them as 20, 40 and 60 phon, respectively, since these loudness levels seem more reasonable than the original labels of 33.5, 53 and 70.5 phon when comparing with the other data in the same frequency area.

The figures clearly show large differences between equal-loudness-level contours from

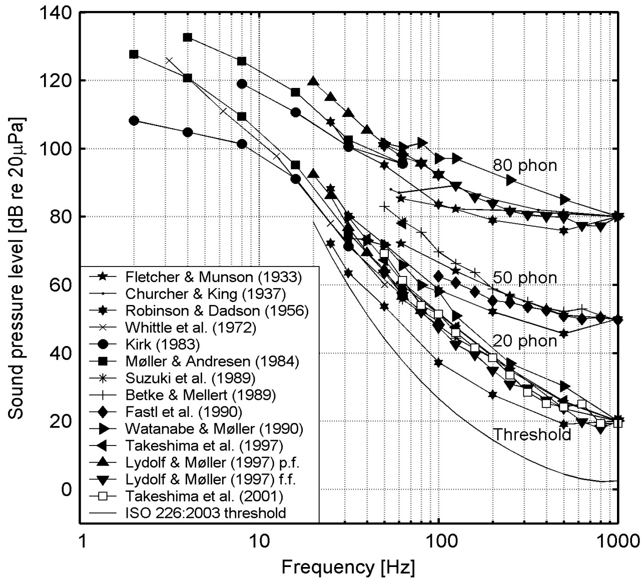


**Figure 16. Low-frequency equal-loudness-level contours for 20, 50 and 80 phon.**

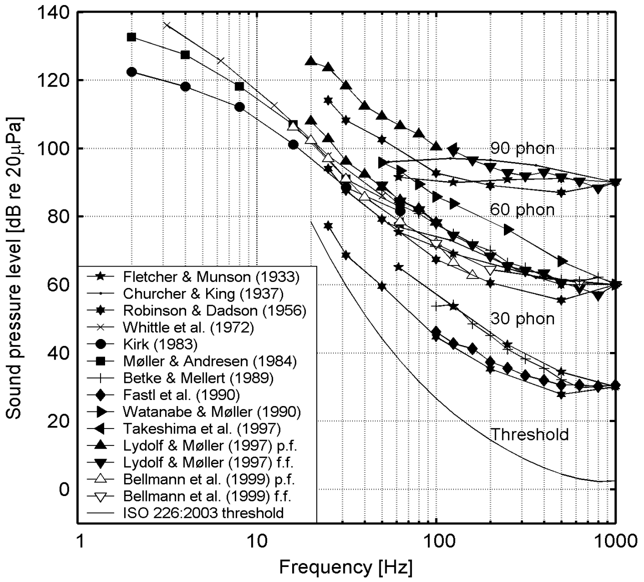


**Figure 17. Low-frequency equal-loudness-level contours for 30, 60 and 90 phon.**

different investigations. These differences are not only in the low-frequency region but also at higher frequencies.

**Standardization of equal-loudness-level contours**

The first international standard about equal-loudness-level contours is ISO R226:1961. The contours in this were solely based on the study by Robinson and Dadson (1956), despite the fact that also other studies were present at that time. As already mentioned in the section on standardization of hearing thresholds, the document was revised and issued as ISO 226:1987, however without changes in data.

Virtually all other investigations show data that are significantly higher than those of Robinson and Dadson (1956) in the frequency area below 1 kHz. The difference has been ascribed to the different psychometric methods used. The data from Robinson and Dadson seem significantly biased towards lower levels. Awareness of bias problems and the use of computerized adaptive psychometric methods in later studies have provided data that are believed to be more reliable.

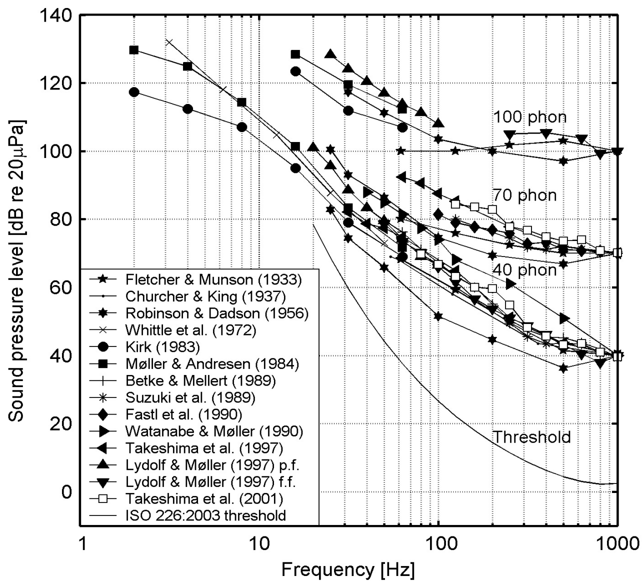


**Figure 18. Low-frequency equal-loudness-level contours for 40, 70 and 100 phon.**

Most recently agreement has been obtained for a complete set of hearing thresholds and equal-loudness-level contours, and a revised standard has been issued (ISO 226:2003). Below 1 kHz the equal-loudness-level contours are based on the investigations by Kirk (1983), Møller and Andresen (1984), Betke and Mellert (1989), Suzuki et al. (1989), Fastl et al. (1990), Watanabe and Møller (1990), Lydolf and Møller (1997), Takeshima et al. (1997), Bellmann et al. (1999) and Takeshima et al. (2001).

Figure 19 shows the standardized equal-loudness-level contours for the frequency range below 1 kHz, and the difference between the two old and the new standard is obvious.

### Proposed normal equal-loudness-level contours below 20 Hz

No standardized equal-loudness-level contours exist for frequencies below 20 Hz, and only four investigations provide data in this frequency region. Whittle et al. (1972) and Møller and Andresen (1984) produce quite similar contours, and the two points provided by Bellmann et al. (1999) at 60 phon, 16 and 20 Hz, fit well with these. The contours by Kirk (1983) deviate considerably, and the authors take the liberty of disregarding these data in the following. The contours from the three other investigations are shown in Figure 20. Based on these data the authors have presented their best guess of general contours of 20, 40, 60 and 80 phon for frequencies below 20 Hz in Figure 21. However, these contours should be taken with great reservation because of the sparse amount of data and the uncertainty connected to the exact phon values they should be labelled with. On the other hand it seems beyond any doubt that the contours are very close in this frequency region.

More definite contours at low and infrasonic frequencies - in particular at high loudness levels - require that more experimental data become

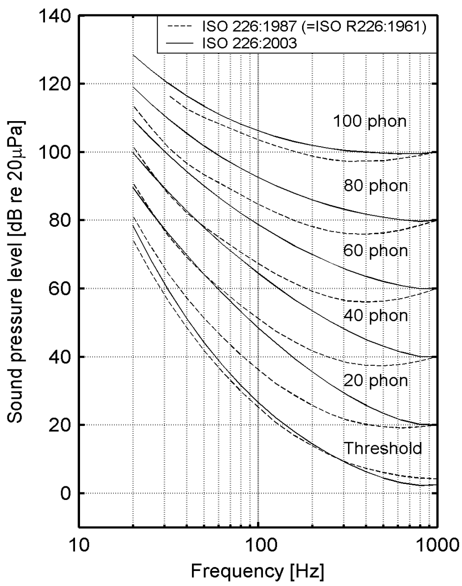


**Figure 19. Standardized equal-loudness-level contours.**

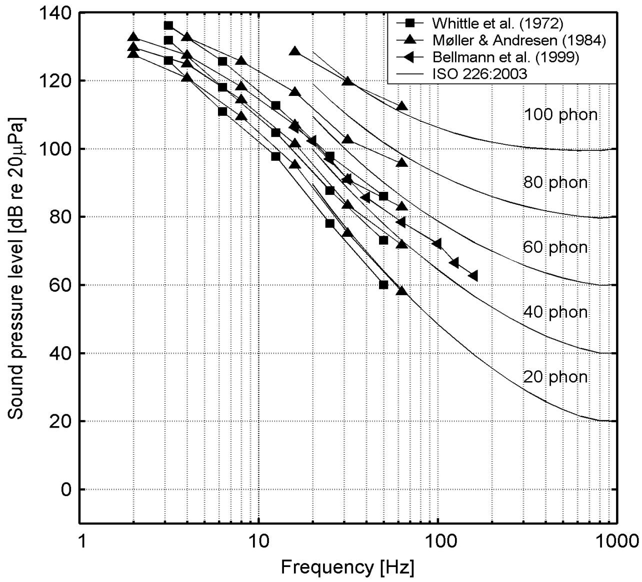


**Figure 20. Standardized equal-loudness-level contours above 20 Hz and results from investigations covering frequencies at and below 20 Hz.**

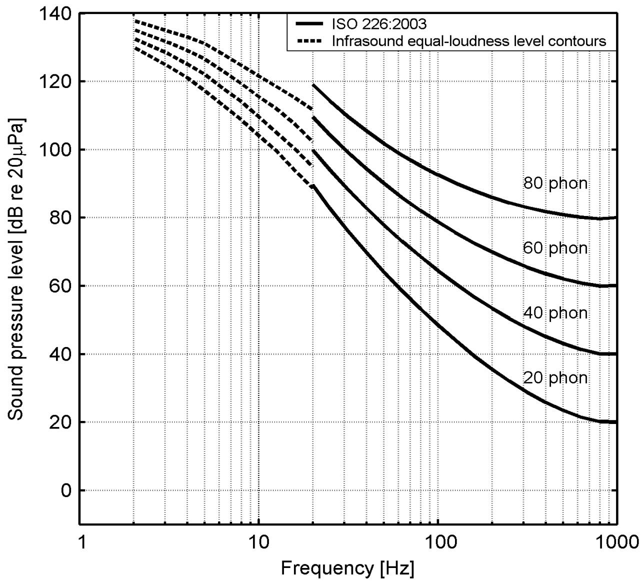


**Figure 21. Proposal of equal-loudness-level contours for the infrasonic region together with standardized contours above 20 Hz.**

available. Unfortunately, it is not a trivial task to produce the high sound pressure levels needed without significant harmonic distortion.

**Conclusion**

The human perception of sound below 200 Hz has been reviewed, and on the basis of results from various investigations it is possible to draw some general conclusions.

The hearing becomes gradually less sensitive for decreasing frequency, but there is no specific frequency at which the hearing stops. Despite the general understanding that infrasound is inaudible, humans can perceive sound also below 20 Hz. This applies to all humans with a normal hearing organ, and not just to a few persons. The perceived character of the sound changes gradually with frequency. For pure tones the tonal character and the sensation of pitch decrease with decreasing frequency, and they both cease around 20 Hz. Below this frequency tones are perceived as discontinuous. From around 10 Hz and lower it is possible to follow and count the single cycles of the tone, and the perception changes into a sensation of pressure at the ears. At levels 20-25 dB above threshold it is possible to feel vibrations in various parts of the body, e.g. the lumbar, buttock, thigh and calf regions. A feeling of pressure may occur in the upper part of the chest and the throat region.

There is a reasonable agreement between studies of hearing thresholds. For frequencies down to 20 Hz, a normal threshold has been standardized by ISO, and the present article presents a proposed normal threshold one decade further down in frequency. The proposed curve corresponds roughly to a G-weighted sound pressure level of 97 dB. More data are needed to give a more conclusive curve.

It cannot be finally concluded whether thresholds for noise bands are the same as pure-tone thresholds. Below 20 Hz it is possible that the peak sound pressure determines the sensation. The differences are small, though, and it seems reasonable to use the pure-tone threshold as a guideline also for non-sinusoidal sound.

The hearing threshold is the same for men and women. Degradation with age takes place only above 50 years. The threshold is the same in free and pressure field. Like at higher frequencies, the binaural advantage is around 3 dB, and the standard deviation between individuals is around 5 dB. However, there is evidence of individuals that have a hearing that is much better than normal (several times the standard deviation away from the mean). It has also been shown that the hearing threshold may have a microstructure that causes a person to be especially sensitive at certain frequencies. These two phenomena may explain observations from case studies, where individuals seem to be annoyed by sound that is far below the normal threshold of hearing. It should be stressed that the explanation has not been confirmed in specific cases.

Thresholds are the same, whether the whole body or just the ears are exposed, thus is can be concluded that the sensation takes place in the ears even at frequencies below 20 Hz. However, it is not totally clear, whether the sensory pathway for infrasound is the normal pathway for hearing. The observation that deaf people can only detect infrasound through vibrotactile sensation - and for that they have the same threshold as normal-hearing persons - suggests that the normal auditory system is used. A hypothesis that these frequencies are heard in terms of harmonic distortion in the ear is not supported.

In addition to direct detection, infrasound may be detected through amplitude modulation of sound at higher frequencies. This modulation is caused by the movement of the eardrum and middle-ear bones induced by the infrasound, which results in changes of transmission properties. At very high levels, modulation of speech can occur due to a pulsating airflow in the throat caused by the sound.

The perceived intensity of the sound rises more steeply above threshold than at higher frequencies. This is especially pronounced for frequencies below 20 Hz, where a sound only few decibels above threshold may be perceived as quite intense. Combined with the natural spread in thresholds, this may have the effect that a sound, which is inaudible to some people, may be loud to others. The compression of the dynamic range of the auditory system is reflected in the equal-loudness-level contours. Such contours have been standardized for frequencies down to 20 Hz, but there is a reasonable agreement between data also below this frequency, and contours have been proposed down to 2 Hz. However, this is based on only few investigations and more data are needed.

**Acknowledgements**
The authors want to thank their local and international colleagues for fruitful discussions about our perception of low frequency sound. Many discussions have taken place in an international collaboration on the loudness function, the NEDO project, which was only made possible thanks to the effort of Professor Yoiti Suzuki, Tohoku University, Japan. We also want to thank our former colleague, Morten Lydolf, who started the aggregation of the large amount of data and made it available to us. The work was supported by the Danish Technical Research Council and Aalborg University.

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# A new low-frequency test facility

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**ABSTRACT**

The two largest problems in controlling the reproduction of low-frequency sound for psychoacoustic experiments is the effect of the room due to standing waves and the relatively large sound pressure levels needed. Anechoic rooms are limited downward in frequency and distortion may be a problem even at moderate levels, while pressure-field playback can give higher sound pressures but is limited upwards in frequency. A new solution that addresses both problems has been implemented in the laboratory of Acoustics, Aalborg University. The solution uses one wall with 20 loudspeakers to generate a plane wave that is actively absorbed when it reaches the 20 loudspeakers on the opposing wall. This gives a homogeneous sound field in the majority of the room with a flat frequency response in the frequency range 2-300 Hz. The lowest frequencies are limited to sound pressure levels in the order of 95 dB. If larger levels are needed, a hybrid mode can be used to utilize the pressure-field conditions at frequencies up to approx. 30 Hz while the higher frequencies are controlled by plane-wave generation. This approach allows for playback of levels at the lowest frequencies in the order of 125 dB while maintaining a homogeneous sound field for the entire frequency range 2-300 Hz.

## 1. INTRODUCTION

For psychoacoustic research, it is very important to have complete control over the sound that the test subjects are exposed to. Therefore, it is necessary to use a test facility with low background noise, and where the inherent noise and distortion in the sound equipment is sufficiently low. However, a parameter that is sometimes overlooked is the exact transfer function from the input of the acoustical transducer to the ears of the test subject. If this transfer function is not corrected for somewhere in the reproduction chain, it can influence the results of the experiment and in the worst case, render them invalid. For sound reproduction via headphones, it is fairly simple to make equalization filters, but for sound reproduction via loudspeakers, the test room contributes to the transmission, and the problem becomes more complex. Reflections from surfaces in the room – like walls, floor and ceiling – interfere with the direct sound (and other reflections). This causes frequency dependent standing wave patterns – meaning that the sound pressure for each frequency varies with position in the room. For signals in general the shape of the standing wave patterns in a room depends on a number of different parameters: The dimensions and shape of the room, absorption coefficients and shape of reflecting surfaces, position and directivity of the sound source(s) and finally the time and frequency content of the reproduced signal. This illustrates the complex problem of controlling the sound that reaches the ears of the test subjects.

### 1.1 Problems at low frequencies

At low frequencies, the pressure variation becomes larger since it is practically impossible to remove the reflections by passive absorption (because of the wavelength). Furthermore, pressure nodes and antinodes are distinct and therefore more severe at low frequencies whereas they overlap at higher frequencies because of the relationship between the dimensions of the room and the wavelengths.

Another challenge in reproducing low-frequency sound for psychoacoustic experiments is the high sound pressure levels that are needed due to the high hearing threshold in this frequency range. This requires larger movement of the loudspeaker membranes, which causes movement in a less linear range, and harmonic distortion is increased as a by-product of the non-linearity. Since the higher harmonics are in a more sensitive frequency range than the fundamental (due to the slope of the hearing threshold), low harmonic distortion is very important in reproduction of low-frequency sound.

### 1.2 Previous solutions

Several solutions have previously been used in psychoacoustic experiments, but they all have significant limitations.

An obvious way of removing the effect of a room is to use a setup in an anechoic room, where the loudspeakers are placed as close as possible to the subject (without entering the near field, where the sound pressure might not be homogeneous), in order to increase the maximum pressure (in a free field, the pressure is inverse proportional to the distance to the sound source). This approach has been used in many studies; e.g. [1], [2], [3], [4], [5] (lowest frequencies measured in a duct), [6], [7]. However, even the largest anechoic rooms are frequency limited, and extreme excursion of the loudspeaker membrane is required as the frequency is lowered, since the pressure generated by a loudspeaker in an anechoic room is proportional to the volume acceleration. Therefore, distortion quickly becomes the limiting factor.

At very low frequencies, it is much more efficient to use a pressure-field chamber. In a pressure-field chamber, the pressure is proportional to the volume displacement of the loudspeakers, and a homogeneous sound field will exist for sounds with wavelengths considerably larger than the inner dimensions of the chamber. Such chambers are usually small, and the sound is generated by a number of large loudspeaker units placed in the walls and/or ceiling. As an alternative, the room may be coupled to another chamber with large loudspeaker units. The construction and verification of pressure field chambers are reported in [8] and [9]. Examples of studies using pressure-field chambers are [10], [11], [12], [13], [14], [15], [16], [17], [7]. The lower frequency limit of the room depends on how airtight the room is, since a leakage will allow air to escape and thus introduce a lower limiting frequency. The upper frequency range for a homogeneous sound field is limited by the dimensions of the room, and a room that accommodates a person with only moderate discomfort due to the narrow space can hardly have a usable frequency range higher than 80-100 Hz. Also, the maximum obtainable sound pressure level depends on the volume of the room.

A solution that greatly expands the usable frequency range upwards is to use an even smaller enclosure and connect this to the ears of the subject. Examples of studies using an approach with enclosures connected to the ears are [18], [19], [20], [21], [22], [11]. This solution might introduce other problems. The fitting to the ears of the subject has to be airtight in order to have full control of the sound pressure level at the lowest frequencies. If the enclosure or fitted region is too small, there is a considerably increase in the physiological noise inside the enclosure, which can cause effects like masking. This effect was studied by Anderson and Whittle [23] who also list studies that have used small enclosures in threshold determinations. Another possible drawback is that this solution only gives exposure to the ears and not the rest of the body, and finally it can lead to discomfort due to the tight fit to the head.

Another solution is to equalize for the whole exposure system including the room. This can be done by measuring the transfer function of the exposure system to the listening point in the room, and then apply an inverse filter in the signal chain. An example of a study using this approach is [24]. This approach generally gives good control of the sound, but only for one single point in the room. Peaks in the transfer function can be corrected fairly well; however, dips are more narrow in space and frequency, and thus often impossible to equalize. If this is done anyway, the result will be peaks in other positions close by. Since the subject cannot have both ears in the same position, the control of the sound at the ears is impaired, and slight movements can lead to large changes. Some equalization techniques equalizes for the average of multiple positions (e.g. [25]), which can slightly improve the sound reproduction in an area, but this solution will not be perfect in any position and it does not remove the difference between positions.

If the requirements are to cover all frequencies in the low-frequency area (usually meaning for frequencies below 200 Hz) in a sound reproduction system with whole-body exposure then none of the previous solutions can be used.

### 1.3 New solution

A new solution based on a global equalization method [26] has been implemented in the laboratory of the Acoustics, Aalborg University. The principle idea behind the equalization method is to use loudspeakers covering one wall in a rectangular room to generate a plane wave that propagates through the room before it is actively absorbed by loudspeakers on the opposite wall. This approach is advantageous as reflections from the wall opposite the sound generating wall are avoided. Furthermore, reflections from the remaining surfaces are minimized, since the plane wave propagates perpendicular to the surfaces and a homogeneous sound field is obtained. The sound pressure is proportional to the volume velocity, which means that it is more economic with respect to membrane movement than anechoic playback, but less economic than pressure-field playback.

The implementation of the signal processing has previously been explained and verified by Santillan et al. [27], but at that stage, the complete test facility was not functional, and the ventilation system was not installed. Too many changes have been made to the room and loudspeaker units and equipment since then and new impulse response measurements are made in order to calculate a new set of filters for plane-wave playback. Therefore, the results will be different from those presented in [27].

This article will briefly explain the theory behind the equalization method and describe in more detail the implementation of the test facility including some improvements of the plane-wave playback at the lowest frequencies compared to the previous implementation [27]. Furthermore, a hybrid sound field is introduced, where the lowest frequencies are presented in a pressure field, while the higher frequencies are presented using plane-wave playback. This “playback mode” utilizes the best aspects of both pressure-field and plane-wave playback, namely homogeneity in the sound field and high efficiency at the lowest frequencies. Finally, the verification measurements of the complete test facility will be presented.

## 2. THEORY BEHIND THE PLAYBACK SYSTEM

In the following, a simplified approach to the principles behind the sound field control is presented.

### 2.1 Sound-field control using plane waves

Consider a rectangular piston occupying a full cross-sectional area of an infinitely long rectangular duct with perfectly smooth and rigid surfaces. If the piston moves in a sinusoidal manner (particle velocity in x-direction, $v_{1,x} = A \cdot \sin(2\pi \cdot f \cdot t)$), a plane wave will propagate through the duct. Since the plane wave propagates perpendicular to smooth and completely rigid surfaces there will be no absorption or reflection from any surface in the duct. This means that, if air absorption is neglected, the sound field is homogeneous in the duct as seen in Figure 1 (simulated using the finite-difference time-domain (FDTD) method [28])


Figure 1: Simulation of the sound field at 250 Hz generated by a square piston in an infinite duct.

If the duct is terminated in one end by a rigid surface, then the plane wave will be reflected and travel back towards the moving piston while interfering with the direct wave from the piston. When it reaches the moving piston, the amount of reflection/absorption will depend on the movement of the piston at that specific time. This scenario generates a standing wave pattern with pressure peaks and dips as seen in Figure 2. A pressure peak will exist at the reflecting surface, while a pressure dip will occur a quarter wavelength from the reflecting surface and another pressure peak half a wave-length from the reflecting surface and so forth.

