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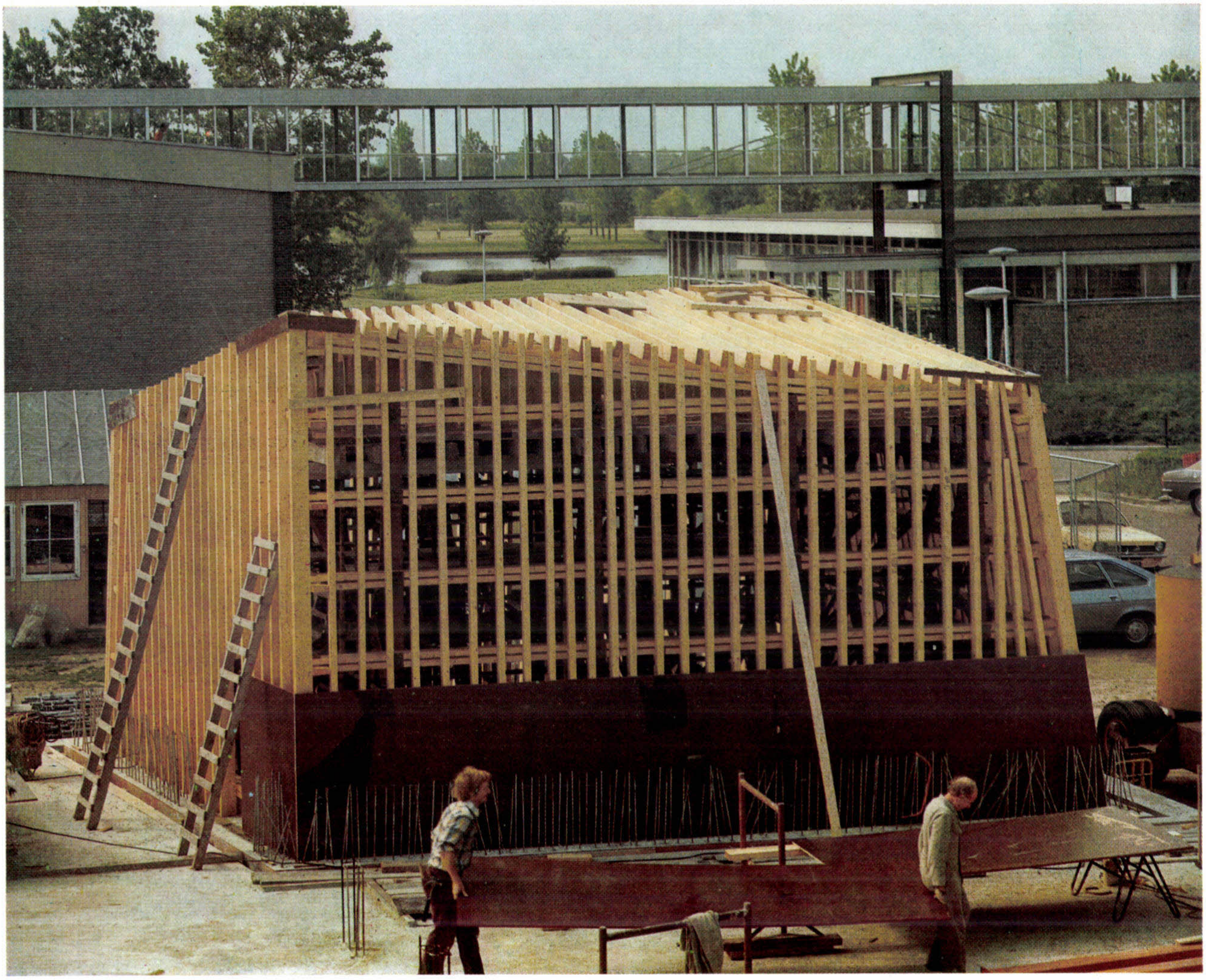

The design and construction of a non-rectangular reverberation chamber

The rather strange structure now taking shape at the Philips Research Laboratories complex in Eindhoven is a reverberation chamber. This is a chamber with hard sound-reflecting walls and is of great value in acoustic measurements. The chamber now being built should be ready by about March 1978; it will be used for investigations connected with noise abatement. These will include measurements on appliances such as vacuum cleaners and washing machines, to help in the design of quieter products, and measurements on production machines, so that noise can be reduced in workshops and factories. A reverberation chamber is also necessary for for testing the quality of sound-absorbent material.

