Construction of a test chamber for human infrasound exposure

Møller, Henrik

Published in:
Journal of Low Frequency Noise, Vibration and Active Control

Publication date:
1982

Construction of a Test Chamber for Human Infrasound Exposure.

Henrik Møller.
Institute of Electronic Systems, Aalborg University, Denmark.
(Received 12 December 1982)

Abstract

The report describes the construction of an infrasound test chamber, in which subjects can be exposed to controlled infrasound signals.

The infrasound is produced by 16 electrodynamic loudspeakers, mounted in one wall of the 16 m^3 chamber. The maximum sound pressure level that can be obtained is 125 dB rms in the frequency range 0.05 Hz–30 Hz. At a level of 120 dB the 2nd and 3rd harmonic distortions are below 1%. The system does not utilize any acoustical resonances, thus giving a flat frequency response. In this way it is possible to reproduce a real environmental infrasound signal recorded on tape.

For the purpose of experiments of longer duration, the room is equipped with a ventilating system, which gives sufficient air exchange for 3 persons. When in use, this system increases the lower limiting frequency to 0.3 Hz.

Introduction

It has often been claimed that infrasound may influence the human being. The proposed effects are physiological effects such as changes in heart rate and blood pressure, effects on task performance, and a number of nuisances like dizziness, nausea, loss of concentration and headache. Therefore a number of investigations have been carried out involving both field studies and laboratory experiments.

The main advantage of field studies are the possibilities of having a large number of people involved and of using long exposure times. Field studies may be the only possible way of finding long term effects. However, it is a very severe disadvantage that the characteristics of the exposure are less known than in laboratory experiments. Especially when considering infrasound this is a problem, since infrasound is usually found together with other environmental factors, for example audible noise, vibrations, heat and chemical factors. Even in laboratory experiments it is very difficult to produce infrasound without vibrations and with a sufficiently low distortion.

At Aalborg University it was decided to build a test chamber where subjects could be exposed to infrasound in the frequency range from below 1 Hz to 20 Hz. The dynamic range which was to be covered was that of everyday environmental infrasound, for example up to 120-130 dB. The infrasound should have a low harmonic distortion and be free from any noise in the audio frequency range. It would be preferable if the infrasound could be electronically controlled with a flat frequency response, so that not only pure tones could be reproduced but also noise bands and environmental infrasound recorded on tape. The vibration levels at the floor and the walls should be kept as low as possible. The chamber should be sufficiently large for two or three subjects to be under test at a time, and that the psychological influence of being in a "test chamber" can be ignored.

A chamber which fulfils these requirements to a reasonable extent has been built, and it has already shown its usefulness in a number of experiments. The first approach was a room with a 2 square metre aluminium membrane driven by a hydraulic system. It was able to produce sound pressure levels up to 135 dB. However, both the harmonic distortion and the vibration level at the floor were too high, and other solutions were considered.

The most obvious generator of infrasound with low distortion is electrodynamic loudspeakers. A low vibration level could also be expected since the mass of the membranes is very low. The reason why loudspeakers were not used at first was that they are not made for use at such low frequencies, and consequently the maximum amplitude of the membrane stroke was expected to be too low. But after the hydraulic system had failed to give sufficient low distortion, a number of electrodynamic loudspeakers were tested concerning their properties at high amplitudes [1]. Two different loudspeakers were shown to be equally good, as they were both able to move about 0.75 litre of air peak to peak. One was a 10 inch loudspeaker with an extremely long stroke, and the other was a more ordinary 13 inch. The smaller one was made especially to order, but as the bigger one was already in normal production, this one was chosen.

Description of the Room

Figure 1 shows the test chamber from above. Actually there are two rooms, the loudspeakers operate between. The experiments are carried out in the biggest room, the test chamber, whereas the smaller one, the back volume, encapsulates the back side of the loudspeakers, so that the infrasound is not radiated from the system.

The chamber is built of concrete in a corner of the laboratory. Concrete is chosen as it is stiff and heavy, so vibrations and bending of the walls are largely avoided. Unfortunately concrete is also very porous, and in order to keep the room reasonably tight, it has been necessary to cover all surfaces with a thick polyurethane paint. In spite of this there is a small leakage, and the room does not work down to DC.

The volume of the chamber is 15.8 cubic metres, and the largest dimension is 2.9 metres. The wavelength of a 20 Hz pure tone is 17 metres, so the room performs approximately as a pressure chamber in the infrasound range. The connection between the instantaneous sound pressure $\Delta p(t)$, and the instantaneous volume displacement $\Delta V_1(t)$, is as follows:

$$\Delta p(t) = -\gamma p_0 \Delta V_1(t)/V_1$$

where γ is 1.4 because the process is adiabatic, p_0 is the atmospheric pressure (10^5 Pa), and V_1 the volume of the chamber.

16 loudspeakers are installed, and as the maximum obtainable volume displacement for one loudspeaker is 0.75 litre peak to peak, the maximum sound pressure level can be calculated as 106 Pa (134 dB) peak to peak, or for pure tones 38 Pa (125 dB) rms.