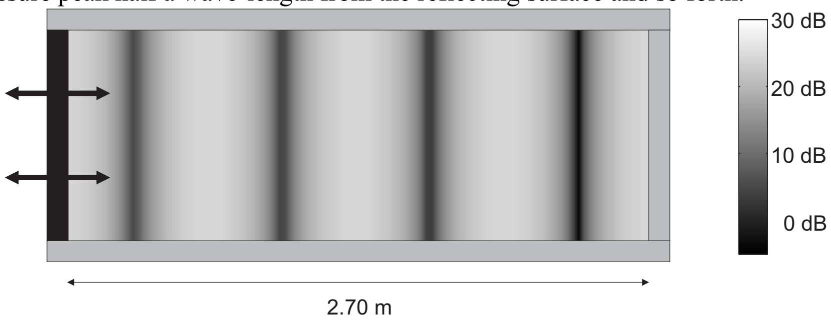


Figure 2: Simulation of the sound field at 250 Hz generated by a square piston in a duct terminated by a rigid surface.

Then imagine that the rigid termination is replaced by a rectangular piston moving with the same amplitude but 180 degrees out of phase with the other piston ( $v_{1,x} = A \cdot \sin(2\pi \cdot f \cdot t), v_{2,x} = -A \cdot \sin(2\pi \cdot f \cdot t)$ ). This will create a standing wave pattern, which is symmetric around the centre point between the two moving pistons as seen in Figure 3.

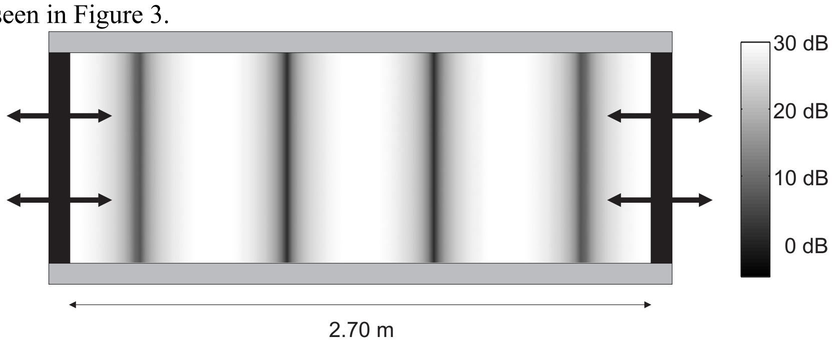


Figure 3: Simulation of the sound field at 250 Hz generated by two square pistons moving 180 degrees out of phase in a duct.

If the two pistons are moving with the same amplitude in phase ( $v_{1,x} = v_{2,x} = A \cdot \sin(2\pi \cdot f \cdot t)$ ) then the pressure at the midpoint between the two pistons will become zero since the two travelling waves will cancel each other out in this point, while another symmetric standing wave pattern will form in the rest of the duct as seen in Figure 4.

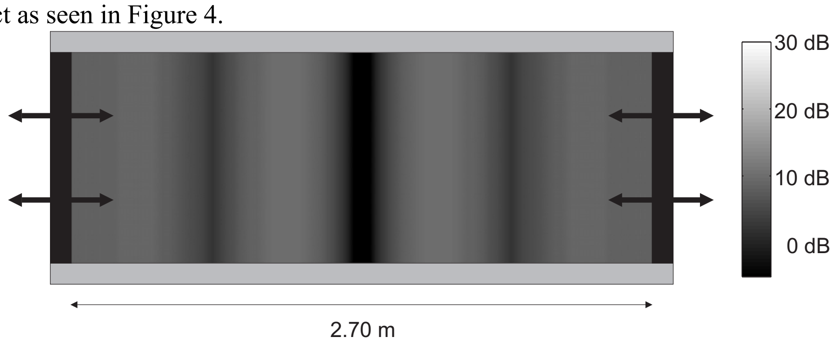


Figure 4: Simulation of the sound field at 250 Hz generated by two square pistons moving in phase in a duct.

However, if the second piston is moving similar to the first piston, however delayed by the time it takes the wave to travel from one piston to the other ( $v_{1,x} = A \cdot \sin(2\pi \cdot f \cdot t), v_{2,x} = A \cdot \sin(2\pi \cdot f \cdot (t - delay)), delay = 2.7m / c$ ), where $c$ is the speed of sound, then when the travelling wave reaches piston 2 it will be absorbed by the movement of piston 2. This means that the sound will only travel in one direction and no interference and therefore no standing wave patterns will occur as seen in Figure 5.

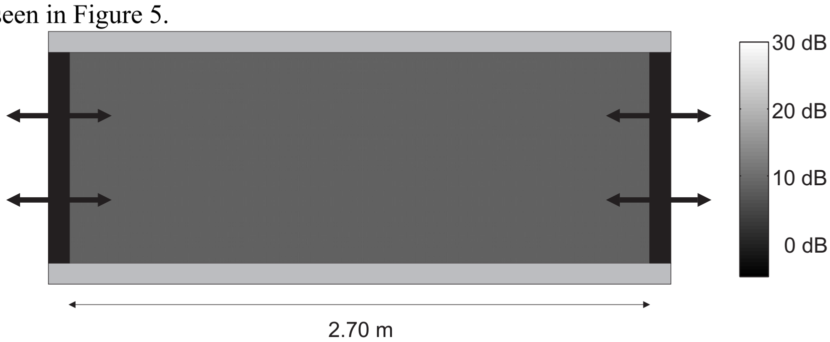


Figure 5: Simulation of the sound field at 250 Hz generated by two square pistons moving in phase (except for the propagation delay from one piston to the other) in a duct.

It is observed that this gives a sound-pressure distribution equivalent to the case where the duct was infinitely long as seen in Figure 1, and a homogeneous sound field is obtained. However, the pressure is in the order of 15 dB lower than the pressure found in the cases with termination (Figure 2) and in the order of 20 dB lower than the case with the pistons moving 180 degrees out of phase (Figure 3).

### 2.2 Filter design for plane-wave playback

The principle behind the sound field control using plane waves as described in section 2.1 works well in theory, but in practice, it is not that simple. First of all, it is not possible to create a square piston that covers a complete wall. Furthermore, rooms are rarely completely symmetrical. A practical implementation is to use a number of electro-dynamic loudspeakers distributed on two walls facing each other in a fairly symmetrical rectangular room. Any errors caused by the deficiencies in the physical setup are then minimized by the use of digital filters.

The method used for minimizing the errors is based on a multiple source multiple-error-sensor method, where the error terms are minimized using least-mean squares (LMS) [29]. Figure 6 shows the simplest case of multiple sources and multiple error sensors (two of each), where $x(n)$ is the input signal at sample number $n$, while $d_1(n)$ and $d_2(n)$ is the desired signal in error sensor position 1 and 2. The desired signals are delayed versions of $x(n)$, where the delays account for the time it takes the sound to travel to the error sensor positions. $\hat{d}_1(n)$ and $\hat{d}_2(n)$ are the measured signals at the error sensor positions and the differences between the measured and the desired signals are the errors, $e_1(n)$ and $e_2(n)$. The transfer functions from the sources to error-sensor position 1 are denoted $c_{11}(n)$ and $c_{21}(n)$ respectively, while the transfer-functions from the sources to error-sensor positions 2 are denoted $c_{12}(n)$ and $c_{22}(n)$ respectively. $h_1(n)$ and $h_2(n)$ are filters for each source that minimize the errors $e_1(n)$ and $e_2(n)$ in a least squares sense. The simple case can be extrapolated to any number of sources and error sensor positions.

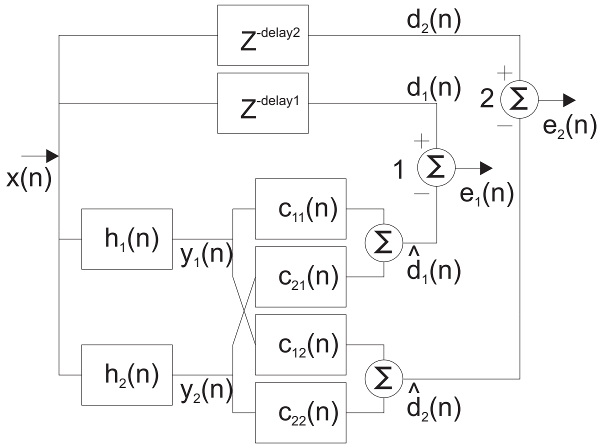


Figure 6: Block diagram of a two source, two error sensor position case. *x(n)* is the input signal, *d(n)* is the desired signal, *h(n)* is the filter that minimizes *e(n)* in least squares sense and *c(n)* is the transfer function from the source to the error sensor position. The block diagram can be extrapolated to any number of sources and error sensors.

In order to calculate filters for generation of a plane wave, the error sensor positions are arranged in two vertical planes perpendicular to the desired direction of the travelling plane wave as shown in Figure 7 (with only two error sensor positions and two sound sources for simplicity). Ideally, the desired signal in the planes is a Dirac delta function with a delay between the two planes, which would result in a flat frequency response. The delay between the planes must correspond to the time it takes the sound to travel the distance between the planes and for practical reasons it should be an integer sample delay.

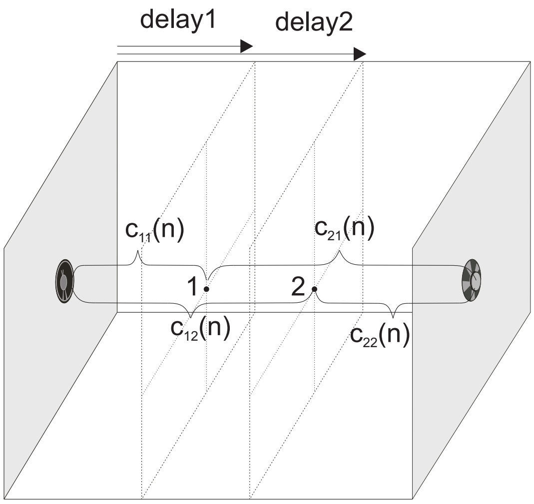


Figure 7: Illustration showing the placement of vertical planes in a rectangular room for generation of a plane wave. Here the simplified version from Figure 6 with two loudspeakers and two error-sensor positions (denoted 1 and 2) is shown with the corresponding impulse responses *c(n)*.

## 3. DESIGN AND IMPLEMENTATION OF THE TEST FACILITY

### 3.1 Room

The room is a double box construction where the inner room has the dimensions 2.68 m x 2.70 m x 2.38 m (see Figure 8). The walls are made of concrete covered with thick white paint in order to reduce leakage of air through the concrete. The two loudspeaker "walls" each consist of 20 electro-dynamic loudspeakers distributed in five columns of four units. The baffle for each column is made from MDF bolted to a metal frame. The 20 loudspeakers on a wall share the same back-volume (0.75 m x 2.60 m x 2.38 m). The boundaries of the back volumes are covered with mineral wool in order to minimize standing waves (at higher frequencies) inside the volume. The walls, door and the ceiling are covered with sound absorbing material that minimizes reflections at higher frequencies. The arrangement of the loudspeakers on each wall has been optimized for plane wave generation with the limitations introduced by the physical placement of the ventilation inlet and outlet [27]. Metal frames with grey fabric are used to cover each loudspeaker wall in order to hide the sound generation.

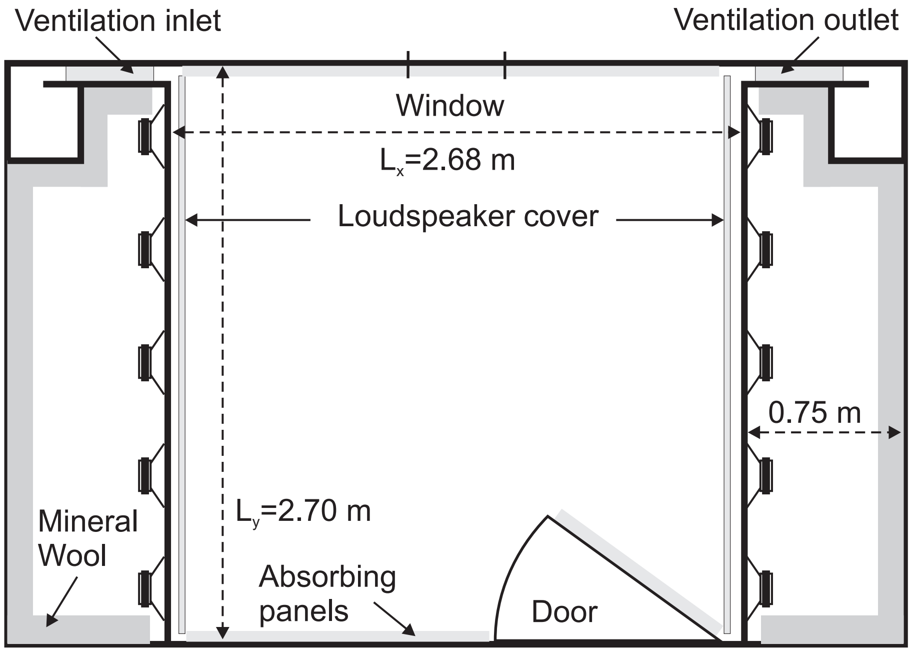


Figure 8: Diagram of the low-frequency room seen from above.

### 3.2 Ventilation system

The room is coupled to the main ventilation system of the laboratory through an inlet and an outlet duct with over- and under-pressure respectively. The ventilation system is designed to have low noise while providing sufficient fresh air for test subjects and cooling. Ideally, the room should be as airtight as possible in order to prevent the sound from "escaping". However, it is not possible to ventilate an airtight room. But if a small controlled leakage is allowed it is possible to get sufficient air while preventing all but the lowest frequencies from escaping through the leakage. The controlled leakage is obtained by placing a specific amount of filter-material in the inlet and outlet of the room. The filter material also helps attenuating the noise from the ventilator fans (together with the ventilation ducts lined with mineral wool). The ventilation system is designed for giving sufficient air for breathing and cooling for two persons in the room. With an intake temperature of 14 degrees centigrade and an approximate heat generation of 300 W (two persons of 100 W each and light of 100 W) this requires a minimum airflow of approx. 150 $m^3$/hour to keep the room temperature at 20 degrees centigrade. An airflow of 150 $m^3$/hour is considered by far to be sufficient for keeping the air fresh. The lower limiting frequency is chosen to 0.2 Hz, which requires a resistance for each leakage (inlet and outlet) in the order of 13100 $N/m^5$. With the chosen filter material ("CC 600G" from Camfill A/S, specific acoustic resistance of 4000 $Ns/m^4$ and the area of the cross-section of the inlet/outlet (0.189$m^2$) this requires a thickness of 0.62 m or 31 filters in each side. The pressure difference over the filter material required for obtaining an airflow of approx. 150 $m^3$/hour is approx. 540 Pa ($N/m^2$). The ventilator fans are capable of maintaining a pressure in the order of 700 Pa, which is more than sufficient for keeping the minimum airflow. However, the ventilation system proved to be a difficult challenge and eventually delayed the use of the room for more than a year. First of all, it was observed that very little air went through room. Large leakages in the concrete ducts leading to and from the room were found and sealed until a pressure in the order of 500 Pa could be maintained behind the inlet/outlet filters (large leakages in the whole laboratory ventilation system were found and sealed in the same process). One filter was removed from each side and the resulting airflow is in the order of 140 $m^3$/hour (and a lower limiting frequency of 0.21 Hz), which is enough for removing 280 W of heat. Therefore, low-power bulbs were installed in the ceiling in order to maintain enough cooling for two persons with the light on. .

After several months, a degradation of the sound field obtained with the plane-wave playback was observed. It was discovered that leakages had developed from the ventilation ducts into the back-volumes thereby creating a significant pressure difference over the loudspeaker units, which moved the diaphragms out of equilibrium and even made leakages in some diaphragms. After this discovery, all old sealing material was removed and new sealing was applied in now sufficient quantities. Furthermore, an airtight rubber membrane was applied in the floor of each back volume and the leaking membranes were sealed with silicone. Pressure gauges were installed so that pressure difference between back volumes and room (should be zero) and pressure difference over the ventilation filters (should be high enough to ensure sufficient air being pushed through the filter material) can be monitored.

### 3.3 Equipment

The equipment for the test facility consists of a computer with two digital multi-channel soundcards connected to five eight-channel D/A-converters connected to eight six-channel power-amplifiers that drive the 40 loudspeakers. A block diagram of the system is shown in Figure 9.

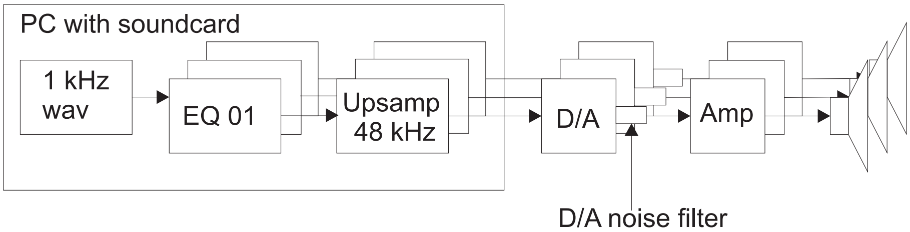


Figure 9: Block diagram of the equipment used for the test facility.

#### 3.3.1 Computer and sound card

The computer is a Pentium 4 3.2 GHz PC with 2.5 GB RAM running Windows XP SP2. It has two RME 9652 Hammerfall 24-bit digital soundcards with 48 channels on ADAT outputs. The soundcards are controlled through ASIO 2.0 drivers that offer low latencies and full control of the audio playback with little load on the CPU. All the channels are completely sample aligned, which is important for the plane-wave playback.

#### 3.3.2 D/A-converters

The D/A-converters consists of five Swissonic 24-bit 48 kHz eight-channel D/A-converters. The converters are DC-coupled and deliver in the order of 7 volt r.m.s. for a full-scale sinusoidal signal. The converters had to be modified, since they by default utilize the "Auto-mute" feature of the Crystal CS 4390 D/A-converter chip. This feature turns off the output if no sound is send to the D/A-converters. However, the switching between on and off during operation results in small changes of the DC value at the output, which result in audible clicks at the output. For this reason, every channel was modified in order to turn this feature off. This modification results in a higher noise floor, when no signal is present. In order to reduce this high-frequency noise an analogue passive 1st order low-pass filter with a -3 dB frequency of 530 Hz was inserted in the connector of the cables to the power amplifiers.

#### 3.3.3 Power amplifiers

The power amplifiers consists of eight six-channel Rotel RB-976 MK II power amplifiers that are capable of delivering 70 W per channel if only five channels are used (which is the case in this setup). These amplifiers are not DC-coupled and they had to be modified in several ways before they worked satisfactory. A digital controllable volume control with fixed gains of -40, 0 and +6 dB was made and the high-pass filter was changed from 4 Hz to 1.6 Hz, which was the lowest frequency possible for stable operation. A 100 Hz (and higher harmonics) hum problem, which originated from ripple from the power supply was lowered by inserting voltage regulators for the power supply to the line-driver side of the amplifiers. Further reduction of the hum was obtained by lowering the internal gain (from 26 dB to 17 dB) and the total attenuation of the 100 Hz was in the order of 45 dB. This modification also removed a problem, where the signal was distorted in all right channels of the power amplifiers when driving the power amplifier close to maximum at very low frequencies (<10 Hz).

### 3.3.4 Loudspeakers

The 40 loudspeakers are of the type Seas 33F-WKA 13 inch woofers rated at 70 W. They were chosen because of their ability to move large amounts of air with low distortion (these are the same type as was used for the first infrasound chamber at Aalborg University [8]). The 40 loudspeakers were all connected to move into the room when positive DC is applied. The loudspeakers had to be tested for off-centre suspension and leakages. Off-centre suspension was found by moving the diaphragm in and out gently by the hand. If the suspension is off-centre a scraping sound is heard when the coil rubs against the magnet. These loudspeakers had to be replaced. Leakages were found by exiting the loudspeakers by a strong 5 Hz signal and listening for swishing sounds. In some cases, leakages were found in the dust cab mount and these were sealed by applying small amounts of silicone.

## 3.4 Filter design

### 3.4.1 Impulse response measurements

As mentioned in section 2.2 the microphone positions should be in two vertical planes perpendicular to the direction of the plane wave. The vertical planes were chosen; one in a distance of 1.032 m from the sound generating wall and the next at a distance of 1.370 m which corresponds to three and four sample periods at 1 kHz. The microphone positions where distributed in the two planes with 36 positions in each with a vertical distance of 0.390 m and a horizontal distance of 0.453 m. This grid of 36 microphone positions in each plane had proven to be sufficient [27] for obtaining good sound field control.

The impulse responses from each of the 40 loudspeakers to each of the 72 microphone positions (a total of 2880 measurement) were measured using MLSSA, with a GRAS 40EN 1-inch microphone with a GRAS AK26 preamplifier connected to a B & K Nexus 6290 conditioning amplifier (combined -3 dB lower limiting frequency < 1 Hz). The impulse responses were measured at 4 kHz with an MLS order of 12 with 16 pre-averages. During the measurements, the remaining loudspeakers were all connected to their power amplifier channel (with D/A-converters and computer turned on) in order to keep them in equilibrium and act more stiff (approximating a reflective wall). Otherwise, significant measurement errors would occur, as they would move during the measurements.

The measured impulse responses were down-sampled from 4 to 1 kHz using the 'resample' function in Matlab, which uses linear-phase filters.