When a reverberation chamber is available it is possible to obtain a quick and reliable measurement of the acoustic power radiated from an acoustic source. In the ideal case an acoustic source in a reverberation chamber produces a homogeneous and isotropic acoustic field, whose level is directly related to the power of the source. The acoustic field is homogeneous and isotropic because a large number of standing-wave patterns are excited simultaneously. As a result of the superposition of all these standing-wave patterns there is no preferential excitation of any one frequency, and no one place or direction is systematically favoured. The result is an almost continuous spectrum of resonant frequencies. Any chamber in the form of a rectangular parallelepiped and with a volume of 200 m^3 corresponds fairly well with this ideal picture at frequencies above about 250 Hz, i.e. at wavelengths shorter than about 1.4 m. For longer waves, however, the possible number of standing-wave patterns in such a chamber is limited, and the chamber then has a clearly discontinuous spectrum of resonant frequencies.

It has long been known that a better approximation to the ideal behaviour of a reverberation chamber can be obtained at these low frequencies by making the walls oblique in such a way that the chamber is asymmetric in all three dimensions. This has the effect of producing irregular spatial patterns of standing waves. Superposition of the few standing-wave patterns occurring at low frequencies then leads to a more homogeneous acoustic field than in a 'rectangular' chamber. This asymmetry also has the effect of producing the desired uniform distribution of the resonant frequencies over the frequency scale.

The standing-wave patterns and resonant frequencies of a rectangular reverberation chamber can be calculated analytically [1]. This is not possible if the chamber is not rectangular. In the past this was often held to be a major drawback of a non-rectangular chamber. Nowadays, however, the behaviour of a non-rectangular chamber can be calculated numerically by means of the finite-element method [2].

In spite of the greater technical problems, we therefore decided to build a reverberation chamber of irregular shape. In calculating the sound-pressure distribution with the finite-element method the total volume of the chamber is divided into a large number of tetrahedral elements, and the differential equation for the acoustic field in the chamber is replaced by a set of equations for the field at the nodes of the tetrahedral network. The results of such a numerical calculation will be more accurate the finer the meshes of the network. To keep down the amount of calculation required, we only considered the frequency range below 125 Hz; this is the range where the various resonant frequencies are relatively far apart.

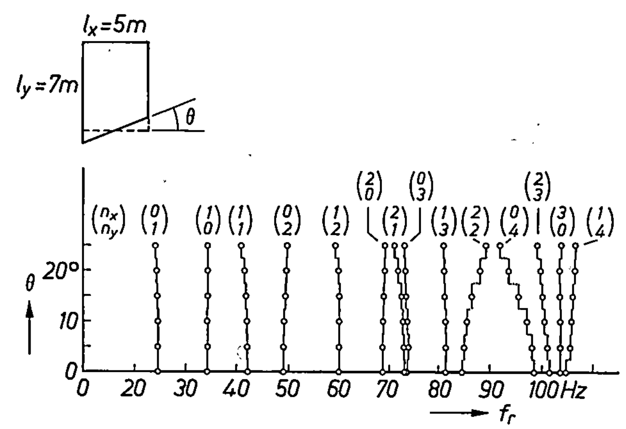

Fig. 1. Behaviour of the resonant frequency f_r of a two-dimensional rectangular chamber of total area 5×7 m^2, when one of the short walls is rotated through an angle θ. Each of the resonant frequencies is characterized by a pair of numbers $(n_x n_y)$ that indicates the number of half-periods in the standing-wave pattern in the x- and y-directions of the rectangular chamber.

We calculated a number of standing-wave patterns in this frequency range, for both two-dimensional and three-dimensional chambers [3].

The first thing that we noticed during these calculations was that if the angle of one of the walls was changed slightly, the effect on the resonance spectrum was completely unpredictable. *Fig. 1* shows the calculated behaviour of a number of resonant frequencies in a two-dimensional chamber, with a surface area of 5×7 m^2, as one of the walls is rotated through an angle. The result of changing the angles of two walls cannot be found by superimposing the results of changing the angles of each of the two walls separately. *Fig. 2* shows a number of calculated standing-wave patterns for the two-dimensional rectangular chamber and for a non-rectangular chamber with the same area. At higher frequencies in particular there is hardly any agreement between the pattern in a rectangular chamber and that in a non-rectangular chamber.

