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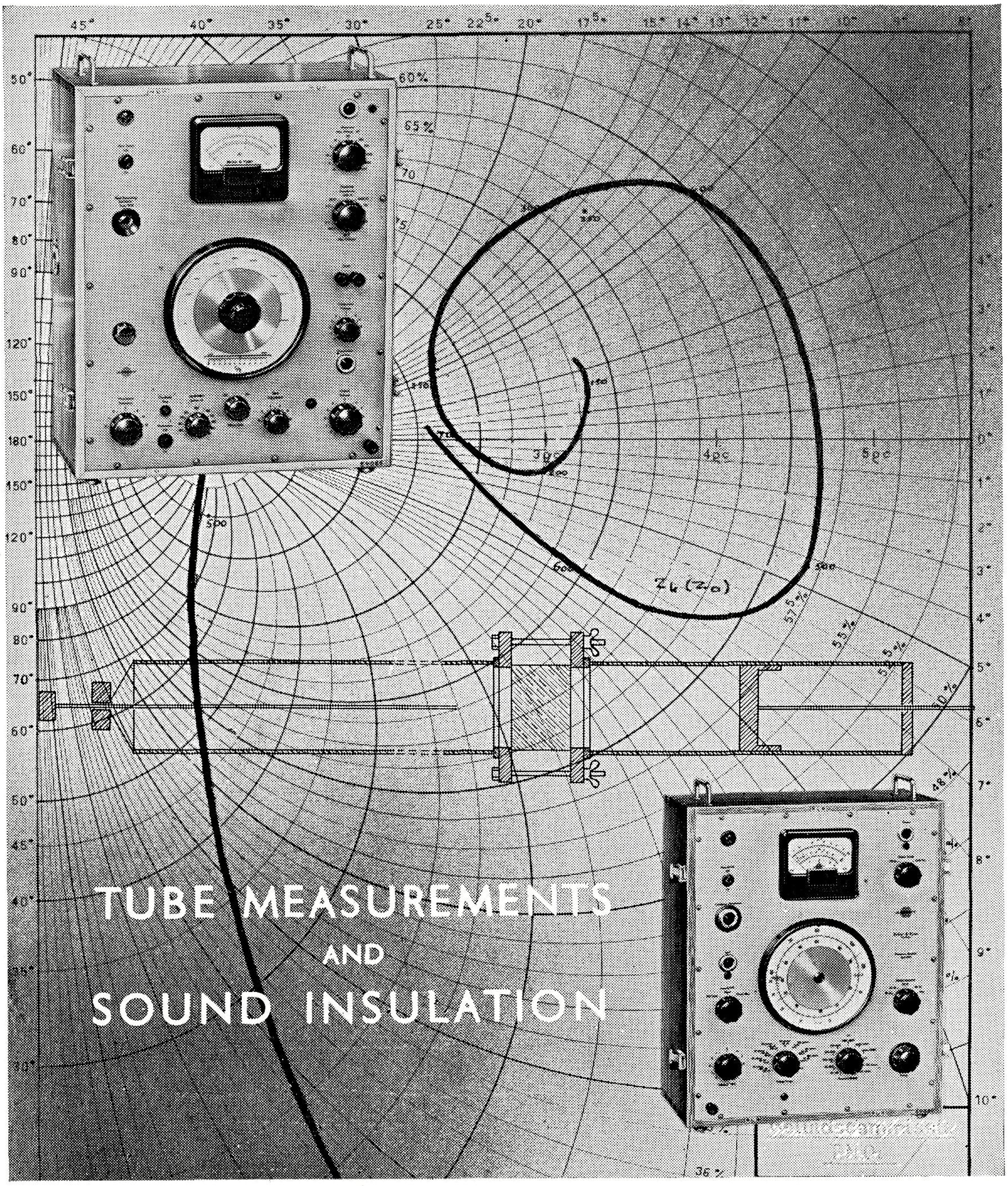

No. 4 October 1954

TUBE MEASUREMENTS AND SOUND INSULATION

by

Willem Brand M. Sc.