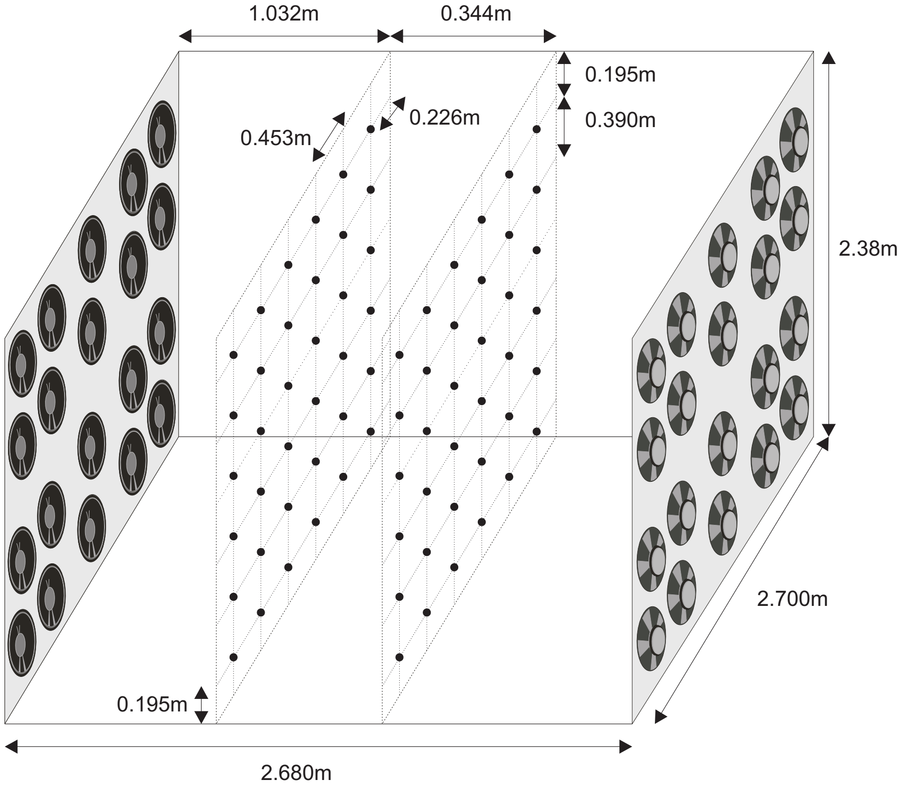


Figure 10: Measurement points for impulse response measurements used for calculation of filters.

### 3.4.2 DC-correction of measured impulse responses

The measurement system is measuring very low in frequency and consequently the measurements are affected by wind-noise and other very low-frequent noises. Because of the limitations imposed by the measurement signal and duration, the measured impulse responses are affected at the lowest frequencies down to DC. Therefore, measurements were only made with the ventilation system turned off on quiet days where wind speeds were below approx. 5 ms. During the measurements the frequency responses were often inspected and measurements were remade if they were significantly affected by noise. Since the impulse responses should not contain any DC as both the room and the power-amplifiers have a lower limiting frequency, they were all corrected to have a DC-value of zero.

### 3.4.3 Plane-wave playback

The filters for the plane-wave playback were calculated in Matlab by minimizing the squared error between the measured and the desired response in the microphone positions as explained in section 2.2.

From the earlier implementation [27], it was observed that there were deviations in the sound field at the lowest frequencies especially below approx 20 Hz. It was later discovered that these deviations are the by-product of the ideal approach of trying to minimize the error all the way down to DC, which is not physically possible and at that time no DC correction of the measured impulse responses was applied. Filter errors at DC do not only affect the DC component, but also influence the interpolated values between exact filter frequencies at low frequencies as well (for examples of this see [30] pp. 242). The solution to this problem was (besides DC-correction) to high-pass filter the desired signal in the microphone positions with a first order Butterworth filter with a lower -3 dB frequency at 1.6 Hz corresponding to that of the power-amplifiers used in the system as seen in Figure 11. By doing this, the filter algorithm tries to match the physical response limited by the amplifiers instead of boosting the lowest frequencies down to DC. Furthermore, the desired signal was generated at 4 kHz and resampled to 1 kHz using the same filters as for the measured impulse-responses. Finally, the desired signal was low-pass filtered using a filter with a 480 Hz cut off frequency in order to attenuate the highest frequencies near the Nyquist frequency (500 Hz) in the filter design. These frequencies are in a critical frequency range that can potentially be audible. The advantage of using this low-pass filter at 480 Hz introduces is questionable as the attenuation is not large and pre- and post ringing of the desired signal is observed. In future calculations, this filter should be modified or removed completely.

The delay between the two vertical planes of microphone positions was set to the physical delay of 1 ms, while the delay from the loudspeaker wall should be set to at least 3 ms, which is the physical delay in the measurement setup. For the implemented filters, a delay of 9 ms was used as this gave the optimal load-distribution on the loudspeakers (see the discussion for more details on this).

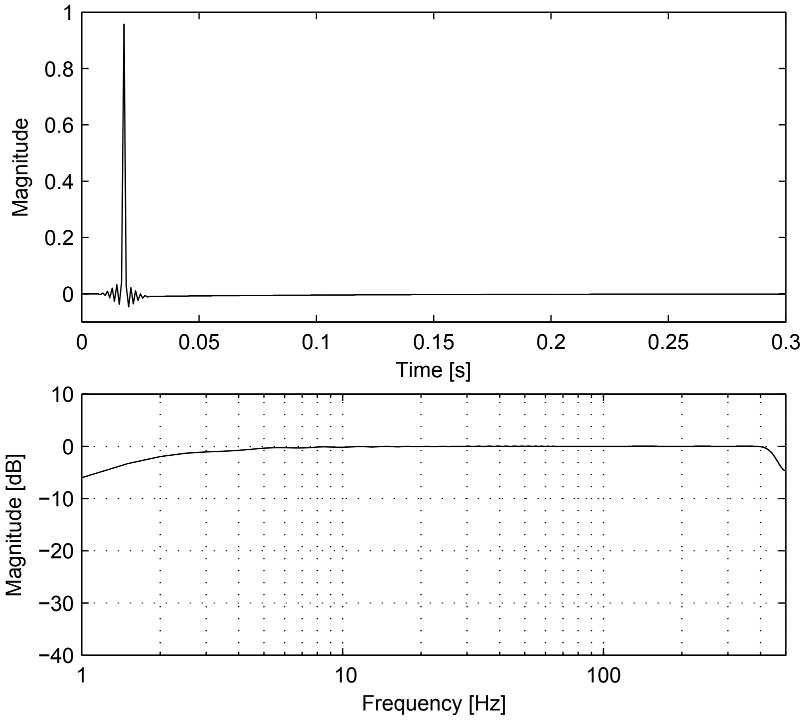


Figure 11: Desired signal in the error sensor position in the first plane and it's corresponding frequency response.

### 3.4.4 Pressure-field playback

Pressure-field playback does not require any filters as it is obtained simply by sending the same signal to all of the 40 loudspeakers. This approximates the theoretical conditions seen in Figure 3 where the standing wave pattern is symmetrical around the midpoint between the two loudspeaker walls. At wavelengths considerable larger than the dimensions of the room the sound field is homogeneous.

### 3.4.5 Hybrid-field playback

The idea of the hybrid field is to combine the efficiency of the pressure-field playback at the very low frequencies with the homogeneous sound field from the plane-wave playback at the higher frequencies. The pressure-field playback only gives a homogeneous sound field up to approx. 30 Hz, so above this frequency the plane-wave playback must be used in order to maintain a homogeneous sound field. The hybrid field is implemented as a set of crossover filters, where the lowest frequencies are sent directly to the loudspeakers while the higher frequencies are sent through the plane-wave playback filters before going to the loudspeakers.

The crossover filters are implemented as Linkwitz Riley crossover filters [31] because these types of filters have equal shape of the phase responses, which is critical in the implemented sound field control. As an example for this article, a pair of second-order filters with a crossover frequency of 10 Hz was chosen so that the plane wave becomes dominant before larger spatial variations in the sound field occur (which happens from approx. 60 Hz), but other designs can be implemented depending on the requirements.

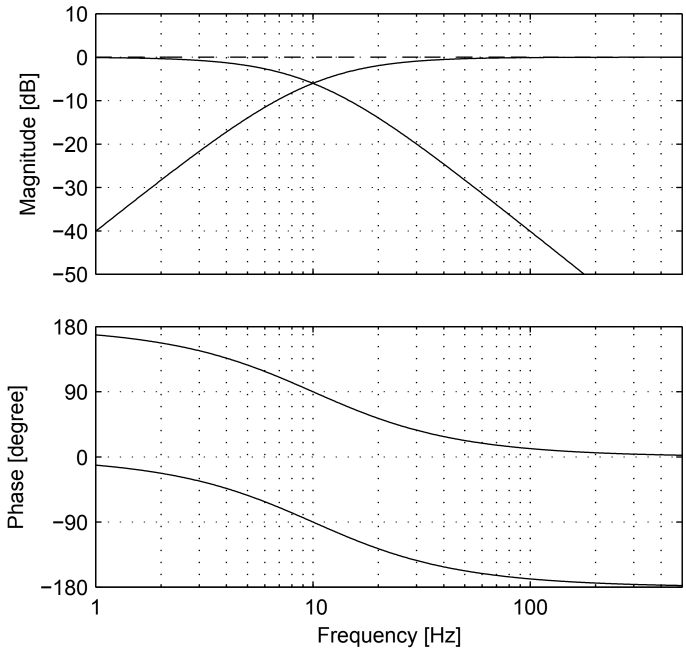


Figure 12: Magnitude and phase response of the 2nd-order cross-over filters for implementation of the hybrid-field playback.

### 3.5 Real-time processing

The signal processing was implemented as a real-time processing of the unfiltered wave files on the computer (see Figure 9). The input signal to the system is a monophonic 16 or 32-bit PCM wave file with a sampling frequency of 1 kHz, and the plane-wave playback filtering for each channel is done at 1 kHz before upsampling to 48 kHz and applying an anti-aliasing filter. This anti-aliasing filter must have an extremely high attenuation in the stop band since playback of e.g. a 10 Hz tone at 125 dB will give an aliasing artefact at 990 Hz (and 1010 Hz etc.) which would be audible if it is not attenuated in the order of 123 dB. For this purpose, the filter was implemented as a windowed linear-phase FIR filter of 960 taps at 48 kHz. This filter has a wide transition band with a -3 dB frequency at 370 Hz, but attenuates in the order of 130 dB in the stop band as seen in Figure 13. Because of the poly-phase implementation of the filter, the filtering only requires convolution of 20 filter taps at 48 kHz for each channel.

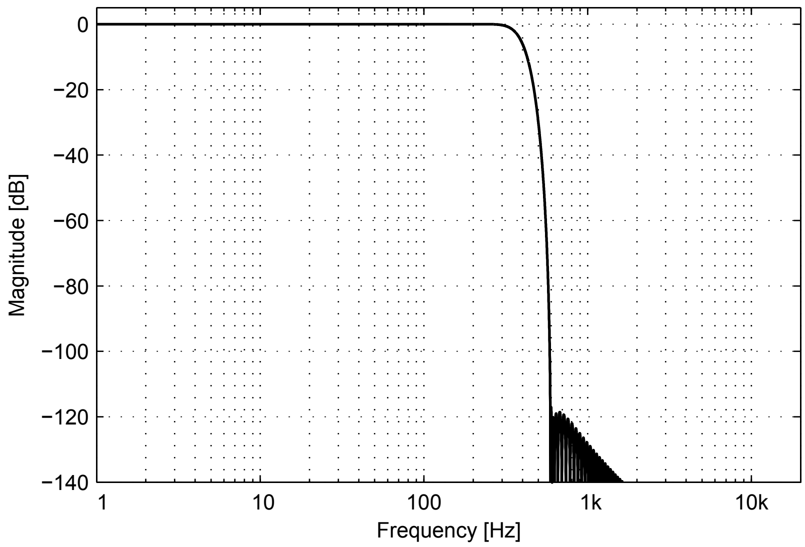


Figure 13: Frequency response of the filter used in the upsampling of the 1 kHz signal to 48 kHz.

## 4. VERIFICATION OF THE TEST FACILITY

In the following, the important parameters of the test facility were verified through measurements.

### 4.1 Background noise

Several sources can contribute to the overall background noise level in the room such as ventilation system, power amplifiers and D/A-converters. Background noise measurements were performed in the centre of the room, which is assumed to be the normal listening position. The noise was measured using a B & K 2660 microphone and preamplifier set connected to a B & K 2133 frequency analyzer. The background noise from the D/A-converters and power amplifiers is shown in Figure 14. The background noise from the ventilation system is shown in Figure 15 with the D/A-converters and power amplifiers turned on.

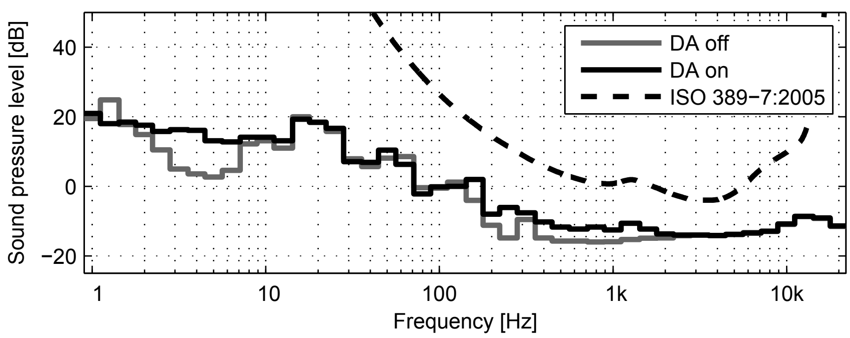


Figure 14: Third-octave spectrum of noise measured in the room with (black) and without (grey) the D/A-converters. The dashed black curve shows the diffuse-field hearing threshold [32]. The increase in noise levels from the D/A-converters is seen in the frequency range from approx. 200-2000 Hz. Above approx. 2 kHz the measured levels are the noise-floor of the microphone and preamplifier.

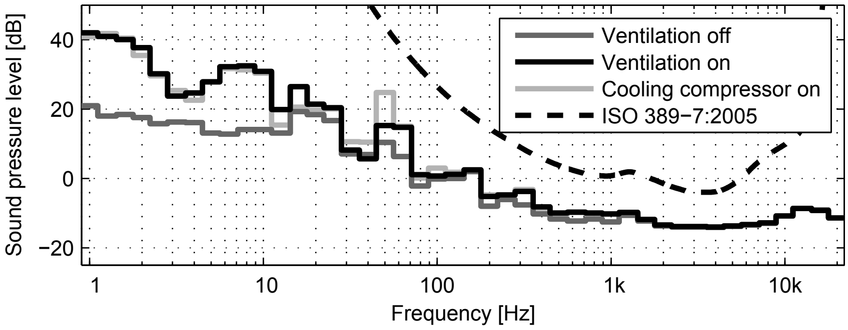


Figure 15: Third-octave spectrum of the background noise measured at the listening position: Ventilation off (dark grey), Ventilation on (black) and cooling crompressor and ventilation on (light grey). The dashed black curve shows the diffuse-field hearing threshold [32]. Above approx. 2 kHz the measured levels are the noise-floor of the microphone and preamplifier.

As seen in the figure the ventilation system mainly contributes to the noise at the lowest frequencies, while the cooling compressor has a 50 Hz component. For the complete low-frequency region, the background noise level is more than 10 dB below the diffuse-field hearing threshold [32] for each third-octave level. During use the cooling compressor is rarely running and it is seen that for frequencies below 100 Hz the noise is more than 20 dB below the threshold and much more in the infrasound region.

### 4.2 The sound field

The sound pressure distribution inside the room was measured by impulse response measurements of the system in 5 vertical planes (placed with a distance of 0.344 m in between) of 36 measurement points in each covering most of the space inside the room from 0.69-2.06 m (distance from loudspeaker wall) (except for the area in front of the door). The measurements were performed using a Matlab generated 14 order MLS played back through the playback system and MLSSA was measuring in *asynchronous cross-correlation* mode with an external clock of 8 kHz generated from the soundcard of the playback system. Measuring in asynchronous cross-correlation mode means that the initial delay in the measured responses is arbitrary. In order to give a better spatial resolution (mainly relevant for higher frequencies), a finer measurement grid of 6*19 points was used for measurements in the horizontal plane at 0.34-2.41 m (distance from front loudspeaker wall), 0.23-2.49 (from side wall) in the height of 1.35 m (except for six points in the area where the door opens inward).

The sound pressure distribution in this horizontal plane is plotted for several frequencies for each playback mode in the following.

### 4.2.1 Pressure-field playback sound pressure distribution

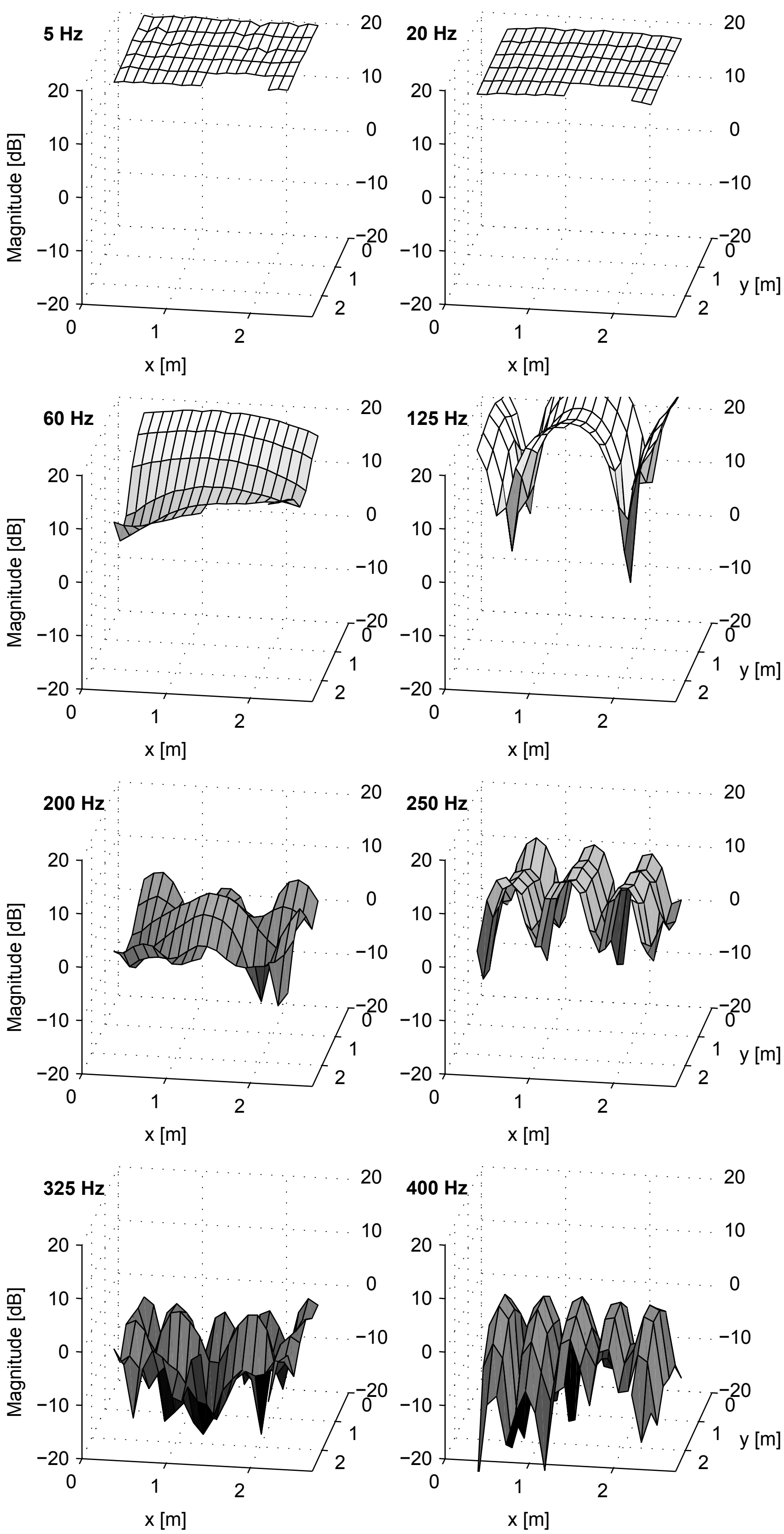


Figure 16: Sound pressure distribution in the horizontal plane at 1.35 m for pressure-field playback for eight different frequencies.

### 4.2.2 Plane-wave playback sound pressure distribution

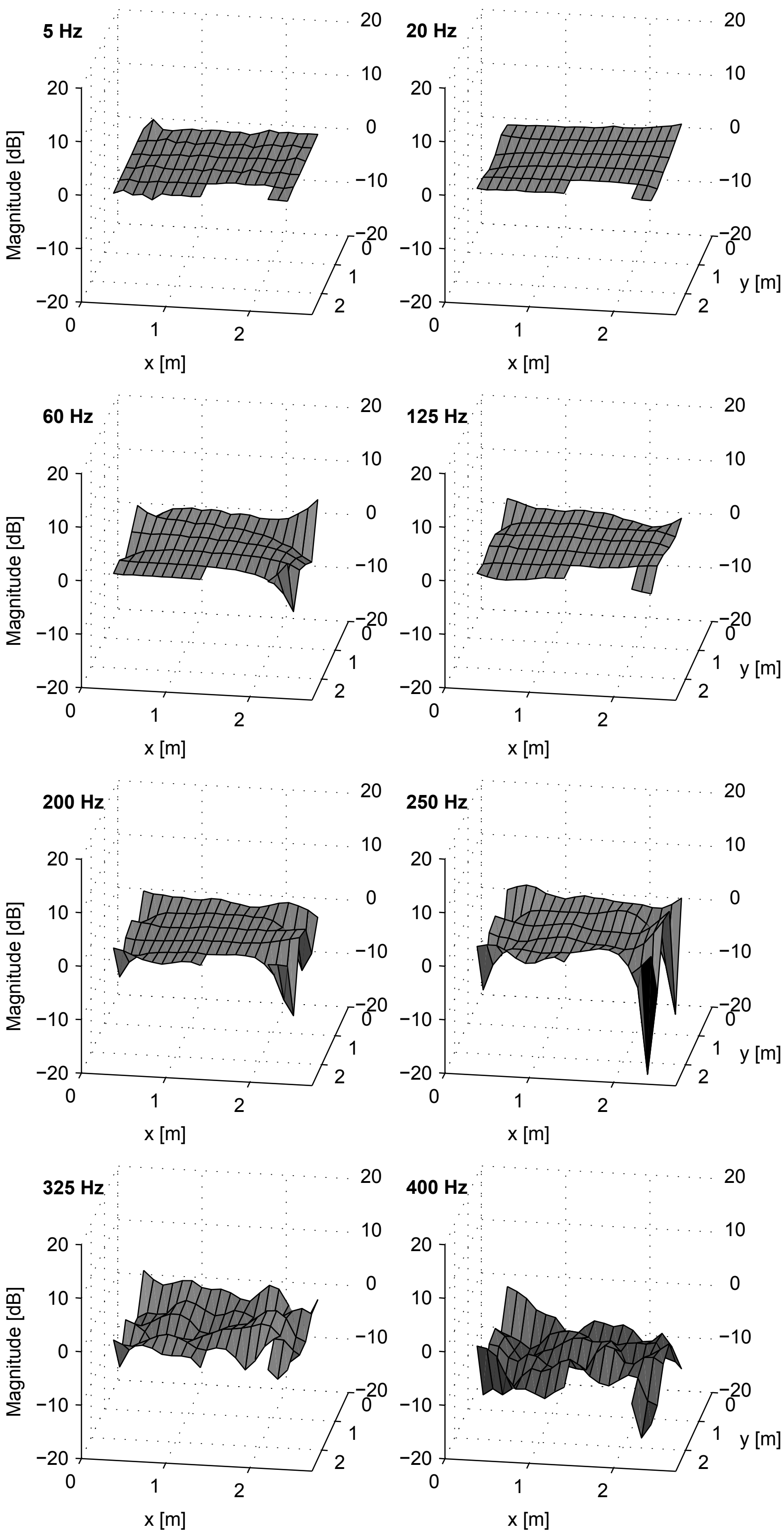


Figure 17: Sound pressure distribution in the horizontal plane at 1.35 m for plane-wave playback for eight different frequencies.

