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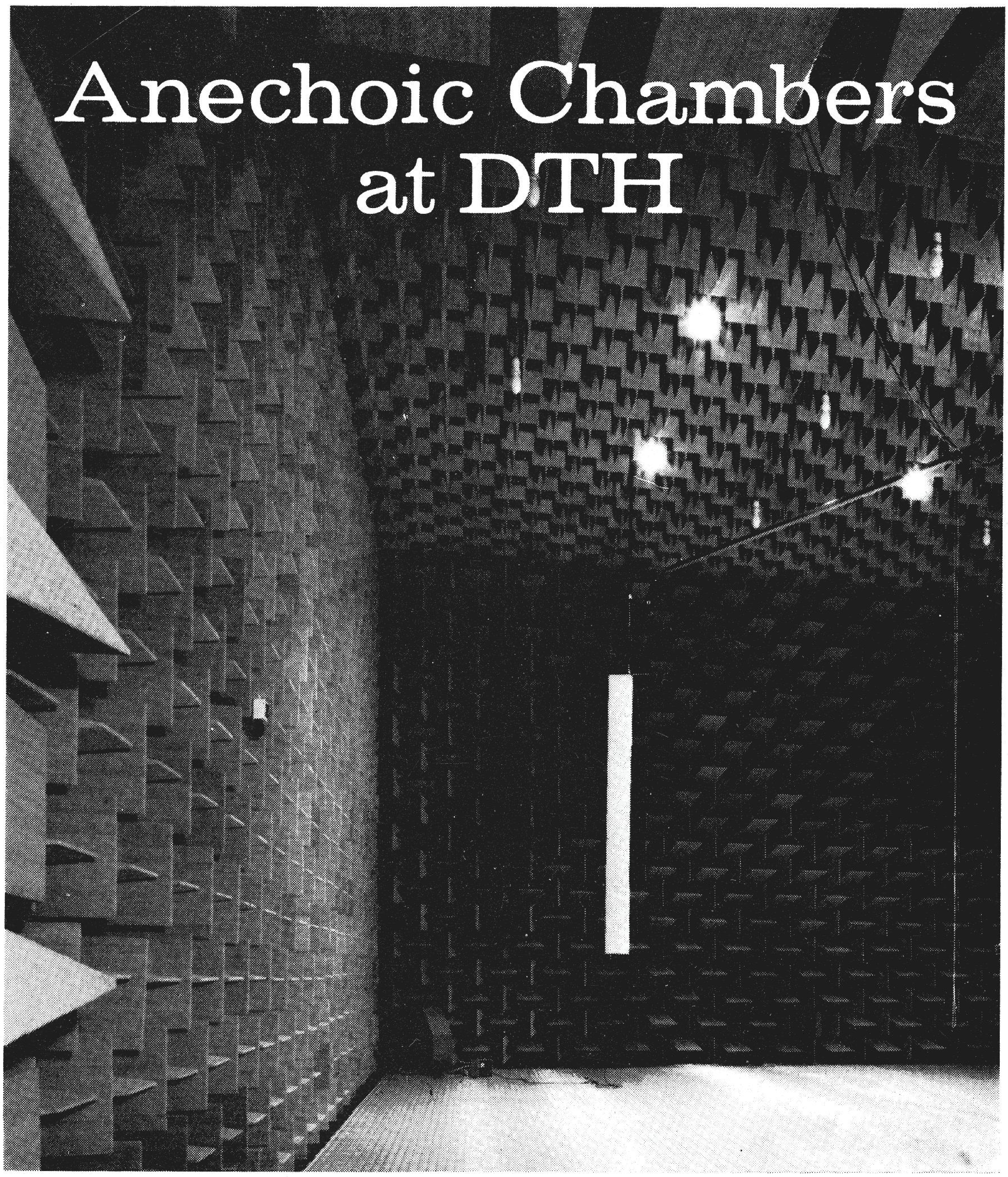

Anechoic Chambers at DTH

No. 2

1968

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TECHNICAL REVIEW

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The Anechoic Chambers at the Technical University of Denmark

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ABSTRACT

In connection with the extension of the Technical University of Denmark at Lyngby the Acoustics Laboratory has aquired new and larger measurement facilities. Two of the new rooms are built as anechoic chambers using wedge-type construction. The acoustical design of these rooms as well as a number of investigations carried out on the wedge-construction itself are described and discussed. Mention is also made of the electrical installation, the ventilation system and the measurement cable installation. Finally some measurements on the completed rooms, both with regard to their free-field performances, and with regard to sound and vibration insulation are described. These measurements show that the rooms can be used even for very exacting measurements, and under extreme outside conditions.

SOMMAIRE

En corrélation avec l'extension de l'Université Technique du Danemark à Lyngby, le Laboratoire d'Acoustique a acquis de nouvelles et plus amples installations de mesure. Deux des nouvelles salles sont construites en chambres anéchoïques par le recours à une structure du type à coins absorbants. La conception acoustique de ces chambres est décrite et discutée, comme un certain nombre d'investigations menées sur l'emploi de coins absorbants. Il est aussi fait mention de l'installation électrique, du système de ventilation et de l'installation du câblage de mesure. Pour terminer sont décrites quelques mesures effectuées sur les chambres parachevées, tant sous l'aspect du fonctionnement en champ libre que sous celui de l'isolation aux sons et aux vibrations. Ces mesures montrent que les chambres peuvent être utilisées même pour les mesures les plus ardues et dans des conditions extérieures extrêmes.

ZUSAMMENFASSUNG

Es werden zwei schalltote Räume beschrieben, welche bei der Erweiterung der Dänischen Technischen Universität für das Akustische Laboratorium im neuen Hochschulzentrum bei Lyngby eingerichtet wurden. Beide Räume sind mit keilförmigen Absorbern ausgestattet, deren Eigenschaften besprochen werden. Erwähnt wird auch die elektrische Installation, die Belüftung, sowie die Verlegung der Meßkabel. Endlich sind Messungen in den Räumen ausgeführt, die sich auf die Freifeld-Eigenschaften sowie auf die Luft- und Körperschalldämmung beziehen. Die Ergebnisse zeigen, daß die Räume selbst bei ungewöhnlichen Umgebungsbedingungen für genaue Messungen verwendbar sind.

Introduction

In connection with the extension of the Technical University of Denmark at Lyngby just north of Copenhagen, the Acoustics Laboratory has acquired three new buildings with a number of special purpose rooms (two anechoic chambers and six reverberation rooms). The new buildings were taken into use in 1965.

The two anechoic chambers, which are situated in a separate building, were constructed as one large room for precision measurements and research

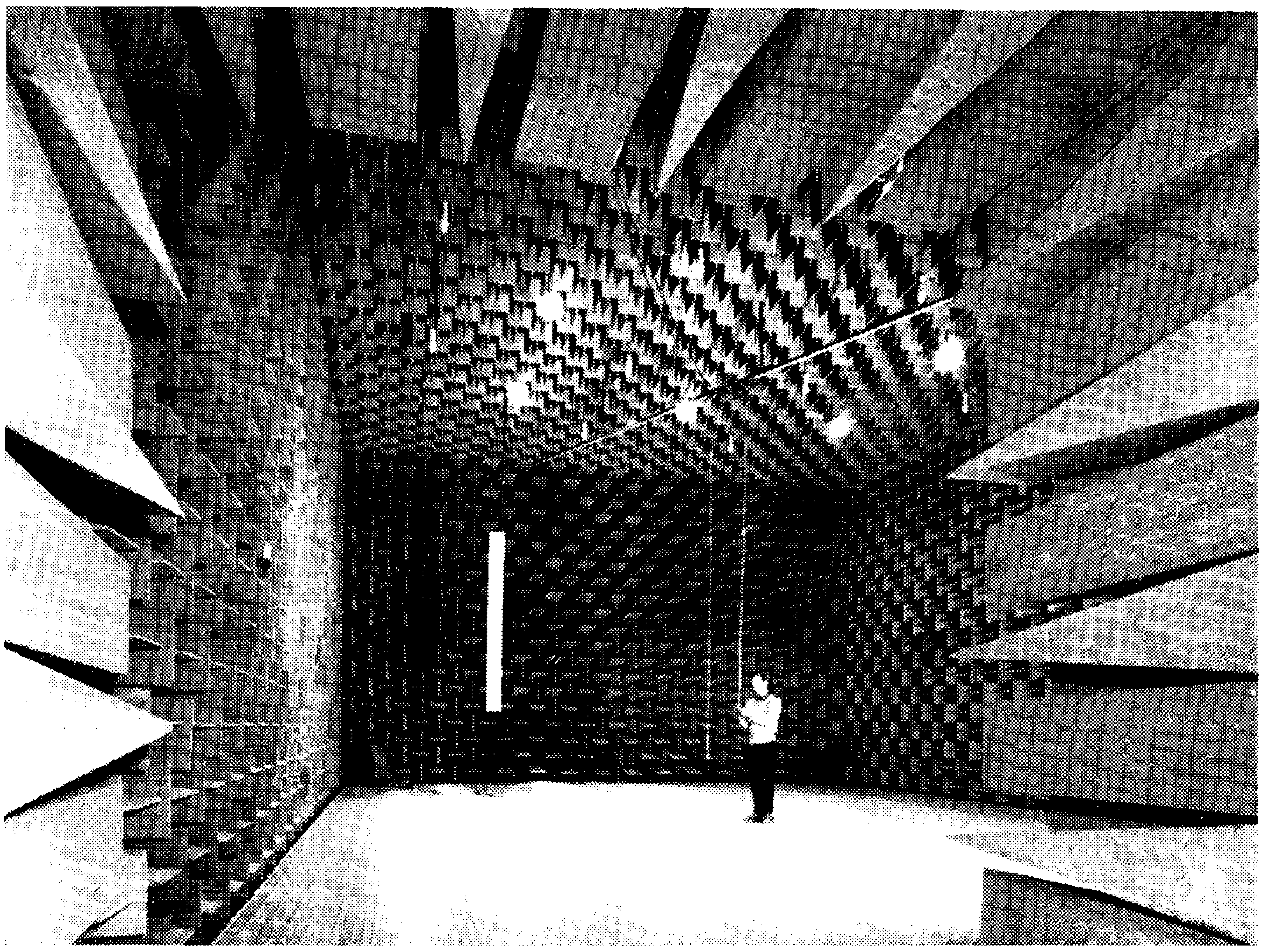

Fig. 1. The large anechoic room.

purposes (Fig. 1), and one smaller room for routine measurements, for example in connection with the undergraduate teaching.

The anechoic chambers are designed jointly by the architects and engineers constructing the new technical university and the staff of the Acoustics Laboratory. Fig. 2 shows a plan of the building with the anechoic chambers and the associated rooms.

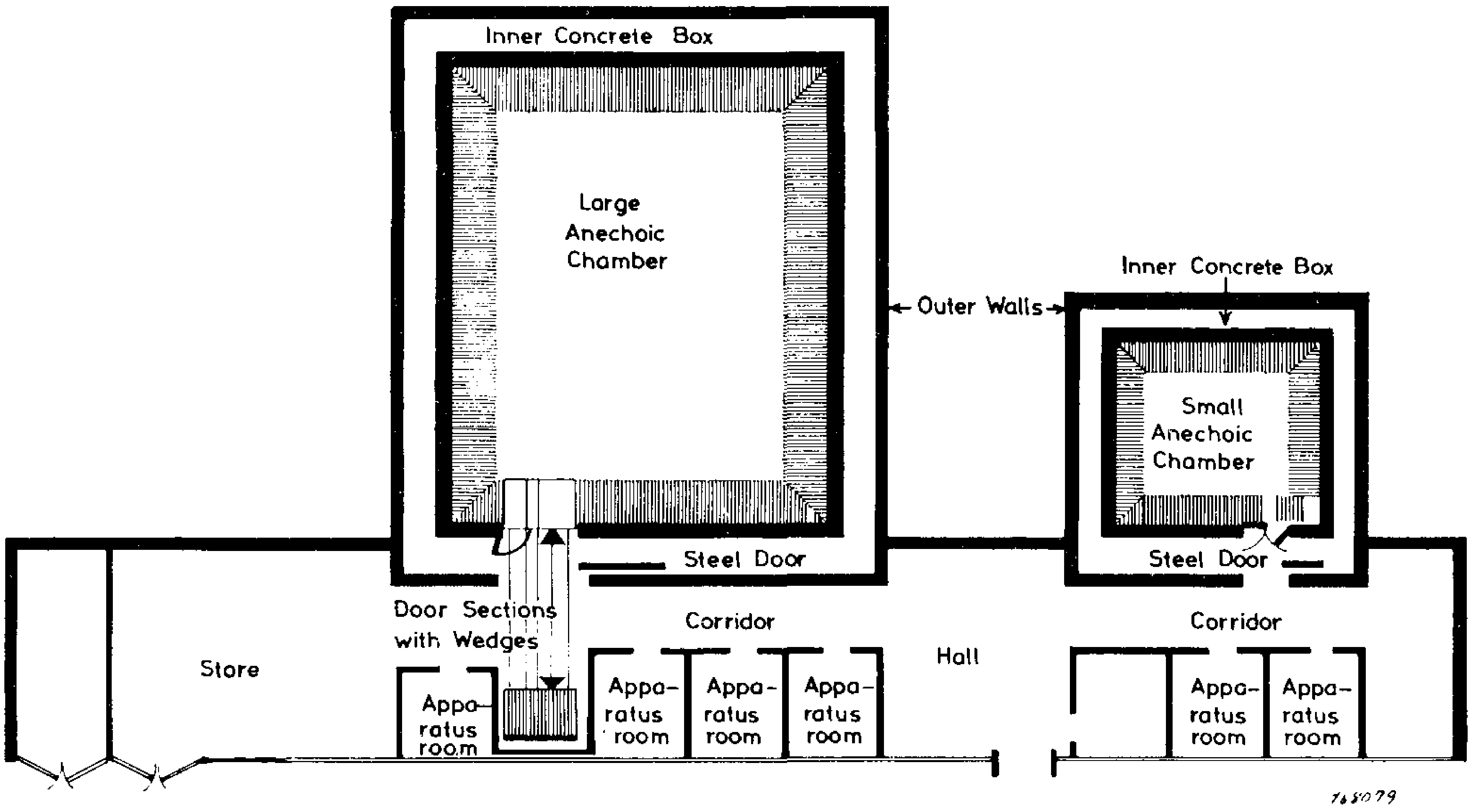

Fig. 2. Plan of the building with the anechoic rooms.

Design Considerations

Dimensions.

The dimensions of the large anechoic room were chosen mainly with regard to the largest measuring distance to be used. As it was desirable to be able to measure in the far field of large sound sources such as loudspeaker columns of 1–3 m length, measuring distances of up to 15 m were considered suitable. Another factor which also influences the room dimensions is the lower limiting frequency, i.e. the lowest frequency for which a free field is obtained in the room. This frequency is not only determined by the nature of the material covering the walls, but also by the ratio between room dimensions and wavelength. From the theory of sound transmission in heavily damped ducts we know that the condition for undisturbed sound transmission parallel to heavily damped surfaces is that

$$\frac{h}{\lambda} > \frac{|z|}{1.2\,\varrho \cdot c}$$

where h is the width of the duct, λ is the wavelength and z is the acoustic impedance of the walls.

With a view to the electro-acoustical measurements, which are to be carried out in the room, the lower limiting frequency was chosen to be 50 Hz, which gives $h > 6$ m.

As a result of all the considerations to be taken the free part of the room was fixed at 12.1 m × 9.7 m × 8.5 m. The free part of the smaller anechoic room was fixed at 4.8 m × 4.1 m × 2.9 m, which should give a lower limiting frequency of about 100 Hz.

Wall lining.

The absorption lining of anechoic rooms can have widely different thicknesses, depending upon the size of the room and the frequency range of the measurements to be carried out, and widely different absorption qualities depending upon the type of material used and its physical structure.

When investigating the lining of anechoic rooms the concept of the reflection coefficient is usually employed. This is the ratio between the sound pressure of the reflected sound and the incident sound. For a suitable absorption lining the reflection coefficient is generally a decreasing function of frequency and the lowest frequency for which the reflection coefficient is 0.1 is usually taken to be the limiting frequency. This term is used in the following.

The lining of anechoic rooms can be constructed in different ways. In recently built rooms the lining is usually made up of wedges of mineral wool or similar absorbing materials. Other types of construction are of course possible. However, on the basis of literature studies, economical considerations etc., it was decided to concentrate further studies upon wedge constructions only.

The investigation of the reflection qualities of absorbing materials should be carried out for various angles of incidence. Measurements at normal incidence may be done with the tube method, which is well known. The measurements at other angles of incidence require extensive instrumentation and suitable measuring rooms, as well as a reliable measuring method and a clear definition of the quantities to be measured. A theoretical consideration of the possibility of measuring the reflection in a free field shows that the necessary test wall should have dimensions several times the wavelength at the lowest measuring frequency. This resulted in a decision to carry out model tests in scale 1 : 8 with a wedge shape which was determined on the basis of tube measurements.