The computer time necessary for calculating the acoustic field in a single three-dimensional chamber is considerable, and the geometry of a three-dimensional non-rectangular chamber is determined by a large number of parameters. The method of calculation is therefore not so suitable for calculating the optimum values of all these parameters, and hence the optimum shape of the chamber. It is however possible to calculate the acoustic field in a given chamber. From calculations of this kind it can be seen quantitatively why a non-rectangular chamber is superior to a rectangular one, both in the homogeneity of the acoustic field and in the regularity of the spectrum of resonant frequencies in the low-frequency region.

We arrived in this way at a shape that promised acceptable behaviour even at frequencies lower than 100 Hz, and which has characteristics that come within the limits recommended in the ISO standards [4]. This means that our future measurements will be immediately comparable with measurements made elsewhere in other reverberation chambers constructed to these standards. This basis for intercomparison is particularly

[1] P. M. Morse, Vibration and sound, McGraw-Hill, New York, 2nd edition 1948, chapter VIII.
J. W. Strutt, 3rd Baron Rayleigh, The theory of sound, Vol. II, Macmillan, London, 2nd edition 1896, sections 267 and 299.

[2] The principles of the finite-element method are described in the article by J. H. R. M. Elst and D. K. Wielenga in this volume of Philips tech. Rev., p. 56 (No. 2/3).

[3] J. M. van Nieuwland and C. Weber, to be published shortly.

[4] International Standard ISO 3741-1975: Acoustics — Determination of sound power levels of noise sources — Precision methods for broad-band sources in reverberation rooms.
International Standard ISO 3742-1975: Acoustics — Determination of sound power levels of noise sources — Precision methods for discrete-frequency and narrow-band sources in reverberation rooms.