### 4.2.3 Hybrid-field sound pressure distribution

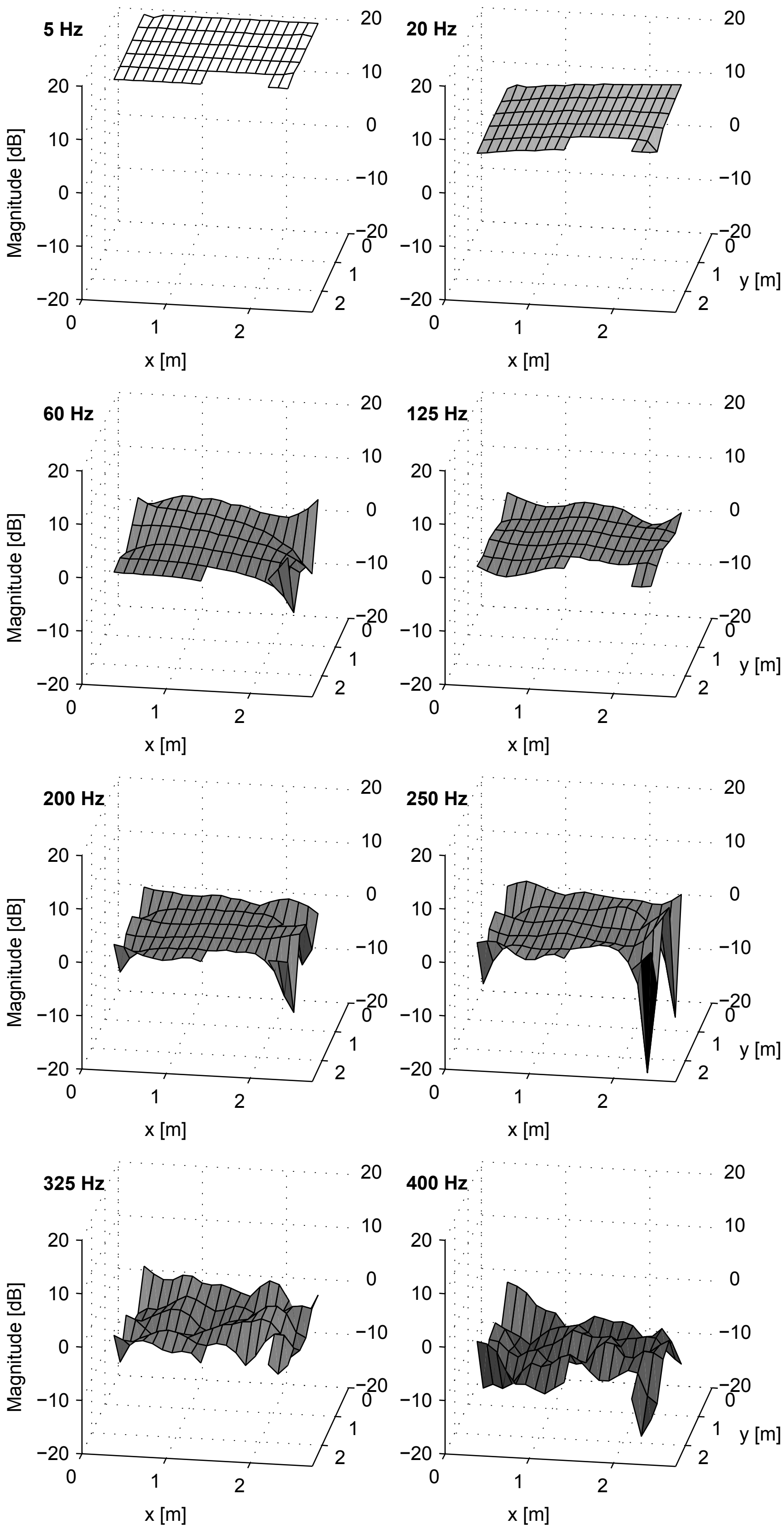


Figure 18: Sound pressure distribution in the horizontal plane at 1.35 m for hybrid-field playback for eight different frequencies.

### 4.2.4 Level variation

The level variation for the horizontal plane at 1.35 m is shown in Figure 19 calculated as the difference between maximum and minimum level in dB frequency by frequency for each playback mode for the whole plane, a large listening zone going from the first control plane to the back 0.80-1.72 m from front loudspeaker wall, 0.68-2.06 m from side wall, and finally an optimal listening zone in the centre of the room 1.15-1.49 m from front loudspeaker wall, 1.13-1.59 m from side wall.

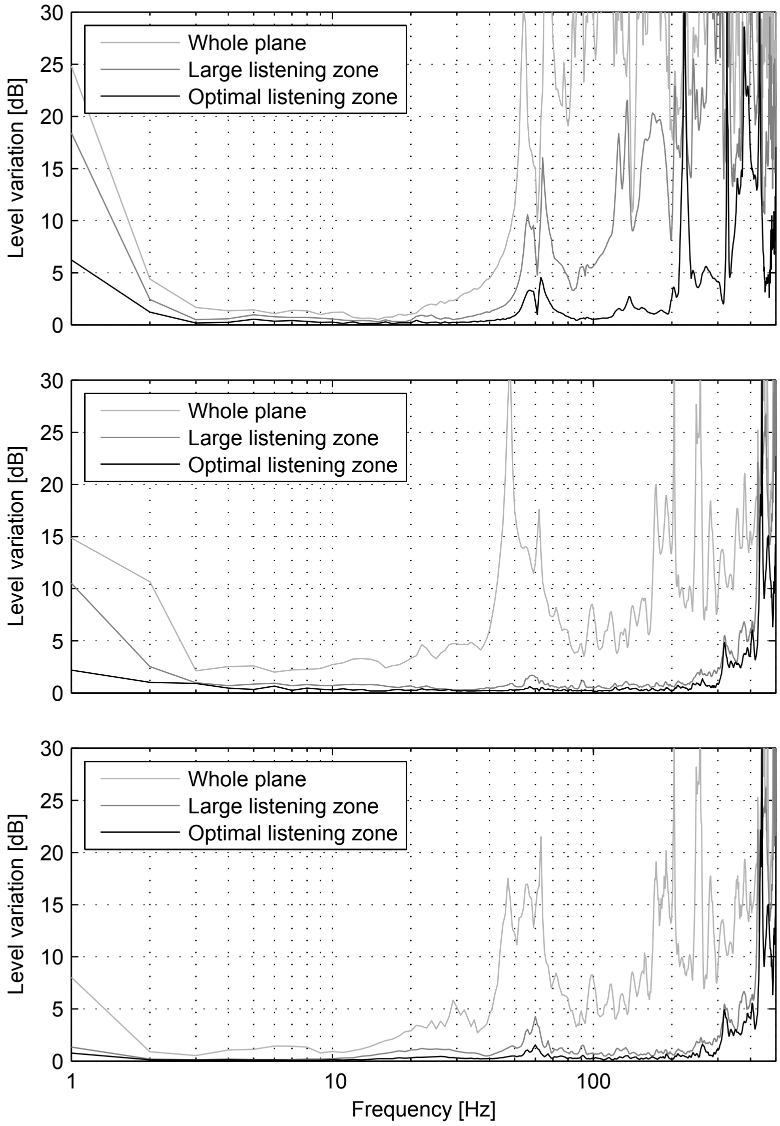


Figure 19: Level variation frequency by frequency for different areas of the horizontal plane using pressure-field (top), plane-wave playback (middle) and hybrid-field playback (bottom).

### 4.3 Time and frequency responses

Examples of the impulse response of each playback mode to a position in the optimal listening zone in the centre of the room are shown in Figure 20 and their respective frequency responses are shown in Figure 21. Time-frequency responses of the same measurements are shown as cumulative spectral decay plots in Figure 22.

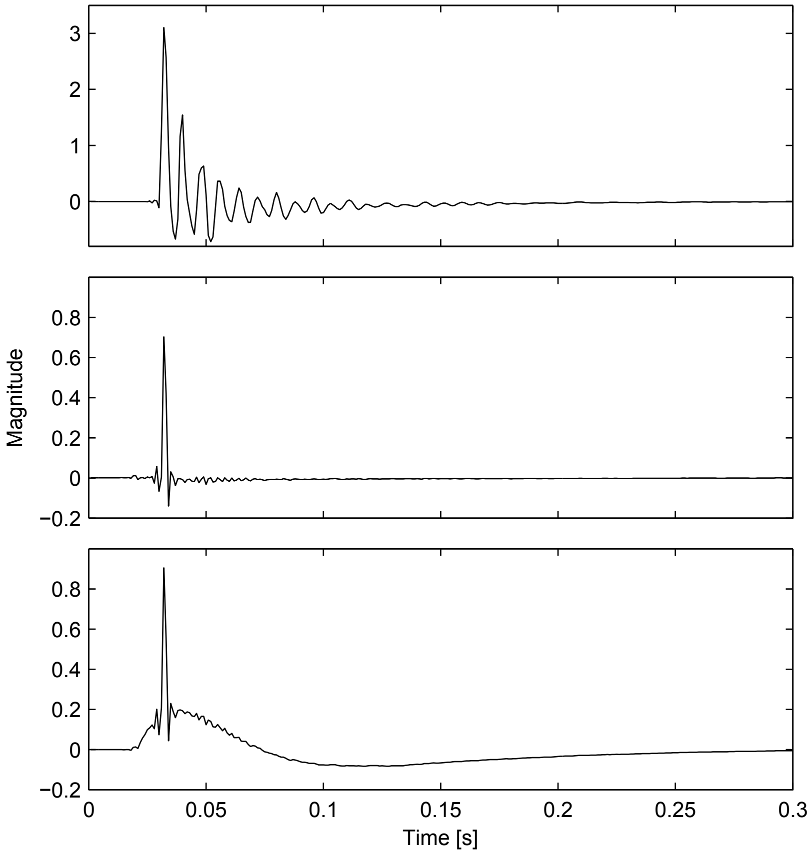


Figure 20: Impulse responses measured near the centre of the room in the horizontal plane at 1.35 m for pressuref-field, plane-wave and hybrid-field playback. Note that the delay before the impulse on the time axis is arbitrary.

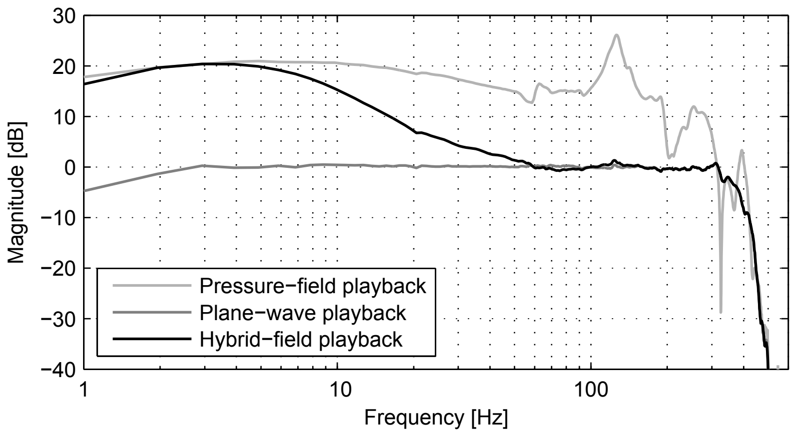


Figure 21: Frequency response near the center of the plane for pressure-field playback (light grey), plane-wave playback (black) and hybrid-field playback (dark grey).

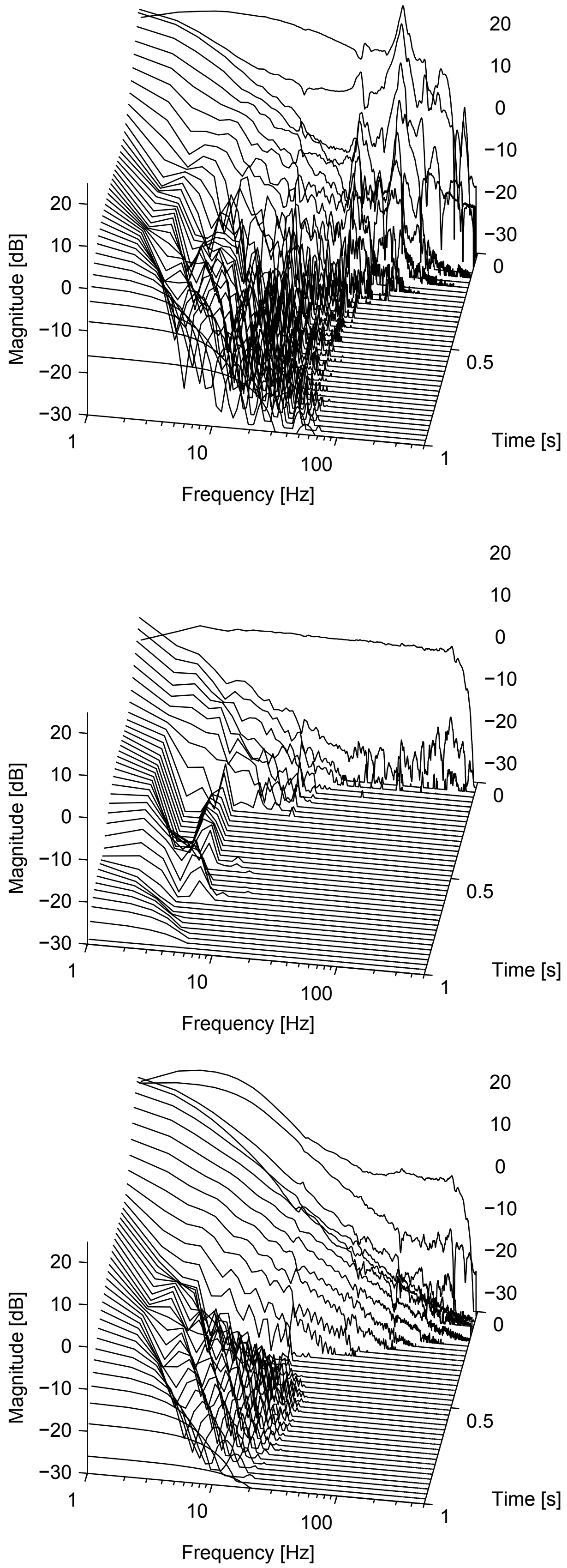


Figure 22: Cumulative spectral decay for the three playback modes: pressure-field playback, plane-wave playback and hybrid-field playback. Note that the delay before the first response on the time axis is arbitrary.

### 4.4 Maximum sound pressure levels and harmonic distortion

The maximum sound pressure level is frequency dependant and is determined by the maximum permissible distortion. Because of the steep slope of the hearing threshold at low frequencies the harmonic distortion is in a frequency range where the hearing is much more sensitive compared to the frequency of the fundamental tone. Therefore, the acceptable limits for distortion have been set rather strict; namely -30 dB for the second harmonic, -40 dB for the third harmonic and -50 dB for higher harmonics. For threshold experiments, this ensures that the fundamental tone will be audible before the higher harmonic components are audible. The maximum sound pressure levels are found by increasing the level until one of the harmonics reaches the specified limit. The measurements in the listening position for pressure-field and plane-wave playback are shown in Figure 23 and Figure 24 respectively.

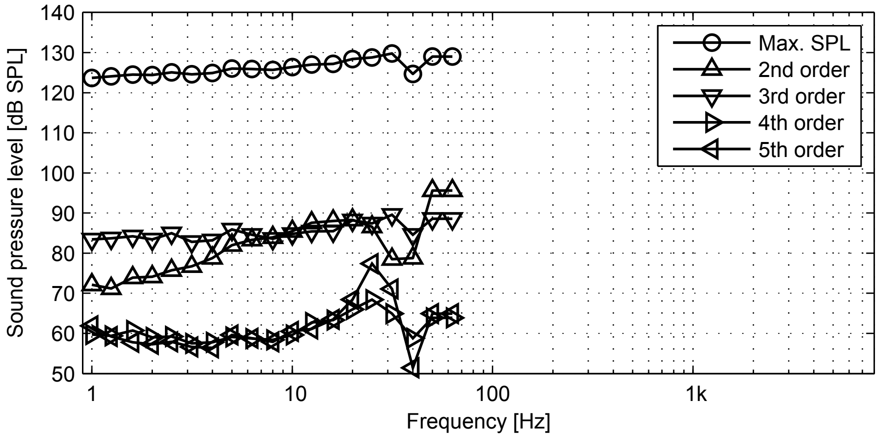


Figure 23: Maximum sound pressure level and harmonic distortion for pressure-field playback measured in the "listening position".

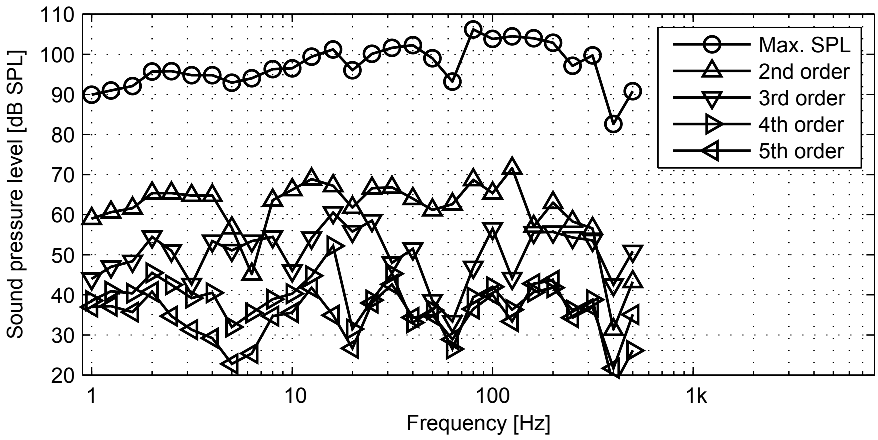


Figure 24: Maximum sound pressure level and harmonic distortion for plane-wave playback measured in the "listening position".

### 5. DISCUSSION

The influence of standing waves is one of the issues to solve in reproduction of sound in a room. It is the reflections in the room that causes the large pressure variations and these variations can only be minimized by removing the reflections. Using one wall of loudspeakers in a rectangular room to generate a plane wave and another wall to absorb the wave again is one solution that effectively removes the reflections in a wide frequency range. This can be seen in the cumulative spectral decay in Figure 22, where generally only background noise is seen after the initial flat response for the plane-wave playback.

The previous implementation of the plane-wave playback presented in [27] showed significant pressure variations below approx. 20 Hz as explained in section 3.4.3. The solution of applying DC-correction to the measured impulse responses and high-pass filtering of the desired signal in order to approach the physical conditions for the filter calculation has solved this problem as seen in the pressure-variation plots in Figure 19. The variations seen below 2 Hz are due to low signal-to-noise ratio in the verification measurements and are not related to variations in the reproduced sound field (measurements not made simultaneously). The present implementation is compared to the previous implementation in Figure 25 for the same area in the room (optimal listening area). Even in this quite limited area, it is seen that the plane-wave playback is improved considerably at frequencies below approx. 60 Hz compared to the previous implementation where there are considerable variation in the sound field increasing with decreasing frequency.

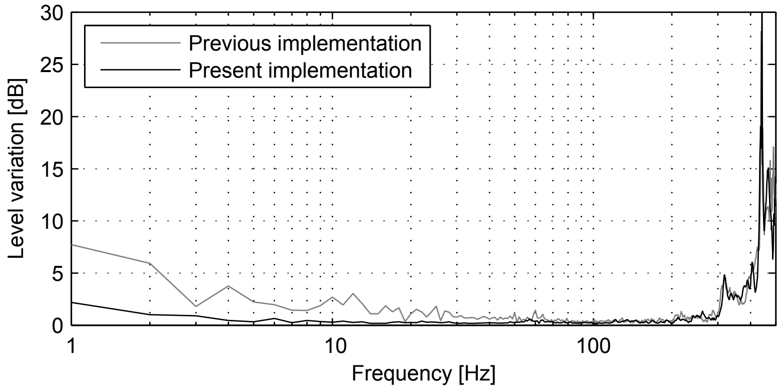


Figure 25: Level variation in the optimal listening area for the previous implementation [27] and the present implementation.

From Figure 19 it can be seen that the sound field in the plane-wave playback is homogenous in the frequency from 2-300 Hz with maximum deviations of ±1 dB for a large part of the room (large listening zone 0.80-1.72 m from front loudspeaker wall, 0.68-2.06 m from sidewall). In the optimal listening zone (1.15-1.49 m from front loudspeaker wall, 1.13-1.59 m) the sound field in the frequency range 2-400 Hz has deviations of maximum ±2.5 dB.

As seen in Figure 19 the sound field in the hybrid-field playback is homogenous for the same frequency range as for the plane-wave playback except for the region around 60 Hz, where both sound-fields contribute equally to the sound field. However, for the optimal listening zone the deviations become negligible. This playback mode does not have a flat frequency response as seen in Figure 21 so equalization of the input wave-files is required in order to obtain an overall flat response.

Several factors significantly affect the performance of the test facility. The higher frequency limits for the plane wave reproduction depends on the distance between the loudspeakers and on the distance between the measurement points used for the filter calculation. This is covered in detail in [27].

The limitations on frequency and dynamic range are closely related, especially at the lowest frequencies. The lower limiting frequency of the test facility is determined by how airtight the room is. The largest contribution to leakage comes from the ventilation ducts, and it can be controlled by adjusting the amount of filter material as explained in section 3.2. However, the dynamic range is severely limited by the maximum displacement of the loudspeakers, and therefore depends on the playback mode.

The plane-wave playback is quite inefficient with regard to reproducing high sound pressure levels. From the frequency responses shown in Figure 21, it is seen that for the same input to the playback system the playback level is in the order of 20 dB below that of the pressure-field playback. This seriously affects the maximum sound pressure level as seen in Figure 24. For studies of human hearing at the lowest frequencies, this is a problem since it is not possible to reproduce sound above the average hearing threshold below 10 Hz as seen in Figure 26. For this purpose, the hybrid-field playback is the optimal playback mode, since it utilizes the efficiency of the pressure-field playback at the lowest frequencies. A rough estimate of the maximum playback with the current crossover filters is also shown in Figure 26. For this mode, it is possible to reproduce levels above the average hearing threshold down to approx. 2 Hz without significant distortion.