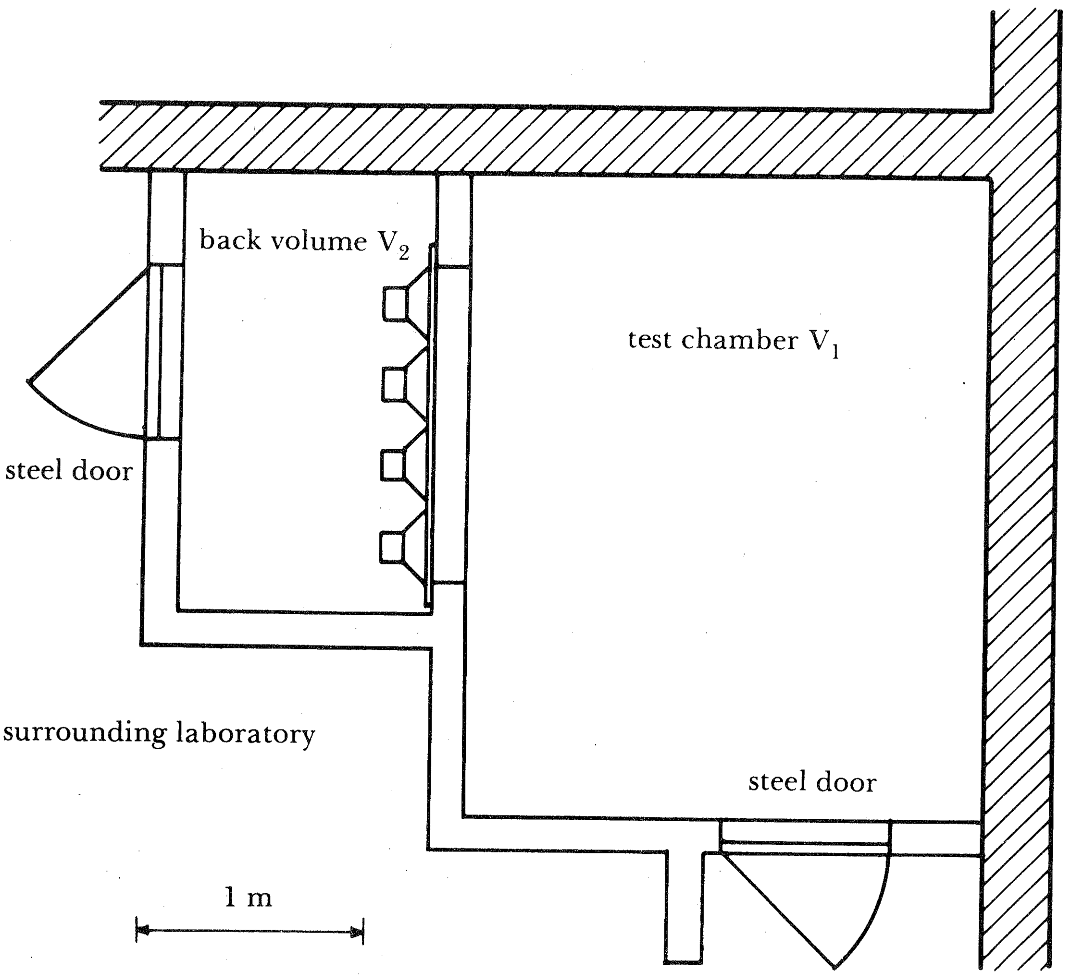


Figure 1 The infrasound laboratory seen from above

Generation of Infrasound with Electrodynamic Loudspeakers

When the 16 loudspeakers are mounted between the test chamber and the back volume, the equivalent diagram in figure 2 is valid. The electrical part consists of the voltage across the terminals u(t), current in the coil i(t), coil resistance R_e, and the feedback from the membrane movement Blv(t), where Bl is the magnetic field multiplied by the coil length, and v(t) the membrane velocity.

The mechanical part includes the force from the electrical current Bli(t), the membrane mass m, mechanical losses r, compliance of the suspension c, and the acoustical load, which is seen through the transformer S:1.

Provided all loudspeakers are identical, and the two chambers perform as pressure chambers, each loudspeaker is loaded with volumes of $V_1/16$ at one side and $V_2/16$ at the other side. This load is given by the acoustical compliances c_1 and c_2. The pressure in the test chamber is indicated in the figure as $p_1(t)$.

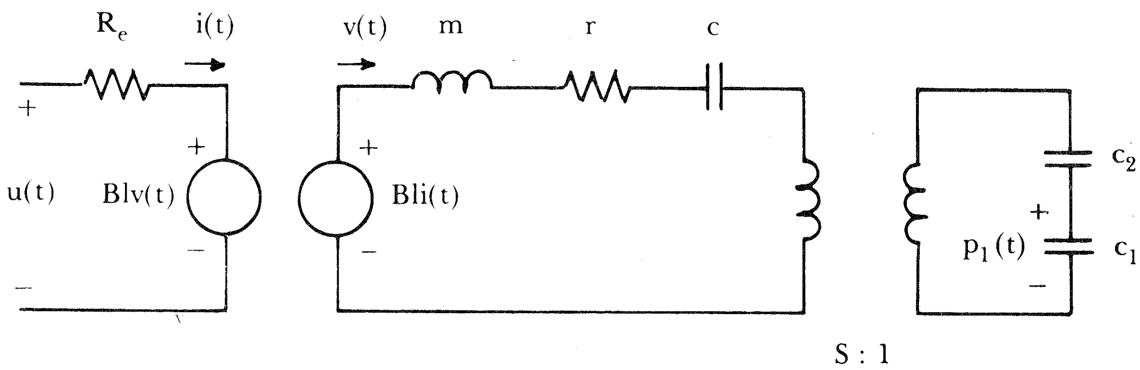


Figure 2 Equivalent diagram of infrasound generating system.
$R_e = 5.6\Omega$, $Bl = 13.7$ N/A, $m = 0.078$ kg, $r = 1.8$ Ns/m, $c = 0.92 \cdot 10^{-3}$ m/N, $S = 0.053$ m^2, $c_1 = (V_1/16)/\gamma p_0 = 7.1 \cdot 10^{-6}$ m^{5}N^{-1}, $c_2 = (V_2/16)/\gamma p_0 = 2.3 \cdot 10^{-6}$ m^{5}N^{-1}

In figure 3 all elements are transferred to the mechanical side, and the transfer function from voltage at the loudspeaker terminals to sound pressure in the test chamber can now be derived. $P_1(s)$ and $U(s)$ denote the Laplace transforms of $p_1(t)$ and $u(t)$, respectively.

$$\frac{P_1(s)}{U(s)} = \frac{BlS}{R_e c_1 m[s^2 + s(r + (Bl)^2/R_e)/m + (1/c + S^2/c_1 + S^2/c_2)/m]}$$

This is a second order low pass filter with a gain:

$$\text{gain} = \frac{BlS}{R_e c_1 (1/c + S^2/c_1 + S^2/c_2)}$$

The resonant frequency is given by:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1/c + S^2/c_1 + S^2/c_2}{m}}$$

and the Q factor by the expression:

$$Q = \frac{\sqrt{m(1/c + S^2/c_1 + S^2/c_2)}}{r + (Bl)^2/Re}$$

If the actual values are inserted, gain = 6.8 Pa/V, f_0 = 30 Hz and Q = 0.41.