In order to investigate the influence of the wedge shape in addition to the influence of the absorption coefficient of the wedge material, measurements were taken with wedges made of Sillan (mineral wool) as well as of lacquered wood. The main results of these model experiments were that the reflections seemed to follow Snell's law, that variations in the wedge pattern had negligible influence upon the reflected energy, and that maximum reflection was obtained for sound incidence parallel to the wedge axis. On the basis of these results it seems reasonable to give more importance to measurements on wedges by the tube method than would have been given without the knowledge gained from the model tests. This conclusion is undoubtedly only valid for wedge linings, and is probably quite wrong for linings such as layers of woven material.

The tube measurements were carried out in a brick tube of dimensions 60 cm × 60 cm, especially built for the purpose, of 23 cm bricks. The tube is constructed vertically in an empty lift duct. A sketch of the tube is shown in Fig. 3. Access to the tube is made at the bottom through a steel door with a

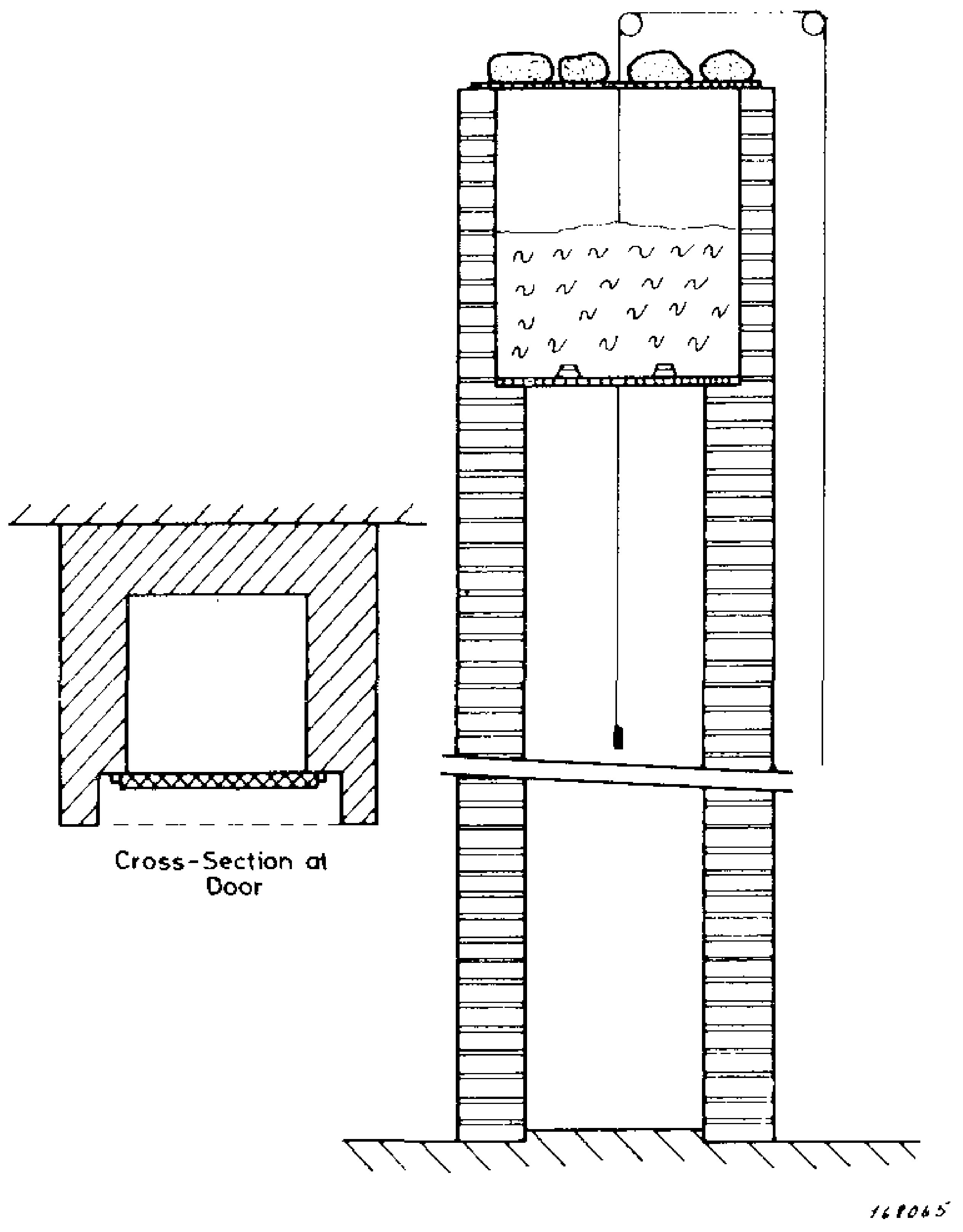

Fig. 3. Duct for reflection measurements on wedges.

4–5 cm concrete lining. The tube is not acoustically entirely loss free, but measurements and calculations show that the inherent damping has negligible influence upon the results obtained. The initial measurements were carried out with wedges made in the laboratory, of glued 2 cm thick layers of Sillan of specific weight 100–110 kg/m^3. Some of the tests were repeated later with Sillan wedges made in a factory.

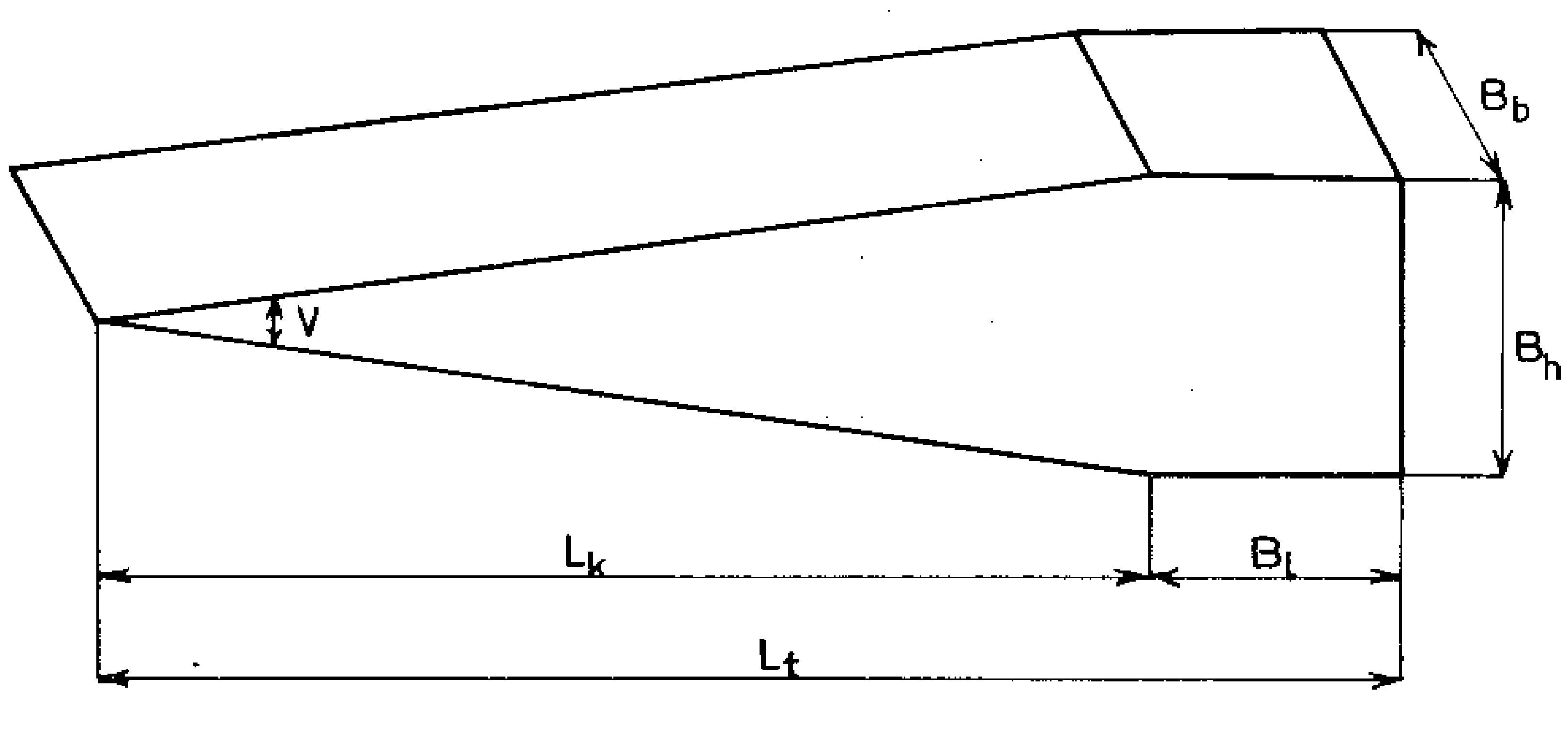

Fig. 4. Wedge.

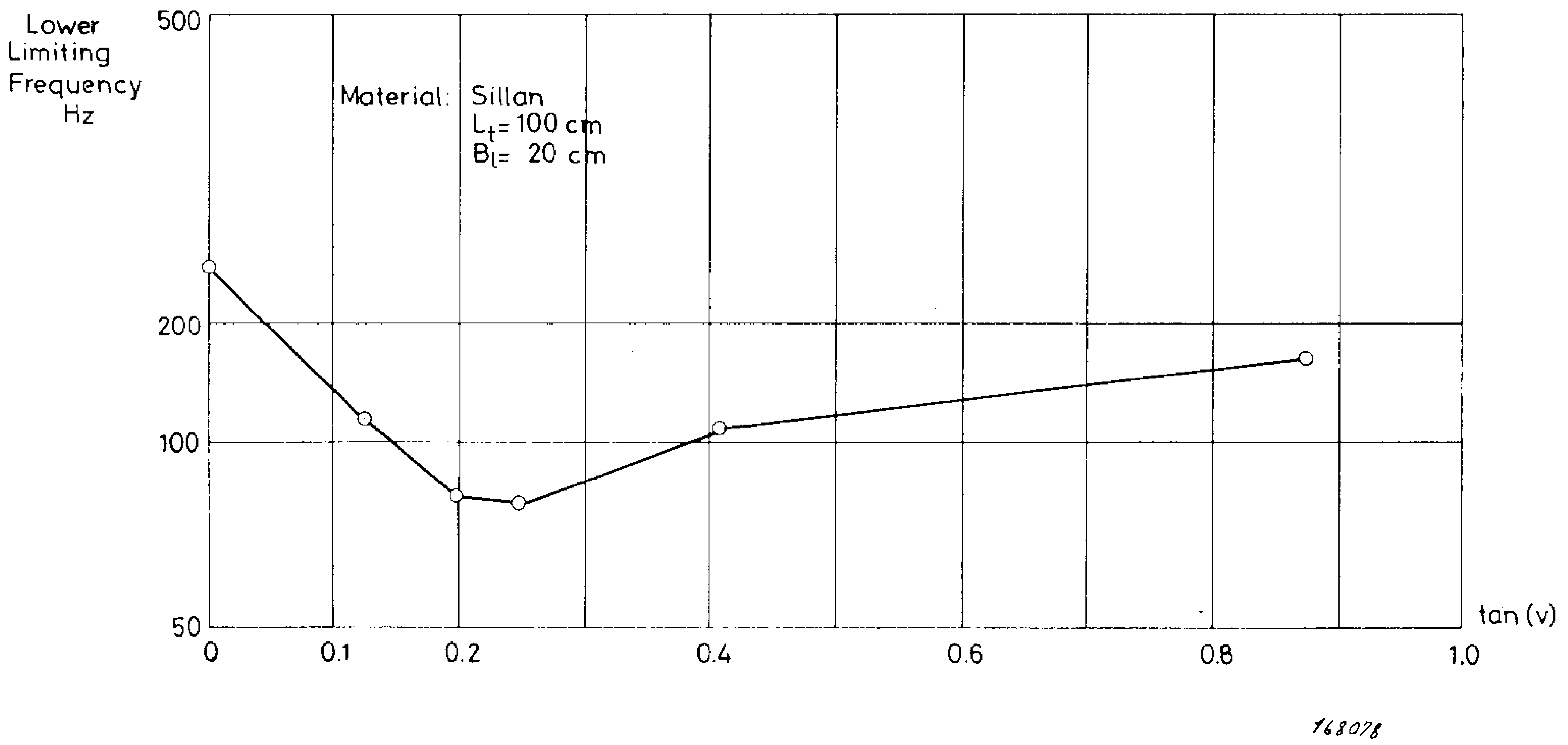

Fig. 5. The lower limiting frequency of the wedge lining as a function of tan (v).

The first part of the investigation was carried out in order to see if the wedge angle *v*, see Fig. 4, had any influence on the absorption, and if so, to find the angle which would give the lowest limiting frequency. The results from these measurements are shown in Fig. 5. The total length of the wedges was kept constant and, except at the limiting wedge angles, also the height of the base as well as the basis length to width ratio, while the wedge angle and base sides were varied. The figure shows the limiting frequency as a function of the tangent to the wedge angle, tan *(v)*. It can be seen that there is a relatively wide range of angles for which the limiting frequency is lower than for the remaining angles.

In order to determine the influence of the length of the wedges, measurements were taken with varying wedge length and constant wedge angle. The results

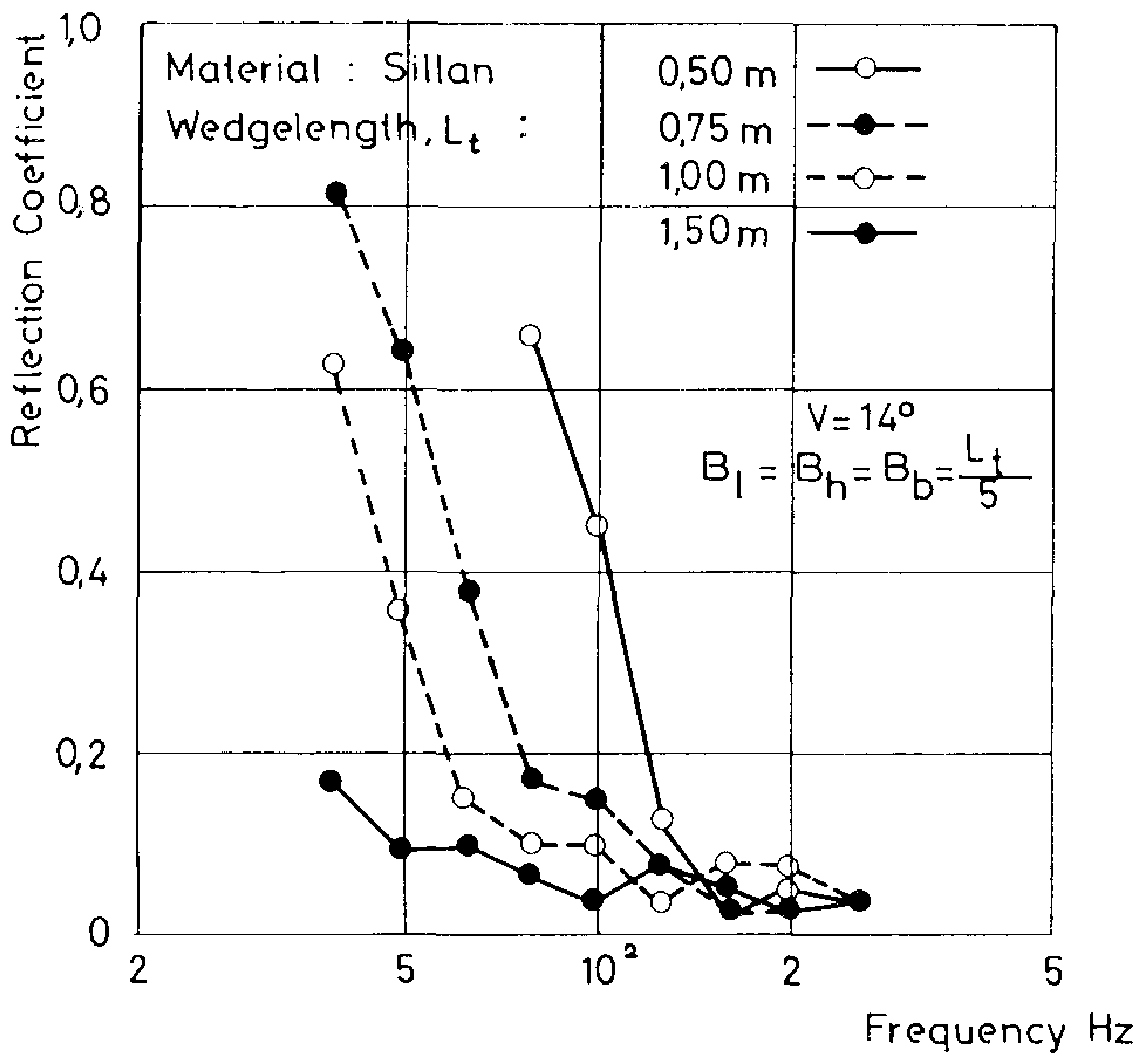

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Fig. 6. The reflection coefficient of the wedge as a function of frequency with wedge length as parameter.

are shown in Fig. 6, where the reflection coefficient is plotted as a function of frequency. From considerations of the relationship between thickness and absorption of porous materials, one would expect the limiting frequency to be inversely proportional to the thickness of the lining, which is also demonstrated by these results.