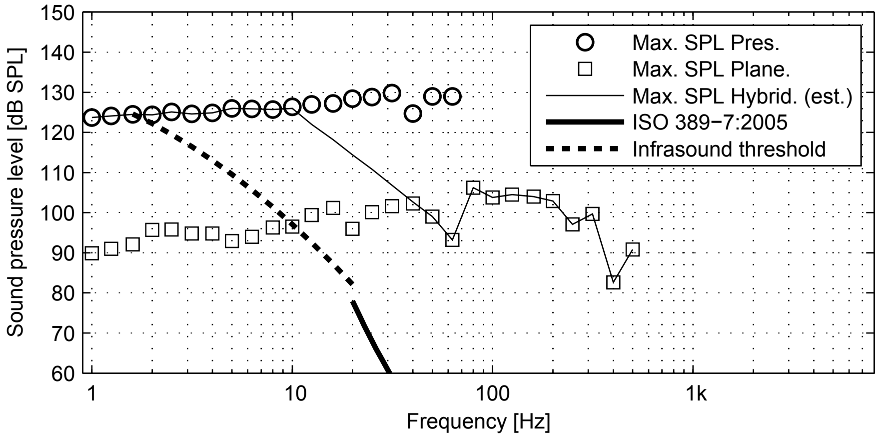


Figure 26: Maximum playback levels and a rought estimate of the maximum playback level for the hybrid-field playback compared to the normal hearing threshold and an infrasound threshold based on [33] with additional data from [34], [35] and [36].

The performance of the plane-wave playback is also affected by the magnitude response of the calculated filters. There is at the moment no way of balancing the load between the loudspeakers in the filter calculation algorithm. The algorithm merely calculates the set of 40 filters that mathematically minimizes the error at the sensor positions. This can give some complications in the physical setup. If for example the smallest error is found by using a set of filters where only two loudspeakers generate the sound, then the algorithm gives that solution. This means that these loudspeakers have much more load than the rest of the loudspeakers, and therefore the dynamic range of the system will be limited by harmonic distortion from these two speakers. For this reason, a number of different filters were calculated by varying the initial delay, which is the only parameter, which can be changed if the filter length is kept constant. The optimum filters were chosen as a compromise between performance and balanced load between loudspeakers. However, at some frequencies some loudspeakers are loaded more than others are, which consequently limit the dynamic range as seen in the irregular frequency dependent maximum sound pressure level seen in Figure 24 and Figure 26.

The lowest playback levels are mainly limited by the noise-floor of the entire system. The limit where quantization noise in the D/A-converters could become an issue depends on the playback mode, but for 24-bit D/A-converters (theoretical 144 dB dynamic range) this limit is well below the noise in the system for all playback modes. The ventilation system causes most noise at the lowest frequencies while the D/A-converters are most dominant at the high frequencies (>1 kHz) when the ventilation system is running as seen in Figure 14 and Figure 15. If the gain in the power amplifiers is lowered to the -40 dB setting the ventilation noise is also dominant at the high frequencies (not shown since this mode is not really used).

As the plane-wave playback filters are calculated from a set of measurements the performance of the sound field control will be degraded by any changes in the system since these measurements were performed. If for example one loudspeaker unit is destroyed, the missing sound contribution from that loudspeaker will affect the sound field in the entire room. Even smaller changes like wear and tear and fatigue in the suspension system of the loudspeaker units can lead to a measurable degradation of the performance. Even the temperature in the room can theoretically cause small changes, if the temperature difference is sufficient to cause significant change of the speed of sound. Placing obstacles in the room will cause degradation – mostly at the higher frequencies where the wavelengths are comparable to the size of the obstacle. This means that putting a chair and a person will lead to a degradation that might need to be minimized by an equalization filter.

During the use of this test facility, a degradation of the plane-wave playback in the order of 1 dB at specific frequencies was found. This degradation was probably caused by changes in the suspension system of the loudspeaker units during normal use and measurements. Therefore, a new set of measurements and filters were made in order to restore the performance of the plane-wave playback. However, after approx. three months time, where the room was unused the loudspeakers seemed to approach the state they were in, when the initial measurements were made as seen in Figure 27. For this reason, all verification measurements presented in this article uses the older filters, although they show less than optimal performance compared to the initial response. This illustrates the limitations in the stability of the plane-wave playback and the importance of regular verification measurements.

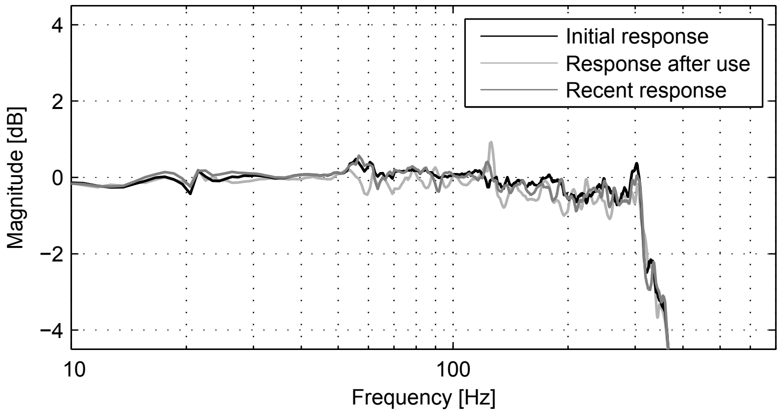


Figure 27: Frequency response of the plane-wave playback in control point 21 measured at different times: Initial response right after measurements and filter calculations (black), response measured more than a year later after use of the facility (light grey) and response approx. three months later (grey).

## 6. CONCLUSION

A low frequency test facility has been constructed which is capable of reproducing low-frequency sound with a homogeneous sound field in a large part of the room in the frequency range of 2-300 Hz (max. deviations of ±1 dB). This is obtained by using digital filters for generating a plane wave from one wall, which is actively absorbed when it reaches the opposite wall. Using plane-wave playback the system is more efficient than anechoic playback, but it is still limited at the lowest frequencies to sound pressure levels in the order of 95 dB while the higher frequencies are limited to levels in the order of 107 dB. If higher levels are needed it is possible to use a hybrid mode, where the lowest frequencies (approx. <50 Hz) are reproduced with pressure-field playback, while the higher frequencies are reproduced with plane-wave playback. In this mode, the playback limit is increased to 125 dB at the lowest frequencies, while the homogeneity of the sound field generally is maintained. The test facility has very low background noise even when the ventilation system is running and provides sufficient air, which means that it can be used for long-term exposure experiments.

## ACKNOWLEDGEMENTS

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# A Detailed Study of Low-Frequency Noise Complaints

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**ABSTRACT**
From 203 cases of low-frequency complaints a random selection of twenty-one cases were investigated. The main aim was to answer the question whether the annoyance is caused by an external physical sound or by a perceived but physically non-existing sound, i.e. low-frequency tinnitus. Noise recordings were made in the homes of the complainants, and the complainants were exposed to these in blind test listening experiments. Furthermore, the low-frequency hearing function of the complainants was investigated, and characteristics of the annoying sound were matched. The results showed that some of the complainants are annoyed by a physical sound (20-180 Hz), while others suffer from low-frequency tinnitus (perceived frequency 40-100 Hz). Physical sound at frequencies below 20 Hz (infrasound) is not responsible for the annoyance - or at all audible - in any of the investigated cases, and none of the complainants has extraordinary hearing sensitivity at low frequencies. For comparable cases of low-frequency noise complaints in general, it is anticipated that physical sound is responsible in a substantial part of the cases, while low-frequency tinnitus is responsible in another substantial part of the cases.

## 1. INTRODUCTION

Many cases of noise annoyance deal with noise that has a significant content of low frequencies. The complainants typically describe the noise as "rumbling". Among the sources are compressors, ventilation systems, and slow-running or idling engines. The cases are often solved, either by use of traditional noise limits and measurement methods, or by use of special low-frequency procedures as introduced by some countries: Austria [1], Denmark [2] (explained in [3]), Germany [4], Poland [5] (explained in [6]), The Netherlands [7], Japan [8] (explained in [9]), Sweden [10] (criteria) and [11] (measurement procedure, translated and explained in [12]).

However, there is a group of cases where persons claim to be annoyed by rumbling noise, but where they are not helped in a way that they find satisfactory. This often leads to repeated complaints, anger at authorities, feeling of helplessness, and reports in the daily press. To a certain extent, these cases have some common characteristics. There is often no obvious noise source, and often only one or a few persons are annoyed. Many of the cases are in areas that are generally quiet, and, if measurements are made, they often show low values.

Because of these circumstances, it is often mistrusted that a real, physical sound is the cause of the annoyance. One explanation could be that the annoyed persons suffer from an internal sound. Such phenomenon is referred to as ***tinnitus*** (*"the sensation of sounds in the ears, head, or around the head in the absence of an external sound source"* [13]; "*the perception of a sound in the absence of any external sound applied to the ear*" [14]). Tinnitus may arise from abnormal activity at several different points in the auditory system, but the exact mechanisms are not fully understood, and tinnitus may occur in individuals with otherwise normal hearing [15], [16], [17], [18], [19], [20]. If the annoyance is caused by a real, physical sound, an explanation could be an unusually low hearing threshold of the annoyed person. The individual growth of loudness above threshold and/or the individual sensitivity to noise may also play a role.

It cannot be excluded that some cases are simply poorly investigated, and that they could have been solved by traditional means, if they had only been given proper attention. In that connection, it may play a role that some complainants use the term *infrasound* for the noise. Since it is usually believed that infrasound cannot be heard, the mere use of this term may have the effect that the complainant is considered less trustworthy, and that, as a consequence, the further handling of such cases is stopped or impeded. This seems to happen sometimes, even when it has been known for long that infrasound is audible, when it is sufficiently intense (review in [21]), and even when it cannot be taken for granted that the annoyed person will know, whether the frequency of a sound is below or above 20 Hz (20 Hz is usually taken as the upper limit of the infrasonic range [22]).

### 1.1 Previous studies

The literature has many reports of single or few cases of low-frequency noise problems (e.g. [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39]). Some are of an anecdotal character, in particular those reported in the daily press. Only few systematic studies of many cases have been made.

For 48 complainants, Walford [40] distinguished between physical sound and internal sound by having the complainants listen to the annoying sound with and without earmuffs. No sound measurements were made. Prior to the test, each complainant had, in the laboratory, adjusted an artificial sound to have the same pitch as the annoying sound, and selected an earmuff that clearly attenuated the artificial sound. The matched sounds were in the 16-196 Hz range. Sargent [41] made a comprehensive study including questionnaires filled out by 295 complainants. Twenty-six of these were selected for further investigations, in which they adjusted an artificial sound to the best possible match of the annoying sound. In an attempt to identify the annoying sound, comparisons were made with noise measurements in their homes. Furthermore, ten of the selected complainants had audiological testing. Berg [42] made noise measurements in nineteen cases of low-frequency noise complaints and compared third-octave levels with national criteria of Sweden [43] and Germany [4], proposed criteria by Vercammen [44], and the normal hearing threshold for pure tones [45]. A German study (anonymous [46]) made noise measurements in thirteen cases of low-frequency noise complaints, and compared low-frequency third-octave levels with individual pure-tone hearing thresholds for the complainants. Moorhouse et al. [47] (also reported by Waddington et al. [48]) investigated eleven cases of low-frequency noise complaints by comparing logs of the occurrence of annoying sound as perceived by the complainants with certain noise events and the time course of certain frequencies as observed in noise recordings.

It is important to note the scope of a particular investigation and be aware of a pertinent interpretation of the results. Comparisons with existing criteria are adequate to show if noise abatement is justified with a legal background, while comparisons with the hearing threshold may tell whether there is an audible sound or not. However, due to loudness summation in critical bands, there is significant uncertainty connected to comparisons of third-octave levels with pure-tone hearing thresholds (normal or individual). Of the five larger studies, only the correlation study [47] tried to demonstrate a causal relationship between the measured noise and the annoyance. Except for an early study of two cases [23], none of the studies reproduced the measured sound to the complainants to get a direct confirmation that they were in fact measuring the annoying sound.

A special challenge to such studies relates to the method used for measuring the sound. Particularly at low frequencies, standing waves result in significant frequency dependent variation in sound level within a room, and, in a single measurement position, certain frequencies may be badly represented {Pedersen, Møller, et al. 2007 1780 /id} [49]. Only few of the investigations mentioned have dealt with the standing wave problem in a systematic way, e.g. by measuring in more than a single position.

### 1.2 Present study

In our department, we have previously registered about 200 cases of low-frequency noise annoyance [50], [51]. It was the objective of the present study to investigate a random sample of these thoroughly and, if possible, explain every single case. Since a variety of explanations might exist, it was considered important to include more than just a few cases, so that some general conclusions could possibly be deducted from the results. Despite the extensive resources needed in each case, it was decided to investigate 22 cases[1].

A key issue was to answer the questions, whether the annoyance was caused by a physical sound or not, and if it was, which frequencies were responsible. Recordings were made at the place, where the annoyance occurred, and played back to the complainants under controlled conditions in the laboratory. The frequency range covered was 2-350 Hz, and the tests made use of a special low-frequency exposure facility in our laboratory [52]. Blind tests were used to reveal, if the complainants could hear the sound from their home. For those who could, recognition tests were performed in order to show, if the recorded sounds were similar to the annoying sound. Based on the outcomes of these tests, complainants can be divided into the following three categories:

1. The complainant could hear the recorded sound and reported that it resembled the annoying sound.
2. The complainant could hear the recorded sound but reported that it did not resemble the annoying sound.
3. The complainant could not hear the recorded sound.

For the first and last categories, natural conclusions are that the annoyance felt at home is caused, or respectively not caused, by a physical sound. For complainants who fall into the second category, there is no obvious and straightforward conclusion, and it may not be possible to make a final conclusion.

For the sounds that were heard, blind tests and recognition tests were made for the sounds divided into four frequency sub-bands in order to reveal, which frequencies are audible and possibly responsible for the annoyance.

The laboratory tests of the complainants also comprised examination of their low-frequency hearing (thresholds and loudness function). In addition, attempts were made to identify characteristics of the annoying sound by playing artificial sounds (tones and noise bands) with various frequencies and levels.

The recordings were made at the place where the annoyance occurred, which in all cases means at home and indoors. Since measurements in single positions in general are insufficient and may virtually fail to reveal certain frequency components [49], recordings were made in many positions in the room. The recordings were not only used in the laboratory test, but also analyzed and compared to environmental criteria in Denmark and Sweden.

It was not within the scope of the study to point at a particular noise source or to enter the individual cases to obtain a reduction of the noise. However, the subjects were informed about the findings in their own case and given copies of the measurement results, which they can use for possible further initiatives.

The recordings were made in the period from August 2003 to December 2004. Due to an unfortunate error in the ventilation system of the exposure facility and even more unfortunate delays in the repairing of it, the laboratory tests had to be

[1] One subject withdrew before the laboratory tests, so the final study comprised 21 subjects.

postponed several times. They were finally carried out during the spring and summer of 2006, when all subjects were invited to Aalborg to participate, each for a full day.

## 2. METHODS

### 2.1 Subjects

Twenty-two subjects were selected from the group of 203 persons who had responded in our previous survey on low-frequency noise problems [50] (full report in Danish in [51]). Twenty subjects were selected randomly, while two were selected because of long-term contact with the university. Before the selection process, 69 persons were removed from the original group (30 persons who had already reported that the problem was solved by noise reduction, because they had moved or for other reasons, 30 persons with whom we had lost contact, and 9 persons for various other reasons). A substitute was selected, if a selected person was not annoyed any more (happened 12 times), or did not want to or was unable to participate (happened 22 times). Constraints were put to the random selection in order to keep the geographical and gender distributions close to those of the original group.

Unfortunately, one subject withdrew from participation just before the laboratory experiments. At that time, it was not possible to have a replacement, and the experiment ended up having only 21 subjects.

The final group of subjects had 38.1% men (34.8% in the original group), 52.4% were from places with zip codes below 3700 (roughly Copenhagen and North Zealand) (53.2% in the original group), and the average age (at the time of submitting the questionnaire) was 53.5 years (55.5 years in the original group). All subjects had reported in the questionnaire that they sense the sound with their ears (98% in the original group), five subjects had reported that they are the only person who can hear the noise, and 13 had asked authorities for help, most of them more than once.

All subjects were examined by an otolaryngologist on the same day as the laboratory experiments took place. These examinations included otomicroscopy, pure-tone and impedance audiometry and caloric testing. The subjects were found otoneurologically normal except for one case of preponderance, two cases of minor left side relative hearing loss, four cases with a dip at 6 kHz indicating a noise induced hearing loss and one case of presbyacusis. One subject (subject O) mentioned at the laboratory tests that the annoying sound had disappeared some time ago, possibly after some changes had been made at a suspected noise source.

### 2.2 Recordings

Recordings were made in the home of each subject in the room where the noise was most annoying, usually the living room or bedroom. The main power was turned off, the windows were closed, and all subjects confirmed that the sound was still present before the recordings were made. Many of the subjects reported that the noise was not always equally loud, and measurements were only made, if it was clearly audible to them. If possible, the subjects were present during the recordings or showed up now and then to confirm that the noise had not disappeared. All subjects except two (subjects K and Q) confirmed the presence of the sound again at least at the end of the measurements. The recording equipment and all persons were outside the room during the recordings.

In all cases, there were disturbing sounds like of passing cars, distant agriculture machinery etc., which were clearly audible. The subjects were asked to identify these sounds, and all subjects confirmed that they were not part of the annoying low-frequency noise. Recordings often had to be repeated or even postponed for hours, days, or even longer periods, if the annoying sound was not present or when there were too many disturbances. Many recordings had to be made in the evening or at night. Recordings were not made on days with rain or with disturbing wind (nearest official measurement < 7 m/s, usually much lower (open area 10 m height, 10-

minute average), much less at the place of measurement).

The problem with standing waves at low frequencies was addressed by recording in 20 microphone positions in each room. The microphone positions were chosen in such a way that it was possible to obtain several outcomes of the Danish [2] and Swedish [11] measurement methods. Measurement positions also comprised three-dimensional corners (3D corners), which reflect better the levels that persons in the room may be exposed to [49]. For details on the measurement methods, see Appendix A.

A four channel recording system (01 dB Harmonie with four GRAS type 40 EN one-inch microphones and type 26AK preamplifiers, combined -3-dB lower limiting frequency below 1 Hz, 6400 Hz sampling frequency) was used. Recordings were made in four positions at a time, thus all recordings were made in five recording periods. Each recording period was three minutes, and attempts were made to have as few disturbances as possible, so that shorter "clean" periods could be found later for use as stimuli and for analysis. This was a time consuming task, and very often recordings had to be repeated due to disturbances. Measurements in one home took from a few hours to more than a full day.

### 2.3 Analysis of recordings and selection of stimuli

Periods of the recordings without disturbing sounds like passing cars etc. were found by listening to the sound (often at higher than natural level) aided visually by spectrograms. These periods were analyzed further using spectrograms and third octave-band analyses as well as listening, and representative 5-second periods were selected for use as stimuli in the blind tests and recognition tests. Linear fade-in and fade-out ramps were applied over the first and last 0.5 s. The stimuli were chosen in such a way that prominent low-frequency components of the recorded noise were represented at the highest levels found in each home. At least two stimuli were chosen for each case, one from a 3D corner and one from another position, but in several cases, it was necessary to include more than two stimuli. The stimuli are denoted *Sl*, *S2* etc.

In addition, a single stimulus was used for all subjects. This stimulus was chosen by the experimenters as a stimulus that fitted well with typical descriptions of the annoying sound as given by complainants. The stimulus was from the home of subject B, and in the following, it is denoted *REF*.

Subjects P and Q were neighbours and believed to be annoyed by the same sound. They appointed rooms only separated by a common wall. However, the recorded sounds differed somewhat; there was a very clear 100 Hz tone in the recordings from subject P, while, in the recordings from subject Q, such component did exist, but it was not particularly prominent. Subject Q was one of the two who did not confirm the presence of the sound during or after the recordings, and a recording from subject P was therefore included in the blind test of subject Q (as S4).

An example of the analysis and the selection of a stimulus is given in the following. Figure 1 shows spectrograms of recordings in four different microphone positions in the same time interval. Since the hearing threshold varies considerably with frequency in the low-frequency range, the sound pressure level of each spectral component has been weighted relative to the normal hearing threshold. The threshold weighting of the spectrograms helps to identify frequency components that are potentially audible, but the spectrograms cannot directly show if they are audible or not, since that depends on, how the frequency components are summed by the hearing function (critical band concept).

The noise from a passing car is seen as a vertical line at about 90 seconds. From listening to the recordings assisted by the spectrograms, the period 0-52 seconds was found as relatively undisturbed. For this period, more detailed spectrograms and third-octave analyses were made; see Figure 2 and Figure 3. From these, as well as repeated listening, channel 1 in the period 15-20 seconds was selected - a period that was virtually undisturbed, and the position where the level of the pronounced frequency component at 100 Hz was highest. Higher harmonics can be seen as grey lines at 200, 300, and 400 Hz. The absence of this 100 Hz component in channel 3 clearly illustrates the problems with standing waves.

Figure 4 shows third-octave analyses of the 53 stimuli used in the blind tests.

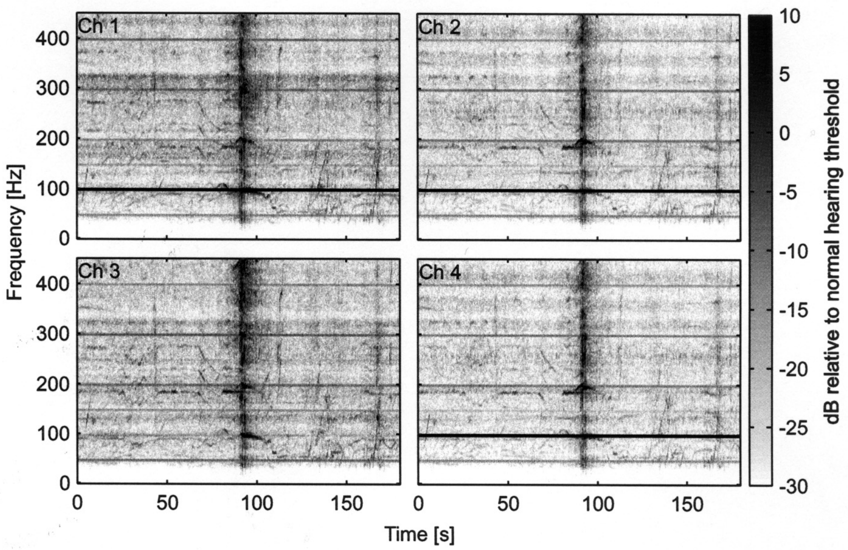


Figure 1: Example of threshold-weighted spectrograms of recordings from four microphone positions in one measurement period (3D corner positions, subject P). Levels more than 10 dB above and 30 dB below threshold are black and white respectively. Pure-tone thresholds from ISO 389-7 [45] and, for the infrasound region, based on Møller & Pedersen [21], with additional data from [53] [54] and [55].