It is well known that the sound insulation of a double wall can be considerably improved by placing an absorbing material in the cavity between the two panels. In building technique this method is often practiced both with the cavity between the two panels filled and half-filled. However, as far as the filling material itself is concerned with its characteristics such as density, stiffness, porosity, etc., and the values these should have to give an optimum damping effect, there is still a lot of trial and error involved.
In the following, a measuring method is given for the determination of the damping qualities of different filling materials for double walled cavities. These measurements can be carried out in a standing wave apparatus, thus avoiding the far more cumbersome normal procedure of measuring the insulation of a double wall between two rooms, each time with a different filling material. The method described makes use of the filling material only, and excludes the damping which the double wall, without filling material, already gives, and which constitutes the greater part of the total wall insulation.
Measurements indicate that differences in transmission loss of 8—12 db can be obtained near the critical resonance frequencies of the unfilled double walls with different filling materials. In a coming number of the T. R. some indications will be given of the filling material characteristics themselves, with the intention of obtaining an increased damping for the total wall construction.

With sound falling at normal incidence on a double wall whose separate panels have mass m and panel spacing l, a theoretical sound insulation is obtained which is shown in fig. 1,
The sound insulation in db is a function of only two variables ωm and m/l, and is drawn for various m/l values. The straight line shows the insulation of a single wall with mass 2 m, according to the "mass law":

$$I_{s\,2m} = 20 \log \frac{\omega m}{\varrho c} \quad \text{dB} \tag{1}$$

This increases linearly with logaritmic ωm scale.[1)]

[1)] See for different derivations: Cremer: Die Wissenschaftlichen Grundlagen der Raumakustik III, p. 207 (Hirzel, Leipzig), or Richardson, Technical Aspects of Sound, p. 113 (Elsevier, Amsterdam, London).

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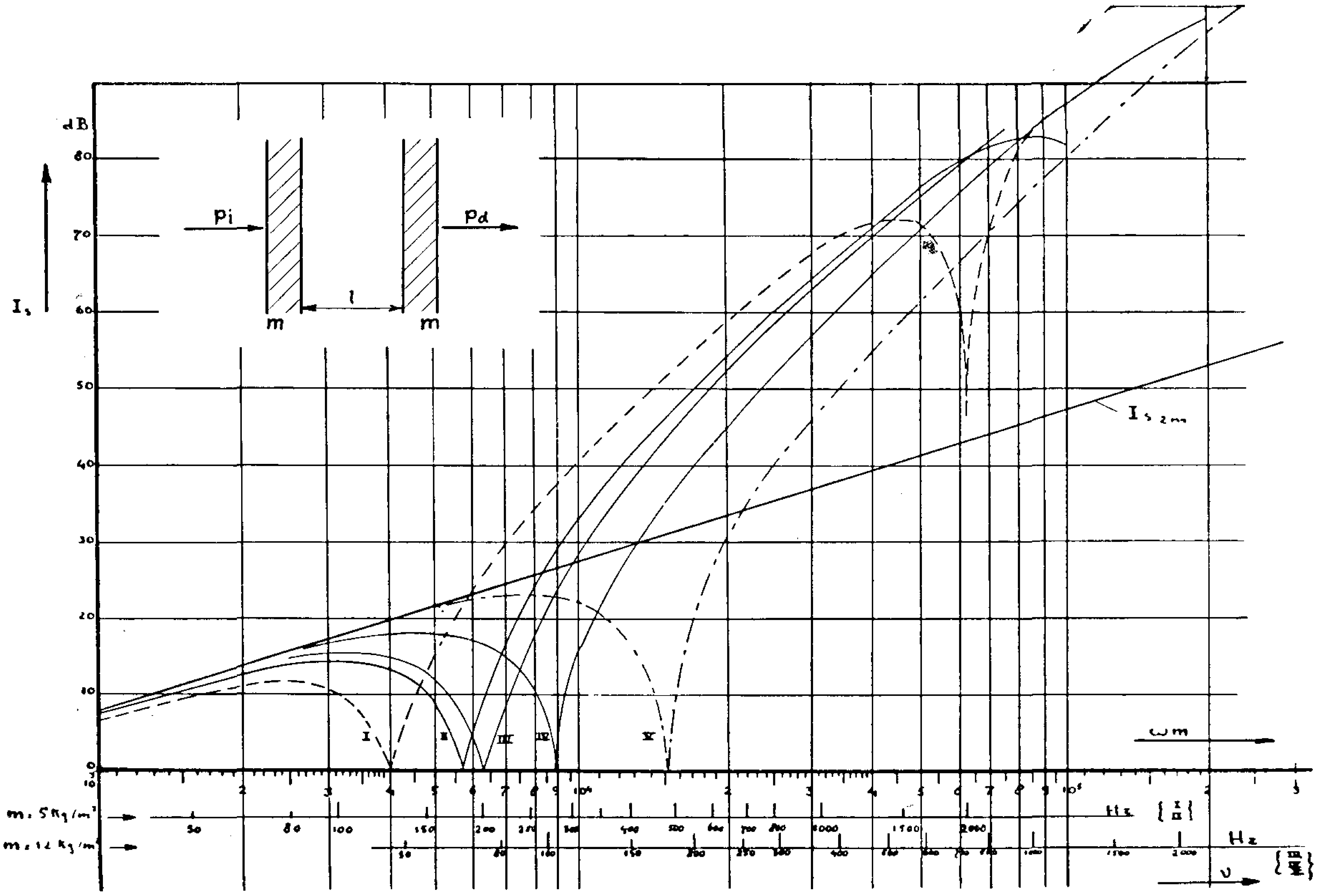