A low-pass filter with an upper limiting frequency of 30 Hz is excellent as a transfer function in a chamber like this. However, it would be preferable if the frequency response were maximally flat in the pass band. This requires a Butterworth characteristic in which the Q factor is 0.707. This value could be achieved with a lower value of the Bl product of the loudspeakers, or by adding a series resistor to R_e, but none of these solutions is attractive from a power point of view.

Therefore an extra frequency equalizing filter has been introduced with two zeros cancelling the original poles and two new poles with Q factors of 0.707.

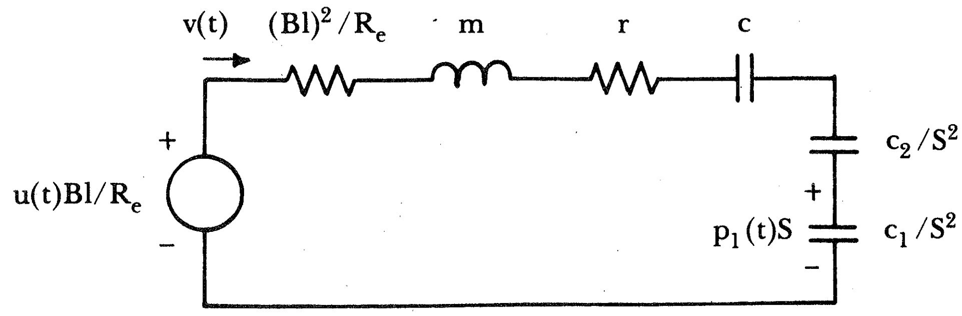


Figure 3 Equivalent diagram of the infrasound generating system, when all components are transferred to the mechanical side

In figure 4 a block diagram of the complete system is shown. The power amplifier is a Brüel and Kjaer Type 2712, 180 VA amplifier, which is able to drive the 16 loudspeakers combined in series-parallel to obtain a resistance of 1.4Ω. The total gain is adjusted to 20 Pa/V, which means that 1 V gives a sound pressure level of 120 dB.

The transfer function is derived provided the test chamber and back volume perform as pressure chambers. This is not the case at frequencies above the infrasound range. Therefore, the low-pass function cannot be expected to be effective at higher frequencies, and a 4th order Butterworth low-pass filter with an upper limiting frequency of 50 Hz is inserted before the power amplifier (not shown in figure 4). This guards against electrical noise and higher frequencies accidentally connected. For the monitoring of the sound, a peak detector and a logarithmic level meter covering the range 70-130 dB is also installed.

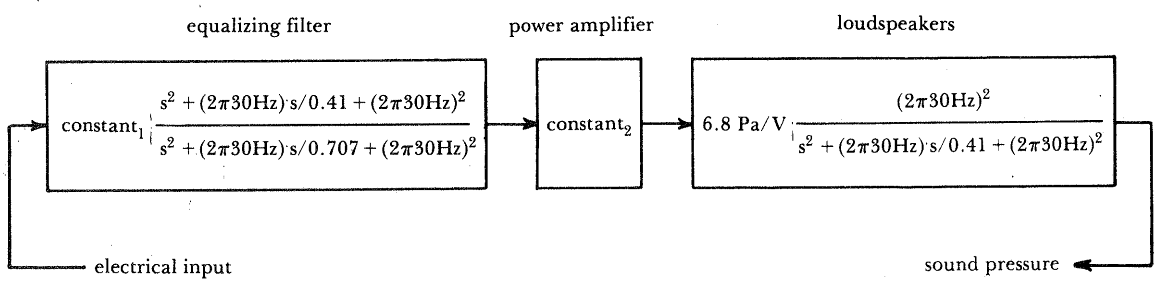


Figure 4 Block diagram of the infrasound generating system

Measurements of Sound Pressure and Vibrations

Figure 5 shows the sound pressure in the center of the room, when 1 V has been applied to the input of the system. As expected, the frequency response is flat in a very wide range. There is a fall at higher frequencies, although the curve does not exactly follow a Butterworth characteristic. The deviations are due to the unequal sound distribution in the room.

There is an unexpected decrease in sound pressure at very low frequencies. This is caused by the air leakage through the pores of the concrete walls. With no special care taken, a lower 3 dB point of 0.2 Hz was reached, and the value of 0.05 Hz in figure 5 was only reached after sealing with a thick layer of polyurethane paint on all surfaces.

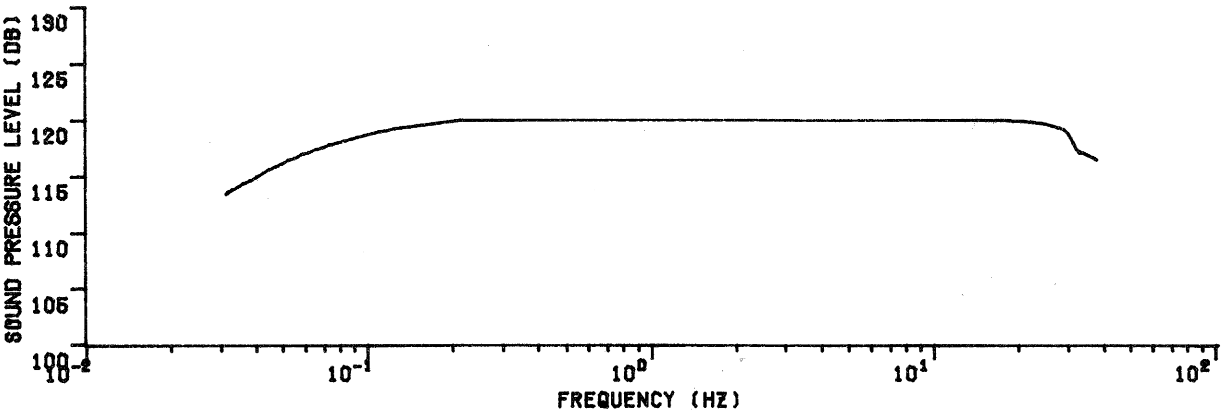


Figure 5 Sound pressure at the centre of the room, when 1 V is applied to the input of the system

In figures 6 and 7 the harmonic distortion is shown when the sound pressure level of the fundamental frequency is 120 and 125 dB respectively. At 120 dB both 2nd and 3rd harmonic distortion are more than 40 dB below the fundamental. Harmonics of higher order are not shown in the figure, but they are much below the levels of the 2nd and 3rd harmonics.