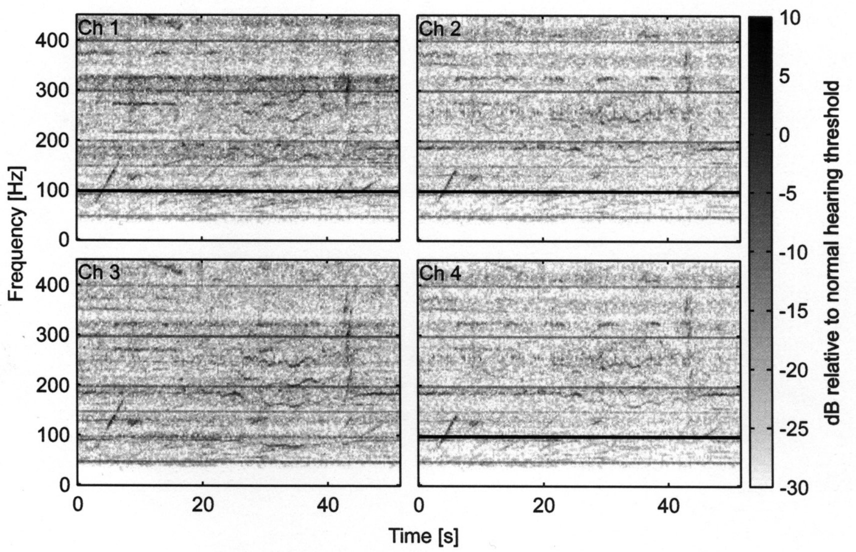


Figure 2: Zoom at the relatively undisturbed 0-52 s period of Figure 1.

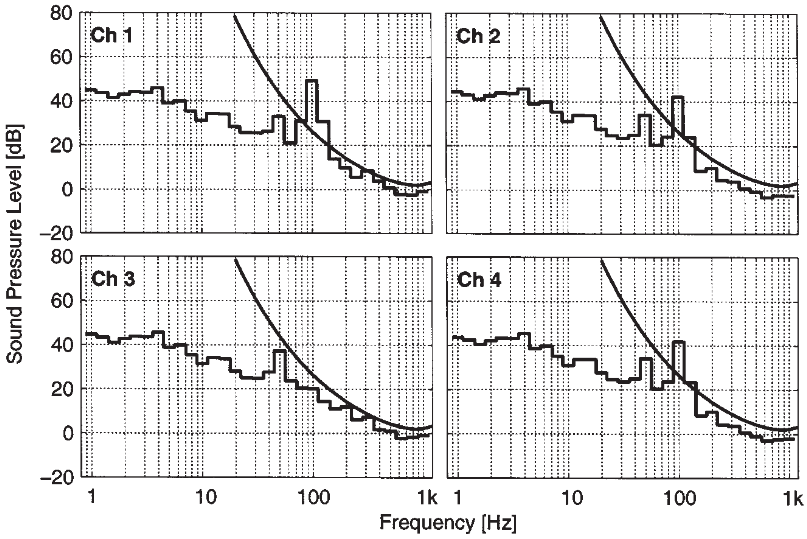


Figure 3: Third-octave analyses of the relatively undisturbed 0-52 s period from figure 1. Smooth curve shows the normal hearing threshold for pure tones (ISO 389-7 [45]).

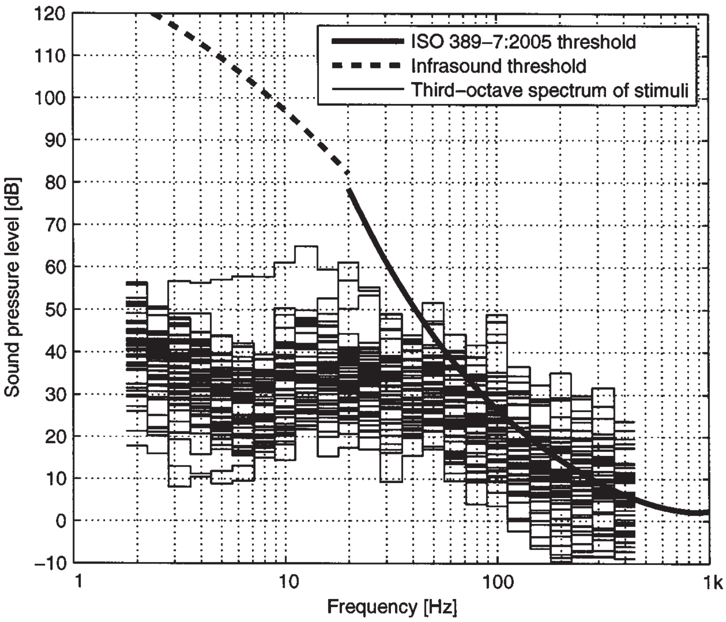


Figure 4: Third-octave analyses of all 53 stimuli plotted with the normal hearing threshold [45] and an infrasound threshold based on Møller & Pedersen [21], with additional data from [53], [54] and [55].

## 2.4 Test setup

A new low-frequency test facility [52] was used for the laboratory experiments. The facility uses advanced digital signal processing to control the signal to each of 40 loudspeakers and thereby creates a homogeneous sound field in a major part of the room. The facility covers the frequency range 2-350 Hz (-3 dB frequencies) thus it allows controlled reproduction of the infrasonic and low-frequency ranges with a fair overlap into middle frequencies. The facility is equipped with a ventilation system that gives sufficient airflow for continuous occupation of the room, while still maintaining a background noise level more than 10 dB below the normal pure-tone hearing threshold for all third-octave bands. The background noise level measured in the listening position is shown in Figure 5 for the condition with ventilation off, ventilation on, and ventilation plus cooling compressor on (the cooling compressor was rarely running). On five days of the experimental period, a broken bearing in a circulation pump resulted in a clearly audible noise from the ventilation system. During these days (experiments with subjects A, E, I, M and R), the ventilation system was turned off during the experiments, and fresh air was obtained by running the system during extended breaks.

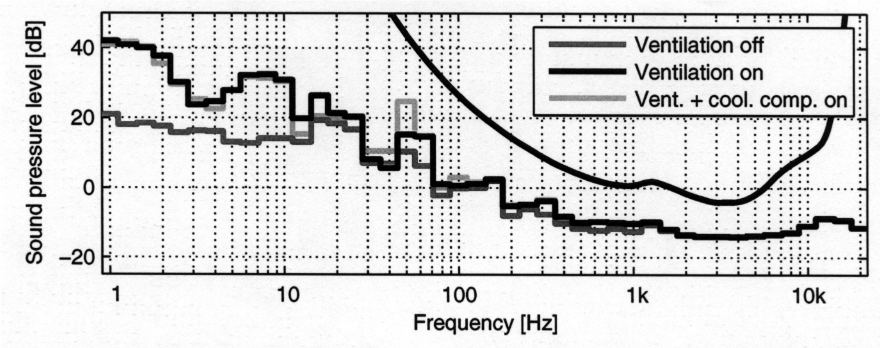


Figure 5: Third-octave analysis of the background noise measured at the listening position in the low-frequency test facility compared to the diffuse-field pure-tone hearing threshold [45]: Ventilation off, ventilation on, and ventilation and cooling compressor on. Values above approx. 2000 Hz reflect the noise-floor of the measurement microphone and preamplifier.

The subject was seated in an armchair facing one wall with 20 loudspeakers and with another wall with 20 loudspeakers behind him/her as shown in Figure 6. The loudspeaker walls were covered with a grey fabric so that the loudspeakers and the movements of the membranes were hidden. During the experiments, the subject was monitored through a camera, and an intercom was used so that the experimenter could communicate with the subject.

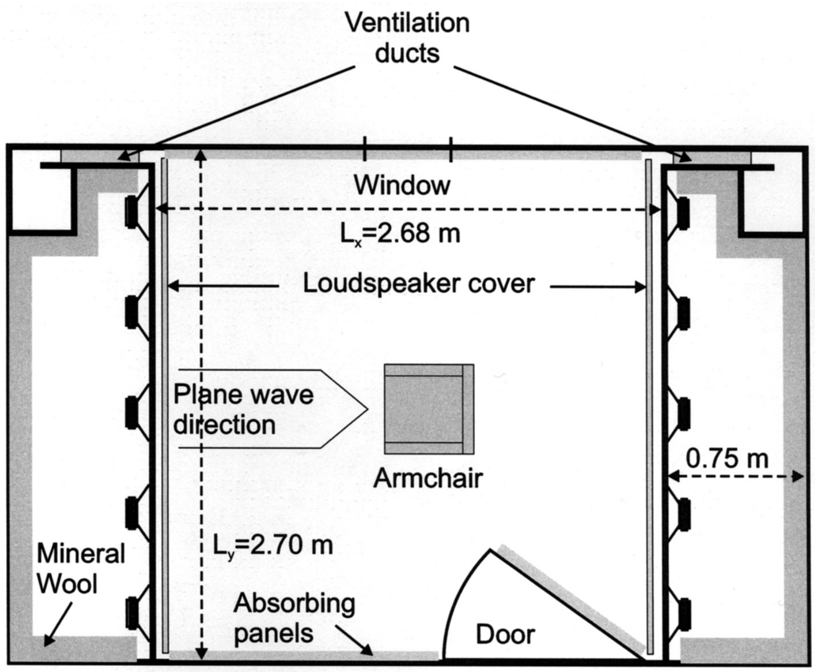


Figure 6: Diagram of the low-frequency test facility seen from above. The subject was seated in the armchair facing one loudspeaker wall.

### 2.5 Measurements of the low-frequency hearing function

The pure-tone low-frequency hearing threshold of each subject was measured at the octave frequencies from 8 Hz to 250 Hz using a slightly modified version of the standard ascending method [56]. The modification consisted of having level steps of -7.5 dB rather than -10 dB after each ascend, a modification that was proposed by Lydolf et al. [57] to give interlaced presentation levels and thus a higher resolution.

An equal-loudness contour was determined for each subject at the octave frequencies from 8 to 250 Hz using a two-alternative forced-choice maximum-likelihood procedure as described by Moller and Andresen [58]. A reference tone of 250 Hz at a level of 20 dB above the individual hearing threshold was used. Note that no specific value of loudness level can be assigned to the contour since that would require the comparisons to be made with a 1 kHz tone. However, for a person with average hearing, it would be close to a l9-phon contour [59].

The tone durations for both threshold and equal-loudness determinations were 2 seconds plus linear fade in/out ramps of 250 ms each. Responses were given using an answer box with lights and buttons.

### 2.6 Blind tests with original recordings

The blind tests were based on a three-interval forced-choice paradigm. The stimulus was presented in one five-second interval out of three that were indicated with lights on a small tablet. The interval with the stimulus was selected randomly, and there was silence during the other two intervals. The task of the subject was to indicate with push-buttons below the lights, which interval contained the stimulus. A fourth button could be used to indicate that the subject did not hear any sound. At natural level, the risk of false negatives and positives for heard is in the order of 1%. A detailed explanation of the complete procedure is given in Appendix B.

### 2.7 Recognition tests with original recordings

After the blind tests, those sounds that were heard at natural level or at +5 dB were played back in a sequence, and the subject was asked which, if any, that most resembled the annoying sound at home. If only one sound was audible, the subject was asked if that sound resembled the annoying sound. The subject was also asked, if the selected sound was louder or softer than the sound at home. The sequence of sounds could be repeated as many times as the subject wanted.

### 2.8 Blind tests with filtered recordings

Those of the sounds from the subject's home that were heard in the blind tests were filtered into four frequency ranges, and blind tests were carried out with the filtered sounds, using the same procedure as for the original sounds. The frequency ranges were: <20 Hz (infrasound), 20-60 Hz, 60-180 Hz and >180 Hz (denoted INF, LFl, LF2 and MF respectively). The involved high- and low-pass filters were digital 5th-order Chebychev filters with a pass-band ripple of 0.5 dB.

### 2.9 Recognition tests with filtered recordings

For each sound, the filtered versions that were heard at natural level or at +5 dB were used in a recognition test, similar to that for unfiltered sounds. Note that in this test, filtered versions of the same sound were compared, whereas in the first recognition test, unfiltered versions of different sounds were compared.

### 2.10 Matching of annoying sound

Some physical characteristics of the annoying sound in the home were estimated in a matching experiment. Assisted by responses from the subject, the experimenter adjusted the frequency and level of a tone, until the pitch and level matched as closely as possible that of the annoying sound in the home. In addition, third-doctave noise bands were presented in order to investigate, if the annoying sound was more of a noise-band nature than of a tonal nature. For both signals, a frequency resolution of a third octave was used, and the adjustment process always started with a pure tone at 250 Hz, 31.4 dB, which corresponds to a level 20 dB above the normal hearing threshold.

## 3. RESULTS

### 3.1 Observations in the quiet laboratory

Eight subjects reported of a low-frequency noise in the experimental room, even when no sound was emitted (subjects A, D, G, J, K, M, N and T). Some mentioned it as soon as they were seated, while others reported it later during the experiments. In some cases, it was reported as being similar to the annoying sound in the home, while in other cases, it was reported to be slightly different. In those occasions, the ventilation was turned off during the remainder of the experiment; however, this did generally not affect the subject's sensation of a sound. Fresh air was then obtained by running the ventilation system during extended breaks. The sensation of a low-frequency noise that is more or less constant - and in any case unrelated to the stimuli - might obviously influence the experiments, but the experiments were still carried out as well as possible also for these subjects.

### 3.2 Measurements of the low-frequency hearing function

Three subjects (A, J and N) gave highly inconsistent responses at some frequencies. This resulted in several attempts to meet the stop criteria of the threshold or equal loudness procedures, each time ending at a different level. For one subject (subject F), the equal loudness contour was below the measured threshold at several frequencies, even when responses in each of the procedures appeared reasonably consistent. The procedures worked well for the remaining subjects. Results for these are shown in Figure 7 (hearing thresholds) and Figure 8 (equal loudness contours). Figure 8 also shows (in grey) the equal loudness contours given relative to the individual threshold.

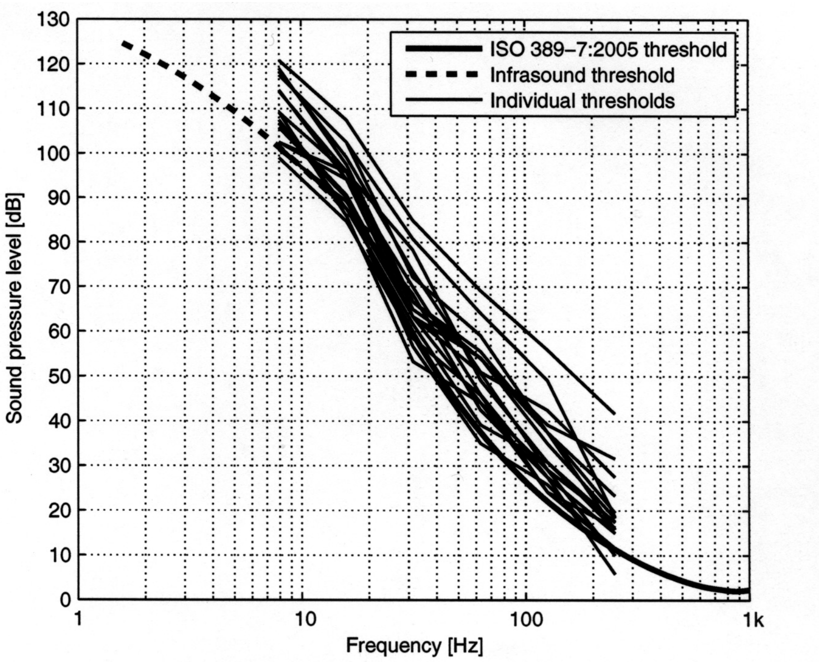


Figure 7: Individual hearing thresholds (thin lines), normal hearing threshold above 20 Hz [45] (heavy line), and infrasound threshold based on Møller & Pedersen [21], with additional data from [53], [54] and [55] (dashed line). (Subjects A, F, J, N not included).

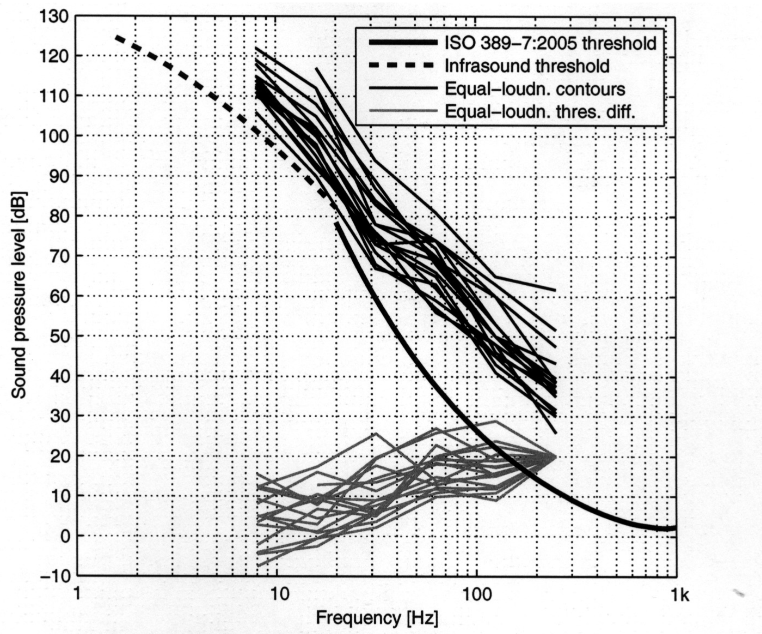


Figure 8: Individual equal-loudness contours (thin lines), the same given relative to individual hearing threshold (grey lines), normal hearing threshold above 20 Hz [45] (heavy line), and infrasound threshold based on Møller & Pedersen [21], with additional data from [53], [54] and [55] (dashed line). (Subjects A, F, J, N not included).

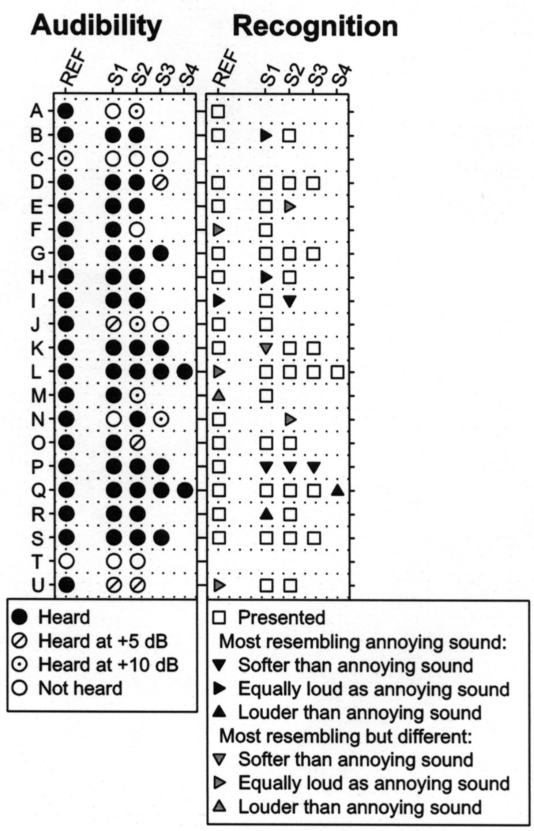


Figure 9: Results from blind tests (left) and recognition tests (right) with original recordings. Each row shows results for one subject. REF denotes the reference sound, while S1-S4 denotes sounds from that particular subject's home. Sounds that were played back but not appointed are denoted.

### 3.3 Blind tests and recognition tests with original recordings

The left frame of Figure 9 shows the results from the blind tests with original recordings.

Right frame of Figure 9 shows the results of the recognition tests with original recordings. The stimulus that resembled the annoying sound most is shown with filled triangles. The orientation of the triangle indicates how loud the subject perceived the stimulus compared to the annoying sound at home. If it was reported that two or more sounds resembled the annoying sound equally well, both (all) are indicated. Sometimes subjects spontaneously reported that although the stimulus resembled the annoying sound, it was qualitatively different (e.g., part of the annoying sound was missing in the stimulus or the stimulus was "not quite" like the annoying sound). In these cases, symbols are grey, otherwise they are black.

In Table I. the subjects are divided into the categories given in the introduction (Section 1.2). An extra category la has been introduced to accommodate for the spontaneous reports on qualitative differences. Subjects in this category are later moved to the main categories (Section 4.4).

**Table I.**

Division of subjects into categories based on the results from the blind and recognition tests with original recordings. Rightmost column gives subjects after adjustment in section 4.4, where those in category Ia are placed in the other categories.

| Category | Description | Subjects | Subjects (adjusted) |
|---|---|---|---|
| I | Heard. Resembles annoying sound | B, H, I, P, Q, R | B, E, H, I, P, Q, R |
| Ia | Heard. Resembles annoying sound but different | E, K, N | |
| 2 | Heard. Does not resemble annoying sound | D, F, G, L, M, O, S | D, F, G, K, L, M, N, O, S |
| 3 | Not heard | A, C, J, T, U | A, C, J, T, U |

### 3.4 Blind tests and recognition tests with filtered recordings

Figure 10 shows the results from the blind tests (left) and recognition tests (right) with filtered recordings. It is noted that all sounds that were heard in the original version were also heard in at least one of the filtered versions.

### 3.5 Matching of annoying sound

Figure 11 shows the results of the matching. Some subjects requested sounds with a combination of several tones or modulated tones but such sounds were not part of the matching stimuli that were available. The matched frequencies are in the 16-100 Hz frequency range.

### 3.6 Summary of individual results

A summary of the individual results is shown in Figure 12. Each frame shows data for one subject. Measured hearing thresholds and equal loudness contours are shown together with third-octave analyses of the stimuli, where frequency ranges that were audible at natural level in the blind tests are marked with thick lines in grey or black, where black represents a frequency range reported as most resembling the annoying sound. Results of the matching tests are also shown. The threshold and equal loudness data for subjects A, F, J and N that were excluded in Figure 7 and Figure 8 are included in their respective frames. For subject Q the stimulus with the highest 100 Hz level is stimulus S4, the stimulus recorded at the neighbour, subject P, see Section 2.3.