Curve	m (kg/m²)	l (cm)	m/l (kg/m³)
I	5	8,5	59
II	5	4,5	111
III	12	8,5	140
IV	12	4,5	266
V	12	1,5	800

Fig. 1. Theoretical sound insulation for normal incidence of double walls with a mass m for each panel, and with a panel spacing l. The straight line shows the insulation of a single wall with the same total mass (2m).

With mass m given, the frequency scales can be inserted as shown. The curves shown are effective for typical light weight structures with mass m from 5 to 12 kg/m^2, and a spacing l of from 2 to 10 cm (see insert in fig. 1). At low frequencies the insulation is found to be unsaticfactory, because the first resonance with light walls and small cavity lies at quite high frequencies. The first resonance frequency follows from

$$f_1 = \frac{1}{2\pi} \sqrt{\frac{K}{l/2 \cdot m}} \tag{2}$$

and is seen to be the resonance of a mass m in series with a spring of half the air spacing. The question is then whether by filling the cavity with the proper material we can eliminate the undesirable effect of the first resonance on the insulation characteristic.

In making practical measurements the sound insulating characteristics of various types of filling material can be investigated by filling a test wall, set up in the normal way between two rooms as sketched in fig. 2, with the different materials.

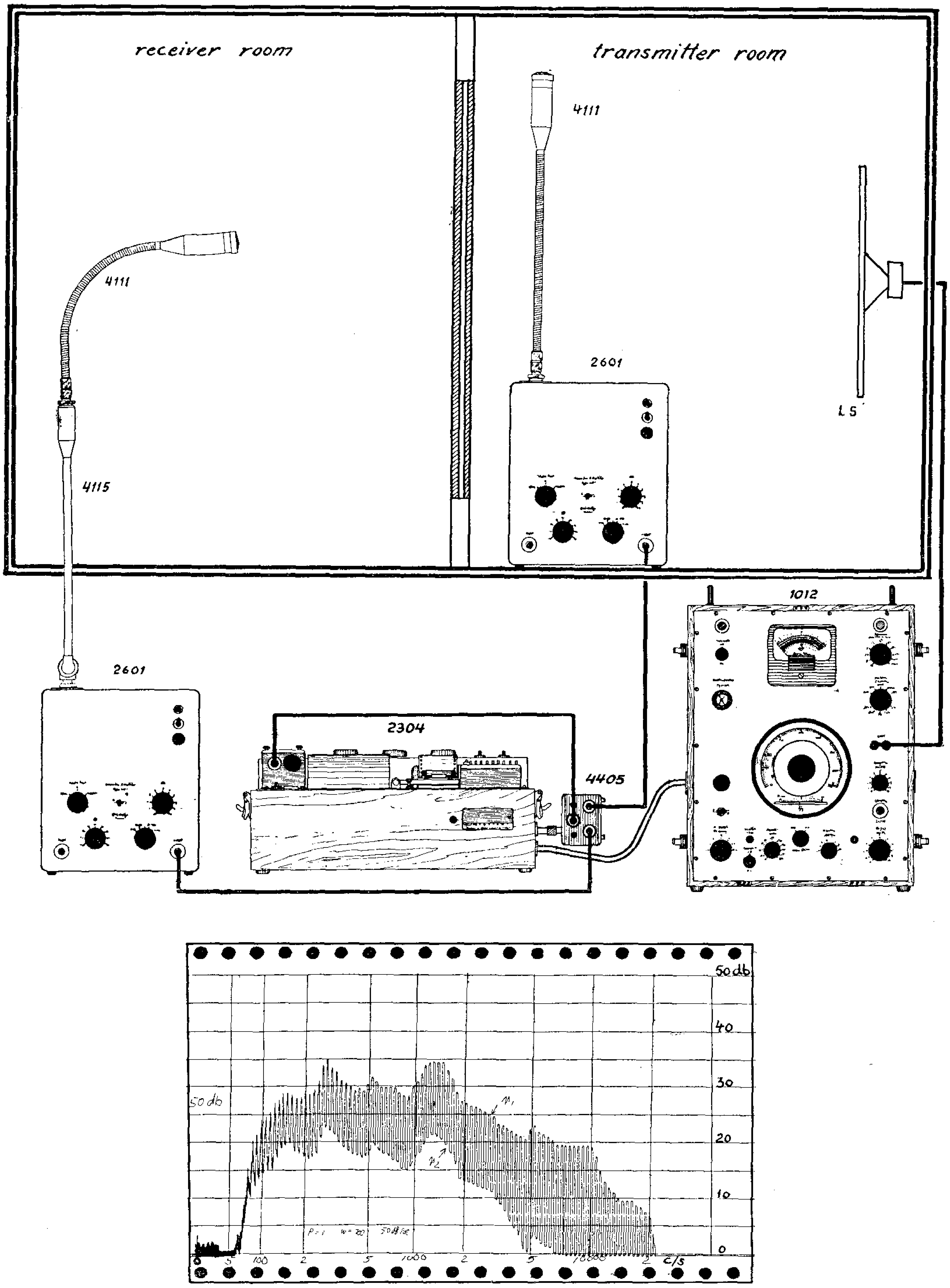

Fig. 2. Automatic recording of airborne sound insulation.

With the aid of the Two Channel Selector 4405, the levels from transmitter and receiver rooms are alternatively recorded via two separate channels on Level Recorder 2304, each channel consisting of Condenser Microphone 4111—Microphone Amplifier 2601. The frequency range 0—20.000 c/s is traversed very slowly by Beat Frequency Oscillator 1012, mechanically driven from the recorder, and each level is recorded about 350 times during a complete recording. At a frequency of for example 1000 c/s this corresponds to a frequency traverse of 20 c/s between two successive recordings of the same level, and only a few c/s between the two different levels, thus approaching a steady state measurement quite closely.
However, an unambiguous result is here obscured by two main difficulties. Firstly, it is very hard to insert the filling material so that both the degree of wedging and the stiffness of the panels is constant the whole time for the different measurements, and on the other hand the improvement in insulation arising from the filling process is often only small compared with the insulation figure of the empty double wall. It is therefore desirable to be able to carry out the measurements on the filling material alone, and preferably under the same conditions as when it is placed between the two panels.