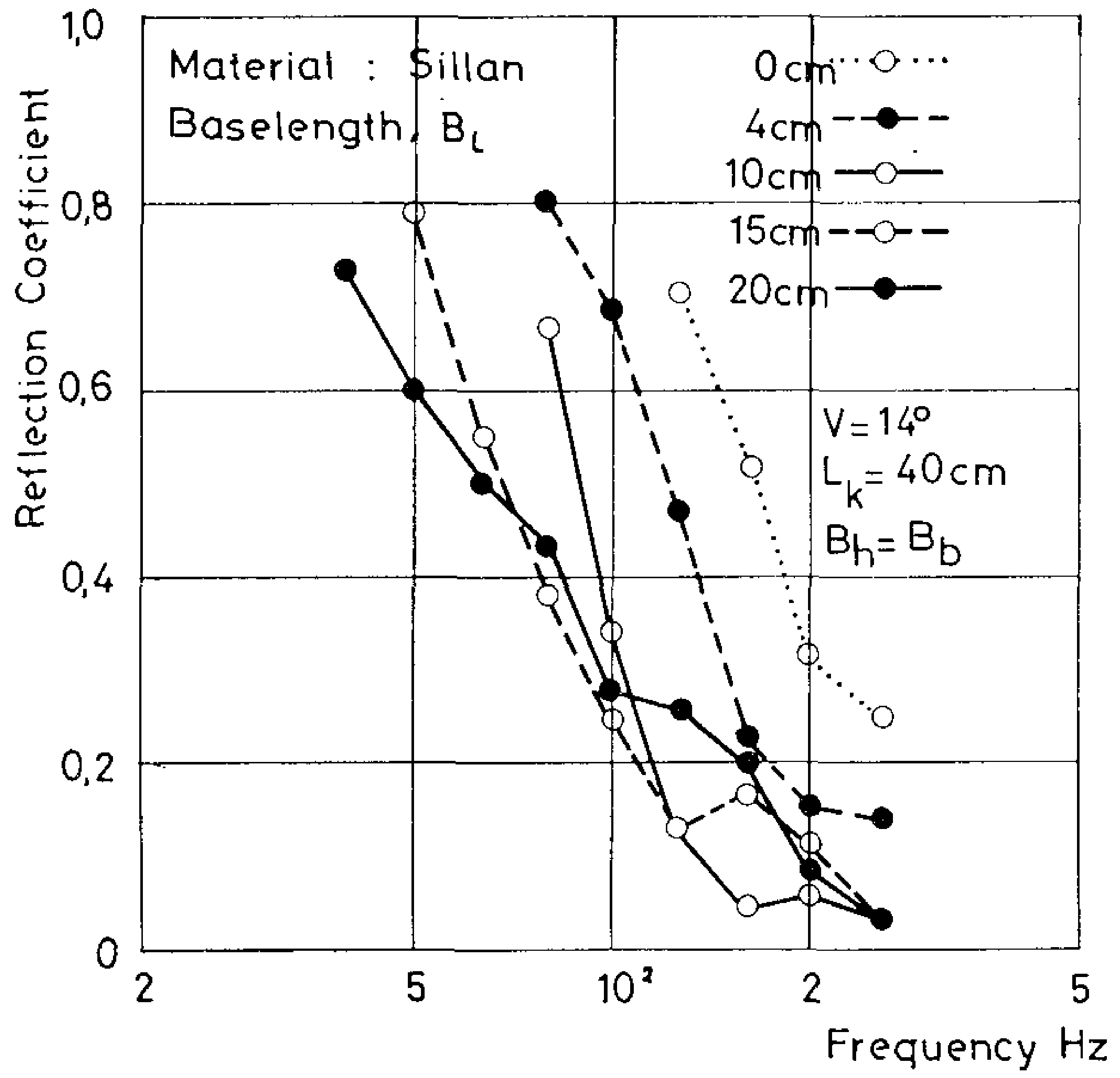

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Fig. 7. The reflection coefficient of the wedge as a function of frequency with base length as parameter.

Small variations in base width B_b seem to have negligible influence on the reflection coefficient, neither did measurements on wedges of parabolic shape give any significant improvement, in fact parabolic wedges would probably have an economic disadvantage because of difficult cutting and larger wastage of material.

The base length B_L may have some influence on the limiting frequency, as can be seen from Fig. 7. All dimensions except the total length of the wedge are here kept constant. It is seen that the lowest limiting frequency is obtained with a base length of about 10 cm, for wedges of length $L_k = 40$ cm.

One might perhaps expect that a built-in resonator below the base of the wedge would improve the absorption of a wedge lining. Fig. 8 shows the results from measurements on wedges placed against a hard termination and in front of a Helmholz slit resonator of resonance frequency 80 Hz, which is just below the lower limiting frequency for the wedges placed against a hard termination.

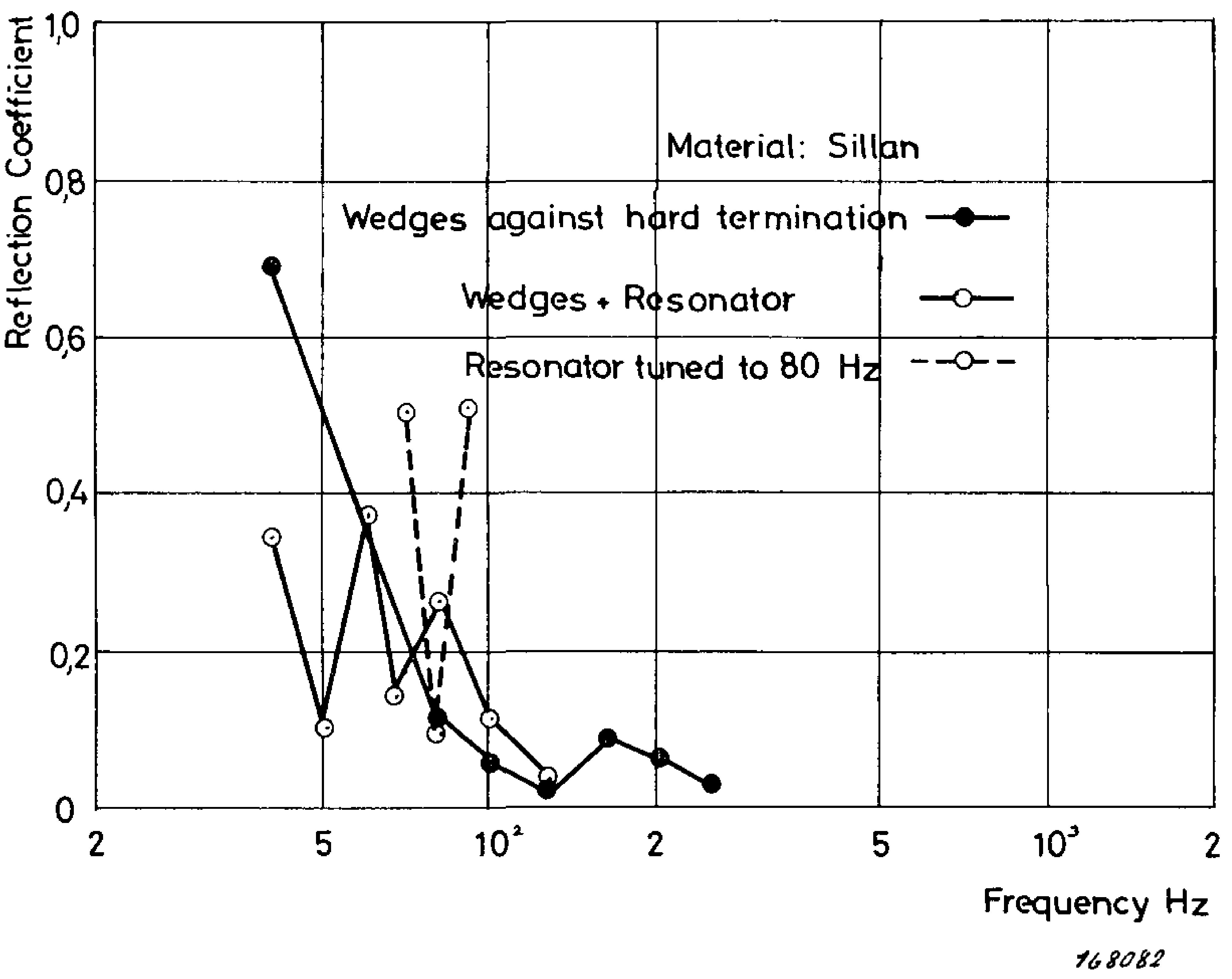

Fig. 8. The reflection coefficient as a function of frequency for wedges placed in front of a Helmholtz resonator.

Masses corresponding to the wedge weight were placed on the front plate of the resonator during tuning. As can be seen from the figure the combination of wedge and resonator gave rather discouraging results. Other experiments gave similar results.

At this point in the investigations it was necessary to fix the wedge module and length, and the dimensions 145 cm × 30 cm × 30 cm with a base length of 25–30 cm and 100 cm × 24 cm × 24 cm with a base length of 15–20 cm were chosen for the large and the small anechoic room respectively. This of course influenced the following part of the investigation. The chosen dimensions give wedge angles of 13°–17°.

In order to gain experimental evidence of the suitability of different materials, measurements were carried out on a variety of glass and mineral wool samples of different specific weight, and on foamed poly-urethane-ether AOP 35. In addition to measurements of absorption coefficient load tests were carried out on the mineral wool wedges in order to compare their mechanical strength. The tests were carried out with the wedges placed in trays of perforated plates and fixed with rods going through the perforation and the base of the wedges. A load of 100 grammes placed at the tips of horizontally mounted wedges for a week gave less than 1 cm deflection for all the mineral wool wedges except for lightweight Rockwool wedges.

Corresponding tests were made with vertically mounted wedges and a load pulling the wedges out. All the wedges except the light Rockwool wedges could stand an extra weight corresponding to their own weight without being pulled out. Loads of twice the wedge weight could be carried by the glass wool types and the heavy Rockwool wedges. Without any proper testing of the ability of the different wedges to withstand mechanical handling, it can be said that except for the light glass wool wedges which could take several large deformations without damage, they were all very brittle and would easily break.

The wedges made of foamed poly-urethane-ether could withstand large deformations without any damage. They would show a considerable extension before breaking, but a very low stiffness made additional support of the wedge tips necessary for horizontal mounting.

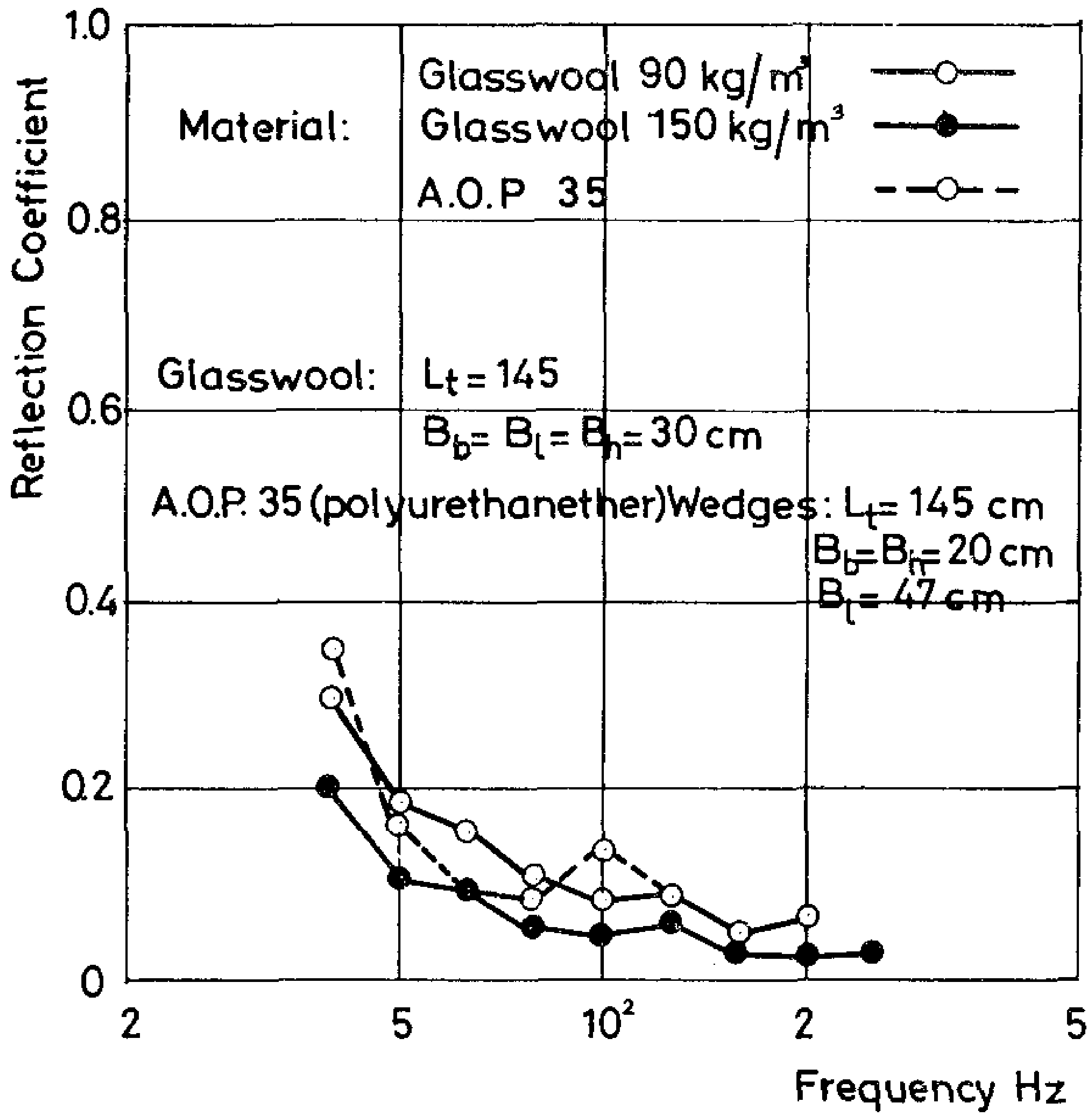

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Fig. 9. The reflection coefficient as a function of frequency for wedges of different materials.

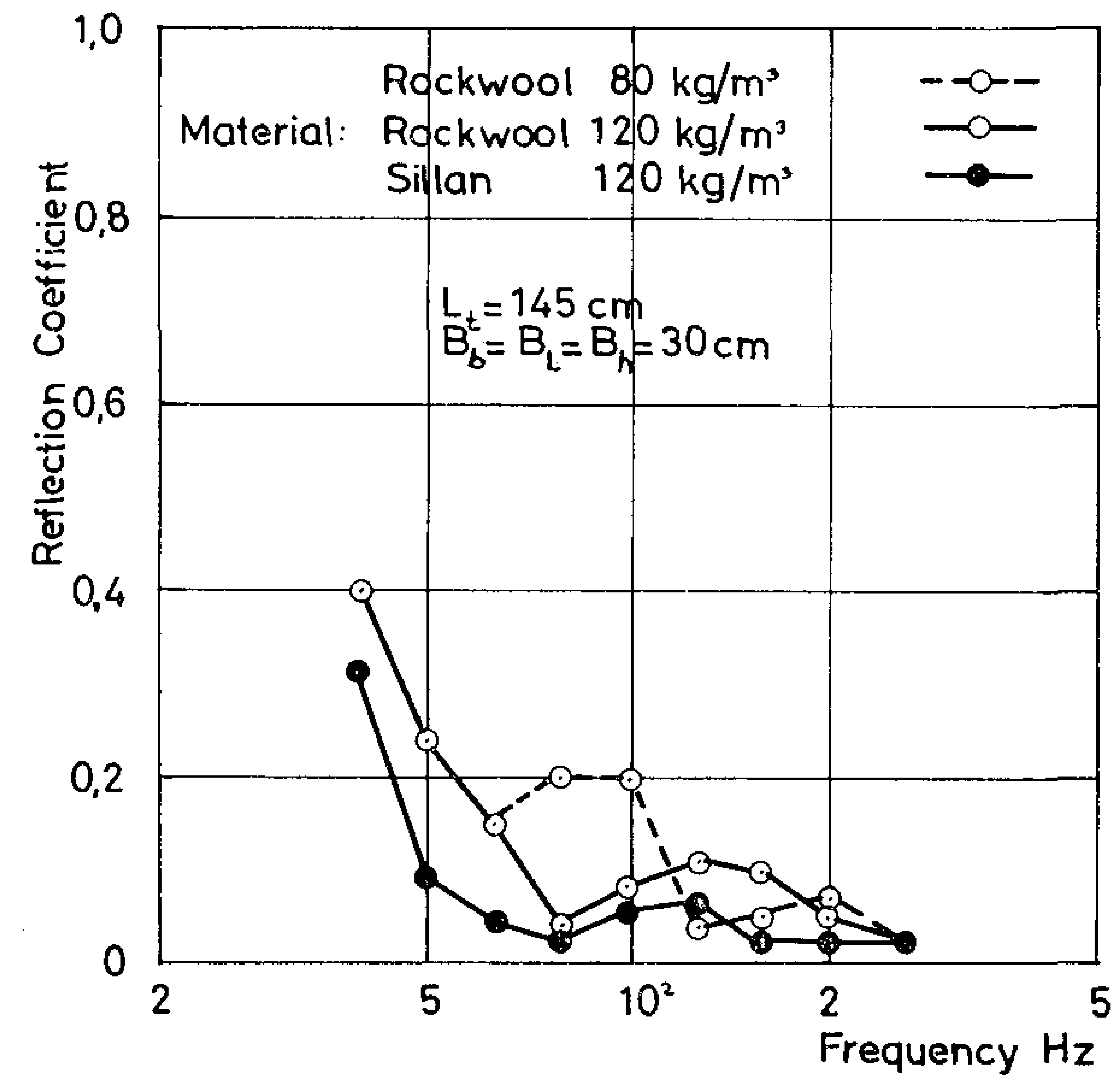

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Fig. 10. The reflection coefficient as a function of frequency for wedges of different materials.