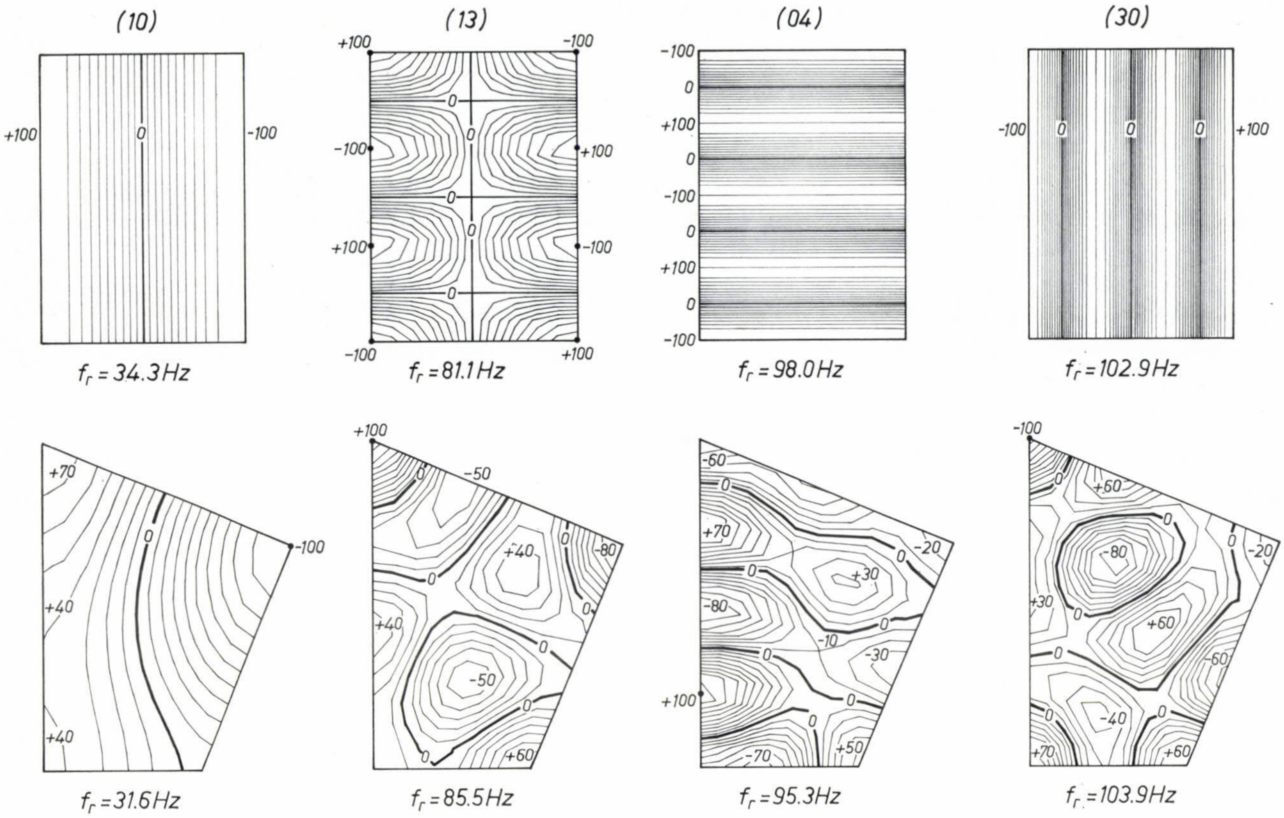

Fig. 2. Calculated sound-pressure distributions in a two-dimensional rectangular chamber and in a non-rectangular chamber of the same area. The calculations were carried out for a number of the lowest resonant frequencies. The resonant frequency f_r is indicated in each case. The nodal lines (zero sound pressure) are the bold contours. The pressure value in relative units is indicated next to the other contours of equal sound pressure. The correspondence in shape between the patterns in the two chambers is soon lost at higher resonant frequencies.

desirable since future recommendations and specifications are expected that will quantify the permitted sound levels from equipment such as domestic appliances.

The shape finally chosen for the reverberation chamber after we had considered the results of our calculations is shown in *fig. 3*. The floor is not rectangular, only two of the four side walls are perpendicular to the floor, and the ceiling consists of two planes that are not parallel to the floor. The volume of the chamber is 227 m^3. To check the calculations we made a model from concrete slabs, at a quarter of full scale, in which

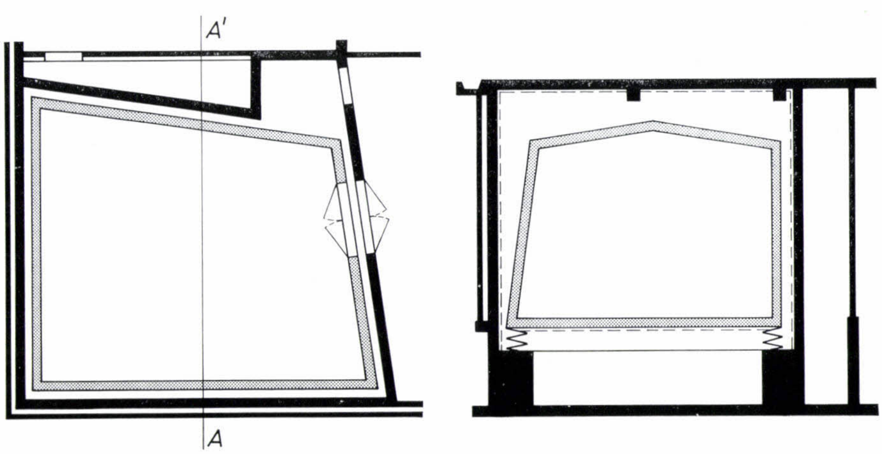

Fig. 3. Plan of the reverberation chamber (*left*) and a vertical cross-section along the line *AA'* (*right*). The concrete wall of the reverberation chamber is shown grey; the sound-insulating brick walls of the enclosure are shown black. To prevent external vibrations from entering the chamber through the floor, the 150-tonne concrete chamber is mounted on 80 steel coil springs.