The results obtained are very satisfactory. The threshold curve has a slope of approximately 13 dB per octave in this frequency range, and the low distortion easily ensures that the fundamental frequency is heard before the harmonics. Even at 125 dB, which is regarded as the upper limit of the dynamic range, the distortion is reasonably low.

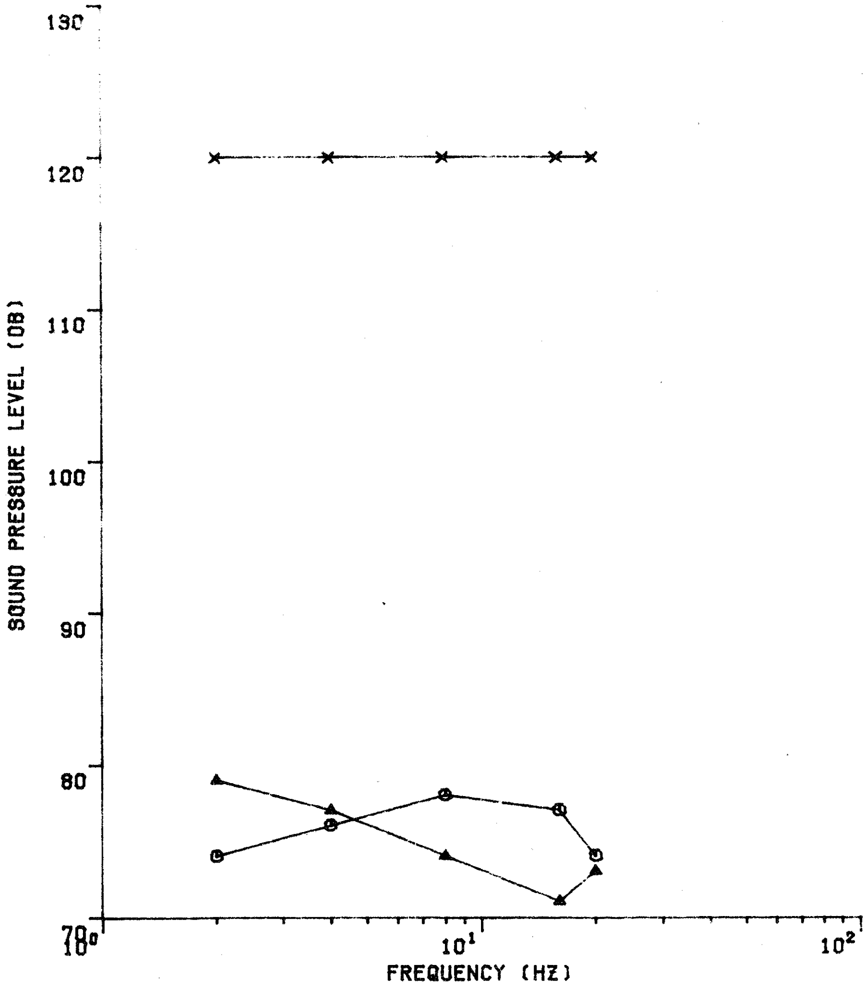


Figure 6 Harmonic distortion when the fundamental is 120 dB.
Fundamental: X, 2nd harmonic: O, 3rd harmonic: △

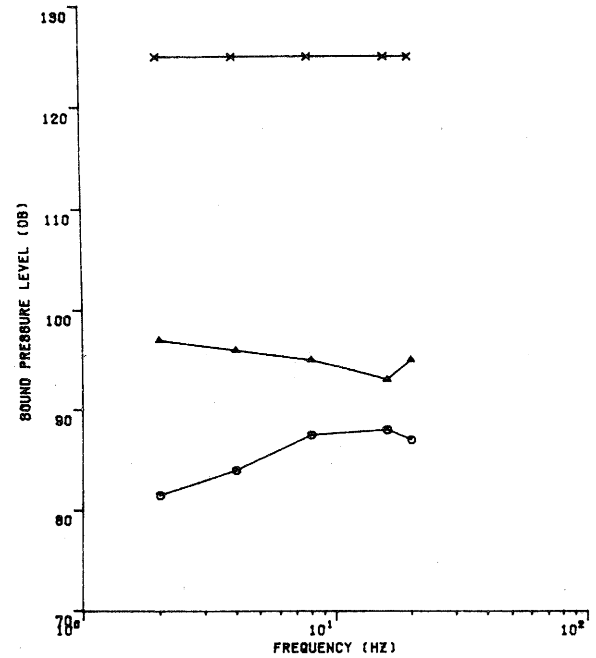


Figure 7 Harmonic distortion when the fundamental is 125 dB.
Fundamental: X, 2nd harmonic: O, 3rd harmonic: Δ

In figure 8 the vibration level of a number of surfaces are shown, when the sound sound pressure level is 120 dB. The "reduced comfort boundaries for 8 hours exposure" of ISO 2631 are also shown. All curves except one, are much below the levels given in the standard. The only curve that approaches the level of the standard, is measured at the door, so subjects will not be exposed to it, and it can be concluded that the vibration levels are satisfactorily low.