Figs. 9 and 10 show the reflection coefficient as a function of frequency for the different materials. On the basis of these investigations four different manufacturers were invited to give in tenders for the supply and mounting of wedges in the two planned anechoic chambers, as the opinion was that the price should also be taken into account in the total considerations.
After a thorough testing of wedges from the two lowest quotations, Sillan wedges of specific density 120 kg/m³, manufactured by Grünzweig und Hartmann, Ludwigshafen (Germany) were chosen as the best alternative.
Fig. 11 shows the reflection coefficient as a function of frequency for the

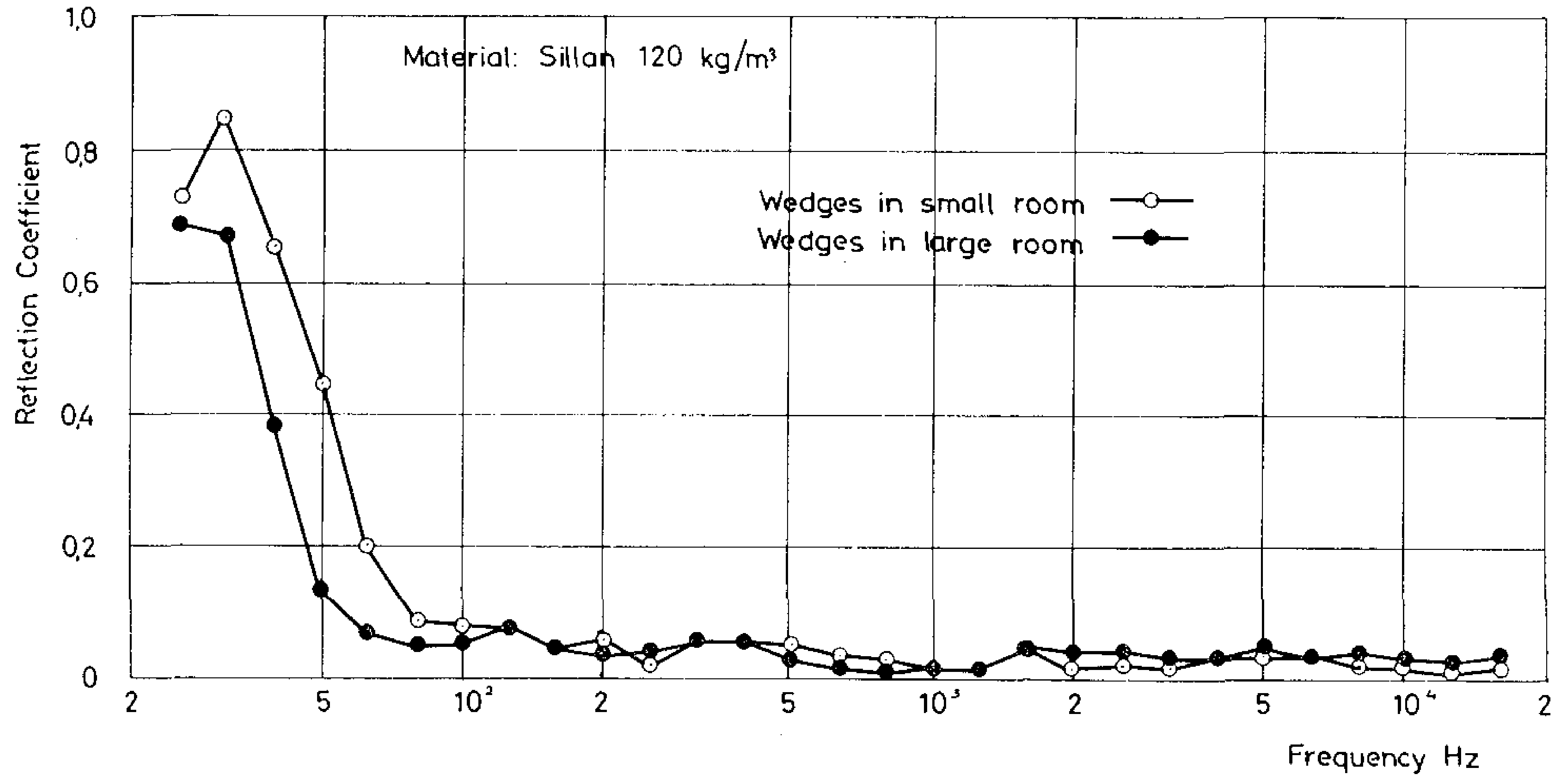

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Fig. 11. The reflection coefficient as a function of frequency for wedges used in the anechoic rooms.

wedges chosen. The measurements at frequencies above 250 Hz are carried out in a smaller tube than that shown in Fig. 3. Both whole wedges and parts of wedges were investigated.

In order to obtain an estimate of the maximum departure from a free field to be expected in an anechoic room lined with these wedges, a digital computer was used to calculate the sound field for a point source in rooms of different size and with different values for the reflection coefficients of the walls. The calculations were made with the assumption that the sound waves were reflected in accordance with Snell's law at the outer walls of the room and that phase coincidence of the reflected sound existed at the measuring point. Calculations were carried out for different positions of the sound source. With these assumptions and a reflection coefficient of 0.1 one should have a departure from free field of maximum ± 1 dB at 2 m and ± 3 dB at 11 m in a room of free dimensions of 12 m × 10 m × 9 m.

Sound insulation

As the anechoic rooms were also intended for a number of psycho-acoustical measurements, it was desirable to have a background noise level of about 10 dB below the threshold of hearing at frequencies above 200 Hz, whereas for frequencies below 200 Hz a level lower than 10 dB re 2×10^{-5} N/m^2 was required.

For extraordinary outdoor sound levels, such as those caused by jet aircraft at low altitudes, slightly higher background levels would be acceptable. It would, however, be an advantage if normal acoustical measurements were not appreciably disturbed even in these cases.

These requirements necessitate a wall construction, which has a transmission loss of about 80 dB at 200 Hz, as a background level of 60–70 dB re 2×10^{-5} N/m^2 must be expected outdoors during working hours. In order to achieve this, a double wall construction must be used where the inner part, the anechoic room itself, has no stiff mechanical connection to the outer building.

The outer walls of the building (Fig. 2) consist of brickwork and reinforced concrete with a layer of heat insulation between, total thickness 30 cm. The roof is made of 20 cm reinforced concrete with heat insulation. The inner boxes, with the anechoic rooms, have walls, floor and roof made af 40 cm reinforced concrete. The space between the inner and outer walls is 1.1 m and acoustically damped by covering both the inner side of the outer shell as well as the outer side of the inner shell with 5 cm wood wool cement slabs. Also the inside of the outer roof is covered with this material. The large and the small room are placed on 24 and 4 rubber vibration isolators respectively, see Fig. 12. Each vibration isolator is loaded by about 50 tons, and a resonance frequency of about 7 Hz was intended for the rooms placed on the rubber pads. The vibration isolators, made from a mixture of natural and artificial rubber (hardness 50° shore) are protected by a layer of neoprene and placed so that they can be inspected and replaced if necessary.

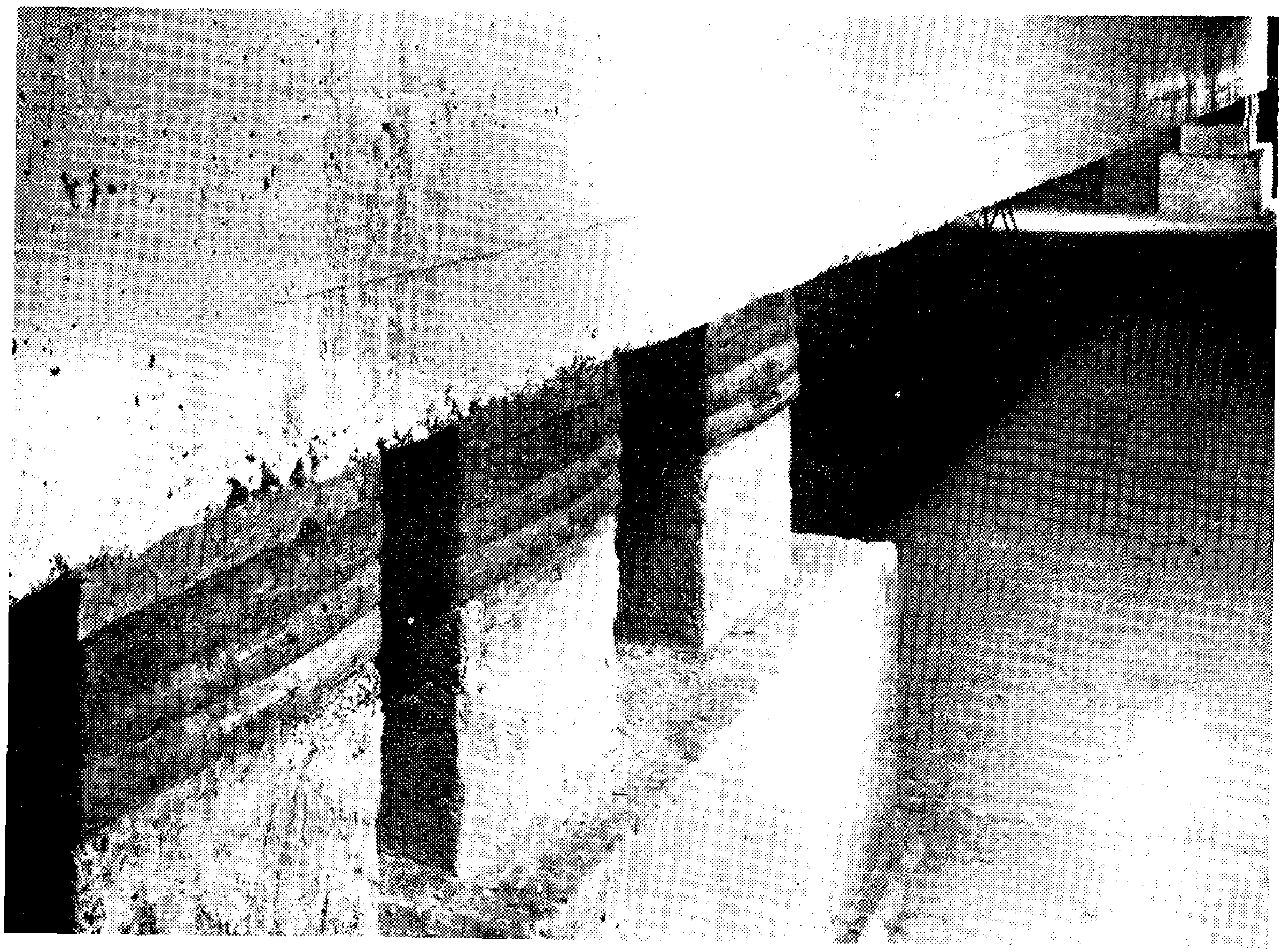

Fig. 12. Vibration isolators for the large anechoic room.

Doors

The doors are important parts of the construction with regard to lining and sound insulation. For the large anechoic room the entrance, which is 2.5 m × 2.7 m, is closed by two door sections travelling on rails and made up from three layers of steel (10 + 5 + 5 mm) with concrete in between and covered with wedges. When the doors are closed the wedge lining of the room is thus continuous. For practical reasons there is also a hinged door covered with mineral wool, which can replace one of the door sections for less critical measurements. The opening in the outer wall is closed by an air tight steel sliding door and the corridor outside the door has no windows and is heavily damped.

The 2.2 m × 1.6 m entrance to the small anechoic chamber is closed by two hinged doors made from steel plate and concrete. One of the doors is lined with wedges. In front of the other, which is lined with a 5 cm layer of Sillan, there is a light, wedge lined, sliding door which can be slided into the corner of the anechoic room where there are no wedges, but only a 5 cm Sillan lining. The wedge lining of the room is thus continuous when the doors are closed, and at the same time the construction is simple and saves space.

Floors

The floors of the anechoic rooms should not influence their acoustical properties appreciably. Wire netting was decided upon, which has been used for many anechoic rooms with satisfactory results. The mesh size was chosen to be 50 mm using 2 mm diameter steel string for the large room and 3.5 mm for the small room. The smaller wire thickness in the large room makes it necessary for people to use large overshoes with wide rubber soles when walking around in the room, in order to protect the strings and to distribute the weight over a larger area.

In the smaller anechoic room, which is used partly by the students, the influence of a thicker wire has been accepted, in order to avoid the use of extra shoes. The wires are fixed to adjustable tension grips situated on the outside of the inner concrete box. Each wire is pre-stressed by 200 kg, so that the deflection with a person (75 kg) situated at the center of the floor is about 1 cm.

The maximum load for each netting is 1,000 kg, however it must be distributed in such a way that the load per meter of the periphery of the load does not exceed 100 kg.

The wire nettings are electrically isolated from the building. This is done in order to reduce the risk of electric shocks from measuring instruments and to make it possible to fix the potential of the floor at any desired level independent of that of the surroundings.

The nettings are placed at the same level as the floors of the outside rooms and the central planes of the anechoic rooms, where most of the measurements will be taken, are situated about 1.5 m above the nettings. Parts of the rooms which are below the nettings can be reached through removeable gratings in front of the doors.

A fine mesh perlon netting is placed below the steel nettings, in order to catch small items accidentally dropped.

Lighting

As the linings of the rooms are highly insulating with respect to heat, the lighting must give a minimum of heat radiation. At the same time it is necessary to have quite a high light intensity in order to be able to work with small microphones, hearing aids etc. As the wall lining is also very light absorbing and as no reflectors can be tolerated around the lamps, which must also be placed as far away as possible from the measuring area, the lighting installation must have the highest possible conversion efficiency.

The main illumination comes from 200 W mercury vapour lamps, 12 in the large room and 2 in the small room. As these lamps ignite slowly and are probably not completely noiseless, there are also a set of ordinary 200 W incandescent lamps which may be used separately, 8 in the large room and 2 in the small room. It is a relatively simple matter to remove the lamps if this should be necessary for acoustical reasons.

Ventilation

The ventilation system is dimensioned with a view to obtaining a suitable rate of change of air in the rooms, and at the same time to avoid any appreciable increase of background noise level with the system operating. In both rooms the ventilation system consists of a row of air inlets along the bottom of the walls of the room and outlets along the top of the opposite wall. The fans are placed in the basement outside the anechoic rooms, and on its way into the rooms the air passes through two long, heavily damped concrete ducts, which are connected by flexible tubes. The exhaust air is similarly taken through two concrete ducts connected by flexible tubes to the fans with outlets into open air.

For the large anechoic room the ducts are 16 m and 10 m long with internal cross-section 70 cm × 80 cm. The thickness of the concrete wall is 10 cm. The acoustical attenuation is obtained by lining one of the inner walls with 50 cm mineral wool, which is divided into sections by thin metal plates to avoid sound transmission through the material along the ducts.

The ducts for the small anechoic room are 7 m and 5 m long, and their concrete walls are 10 cm thick. The internal dimensions are 45 cm × 60 cm and the sound absorbing lining consists of a 20 cm layer of mineral wool along one wall, divided into sections as that for the large room.

The inlet and outlet nozzles in the anechoic rooms are made of sheet metal and to avoid sound radiation from possible vibrations in the nozzles, these are covered externally with a 5 cm layer of mineral wool. The inlets and outlets in the large room have the dimensions 6 cm × 100 cm and in the small room 6 cm × 40 cm.

Also the ducts leading to the open air inlets and outlets are heavily damped so that noise from the fans will not disturb measurements in rooms situated on the same side of the buildings as these openings.

The air can be changed 4 to 5 times an hour in the large room and 12 to 17 times per hour in the small room. The air speed at the inlets and outlets into the rooms is about 2.9 m/sec. Starting and stopping of the ventilation machinery and control of the air temperature is conducted by control knobs outside the doors for each room. It is not, however, possible to obtain a lower air temperature than that of the outside air as there is no refrigeration system. A refrigeration system was discussed during the planning stages, but due to the particular insulating properties of the wedges, which made calculations difficult it was decided to leave space for a refrigeration unit but to delay the procurement and installation until the room had been used for some time. Experience from 1966–67 does not indicate any need for refrigeration of the air.