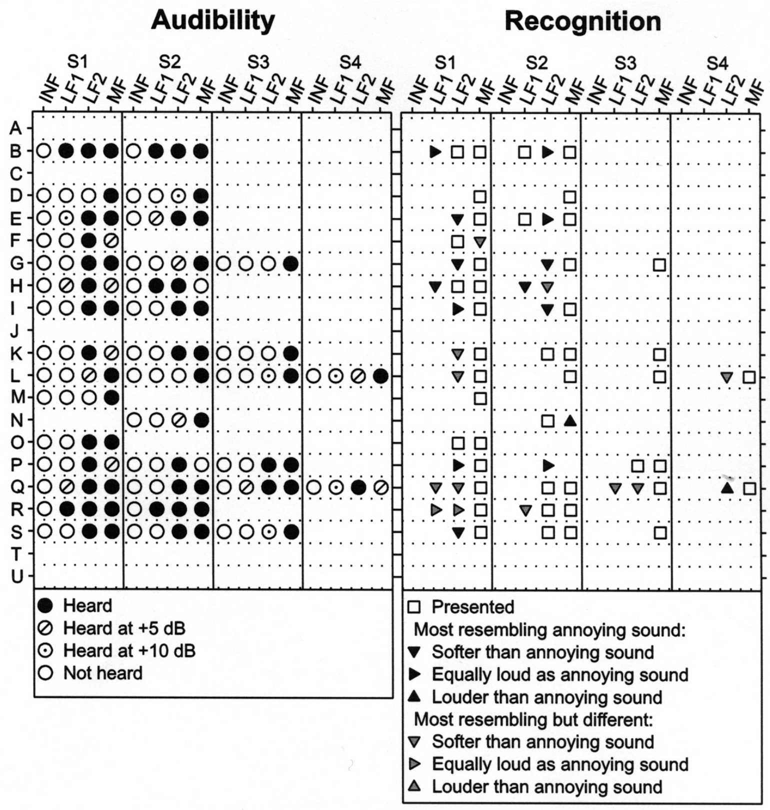


Figure 10: Results from blind tests (left) and recognition tests (right) with filtered recordings. Each row shows results for one subject. INF, LF1, LF2 and MF denote the frequency ranges <20 Hz, 20-60 Hz, 60-180 Hz and >180 Hz respectively. Sounds that were played back but not appointed are denoted.

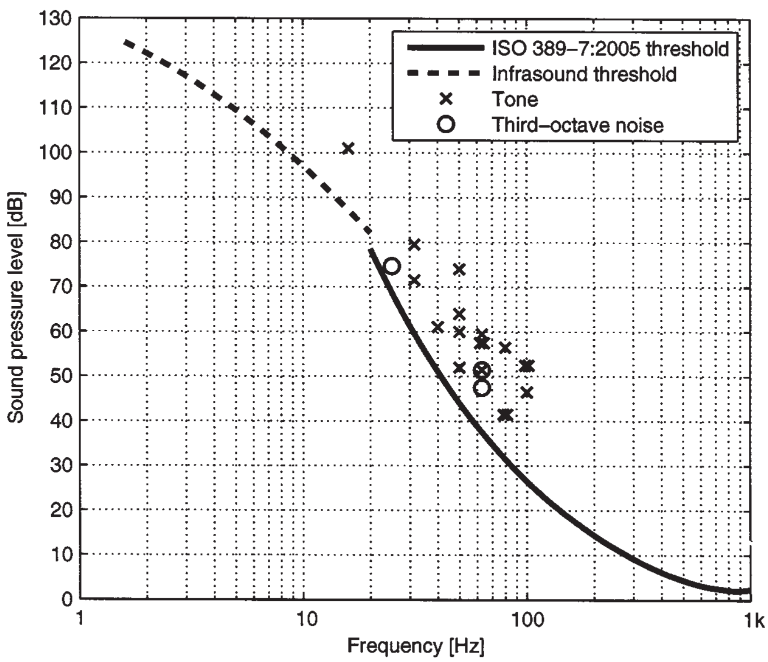


Figure 11: Results from matching experiment, normal hearing threshold [45] (full line) and an infrasound threshold (dashed line) based on Møller & Pedersen [21], with additional data from [53], [54] and [55]. If two results coincide, symbols have been moved slightly horizontally in order to make both visible.

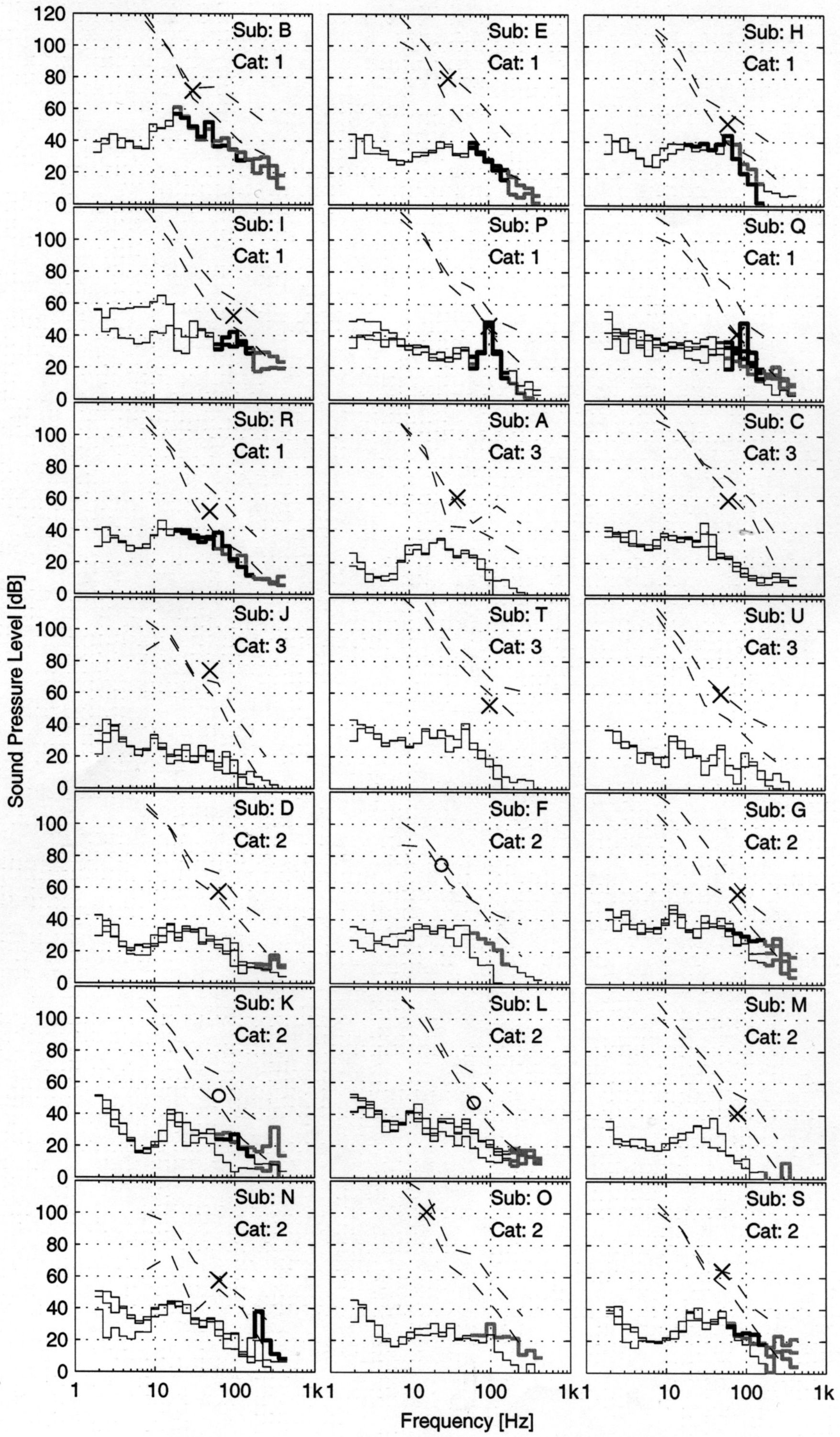


Figure 12: Individual data for each subject shown in the category order 1-3-2: Third-octave analysis of the stimuli, where the thick lines in grey and black represent a frequency range audible to the subject at natural level (from blind tests with filtered sounds) and black is the most resembling frequency range (from recognition tests with filtered sounds). Dashed lines show individual hearing thresholds and equal-loudness contours. Results from the matching experiment are shown as x for tones and circles for third-octave noise.

## 4. DISCUSSION

### 4.1 Measured noise levels

The measurements in the complainant's homes showed a large range of noise levels. As seen in Figure 4, the third-octave levels are all below the normal hearing threshold at frequencies below 50 Hz, while some exceed the threshold at higher frequencies. It was observed that the sound varied much between the different microphone positions in the individual case, which supports the findings by Pedersen et al. [49], and illustrates how important the microphone position is in indoor measurements at low frequencies (see section 4.8.1 for more details on the effect of measurement methods).

### 4.2 Hearing function

It is seen from Figure 7 that the subjects generally have a hearing threshold around or slightly above the normal hearing threshold in the low and infrasonic frequency ranges. This pattern seems to be in agreement with what could be expected for a group with the actual age distribution (maybe except for a single case, subject T, upper curve at all frequencies).

Extraordinary hearing sensitivity at low frequencies is often proposed as a possible explanation for low-frequency noise complaints. Examples of extraordinary sensitivity at low frequencies are reported in [60] and [61] (summarized in [21] with additional unpublished data from Lydolf (1997)). Such cases are however, not revealed in the present investigation. Also three previous studies failed to show extraordinary hearing sensitivity of complainants ([40] with 30 complainants measured, [62] with four complainants, [54] with ten complainants). In the German study [46], extremely low hearing thresholds were shown at some frequencies for a single complainant, but the method used was not described.

Microstructure of the hearing threshold is another phenomenon that has been mentioned as a possible explanation of low-frequency noise complaints [63]. If a microstructure is present, a narrow dip in the hearing threshold at the same frequency as a significant component of the noise may make the sound audible, even when this would not be expected from the spectrum and the general threshold. The present study did not investigate microstructures of the hearing threshold, but, when some critical-band summation is taken into account, all audible frequency ranges in Figure 12 are easily explained from the spectrum and the individual puretone hearing thresholds.

As reported, three subjects gave highly inconsistent responses at some frequencies during threshold determination. Since the ascending method is quite sensitive to this, it resulted in repeated runs and potentially unreliable data. In these cases, a forced choice procedure could have provided data that are more reliable. The inconsistent responses could very well be related to a more or less permanent sensation of sound, and it is observed that the three subjects are all among those who reported on sound in the experimental room even when no sound was emitted.

The measured low-frequency equal-loudness contours seen in Figure 8 follow the ''normal' trend of compression towards low frequencies (see e.g. [21] and [64]), meaning that the contours lie closer to the hearing threshold (particularly obvious from the grey curves). This implies that slight changes in level lead to considerable changes in the perceived loudness of a low-frequency sound.

Some subjects have a tendency of a sudden narrowing of the gap between their threshold and equal-loudness contour. However, the measurement uncertainty from both threshold and equal-loudness measurements is too large to conclude on this. Measurement uncertainty can also explain a few cases, where the hearing threshold and loudness curves intersect. Of course, such phenomenon may also be due to time varying hearing functions.

### 4.3 Audibility of various frequencies of recorded sound

An important result from the blind tests with filtered recordings (Figure 10) is that the frequencies below 20 Hz (infrasound) were not audible in any of the cases - not even at 10 dB above the recorded level. It is not known how wide the critical bandwidth is in this frequency region, but this result could be expected since the third-octave levels at these frequencies were considerably (>20 dB) below the hearing threshold as seen in Figure 4. Noise in the frequency range 20-60 Hz was audible at natural level in a few cases (5 out of 36 sounds that were presented in filtered versions), but in most cases, it was only the 60-180 Hz and/or the >180 Hz ranges that were audible at natural level.

### 4.4 Adjustment of categories

Before discussing, whether the annoyance is caused by physical sound or not for categories and individual cases, it is appropriate to make minor adjustments of the categories.

If the typical stimulus (REF) was comparable to the annoying sound in a subject's home, the subject could - by coincidence - have chosen this in the recognition test rather than a sound from the home. It is therefore necessary to consider, if there are subjects who have accidentally been placed in category 2 due to the existence of the typical stimulus. This is done by having a closer look at the relevant subjects' responses for the filtered sound. Three subjects of category 2 (subjects F, L, M) appointed the typical stimulus in the recognition test. Subjects F and L reported one respectively two filtered sounds being similar to the annoying sound, but none of these was audible at natural level. Subject M could only hear one frequency range of one recording, and that was not reported similar to the annoying sound. Thus, these observations do not suggest that any of the three subjects have been misplaced.

It is also relevant to have a closer look at the three subjects of category la, and if possible find arguments from the tests with filtered sounds for moving them to one of the main categories. In the tests with filtered sounds, subject E appointed the same frequency range for two sounds, both times without reservation, and there is ample reason to consider this as a positive recognition. Thus, it is justified to move this subject to category 1. Subject K appointed one filtered sound, again with reservation, and another sound with similar levels in that frequency range was not appointed. Furthermore, the reservation of this subject was substantial ("it resembles, but it is not at all the same"), and it is justified to move this subject to category 2. In the tests with filtered sounds, subject N only heard the >180 Hz frequency range and appointed this. The particular sound had a prominent tone around 200 Hz. A variety of low-level tones was present in all recording, but this exceptional tone was only found in one of five recording periods. No explanation of this is known. The sensation evoked by a 200 Hz tone would normally be less rumbling than what is often associated with low-frequency noise, and the subject reported that the tone was louder than the annoying sound. It is thus somewhat uncertain, if the annoyance is caused by this tone, and it is justified to move the subject to category 2. The categories after these adjustments are given in the right column of Table I.

### 4.5 Evaluation of individual cases

In the following, additional comments will be given to the categories and, in particular for category 2, to individual cases.

#### *4.5.1 Category 1*

The subjects in category 1 were able to hear the recorded sound, and they reported that the sound resembles the annoying sound at home. Furthermore, for all the subjects, a particular frequency range was successfully appointed in the tests with filtered sounds. For these subjects, it is therefore concluded that the annoyance is caused by a physical sound, and its frequency range has been identified.

Six of the seven subjects in this category matched the annoying sound to a frequency range, where significant energy was seen in the recordings, and they appointed the same frequency range(s) in the recognition test with filtered recordings. These observations further support that the recorded sound is the cause of annoyance. In the matching, two subjects (P and Q) hit even the level surprisingly well, while the others matched a level 7-17 dB above the third-octave levels in the particular frequency range. The somewhat higher level is easily justified by the critical-band loudness summation and the slope of the threshold/equal-loudness contours. None of the seven subjects in the category was among those who reported on sounds in the quiet experimental room.

*4.5.2 Category 2*

Basically, the lack of recognition of the recorded sound would propose that the annoyance is not caused by sound. On the other hand, the human ability to memorize sound is not perfect, and the sensation of a particular sound may be different when it is heard in the laboratory than under more relaxed conditions at home. The recorded sound was indeed audible, and it cannot be excluded that physical sound could be the reason for the annoyance.

Three subjects of the category call for special comments. As mentioned in section 2.1, subject O reported that the annoying sound had disappeared some time ago, and the recognition and matching tests are thus of limited value, and the data will be disregarded in the conclusion. For this subject, it is hardly possible - and of little importance - to clarify if the annoyance was caused by physical sound or not. Subject N appointed a recorded sound with a prominent tone around 200 Hz as resembling the annoying sound (see section 4.4). However, the tone only occurred in one of the five recording periods, and it cannot be unambiguously concluded that this is the annoying sound. If it is not, results imply that the annoyance is not caused by a physical sound (the subject reported on sounds in the quiet experimental room, could not hear other sounds or frequency ranges, and matched to a frequency much below the 200 Hz tone). Subject M had after the recordings found that the annoying sound does not change in level when moving around inside the house, while other low-frequency sounds do because of standing waves. The subject had realized that an internal tone is responsible and found the tone to be around 80 Hz. This was confirmed in the experiments, where the tone occurred in the quiet laboratory, and the matching test even verified the frequency.

For the remaining six subjects in category 2, various cues may suggest that the problem is caused by physical sound, or that is is not. Recognition of filtered recordings tends to propose physical sound. Five subjects (F, G, K, L and S) recognized filtered recordings, two of these (F and L) however only at +5 dB level, and for three of them (F, K and L) the recognition was with reservation. All five subjects reported that the recorded sound was lower than the annoying sound at home, which could be taken as a weakening of the recognition cue. Three subjects heard sound in the quiet laboratory (subjects D, G, K), which suggests that internal noise could be the cause of the annoyance. One subject (subject F) matched the annoying sound to a frequency far from the recognized frequency range, which speaks against physical sound. Adding these cues for the individual subjects does not give clear indications, and it is not considered possible to make conclusions for these six subjects. It is believed that a more interactive process with measuring and immediate playback of the sound can lead to the explanation also in these cases.

*4.5.3 Category 3*

Significant measures were undertaken to ensure that the annoying sound was present during the recordings[2], and that the stimuli presented to the subjects represented the highest levels found. It must therefore be assumed that in all cases, where the subject was unable to hear the stimuli at natural level, the annoyance has other reasons than a physical sound.

It is seen from Figure 12 that, for the subjects in this category, the matched annoying sounds are in general considerably above the levels found in their homes. It is noted that two of the five subjects in the category could hear the sound at +5

[2] It is noted that the two subjects, who did not reconfirm the presence of the sound after the recordings (see section 2.2), are not in this category.

dB (subjects J and U), but they did not find it similar to the annoying sound. It is further observed that three of these subjects (subject A, J and T) were among those who reported a low-frequency sensation while seated in the quiet experimental room. Two of the subjects (subjects A and J) were among those who gave inconsistent responses in the measurements of the hearing function.

It is observed from Figure 12 that for all cases in the category, the matched frequencies are at 100 Hz or below. Since the annoyance is not caused by physical sound, it would therefore be appropriate to use the term *low-frequency tinnitus*. The authors are aware that the term tinnitus is most often - and in particular by the layman - used for a high-pitched sensation ("tinnitus, *a sensation of ringing in the ears*", [65]), but nothing in the general definitions ([13], [14]) speaks against using the term in connection with a low-pitched sensation. This option is also mentioned in information material from professional organizations to the public, e.g. "Tinnitus, Ringing *Buzzing Roaring Whooshing Chirping Beating Humming*" [66] and "*Tinnitus noises are described variously as ringing, whistling, buzzing and humming*" [67].

In the medical literature, low-frequency tinnitus has been mentioned with specific medical conditions [68], [69], [70]. Low-frequency hearing loss and low-frequency tinnitus are characteristic symptoms of Meniere's disease [71], [72], but are by far too frequent to be taken (in isolation) as prodromal signs of this disease [73], [74].

In previous studies of low-frequency noise complaints, the term low-frequency tinnitus was also used by Walford [40] for those cases, where the annoying noise was shown to be internal. In addition to the options of external and internal sound, Walford operated with the hypothesis that a non-acoustic external field could evoke the sensation of sound and thus be responsible. He mentioned an electromagnetic field as a possibility in two cases, but this was never confirmed. Berg [33] also uses the term low-frequency tinnitus. Walford's study [40] also suggested that tinnitus percieved as a low-pitched sound is not unusual. In addition to the low-frequency-noise complainants, he also had a control group of 229 tinnitus patients from a neuro-otology clinic at a hospital. Of these, 55 (24%) matched their tinnitus to sound with a frequency below 200 Hz. Other studies (e.g. Konig et al. [75]) have no patients at all, who matched to frequencies below 1000 Hz, which suggests some kind of pre-screening, possibly connected to a more narrow definition of tinnitus. In clinical practice, lack of equipment for tinnitus matching at low frequencies may also play a role.

#### *4.5.4 Summary of evaluations*

For seven subjects (all subjects in category 1), physical sound is found to be responsible for the annoyance. For six subjects (all subjects in category 3 plus subject M), the annoyance it not caused by physical sound, and these cases are explained by low-frequency tinnitus. For one subject (subject N), a 200 Hz tone was found that is possibly responsible, but low frequency tinnitus cannot be excluded. For one subject (subject O), the noise had disappeared some time ago, and it is hardly feasible to find the reason for the annoyance. The remaining six subjects (subjects in category 2 except subjects M, N, and O) could hear one or more of the recorded sounds, but no specific physical sound could be appointed, and it is not possible to conclude, whether physical sound or low-frequency tinnitus is responsible for the annoyance.

### 4.6 Level of annoying sound

From Figure 12 it is observed that the levels of the matched sounds are generally close to the individual hearing threshold, both for cases with physical sound and cases with low-frequency tinnitus. There are many accounts in the literature that loudness and annoyance rise steeply above thresholds at low frequencies (e.g. [76], [64], [21], [77], [78]). In the present study, the steep rise of loudness is also reflected in the compression of the hearing thresholds and the loudness curves mentioned in section 4.2. The results from the present investigation are insufficient to determine if this steep rise of loudness and annoyance is more pronounced for low-frequency noise complainants than for others. If that is the case, it could be associated with a conditional response to the mere hearing of low-frequency sound that has emerged as a result of long-term annoying exposure (whether the source is physical or internal). As proposed by Persson Waye [79], this could be explained in the light of recent knowledge of the function of our sub cortical system with the amygdala and its unusual capacity to learn and react to adverse sounds and especially sounds that are connected with fear and danger [80], [81].

### 4.7 Generalization of the findings

Even when the present study is focused on clarification of individual cases, these were selected randomly[3] from a specified group, and it is possible to derive statistics that applies generally to similar cases.

The complainants in the group, from which the subjects were effectively[4] selected, can be characterized as *persons who, in their own understanding, have an unsolved problem of low-frequency noise annoyance*. It is obvious that the group is influenced by a large number of factors, e.g. the individual persons' understanding of their problem and motivation to get involved, the method of the previous investigation [50], its registration procedure and announcement, the perseverance of individuals and authorities in finding a solution etc. Some of these factors will appear likewise in any similar group, whereas others are distinct for the group, from which the subjects were selected. If the 30 complainants with whom we had lost contact differed from the group as a whole, this would also have biased our group of subjects. The same applies for the 22 selected complainants, who did not want to participate (see Section2.1). It should be emphasized, though, that participation was quite demanding for the subjects; it is fully understandable that complainants declined, and no-body is blamed for not participating.

For 33% of the subjects (seven out of 21) it was confirmed that the annoyance was caused by a physical sound. Assuming a binomial distribution, the corresponding 80% confidence interval is 20-49%. Low-frequency tinnitus was confirmed to be responsible in 29% of the cases (six out of 21), and for this, the 80% confidence interval is 16-44%. Unexplained cases are due to physical sound or tinnitus in an unknown proportion. With the reservations that follow from the circumstances mentioned in the previous paragraph, it can be concluded in general that physical sound is responsible in a substantial part of such cases (at least 20%), while low-frequency tinnitus is responsible in another substantial part of the cases (at least 16%).