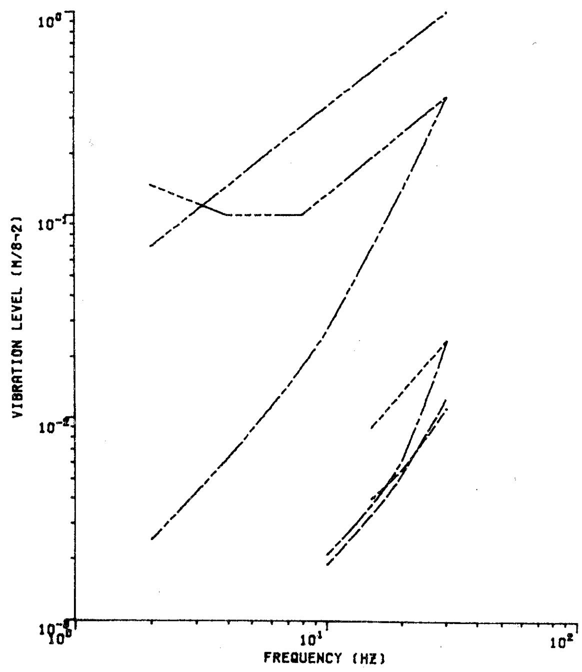


Figure 8 Vibration levels measured at surfaces in the test chamber as a function of frequency, when the sound pressure is 120 dB.
Surface: ceiling: - - - -, floor: ———, wall: — — — —, wall: — - — - — -, door: — - - — - - —. Values are not shown at frequencies where the levels are at or below background level. Reduced comfort boundaries for 8-hour exposure, as given in ISO 2631, are also shown:
vertical movements: — - - - — - - - —, horizontal movements: — - - - - —

Sound Distribution in the Room

Until now it has been assumed that the test chamber and the back volume perform as pressure chambers which means that the sound pressure is the same everywhere in the room. This assumption has been evaluated theoretically and by measurement.

In the calculations the model given in figure 9 has been used. The room is bounded by 5 rigid planes plus one plane where the loudspeakers are mounted. The latter is modelled by a rigid plane and a piston vibrating with a fixed amplitude. Thus the 16 loudspeakers are modelled by one big square covering the same total area and giving the same volume displacement.

The calculations are given in [2] and will not be repeated here. They are based on the wave equation and the boundary conditions and they involve the description of the sound pressure as a sum of waveguide modes.

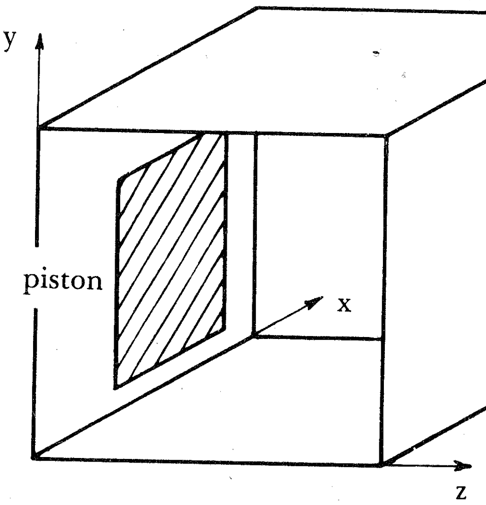


Figure 9 Model of test chamber used in calculation of the sound distribution in the room

Figure 10 shows the sound pressure in a point in the room as a function of the frequency, assuming a fixed piston amplitude. At low frequencies the curve is flat, corresponding to the assumption of a pressure chamber, while at higher frequencies resonances and thus strongly varying sound pressure are seen. The first resonance is at 58 Hz, corresponding to a half wavelength in the direction of the x axis.

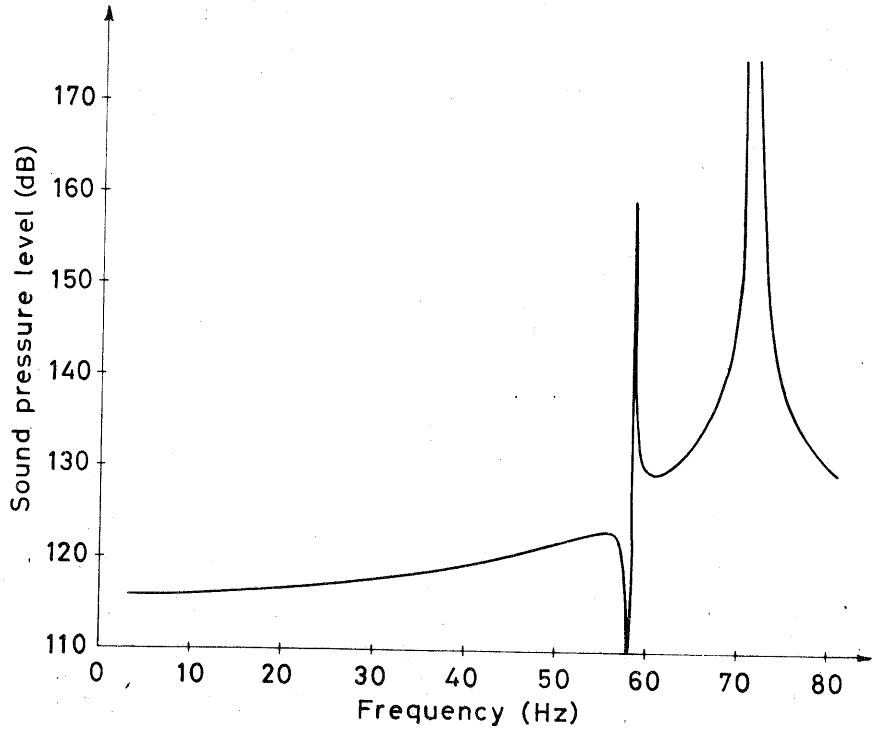


Figure 10 Calculated sound pressure at a fixed point (x,y,z) = (1.5 m, 1.5 m. 1.5 m) as a function of frequency, when the vibration amplitude of the piston is held constant at a level of 2 mm peak to peak

In figure 11 and 12 the frequency is held constant at 10 Hz and the pressure is shown along two axes in the room. Both calculated and measured values are shown, and there is a good agreement between these. The variations in the room at 10 Hz are in the order of 1.5 dB, and will hardly cause any difficulty. At 20 Hz and 30 Hz variations are below 3 dB and 8 dB respectively, provided a 30 cm space nearest to the loudspeakers is omitted. When making very accurate measurements, like threshold and loudness determinations, it will be necessary to use a well specified position of the subjects.