Apparatus and Store Rooms

During the planning of the acoustical building with the anechoic rooms it was considered imperative that rational working conditions were obtained in the finished construction. By having several apparatus rooms available for setting up instrumentation in connection with measurements in the anechoic rooms, it is possible to have instrumentation systems for the most common measurements permanently set up in one or two of the apparatus rooms, while the others are used for special set ups, which can be built up or taken down without disturbing routine measurements.

Three larger apparatus rooms of about 10 m^2 floor area and one smaller room of about 7 m^2 are used in connection with the large anechoic room while the smaller anechoic room has two 10 m^2 rooms. The apparatus rooms are situated along the corridors outside the anechoic rooms as shown in Fig. 2. At the end of each corridor there is a large store room, which may also be used for instrumentation in large measurement systems. See Fig. 25. Between the anechoic rooms and the apparatus rooms there are cable connections terminating on connection boards 0.5 m above the wire netting in the anechoic rooms. All the connections boards are of the same size as the cross-section of the wedges, and they are covered by removeable wedge tips made from foam plastic, when not in use. In addition there is a connection board in the ceiling of each of the anechoic rooms.

All the cables are connected to switch-boards in two of the apparatus rooms, from where connections can be made to connection boards in the other apparatus rooms and in the other laboratory buildings.

There are three types of cable connections:

1. Microphone cables
2. Loudspeaker cables
3. Cables for remote control etc.

The most critical cables are the microphone connections, where the transmission of small signals must be uninfluenced by electrical noise. The connection is made with a special cable containing two pairs of cores with one screen each and surrounded by a common screen. All the screens have a double braid whereby a very efficient screening is obtained even for electrical fields of high frequency. This is considered necessary because of the comparatively strong fields in the university area resulting from radio and television transmitters. There is also a possibility of disturbance from a nearby radar station and from measurements in the electromagnetically anechoic room, which is adjacent to the acoustical laboratory. Because of this all plug connections are specially designed for screening against high frequencies, with screening properties about 50 dB better than normal screened plugs. These measures were found less expensive than total screening of the buildings. It is assumed, however, that the metal shelves for the wedges, which are electrically connected, and the reinforced concrete walls and ceiling will provide an effective screening against stray fields.

It is intended to use one pair of cores in the microphone cable for transmission of the microphone signal, while the other pair may be used for calibration of the microphone amplifier.

The loudspeaker cables also contain two pairs of cores, one pair is used for transmission of the signal from the generator in the apparatus room while the other pair is used for measuring the voltage at the loudspeaker. The third cable system uses a ten-core cable, which may be used for remote control purposes (for example of a turntable in the anechoic room), for temperature measurements, power supply etc.

Each connection board in the anechoic rooms has possibilities for connecting three microphone cables, three loudspeaker cables and two remote control cables. In addition there is an earth connection which is connected via a 16 mm^2 cable to an earthing netting buried in front of the building. The resistance to earth is about 1.5 Ω. All the measuring instruments can be supplied by 220 V AC, which is balanced with respect to earth and supplied by a balancing transformer, which supplies this building only.

This type of power supply, which reduces the hum problems in some of the measuring set-ups was chosen on the basis of experience from earlier work in the laboratories. Furthermore, a maximum distance between power lines and measuring cables has been aimed at throughout, and all the cables are lead through steel tubes whenever possible. At the inlets to the anechoic rooms the steel tubes are substituted by flexible metal hoses in order to avoid sound transmission.

Measurements in the Completed Rooms

Measurement of deviation from 1/R-law

The supplier of the wedge lining for the two anechoic rooms gave certain guarantees with regard to the acoustical quality of the completed rooms. These were in the form of a maximum deviation of the sound pressure from 1/R-law (which indicates inverse proportionality between sound pressure and distance

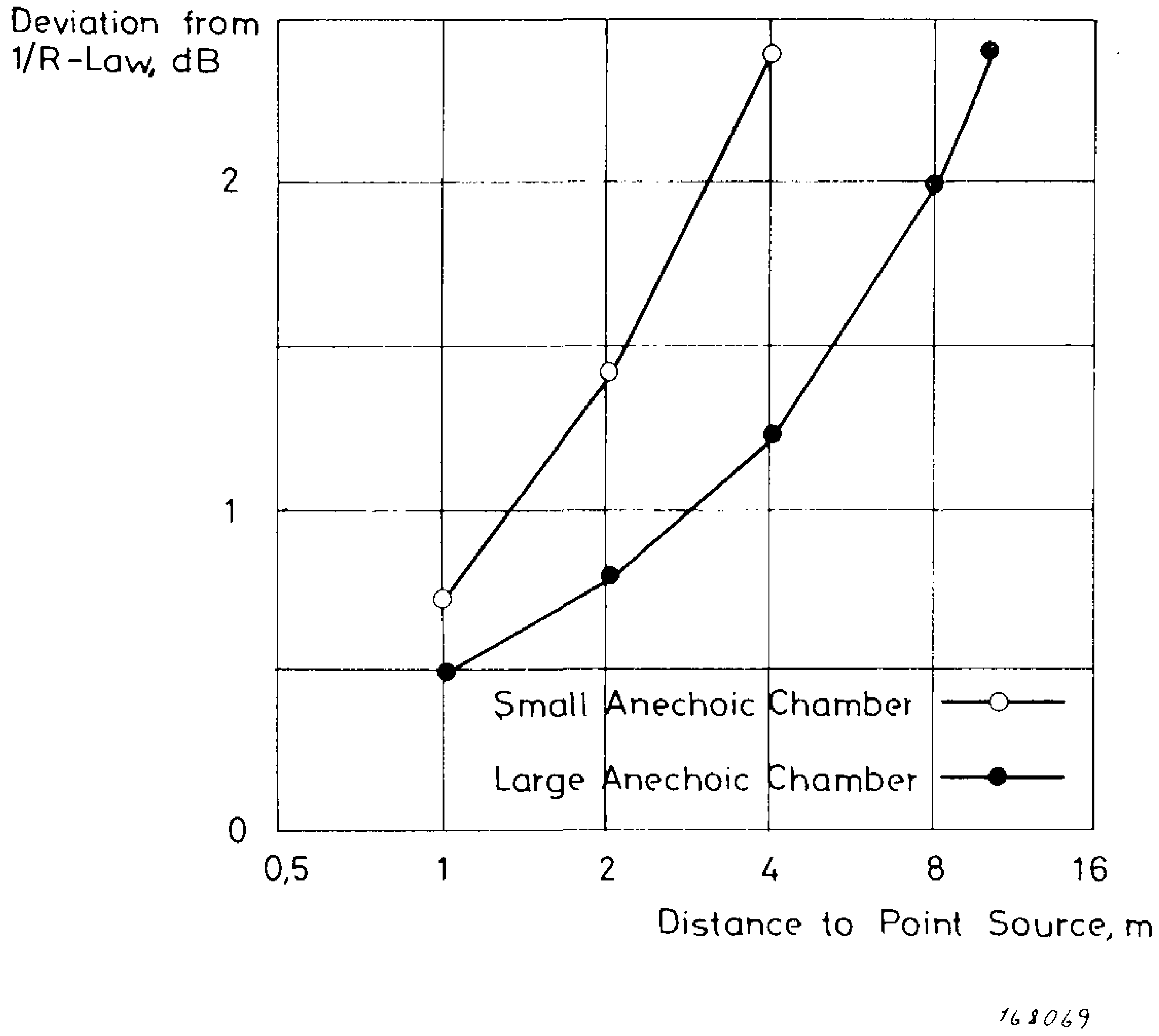

Fig. 13. The maximum values of the deviation of sound pressure from the 1/R-law as a function of the distance from a point source.

from a point source in a free field) for given distances from a point source radiating sinusoidal waves within a specified frequency range. These maximum values and the specified frequency range for each room are given in Fig. 13. The guarantee included any measuring point situated at least 1.5 m and 1.2 m from the wedge tips in the large and the small room respectively. Checking that the limits were not exceeded was left to the laboratory, which had some 2–3 months for the measurements. This time limit and a wish to have an effective and practical method of control led to the development of a measuring system, which would automatically and continuously record the deviations from the 1/R-law in a certain direction in the room. The principles involved in the measuring system are shown in Fig. 14. The microphone, M, is carried away from the sound source, S, on a small electrically driven carriage, and travelling with constant velocity on a rail suspended immediately below the wedges in the ceiling. The microphone is placed at the end of a rod of maximum length 5 m. This suspension of the microphone

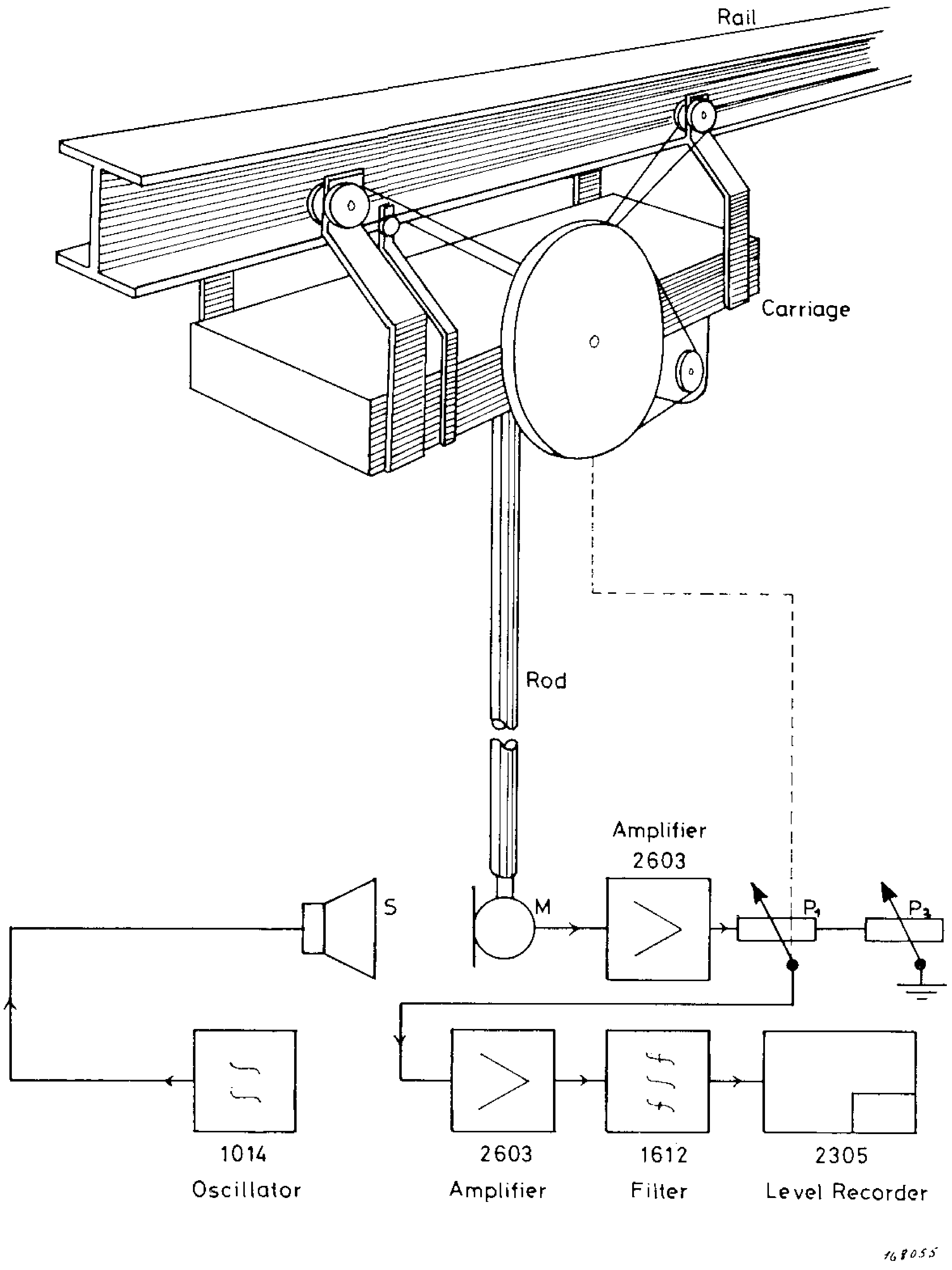

Fig. 14. Arrangement for the measurement of deviations from the 1/R-law.

gives the possibility of measurement in several horizontal planes using different rod lengths. For measurements along the diagonal of the room the carriage and the microphone are each connected to a pulley, so that it is possible to give the microphone a vertical movement and a horisontal movement at the same time.

The amplified microphone voltage is applied to the potentiometer P_1 (linear characteristic, 10 turns) which is mechanically connected to the carriage, so that the attenuation of the signal by the potentiometer is inversely proportional to the distance between the microphone and the source. Thus there will be a constant voltage on the slider of the potentiometer under the following two conditions:

I. The 1/R-law is fulfilled

II. The attenuation of the microphone signal at the starting position of the carriage is adjusted to correspond to the distance between the acoustical centres of the microphone and the source with a second potentiometer P_2.

If condition II is not complied with, there will be either an increase or a decrease of the voltage on the slider of P_1 near the sound source. This fact may be used for correct adjustment of P_2 since deviations from the 1/R-law are especially small near the sound source. Thereby it is not necessary to determine the position of the acoustical centres. After correct adjustment of the potentiometer P_2 the voltage changes on the slider of P_1 will be a direct measure of any deviations from the 1/R-law. After amplification and filtering the potentiometer voltage is recorded and a curve obtained as shown in Fig. 15 where deviations from the 1/R-law are read as deviations from the centre line of the recording paper.

By carefully covering the rail with about 5 cm glass wool, and by consistently checking that the cables for carriage and microphone do not enter into the

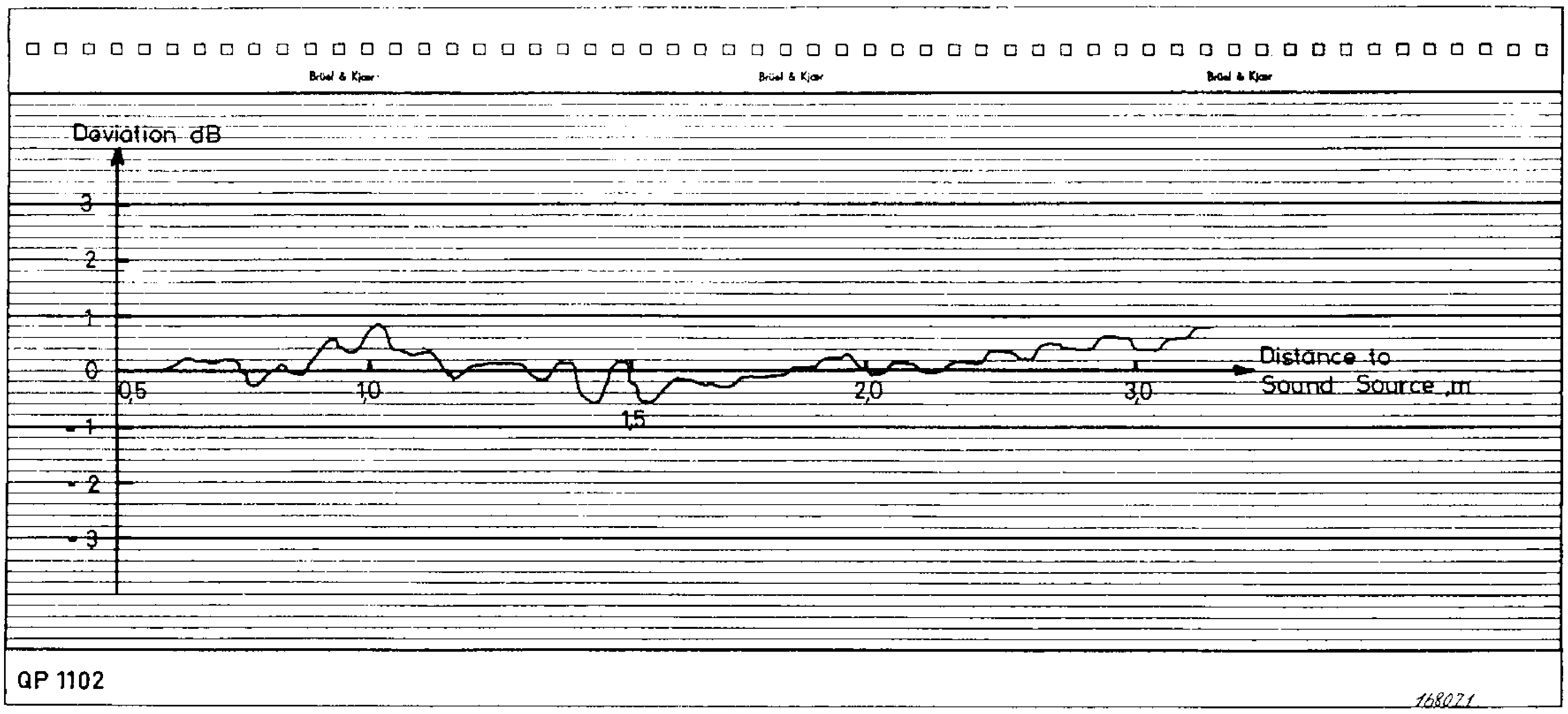

Fig. 15. An example of the recording of deviations from the 1/R-law as measured with the set-up shown in Fig. 14.

measuring field it is possible to obtain a measuring accuracy of about 0.2 dB. The accuracy of the electrical system alone, is about 0.1 dB.