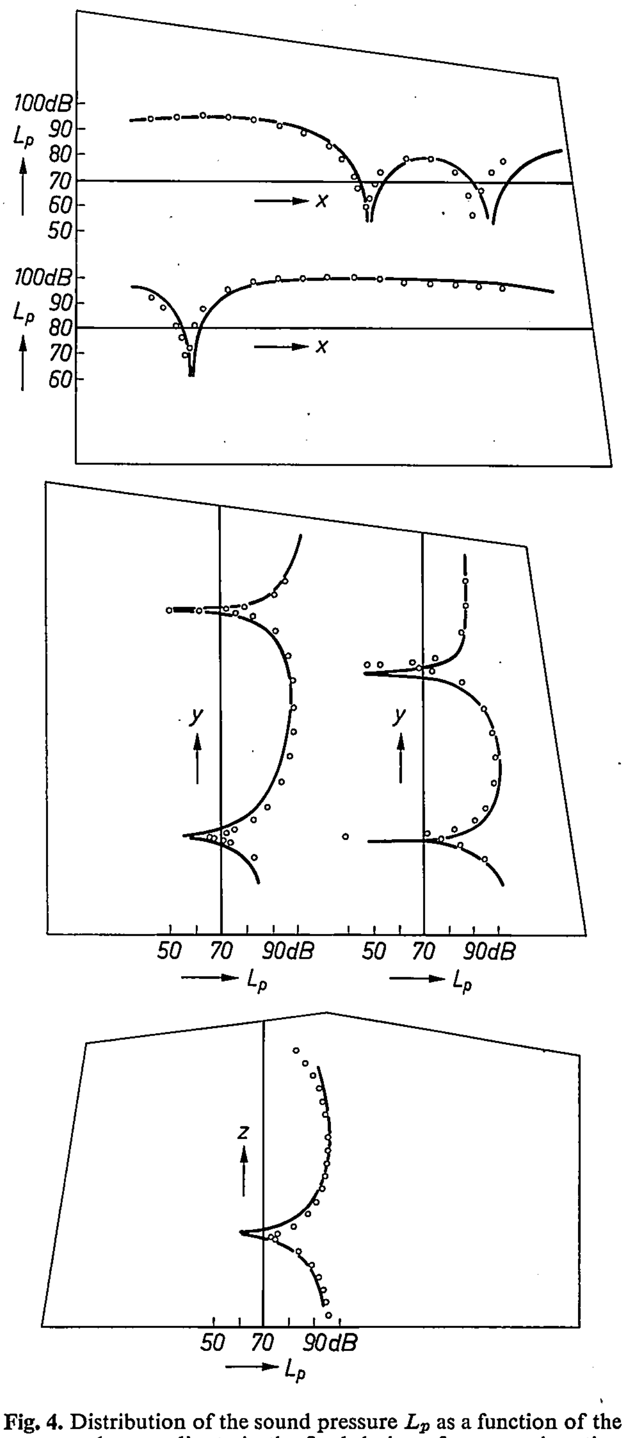

Fig. 4. Distribution of the sound pressure L_p as a function of the x-, y-, and z-coordinate in the final design of our reverberation chamber. The solid lines give the distribution calculated for the full-sized chamber at a frequency of 91.4 Hz, the points give the measurements for the quarter-scale model at a frequency of 365.5 Hz. In the neighbourhood of the nodal lines the difference between measurements and calculations may be relatively large. At these positions small deviations in the location of the microphone used for the measurements result in large errors, and the dimensions of the microphone will also have an effect.

the sound pressure was measured at a large number of locations. As can be seen in *fig. 4*, the results of these measurements are in good agreement with the calculations.

The chamber is built entirely of reinforced concrete. Special precautions were taken to make the inside surface as smooth as possible to give the maximum sound reflection from the walls.

The unpredictable and sometimes drastic effect of a small change in dimensions on the characteristics of the chamber, as mentioned earlier, meant that the dimensions specified in the design had to be adhered to very accurately in the construction. A heavy wooden structure, supported by steel girders, was therefore made for the internal shuttering (formwork) of the concrete chamber, as shown in the title photograph. This wooden structure was later covered with a cladding of special very hard smooth plywood boards. The exterior of the boarded formwork exactly followed the dimensions of the interior of the chamber.

To reduce external interference as much as possible during the measurements the entire reverberation chamber is enclosed inside a space with heavy brick walls. These walls are lined inside with sound-absorbing material to prevent resonances in the gap between the walls and the outside of the chamber. The weight of the chamber will be 150 tonnes, and it will stand on 80 steel coil springs located around the outside edge of the base. The natural frequency of the complete structure is at about 3 to 4 Hz, so that external vibrations at a frequency higher than about 10 Hz will have no noticeable effect on the chamber. Very high frequencies may however be transmitted along the springs; to prevent this, rubber pads are placed between the springs and the foundation. The wall of the reverberation chamber has openings, which can be tightly sealed, for ventilation and for introducing cables. The chamber itself and the surrounding structure are closed with heavy soundproofed doors.

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