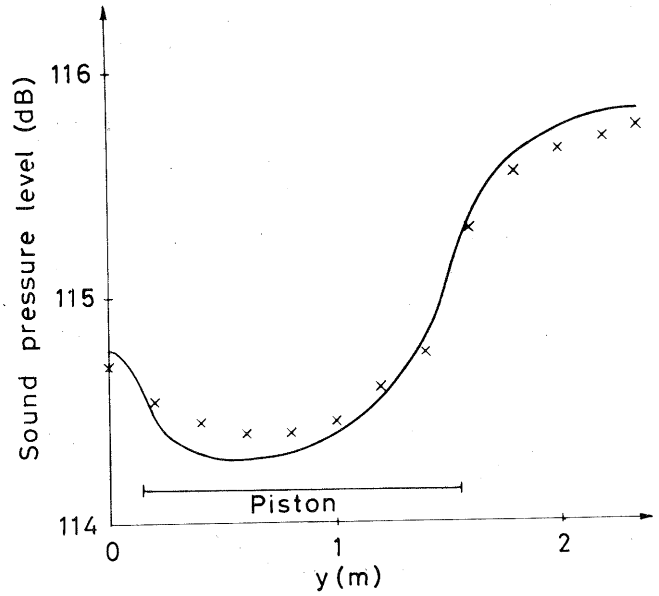


Figure 11 Sound distribution along the axis (x,z,y) = (1.5 m, 0). The solid line is calculated, while points are measured values

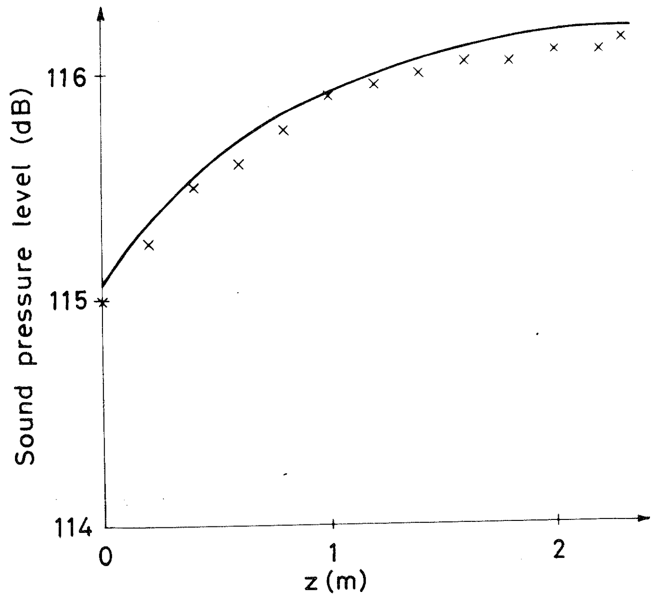


Figure 12 Sound distribution along the axis (x,y) = (1.5m, 1.5m). The solid line is calculated, while points are measured values

Ventilating System

The room is intended to be used for experiments of several hours duration, and some kind of supply of fresh air must be provided. A normal ventilating system cannot be used, since it would enable the infrasound to vanish through the ventilator.

The chosen solution involves a high pressure ventilator and two flow resistances, one leading from the ventilator to the test chamber and the other from the chamber to the ambient, see figure 13.

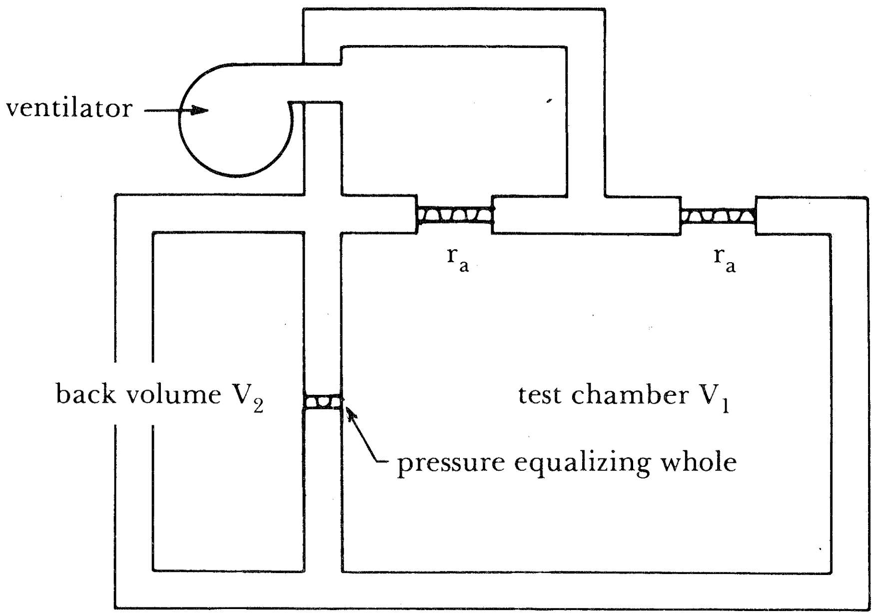


Figure 13 Schematic drawing of the ventilating system

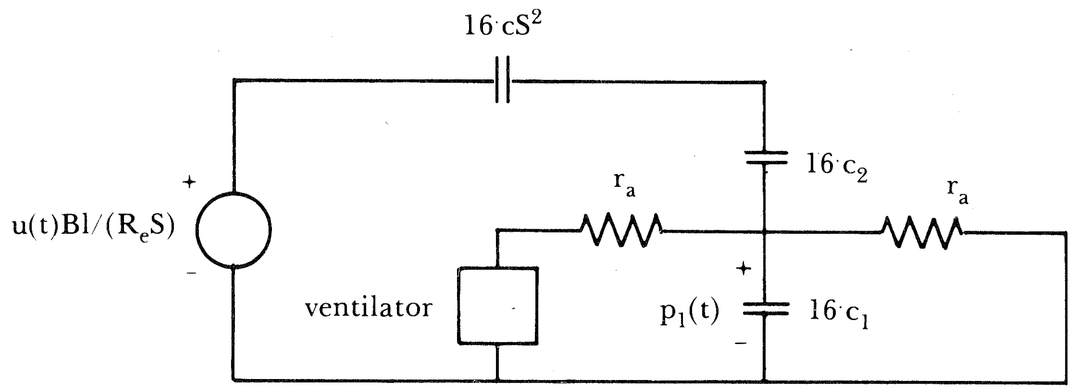


Figure 14 Equivalent diagram of the leakage introduced by the ventilating system. All components are transferred to the acoustical side. The 16 loudspeakers are modelled only by their compliance, since the membrane mass and the mechanical and electrical losses can be ignored at very low frequencies

Also this system introduces a leakage, but the value can be controlled by the acoustic impedance of the leakages r_a. An equivalent diagram is given in figure 14.