The sound sources must have a good omnidirectivity in the frequency range for which they are used. Small deviations will, however, have only secondary influence on the strength of the reflected sound field. If this influence is neglected so that only the effect of deviations in the strength of the direct sound field is considered, it is possible to calculate, quite simply, a set of curves showing the maximum allowable deviation from a spherical characteristic as a function of the maximum deviation from the 1/R-law in the room and with the maximum error of the deviation measurement as parameter. Such curves are shown in Fig. 16. A sound source with up to 1 dB deviation from the spherical characteristic will thus give an error in the measurements smaller than 0.1 dB if the maximum deviation from the 1/R-law is 0.8 dB. By about 1.9 dB deviation from the 1/R-law the error caused by the source would be smaller than 0.2 dB.

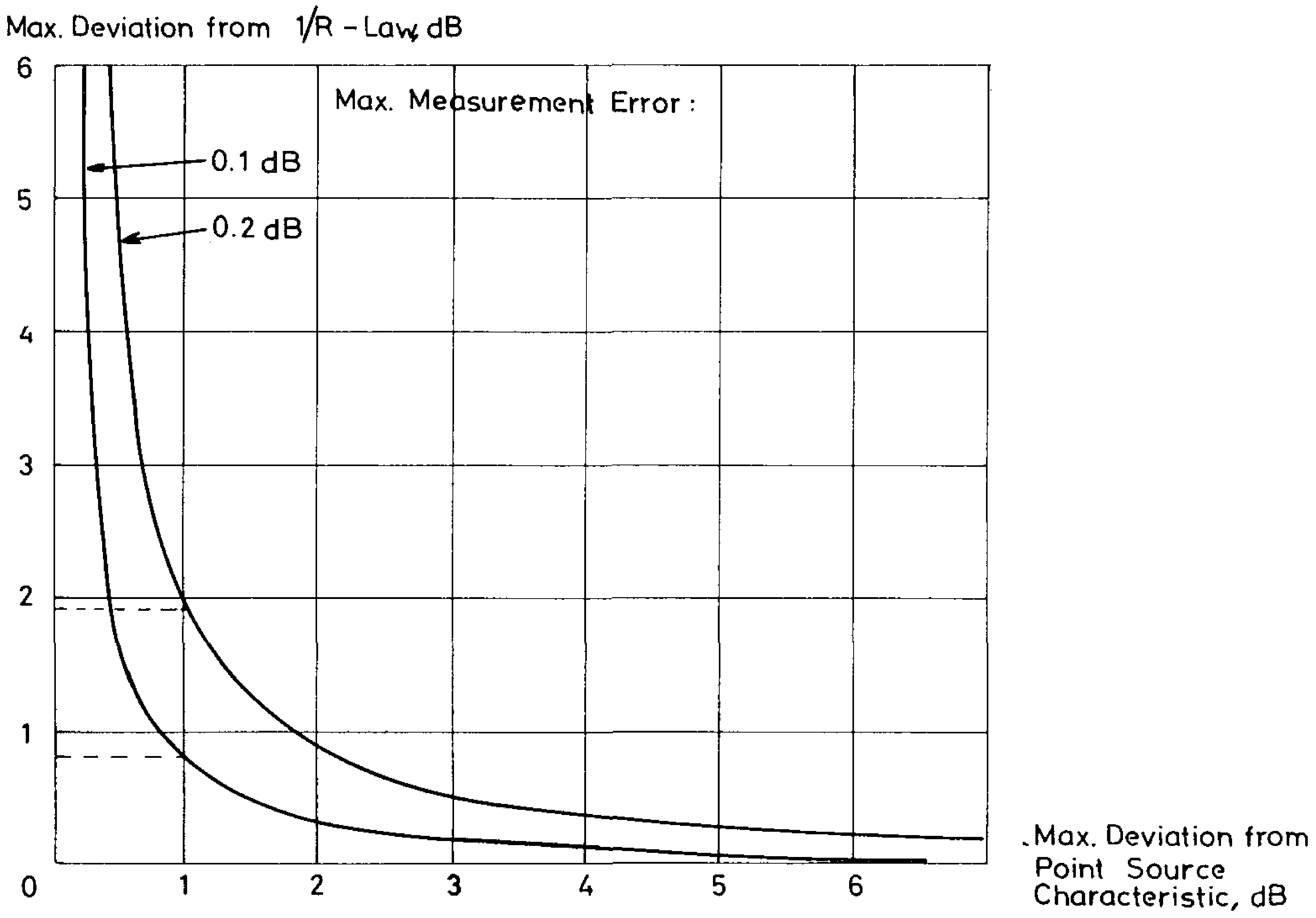

Fig. 16. The maximum allowable deviation of the sound source from the spherical characteristic as a function of deviations from the 1/R-law with measuring error for the deviation as parameter.

In order to cover the frequency range guarenteed by the wedge manufacturer three sound sources were used.

The range 60–250 Hz was covered by an electrodynamic loudspeaker, Lorenz LPT 245 (24.5 cm diameter), in a closed, damped, 18 litres cabinet. The maximum deviation from a spherical characteristics was 0.6 dB.

250–2,000 Hz was covered by two loudspeakers screwed together front to front, type Philips AD 2400 (10 cm diameter). The loudspeakers were connected in such a way that the unit was operating approximately as a sound source of zero order. The maximum deviation from a spherical characteristic was less than 0.6 dB.

2,000–10,000 Hz was covered by a dismounted microphone cartridge, type Sennheiser MD 211, which was closed at the back and furnished with a Brüel & Kjær nose cone at the front. Discs of glass wool were furthermore placed in front of and behind the wire mesh of the nose cone, as shown in Fig. 17. When the cartridge was supplied with a voltage of 2.5 V RMS a sound pressure level of 70 dB re 2×10^{-5} N/m^2 was measured at a distance of 1 m at 10 kHz. The maximum deviation from a spherical characteristic was less than 0.7 dB with careful adjustment of the glass wool discs.

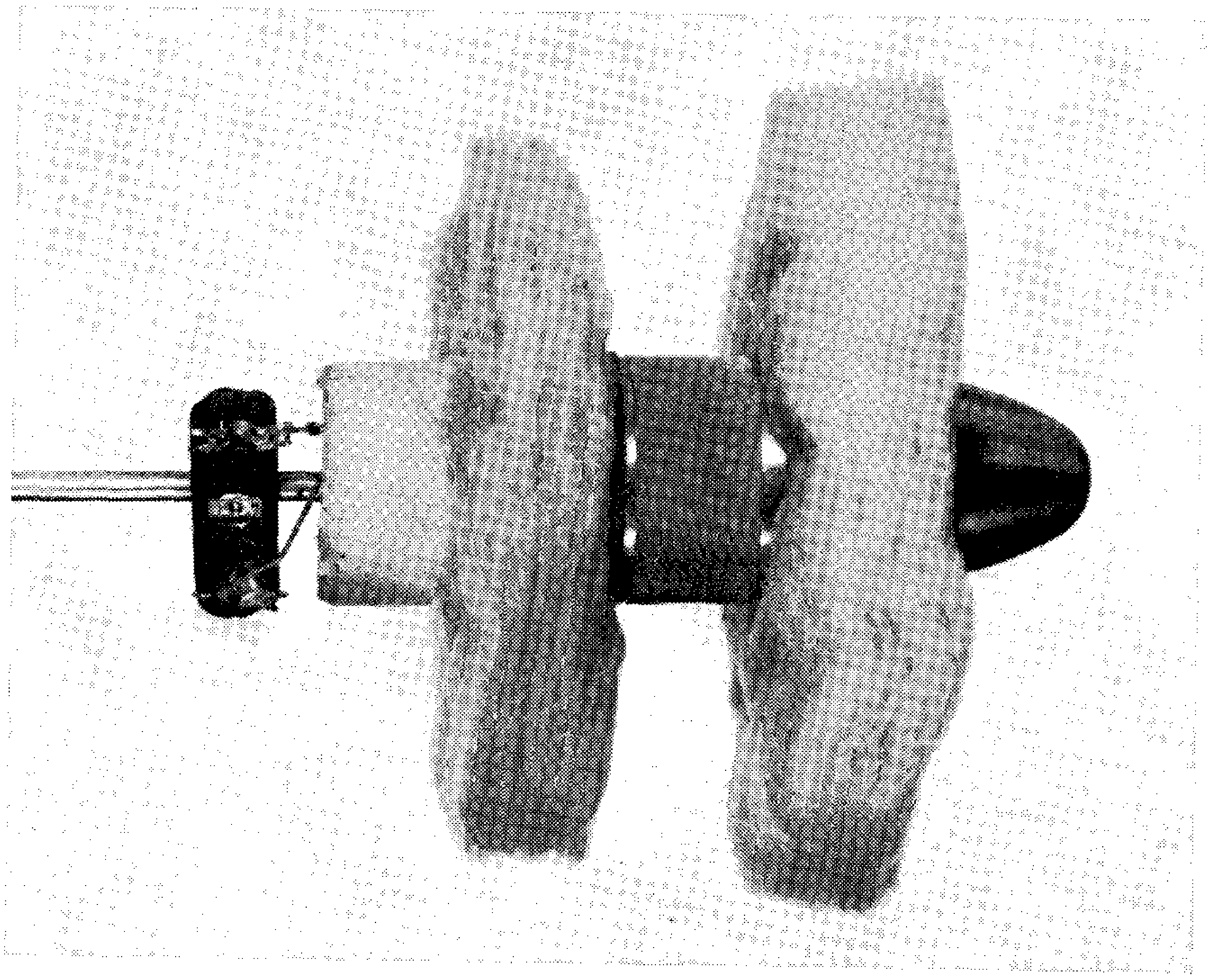

Fig. 17. Sound source with spherical characteristic in the frequency range 2,000 to 10,000 Hz.

In the range 10,000–20,000 Hz, which is outside the guarantee, a hollow polarized barium titanate sphere of diameter 4 cm and about 4 mm wall thickness was used. With 80 V RMS across the silvered inner and outer surfaces the sound pressure measured was 80 dB re 2×10^{-5} N/m^2 at a distance of 1 m at 16 kHz. The maximum deviation from a spherical characteristic was 0.5 dB at 13 kHz and 4 dB at 16 kHz. This rather large variation in deviation was probably due to the rather irregular thickness of the walls of this primitive test sphere.

The same considerations as above are valid for the microphones with regard to directional characteristics. The range 60–10,000 Hz was covered by a ½" Brüel & Kjær condenser microphone with nose cone. The maximum deviation from a spherical characteristic was less than 1 dB.

The range 10,000–20,000 Hz was covered by a ¼" Brüel & Kjær microphone, with a maximum deviation from a spherical characteristic of less than 2 dB. The measurements were taken in steps of ⅓ octave within the guaranteed frequency range except for a single measuring direction in the large room where measurements were taken in the range 25–20,000 Hz. About 550 measurements were taken for each room.

For frequencies above 5,000 Hz the measurements were corrected for absorption in the air.

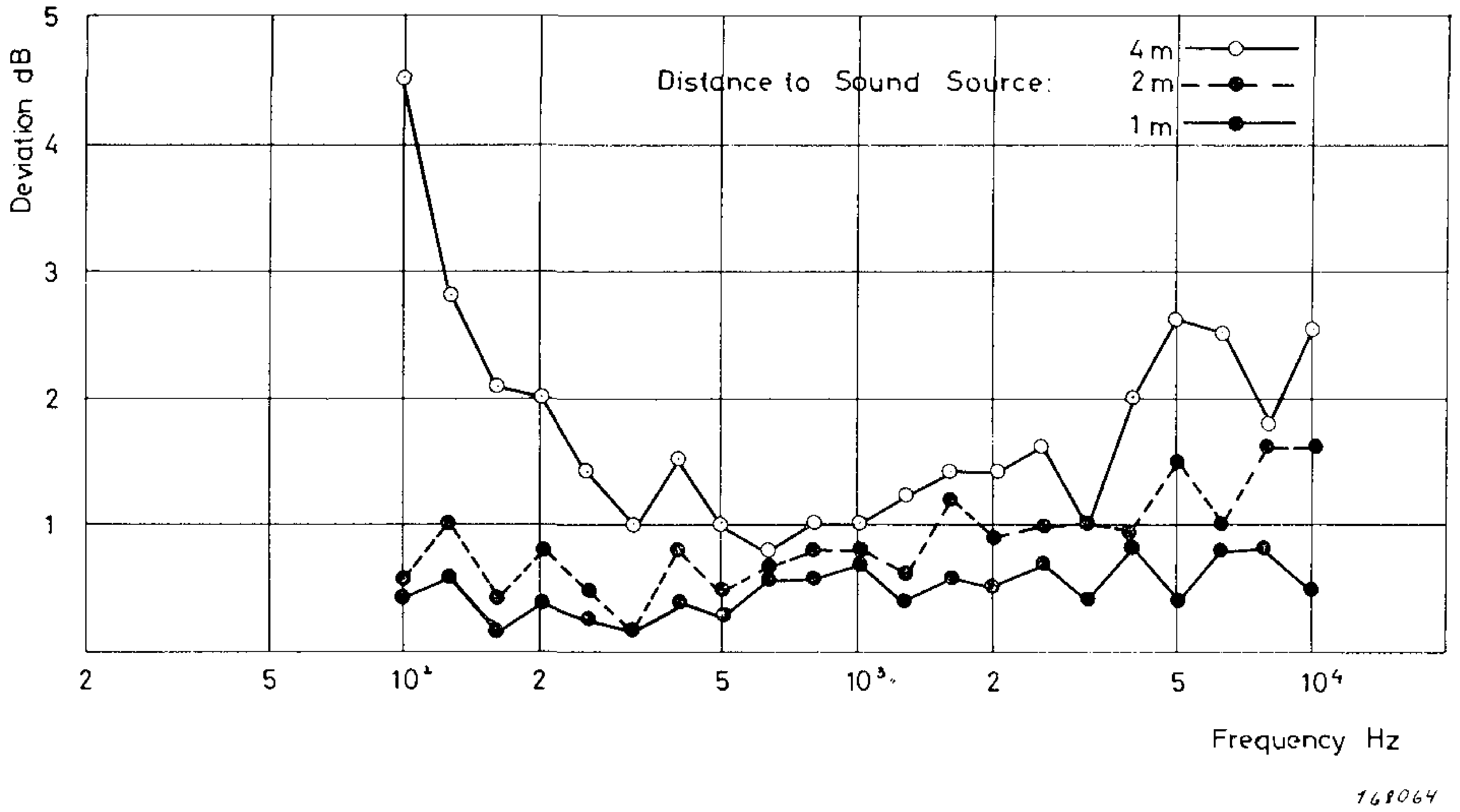

Fig. 18. Maximum deviation from the 1/R-law as a function of frequency for the small anechoic room.