### 4.8 Evaluation of cases by Danish and Swedish low-frequency noise guidelines

The seven cases in category 1, where the annoyance is explained by a specific physical sound, are evaluated using the Danish and Swedish guidelines. Figure 13 shows results of the two methods as well as the power average of the eight 3D-corners for the longest possible undisturbed periods. The requirement to the duration of the measurement period in the Swedish guidelines (30 seconds) is fulfilled in most cases, whereas that of the Danish guidelines (5 minutes) is not fulfilled in any of the cases. However, from spectrograms of all the recordings from subjects in this category, it is observed that the annoying sounds are of a quite steady nature, so the duration does not influence the result.

As reported in Appendix A, with the measurement positions used, three different outcomes exist of the Swedish method and 24 of the Danish method. For all measurement methods, third-octave levels are given as well as G-weighted levels

[3] Two cases were preselected, see Section 2.1; however, this was done without a priori knowledge of possible findings, and the inclusion of these cases is not supposed to compromise data by introducing bias. The two preselected cases turned out to be in each of the categories 1 and 3.

[4] Complainants for whom the problem had been solved, were removed either before or after the random selection, see Section 2.1.

($L_{PG}$) and A-weighted levels for the 10-160 Hz frequency range ($L_{pA,LF}$ as defined by the Danish guidelines). The figure also shows the limits for third-octave levels given by the Swedish guidelines and the limit for dwellings given by the Danish guidelines to $L_{pA,LF}$ (25 dB at daytime, 20 dB evening and night). The Danish limit of 85 dB for $L_{pG}$ is above the scale in the figure.

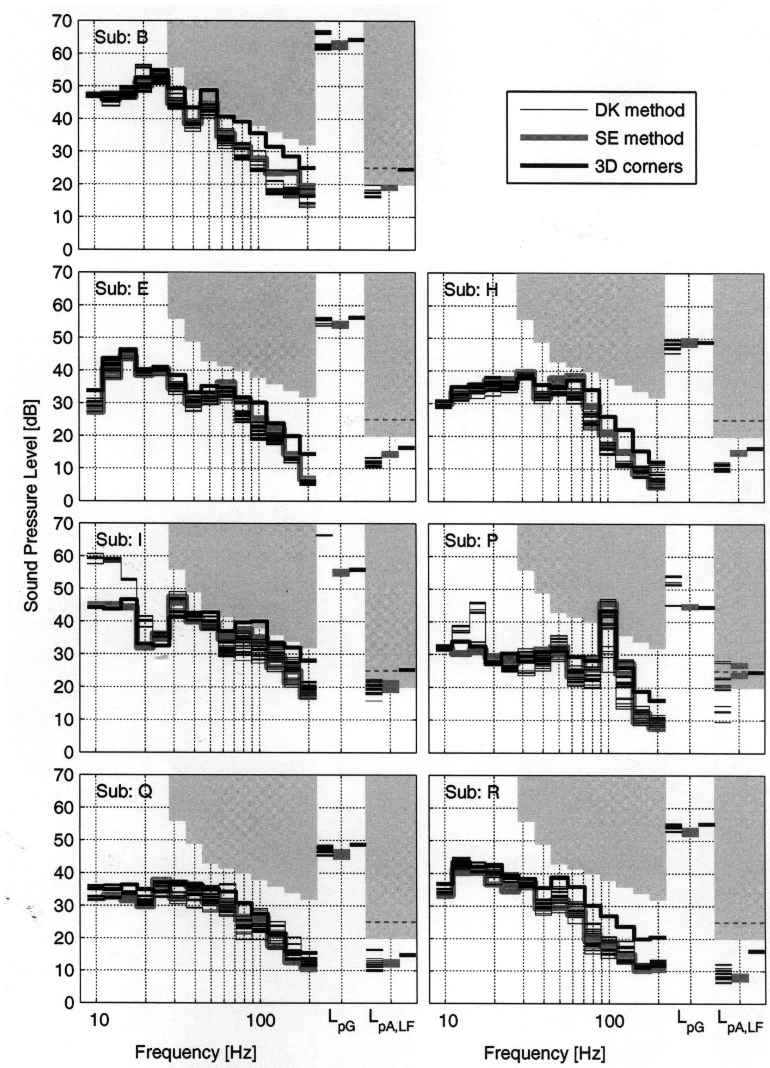


Figure 13: Comparison of all possible outcomes of the measurement methods compared to the Danish and Swedish limits. The grey areas represent the limits in Denmark (for $L_{pA,LF}$) and Sweden (for third-octave levels). The Danish $L_{pG}$ limit of 85 dB is above the scale and not shown. For the $L_{pG}$ and $L_{pA,LF}$ the lines are plotted in the order: DK method, SE method, and 3D corners.

### *4.8.1 Measurement methods*

It is not within the scope of the present investigation to evaluate measurement methods, but a few comments are appropriate. At the lowest frequencies (<25-50 HZ, probably depending on room size), the third-octave levels generally demonstrate a good agreement between methods. This is natural, since at these frequencies, the wavelength is large compared to the room dimensions, and the level varies less within the room than at higher frequencies. Exceptions are seen in the results for subjects I and P, however, these are caused by differences in the sound between measurement periods rather than spatial variation. (The deviating spectra are from the same recording period). The agreement between methods at the lowest frequencies (and disagreement for subjects I and P) is reflected in the results for $L_{pG}$.

At higher frequencies, i.e. above 25-50 Hz, third-octave levels agree less well. There is even significant variation between different outcomes of the Danish method. The highest levels are usually obtained by the power average of 3D corners and the lowest by the Danish method. The variations above 25-50 Hz are also reflected in the results for $L_{pA,LF}$. The largest variation is seen for subject P, where levels obtained with the Danish method span a range of nearly 20 dB. In this case, the sound is dominated by a single third-octave band (actually a 100 Hz tone, see Section 4.9).

The findings are in line with the results by Pedersen et al. [49] who proposed the level that is exceeded in 10% of a room as a target for measurements of low-frequency noise in rooms. This level is close to the highest levels in the room, however avoiding levels being present in only small parts of the room. Thus, it serves as a good estimate of the level that people will normally be exposed to in the room. They showed that, particularly the Danish measurement method has large uncertainty and high risk of giving results below the target.

#### *4.8.2 Comparisons with limits*

Of the seven cases, two (subjects B and P) have levels that exceed the Swedish limit (using the Swedish measurement method), and two (subjects I and P) have levels that exceed the Danish limits (using the Danish measurement method). For the latter, though, only some of the outcomes of the Danish method exceed the limits. However, the power average of 3D corners is above both the Swedish and Danish limits for all three cases.

The large uncertainty in measurement results of particularly the Danish method is a major problem in the assessment of such cases. The extremely large variation in the case of subject P has already been mentioned, but also the case of subject B is an unfortunate example. Values of $L_{pA,LF}$ above the 20 dB limit were actually seen in several of the original measurements (range 16.6-23.2 dB), but the selection procedure for positions in the Danish measurement method made the result end up in the range 16.9-19.8 dB. These are all below the limit of 20 dB, even when there is no doubt that the 20 dB limit is exceeded at many places in the room.

It is not within the scope of the present investigation to evaluate the national limits of Denmark and Sweden. However, it is worth noting that, even when using the best available measurement method (power average of 3D corners), and even when none of the complainants had unusual hearing sensitivity, the limits only indicate low-frequency problems in three out of the seven low-frequency noise cases. There are evidences in the literature that noise below the Danish limits can be annoying even for people who do not complain from low-frequency noise (e.g. [62], [82], [83]).

### 4.9 Analyses of the annoying low-frequency sounds

It is not within the scope of this investigation to find the source of the annoying low-frequency sound; however, a detailed frequency analysis might reveal some information of the nature of the sound. For the cases, where physical sound was found to be responsible for the annoyance, power-averages of 0.1-Hz-resolution FFT-analyses from the eight 3D-corners are shown in Figure 14. These spectra will not be found in any specific position in the rooms, but they represent each frequency component at levels slightly below the highest levels that do exist in the rooms (see section 4.8.1).

A general observation is that the sounds in all cases are of a complex nature where multiple harmonic tones exist. This indicates that the source(s) in each case has rotating parts or pistons running at fixed (revolution) frequencies (e.g pumps/compressors, engines, fans and ventilation systems).

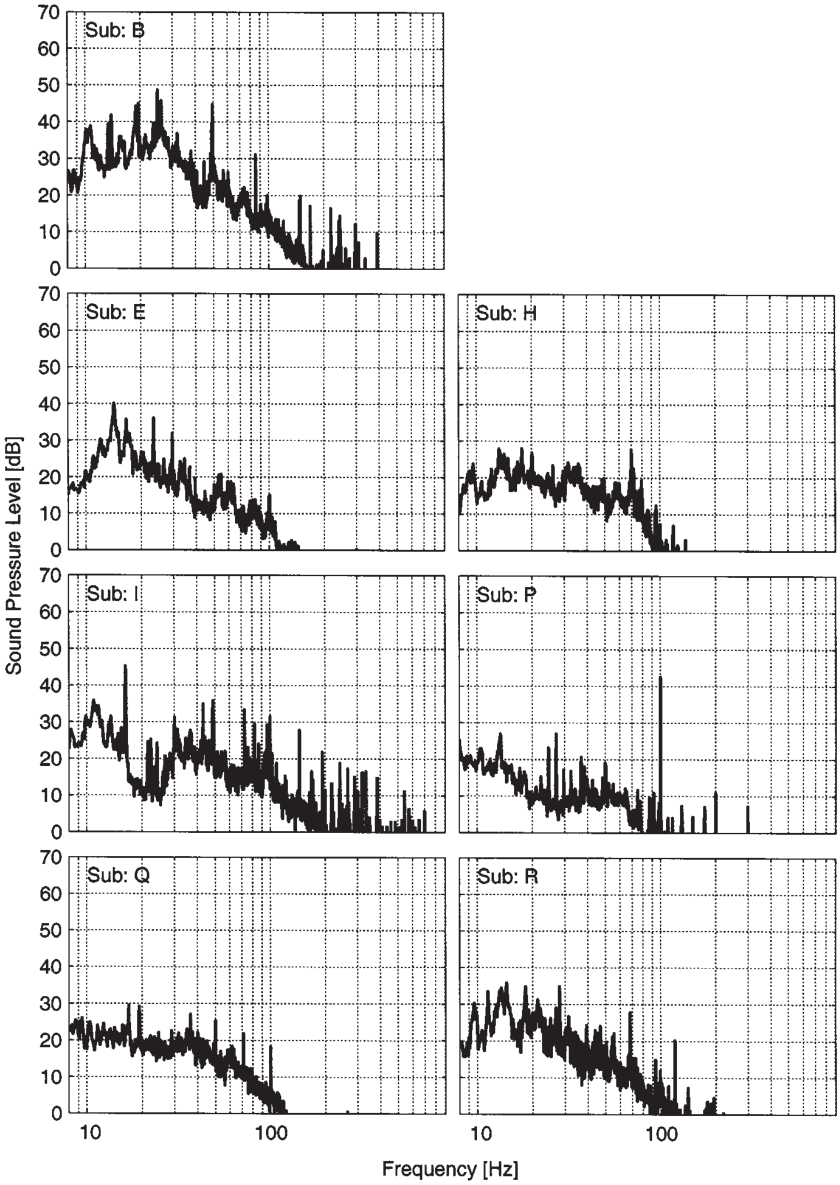


Figure 14: Power-average of FFT spectra with 0.1 Hz frequency resolution (50% overlap Hanning window) from the eight corner positions for each of the clear low-frequency noise cases.

### 4.10 Treatment of low-frequency noise complainants

For cases of low-frequency noise complainants, it is important to identify the nature of the problem before deciding on any actions. If the annoyance is not caused by a physical sound, no noise abatement or fight against potential sources will help. If physical noise is the problem, any mention of tinnitus is inappropriate. As this investigation shows, it is possible that inadequate measurements lead to failure in revealing a potentially annoying sound. On the other hand, since measurement systems are very sensitive, they will always measure some sound, and it is observed that tonal components can be found in all 21 cases of this study. The fact that a sound can be measured does not necessarily mean that it is audible and/or that it causes the annoyance.

The level variations within a room may sometimes serve as a simple mean to investigate if an annoying sound is internal or external. If moving slowly around inside changes the level and character of the sound, this is an indication of standing waves and a hint that an external sound is responsible. If not, it suggests an internal sound. However, the method requires significant cooperation and understanding of the annoyed person and may only be applicable in some cases. Furthermore, it may fail completely at the lowest frequencies. An earmuff test as used by Walford [40] may be useful in some cases, but it is uncertain, since the earmuff may fail to attenuate external low-frequency sound, and it may increase physiological noise [84]. If the sound is heard not only in a specific place but in any otherwise quiet environments and in other geographical locations this could also indicate an internal sound.

A recent study [85] showed that 25% of tinnitus sufferers initially believed (before diagnosed with tinnitus) that the sound was a real sound from e.g. domestic equipment or the neighbours. The study did not address low-frequency cases specifically, but there is no reason to believe that there are more cases of real sound among these than among cases of higher frequencies.

For the complainants where the annoyance is caused by a physical low-frequency noise, the natural solution is to reduce the noise. However, it is sometimes difficult to find the noise source, and, as seen in some of the cases in the present study, the noise may be annoying, even when the limits are not exceeded. In such cases, it can be difficult to convince the owner of the noise source to find a solution. Probably, an evaluation of limits is appropriate.

For the complainants with low-frequency tinnitus, it is possible that the knowledge that the sound is internally generated will help coping with the problem in various ways. Tinnitus can be symptoms of a variety of diseases related to the ears, the cardiovascular system, the metabolism, hormone balance, stress, medication, grinding teeth, etc., and identifying and curing the disease might attenuate or even remove the tinnitus. However, in many cases the cause of a tinnitus is not possible to diagnose. Mental relaxing therapy and hypnosis seems to help in some cases, but scientific proofs for these methods are still lacking. The mere acknowledgement of tinnitus as an official (and not uncommon) diagnosis may help.

The use of higher frequency masking sounds can be used as a last resort if no other cure is found. Here it might be a problem to live in quiet surroundings with a good insulated house or to have hearing loss at higher frequencies since these factors lower the possible masking from higher frequency sounds.

## 5. CONCLUSION

Twenty-one cases of complaints of low-frequency noise have been investigated. In seven cases (33%), the annoyance is caused by physical sound, while in six cases (29%) the complainants suffer from low-frequency tinnitus. In one case, a specific tone is possibly responsible, but low-frequency tinnitus cannot be excluded. In one case, the noise has disappeared some time ago, and it is hardly feasible to find the reason for the annoyance. In the remaining six cases, it is not possible to conclude from the present study, whether the annoyance is caused by physical sound or not, but it is believed that a more interactive process with measuring and immediate playback of the sound can lead to the explanation also in these cases.

Even if the exact proportions of categories may not hold for low-frequency noise complaints in general, it is anticipated that physical sound is responsible in a substantial part of the cases, while low-frequency tinnitus is responsible in another substantial part of the cases.

Frequencies below 20 Hz (infrasound) are not responsible for the annoyance or at all audible - in any of the investigated cases, and none of the complainants has extraordinary hearing sensitivity at low frequencies. For the confirmed cases of physical sound, the annoying components are tones, or combination of tones, in the frequency range 20-180 Hz. In the cases of confirmed or possible low-frequency tinnitus, the frequencies of the perceived sounds are in the frequency range 16-100 Hz. Whether the annoying sound is physical or internally generated, its level or matched level is not much above the individual hearing threshold. This confirms the often-reported rapid increase of annoyance with level above threshold at these frequencies. It is not possible from the material to see if low-frequency-noise complainants differ from other people at this point.

It was not within the scope of the study to point at a particular noise source or to enter the individual cases to obtain a reduction of the noise. However, in all cases, where physical sound is responsible for the annoyance, analyses reveal sound of a complex nature with multiple harmonic tones. This indicates that the source(s) in each case has rotating parts or pistons running at fixed (revolution) frequencies (e.g. pumps/compressors, engines, fans and ventilation systems).

Microphone positions are critical in indoor low-frequency noise measurements. This problem is insufficiently addressed in the Danish guidelines for low-frequency noise measurements, and results obtained with these may be encumbered with significant uncertainty. When appropriate measurement methods are used, the Danish limits are exceeded in three out of the seven cases caused by physical low-frequency noise.

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# APPENDIX A - Measurement procedure

If the subjects could point to areas, where the sound was particularly annoying, three positions were chosen within these areas. If not - and that was very often the case - three positions were chosen in representative living areas in such a way that they fulfilled the Danish guidelines [2] (explained in English in [3]), i.e. height 1-1.5 m, at least 0.5 m from walls and larger furniture, and not in the middle of the room. One microphone position was the "corner" position according to the Swedish guidelines [11], (see [86] for the English version with added explanation and data examples), i.e. the position with the highest C-weighted level near corners of the two-dimensional floor plane (0.5 m from the walls) and at a height between 0.5 and 1.5 m. In the following, this is referred to as the *SE corner*. Often it was not possible or difficult to find a clear maximum, either because the C-weighted level fluctuated much with time, or because the level did not vary much with position. Measurement positions were also chosen as "corner" positions according to the Danish guidelines, i.e. near corners of the two-dimensional floor plane (0.5-1.0 m from the walls) at a height of 1.0-1.5 m. Eight such *DK corner* positions were chosen, four with distances of 0.5 m and four with distances of 1.0 m to adjacent walls, all at a height of 1.25 m. Finally, eight positions were chosen in three-dimensional corners (distance to walls, floor or ceiling of few centimetres), in the following referred to as 3D corners. A recent study [49] showed that *3D corners* are useful positions for measuring low-frequency sound in rooms.

Both the Swedish and Danish guidelines use the power average of one corner (respectively SE or DK corner) and two positions in representative living areas. With the present measurements, it is thus possible to calculate three different outcomes of the Swedish measurement procedure (three options for choosing two positions in representative areas) and 24 different outcomes of the Danish measurement procedure (eight choices of corners times three choices of two other positions)[5]. For small rooms though (<20 $m^2$), the Danish method allows use of the power average of two DK corner positions in each of their floor-plane corner, in which case the present recording positions allow calculation of 24 different outcomes (relevant and used for subjects G, I, J, P and T). In addition, the power average of all 3D corners can be calculated as proposed in [49].

[5] Differences exist in the Swedish and Danish rules for positions in representative living areas, and only the Danish rules are strictly obeyed. In the Swedish rules, appointment by the complainant is not mentioned, areas to be avoided comprise not only the middle of the room but also areas around 1/4 and 3/4 along length and width of the room, heights should be 0.6, 1.2 or 1.6 m.

# APPENDIX B - Blind test procedure

A test of, whether a subject can hear a given sound, consisted of a pattern of *sub-tests*. In a sub-test, consecutive presentations were given, until either three correct responses in a row ("passed") or two wrong responses ("failed") were obtained. A sub-test thus consisted of 2-6 presentations. In the full test, consecutive sub-tests were given. Although the key issue was to determine, whether the subject could hear the sound at its natural level, presentations at 5 and 10 dB above natural level were also included, when the natural level was not heard at first.

A complex pattern of presentations was used in order to achieve good statistical certainty, while keeping the number of presentations low. The complete flow-chart is shown in Figure 15. For each sound, the test started at natural level, and if a sub-test pattern of *pass-pass* or *pass-fail-pass* was obtained, the natural level was accepted as heard. If not, sub-tests were carried out at higher levels, and if both +10 dB and +5 dB were passed, a second attempt was given to obtain a pass-pass or pass-fail-pass pattern at natural level. If this failed, options were given to have +5 dB or +10 dB accepted as heard. Hence, two subtest passes were required for natural and +5 dB, while one pass was required for +10 dB.

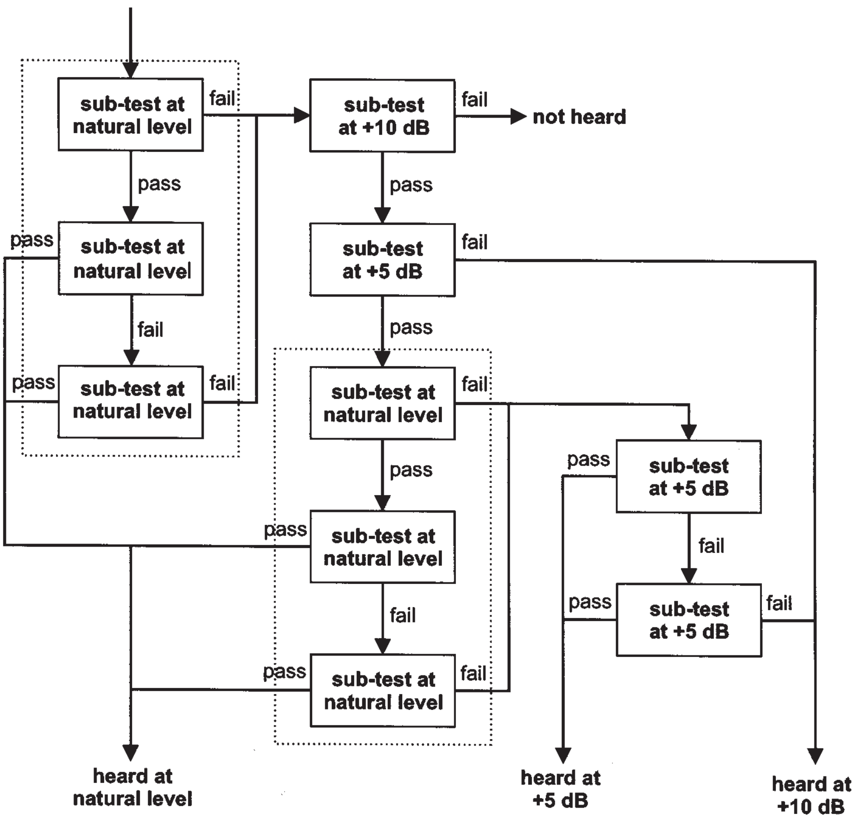


Figure 15: Flow chart of the blind test procedure. One sub-test holds consecutive presentations, until either three correct responses in a row ("passed") or two wrong responses ("failed") are obtained (2-6 presentations). The two options for pass-pass or pass-fail-pass patterns at natural level are shown in the dotted rectangles.

If the stimulus was in fact the annoying sound, wrong responses were not to be expected, in particular not since the stimuli had been chosen among the highest levels within the room. A false negative result, i.e. getting a "cannot hear", when the subject can actually hear the stimulus (type 2 error), was thus, in principle, unlikely. Nevertheless, the test allowed for several accidental wrong responses or for a detection probability lower than 100%. The right column of Table II shows the risk of false negative results, assuming a detection probability of 90%. The left column