Assuming the ventilator to be an acoustic short circuit to the ambient noise the lower 3 dB point will be $f_1 = 1/[\pi r_a\ 16\ (c_1 + c_2 cS^2/(c_2 + cS^2))]$. If $f_1 = 0.3$ Hz is inserted, r_a becomes $8 \cdot 10^3\ \text{Nsm}^{-5}$. This flow resistance is made by a 30 cm · 30 cm sheet of 5 cm rock wool.

The required pressure P from the ventilator can be calculated from the desired air exchange Q. For 3 persons Q should be around 60 m^3 per hour, or 0.017 m^3/s. Then $P = 2 r_a Q = 272$ Pa.

The solution chosen results in an overpressure in the test chamber of 1/2 of the supply pressure. This is a very small pressure and does not cause any difficulty, except that an equalizing hole had to be made from the test chamber to the back volume, in order to prevent the loudspeakers from being pressed away from their equilibrium.

Unfortunately the ventilator itself generates some noise, including infrasound. Therefore an acoustic filter has been installed. The filter simply consists of a 0.86 m^3 box inserted between the ventilator and the flow resistance leading to the chamber. The box and the flow resistance together form a first order low-pass filter. With the filter the noise from the ventilator is below the hearing threshold up to 50 Hz. At 63 Hz and above the ventilator only contributes little to the total background noise in the building, see figure 15.

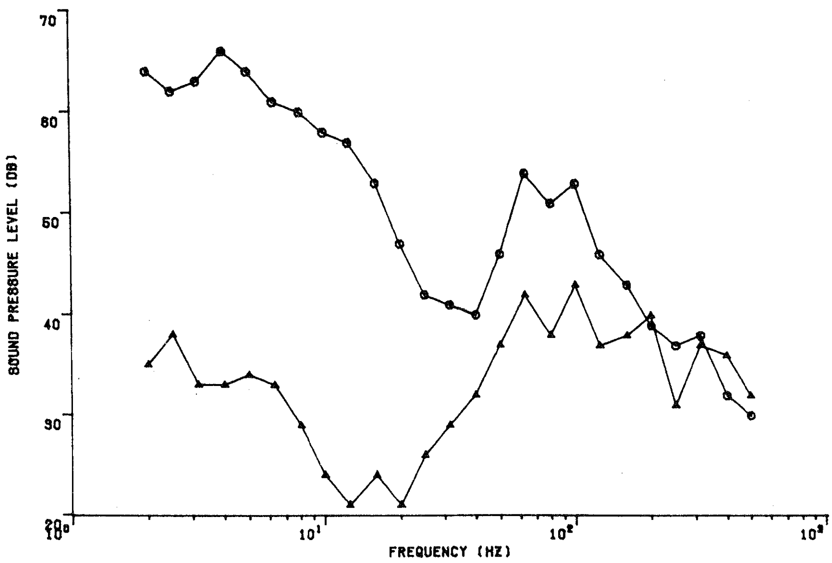


Figure 15 Background noise in the test chamber with (O) and without (Δ) ventilating system turned on. The values without ventilating vary a lot depending on other activities in the building, and it is only possible to obtain these values outside normal working hours

The two-room construction used in this laboratory in principle ensures that no sound is radiated from the system. However, in practice some sound is transmitted to the surroundings. Figure 16 shows the sound pressure in a corner of the surrounding laboratory, when the sound pressure in the test chamber is 120 dB.

With the ventilating system closed, significant radiation mainly occurs at high frequencies, where the walls vibrate. At low frequencies, the sound is transmitted through the air leakages of the walls. When the ventilating system is open, an additional leakage is introduced, and the transmitted sound increases considerably.

Although some sound is transmitted from the infrasound generating system to the surroundings, this is not expected to be a problem. The levels shown in figure 16 are only audible above 20 Hz approximately, and they are measured at a sound pressure level in the chamber near the upper limit of the dynamic range.

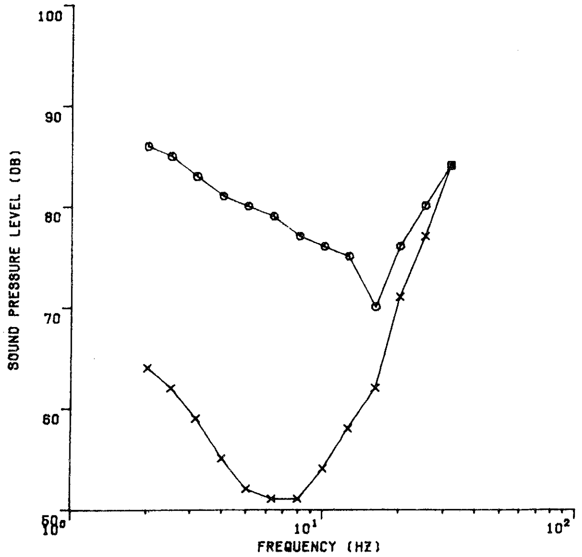


Figure 16 Sound transmitted to the surrounding laboratory when the sound pressure in the test chamber is 120 dB, and the leakages in the ventilating system are open (O) and closed (X)

Conclusion

In the test chamber described, it is possible to make experiments where human subjects are exposed to pure infrasound and low audio frequency sound in the frequency range 0.05 to 30 Hz. The size of the chamber allows two or three subjects to be under test at a time, and a ventilating system makes it possible to carry out experiments of several hours duration.