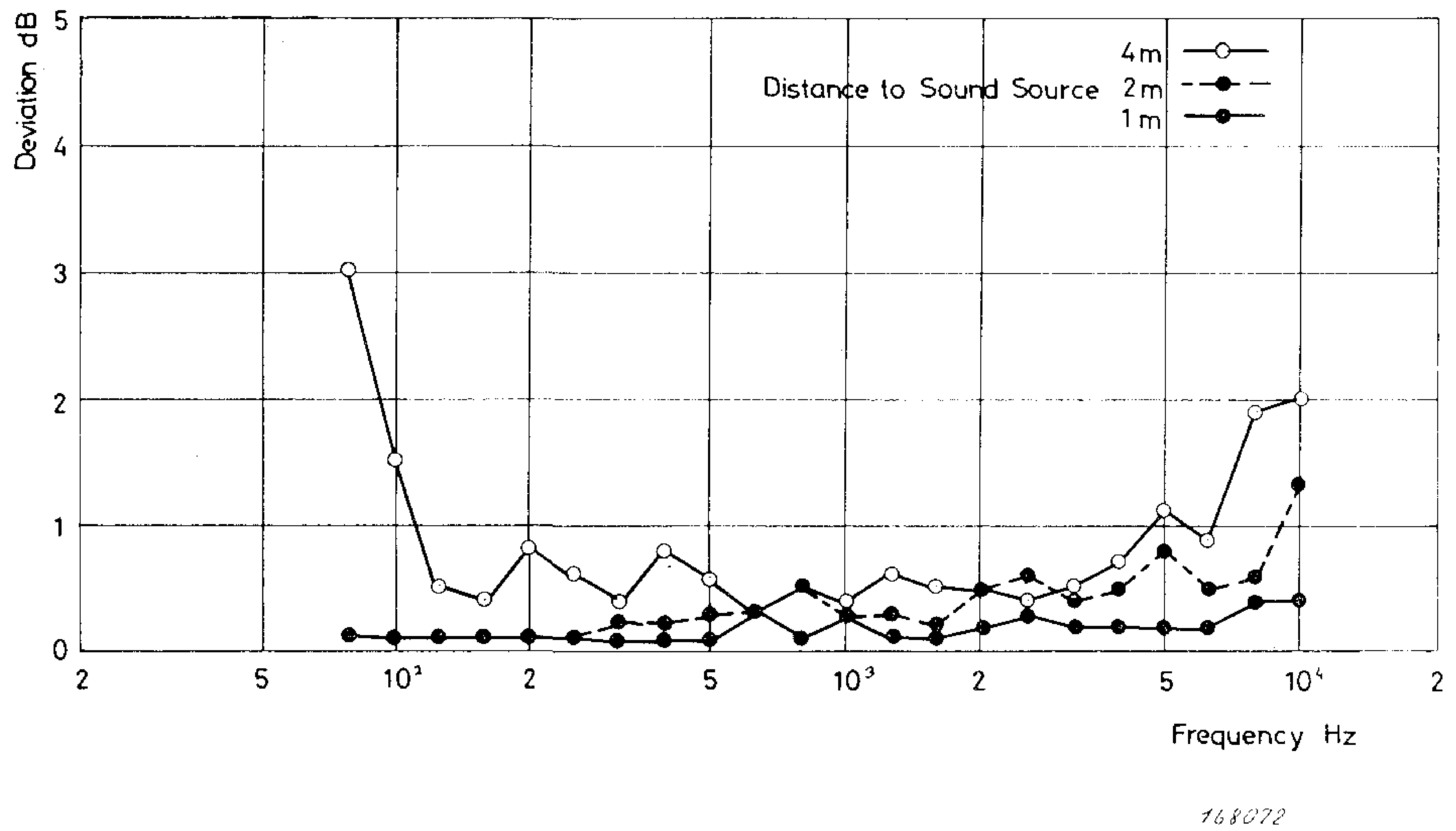

Fig. 19. Maximum deviation from the 1/R-law as a function of frequency in the best measuring direction for the small anechoic room.

Fig. 18 shows the maximum deviations from the 1/R-law for the small room as a function of frequency and with the distance from the sound source as parameter. The curves shown in Fig. 19 were found for the best measuring direction in the room. It is seen that the deviations are smaller than 0.4 dB at a distance of 1 m in the range 100–10,000 Hz.

Fig. 20 and 21 show the corresponding curves for the large room, the latter for the frequency range 25–20,000 Hz. It is seen that in the best measuring direction of the room the deviations are smaller than 0.2 dB from 30 to 16,000 Hz at a distance of 1 m from the sound source.

A comparison with the guaranteed limits shows that the limits have been exceeded to a small extent at certain points. This was nearly always in the

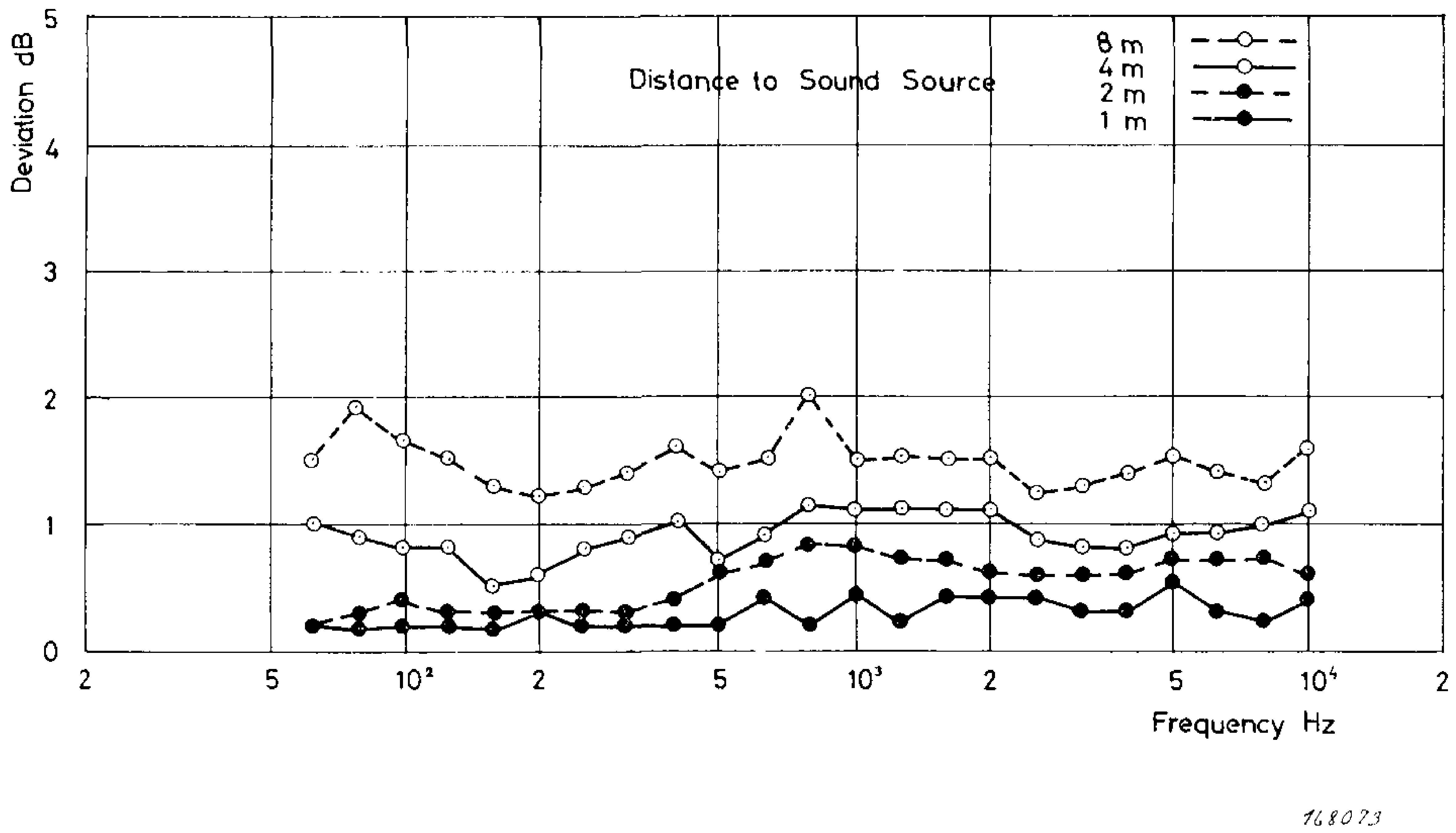

Fig. 20. Maximum deviation from the 1/R-law as a function of frequency for the large room.

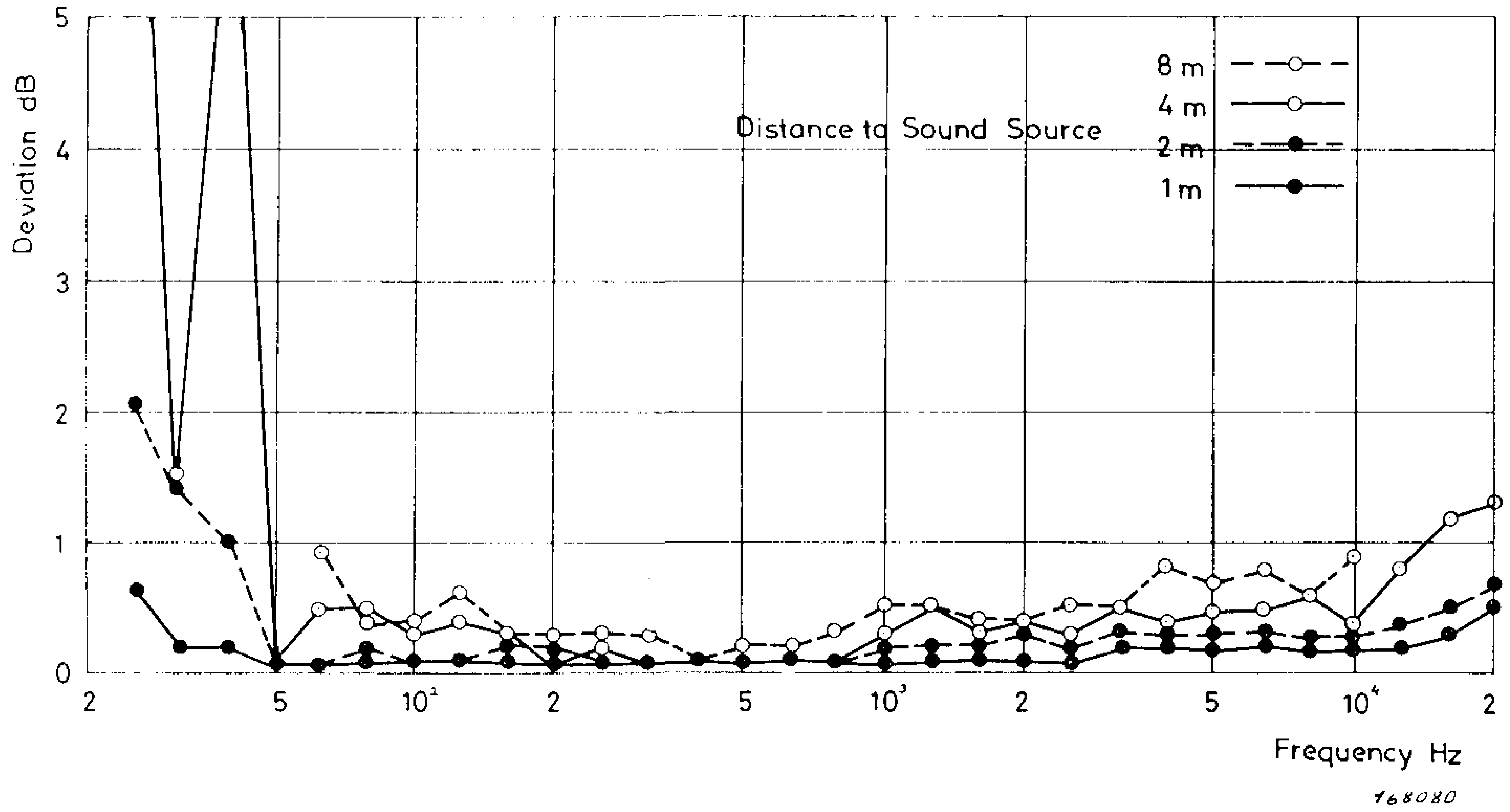

Fig. 21. Maximum deviation from the 1/R-law as a function of frequency in the best measuring direction for the large anechoic room.

direction towards the doors where the gratings mentioned before had to be covered with 5 cm polyurethane foam in order to bring the deviations down to the level shown by Fig. 18 and Fig. 20. It should be noted that 99 % of the total number of measurements were inside the guaranteed limits.

Measurements of background noise

Background noise measurements have been carried out in the anechoic rooms with a noise level in the surroundings of the building which must be considered normal (60–70 dB re 2×10^{-5} N/m^2). An electrodynamic loud-

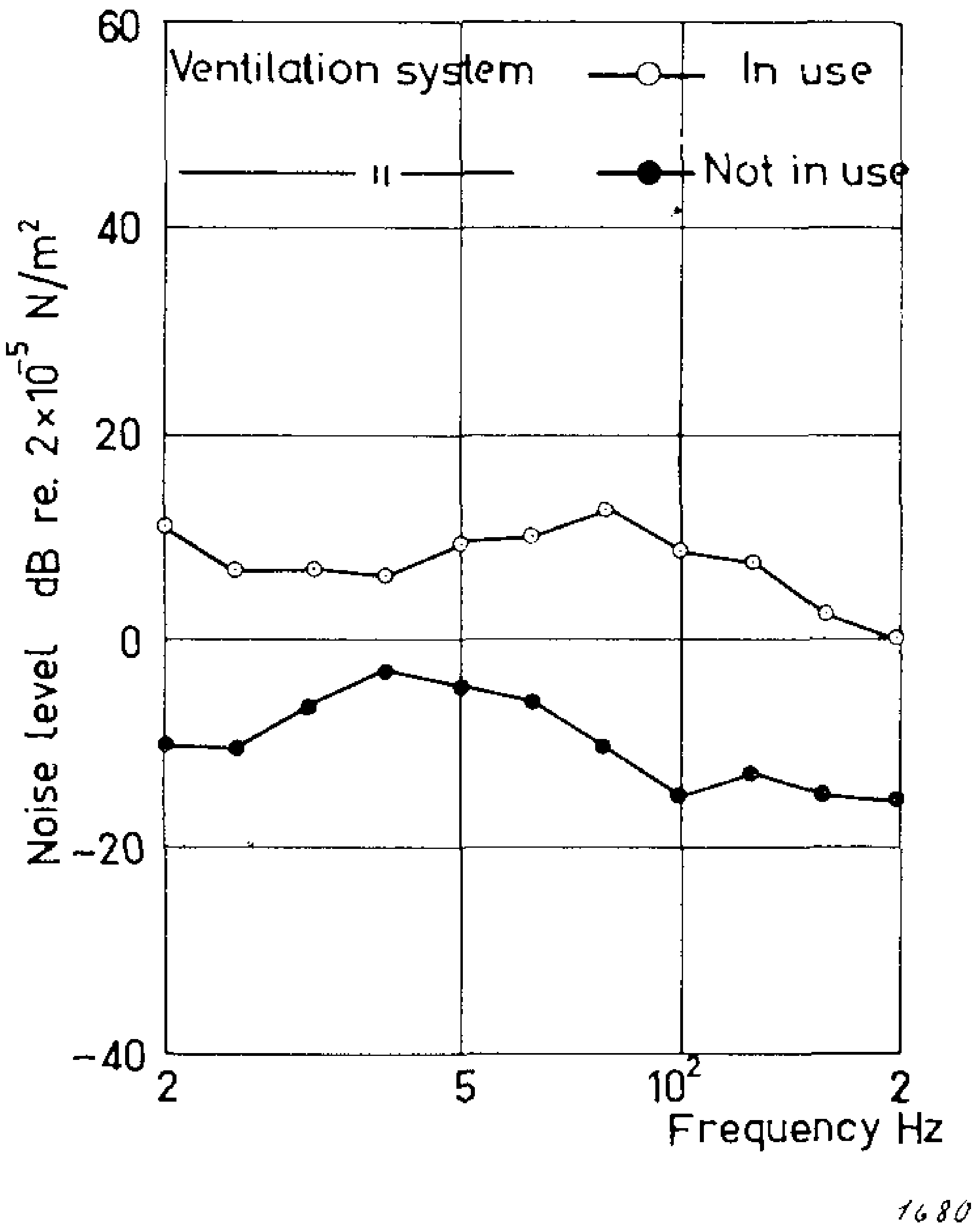

Fig. 22. Background noise level in the large anechoic room.

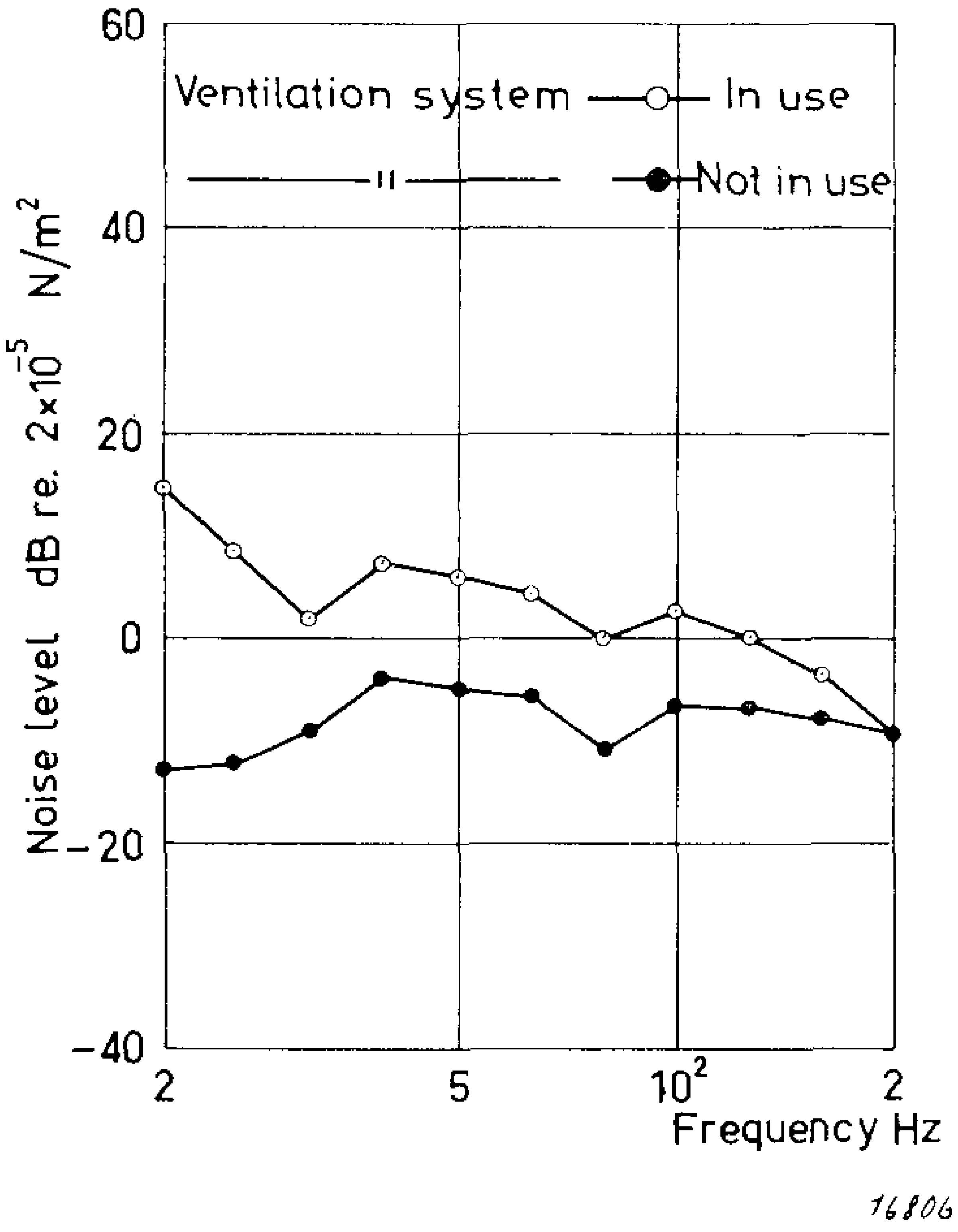

Fig. 23. Background noise level in the small anechoic room.

speaker with a diaphragm diameter of 24.5 cm was used as "microphone". Its output voltage was analysed in the frequency range 20–200 Hz with a bandwith of 3 Hz, the upper frequency limit being set by the signal to noise ratio of the measuring arrangement. This analysis was used together with the diffuse field sensitivity of the "microphone" for a calculation of the sound pressure level in $^1/_3$ octave bands. The results obtained from measurements in the two rooms are shown in Fig. 22 and 23 with and without the ventilation system working. For frequencies above 200 Hz the sound pressure level is bound to be lower than the value obtained at 200 Hz.

The intended values for the background noise are seen to have been reached with the ventilation system not operating. With the ventilation on, the background noise level is still below the normal threshold of hearing.

Measurements of sound insulation

An investigation into the sound insulating properties of the double wall construction meets with certain practical difficulties, especially at the higher frequencies, since as mentioned before it was intended to achieve a trans-

Fig. 24. "Sound source" used for measurement of the sound insulation properties of the double wall construction.

mission loss of some 80 dB at 200 Hz for random incident sound. It is therefore necessary to employ extremely powerful sound sources at this and higher frequencies in order to measure the transmission loss.

In the present case a jet helicopter type S 61 was used, which was positioned about 15 m above the roof of the large anechoic room, as shown in Fig. 24. The S 61 radiates sufficient sound power in all directions up to about 2 kHz. The sound pressure level at a distance of 15 m is about 110 dB re 2×10^{-5} N/m^2, and a ⅓ octave analysis gives values within 6 dB up to about 2 kHz. During the test the sound pressure level was checked at 5 points outside the outer structure for the large anechoic room, at 5 points between the outer and the inner wall, at 2 positions inside the large anechoic room and finally at several places in the building, such as for example inside the small anechoic room.

All the sound pressure levels were recorded both on a level recorder and on magnetic tape, making a later frequency analysis possible. The measuring system is shown in Fig. 25.

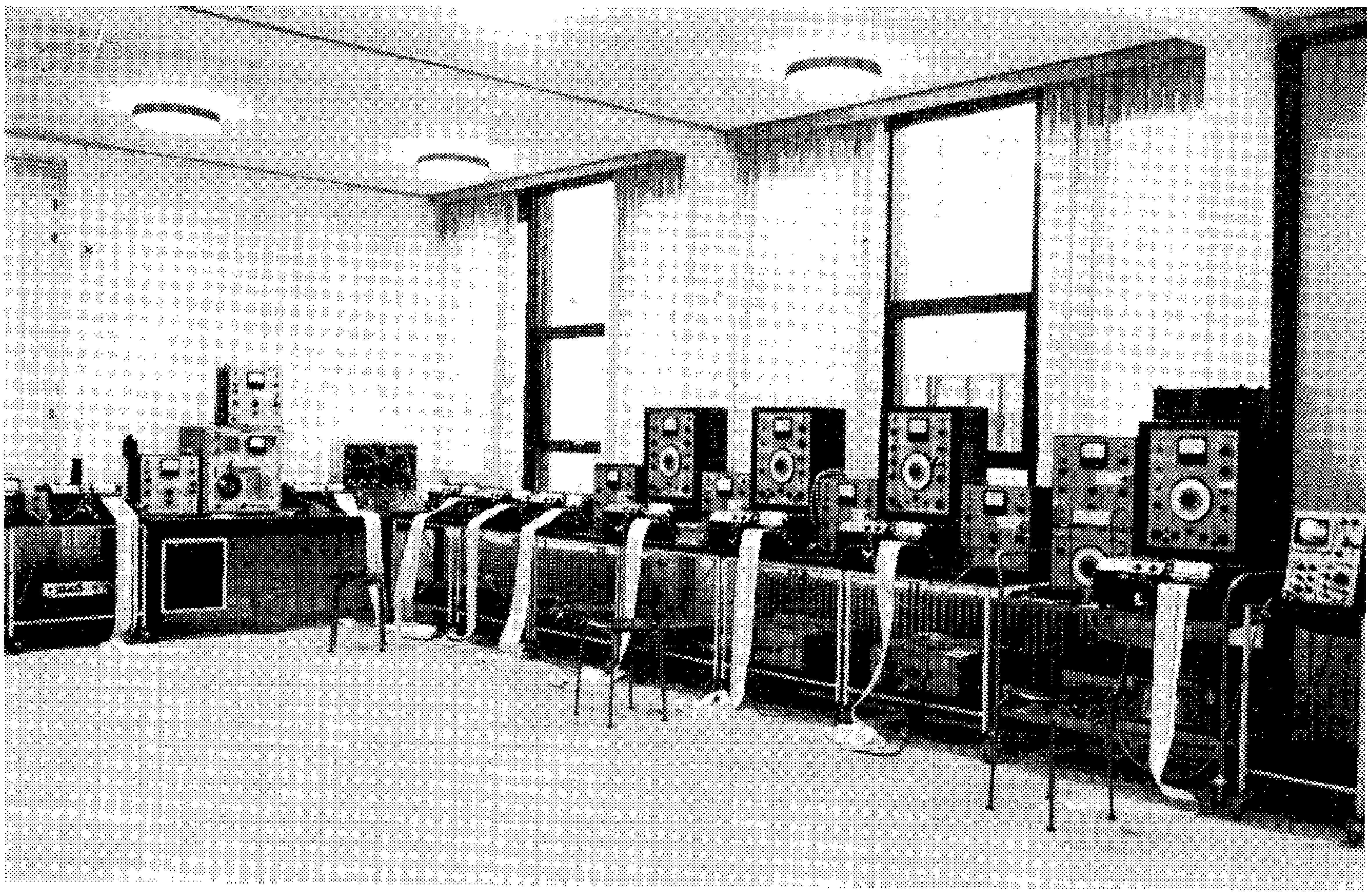

Fig. 25. Arrangement for measuring the sound insulation of the double wall construction.

The results obtained are shown in Fig. 26, where the attenuation of the outer wall and through the two walls is shown as a function of frequency. It is demonstrated that the intended transmission loss has been achieved, as at 200 Hz for example the attenuation is 84 dB for the double wall construction.

In order to investigate the efficiency of the vibration isolators supporting the rooms, a series of vibration measurements were conducted for the large anechoic room. The measurements were taken using a pile driver working at a site nearby as signal source. The vertical component of the vibrations

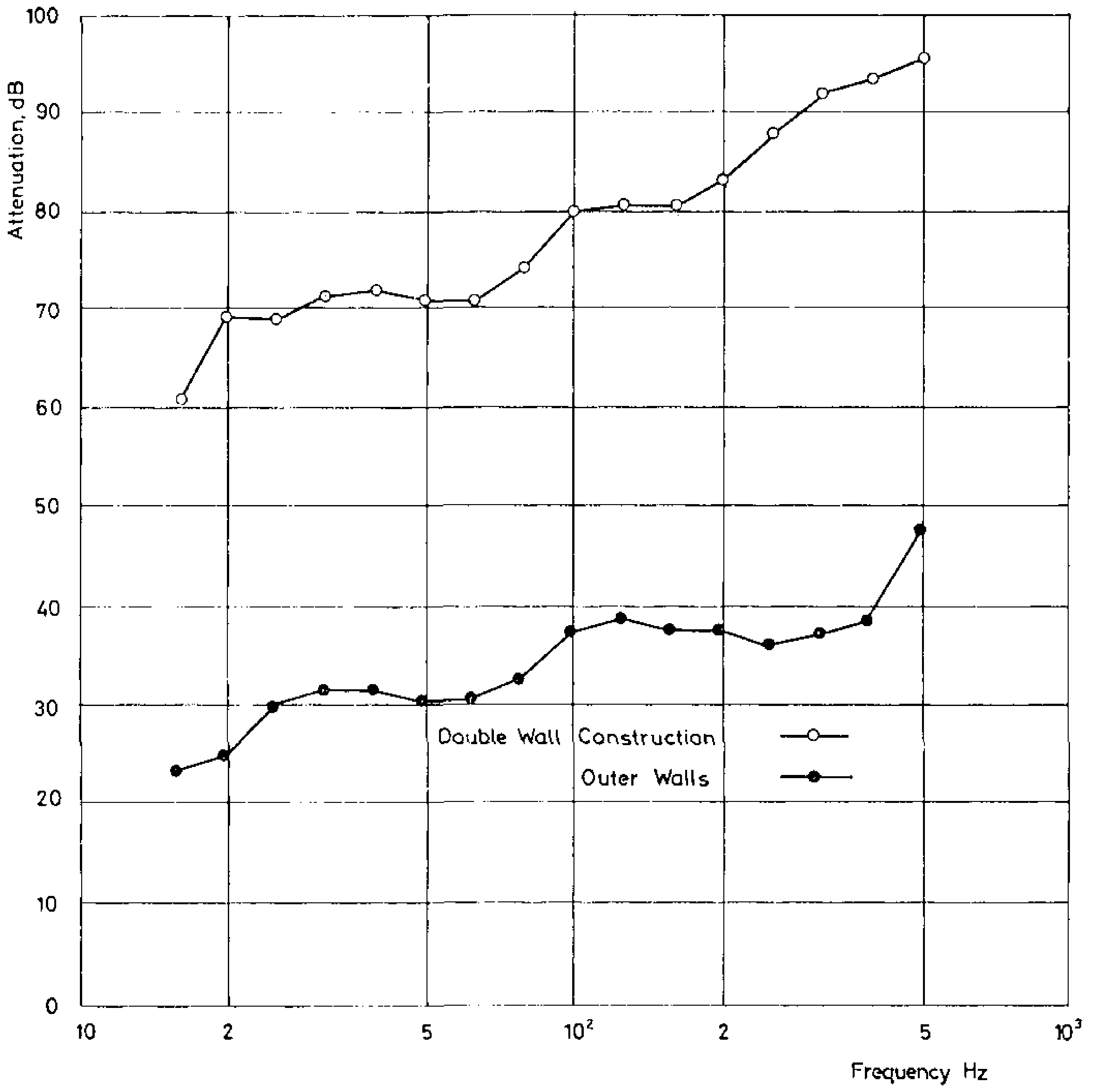

Fig. 26. The transmission loss through the outer walls and the double wall construction for random incidence noise on the large anechoic room.

caused by the pile driver was measured on either side of a vibration isolator at each corner of the large anechoic room using high sensitivity ceramic accelerometers (about 3,000 mV/g).

The accelerometer voltages were recorded on a general purpose tape recorder via an AM system. The modulator was working with a carrier signal of 500 Hz, which was suppressed before recording on the tape. The following frequency

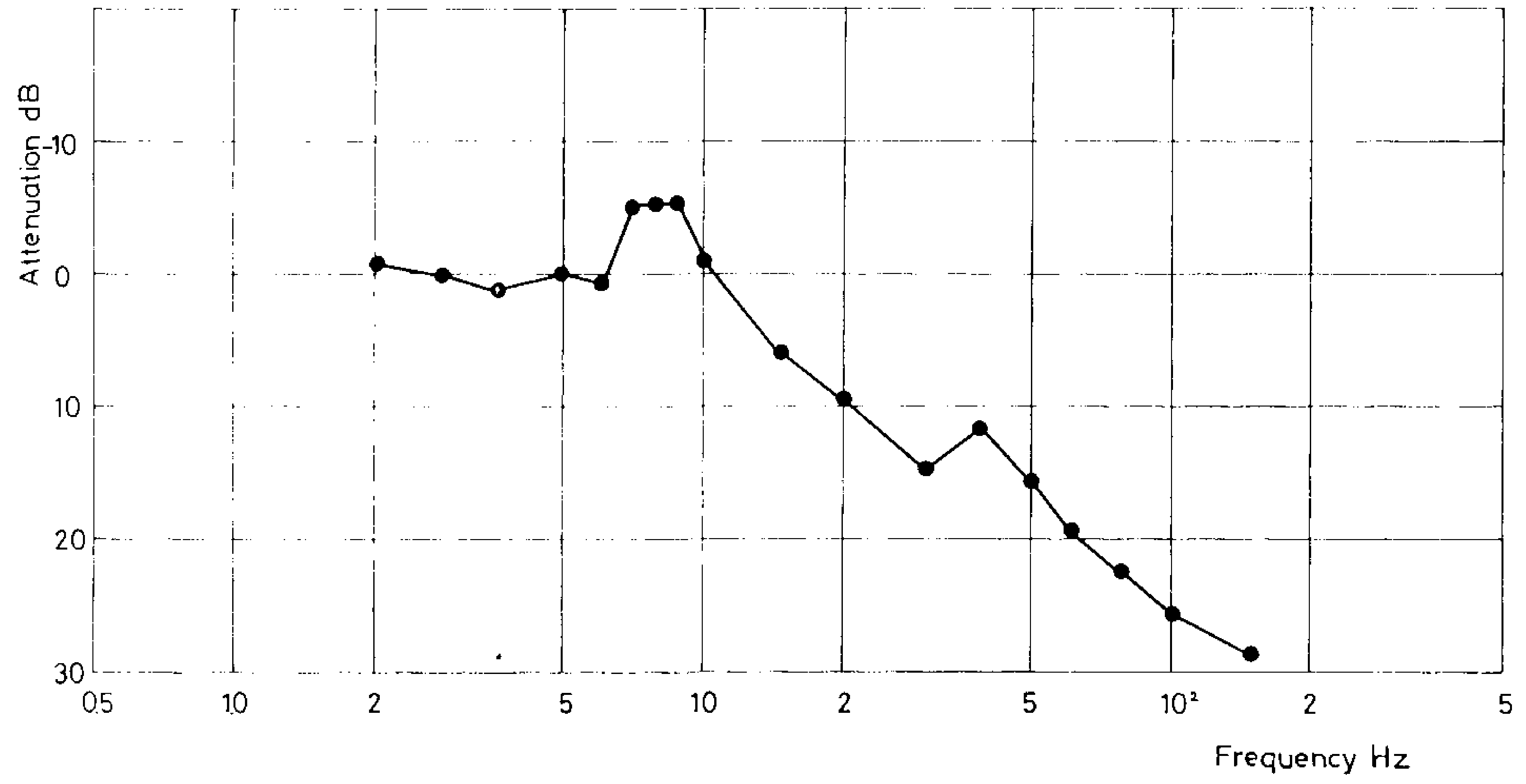

Fig. 27. Attenuation of vertical vibrations through the vibration isolators supporting the large anechoic room.

analysis was carried out with a bandwidth of 3 Hz and with a tape speed 8 times higher than the speed of recording. The lower limiting frequency of the measuring system was around 0.5 Hz. An average of the 4 measurements is shown in Fig. 27. The curve indicates that the resonance frequency of the vibrating system consisting of concrete box and vibration isolators is about 8 Hz, or fairly close to the intended value of 7 Hz.

Conclusion

The measurements carried out show that both anechoic rooms can be used even for very exacting measurements, the data for the large room probably representing something near the limit of what one can achieve today.

From the background noise measurements it is seen that it has been possible to attenuate the noise from the ventilation system to such a degree that the ventilators may be used even during psycho-acoustical tests.

The insulation against noise in the vicinity of the buildings is extremely good, in as much as even with sound pressure levels of the order of 110 dB re 2×10^{-5} N/m^2 the sound pressure inside the room just reaches the threshold of hearing. It is therefore possible to carry out a large number of normal acoustical measurements in these rooms even under extreme outside conditions.

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