The maximum obtainable sound pressure level – 125 dB rms – is sufficient to cover most of the normally occurring environmental infrasound. If a higher sound pressure level is needed, the back volume can be used, since the sound pressure level here is approximately 10 dB higher because of the smaller volume. However, the back volume has no ventilating system, and it does not appear as pleasant as the test chamber itself, so only short time exposures will be carried out here.

The frequency range of the system covers the most important part of the infrasonic range, and it gives an overlap to the audio range. Extensions downward in frequency can only be made by excessive sealing of the walls. Upward in frequency we are restricted by the dimensions of the room, which should be small compared to a wavelength to keep a pure pressure field. Of course, a signal of a higher frequency than 30 Hz can be fed to the loudspeakers, but the sound pressure will then not be the same everywhere in the room.

Unwanted effects from the infrasound generator such as vibrations, harmonic distortion and audio frequency noise have been kept so low that they are not expected to influence the experiments.

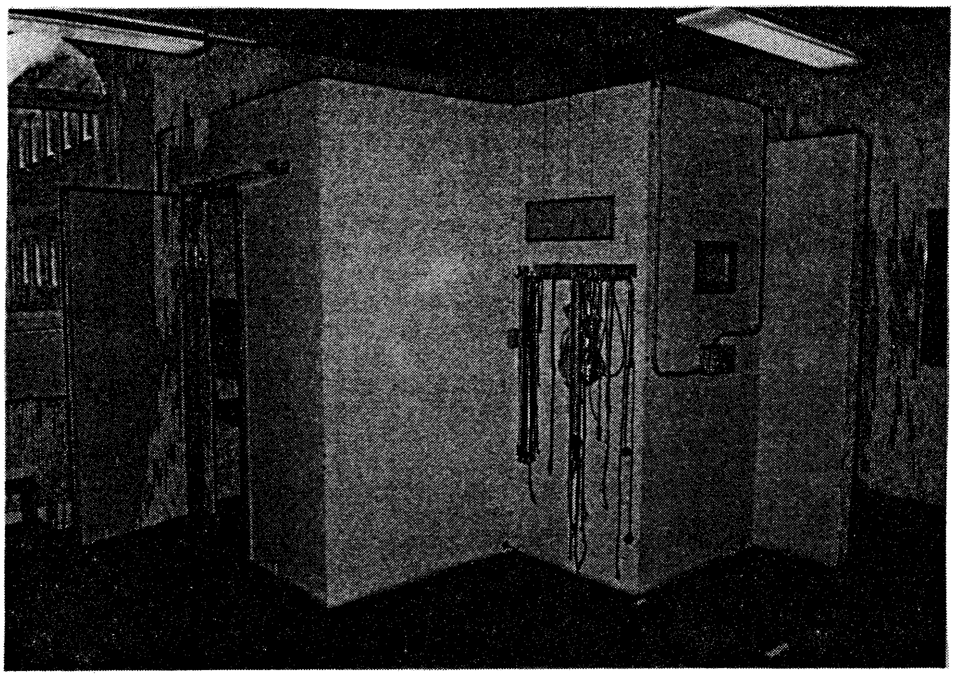
Acknowledgements

The author wishes to thank his colleagues for their advice and encouragement during the building of the chamber, especially Professor. J.B. Andersen and Associate Professor. P. Rubak. The work was financed by Aalborg University.

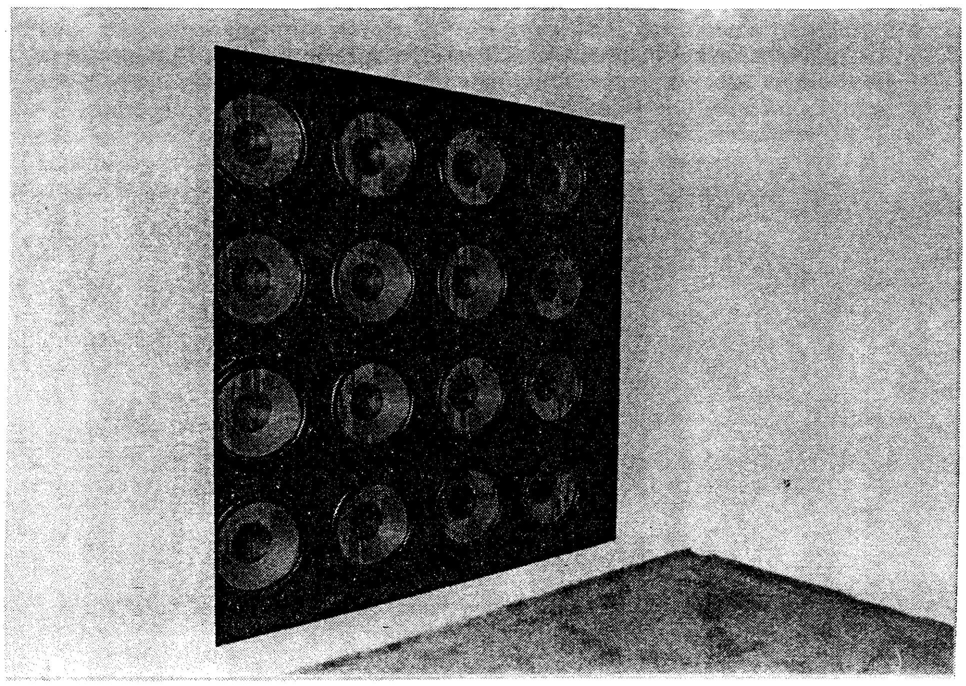
References

[1] **Henrik Møller.** *Construction of an Infrasound Test Chamber. (In Danish). R 77-8 Institute of Electronic Systems, November 1977.*

[2] **Jørgen Bach Andersen.** *Variation of Pressure in the Cabin. Chapter 10 in [1].*



The infrasound chamber is built of concrete in a corner of the laboratory. The open door leads to the back volume, while the door to the test chamber is hidden behind the wall to the right



The infrasound is generated by 16 electrodynamic loudspeakers mounted in a wall. During the experiments they are covered by a cloth