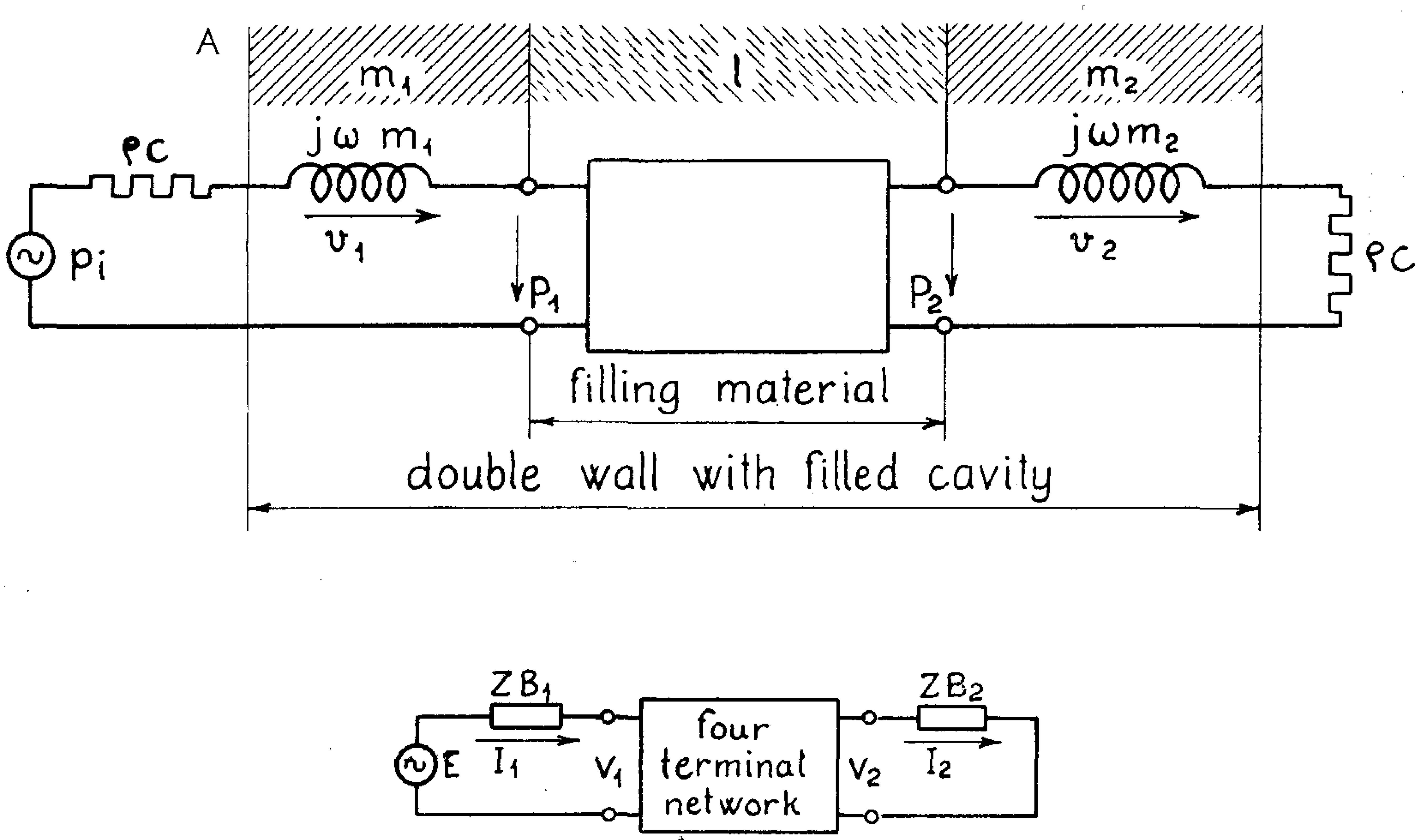

Fig. 3. Analogy between double wall exposed to a normal sound wave of intensity pi and electric four-terminal network.

Now, it is possible to consider the filling between the two panels in this one-dimensional case as an acoustic four-terminal network, determined by that pressure and speed which the filling material gets from the first panel's inner side, and that pressure and speed which it gives the inner side of the other panel. In fig. 3 the analogy is sketched which exists for a double wall under the influence of a normal sound wave of intensity p_i. The panels of the construction are considered as pure masses without any stiffness, between which the acoustic four-terminal network works, while the free medium on the right hand side of the construction is given with the characteristic impedance of air, ϱc. The generator with E. M. F. $2p_i$ and internal impedance ϱc arises from the fact that if the impedance at point A should be infinite, the voltage is $2p_i$ (that is, the pressure at a dense wall), but with a termination ϱc or infinite continuation of the free medium, the voltage is p. The acoustic four-terminal network thus works be. ~en two impedances Z_{B_1} and Z_{B_2}, which are equal if the panel masses are equal. For the operational exponent of such a four-terminal network, defined by

$$g_o = \frac{1}{2} \ln \frac{V_1' I_1'}{V_2 I_2} \tag{3}$$

where V'_1 and I'_1 are the values of V_1 and I_1 with impedance matching, we now have immediately

$$g_o = \frac{1}{2} \ln \frac{p_i^2/\varrho c}{p_d{}^2/\varrho c} \frac{(\varrho c)^2}{(\varrho c + j\omega m_1)(\varrho c + j\omega m_2)} \quad . \tag{4}$$

$p_i^2/2\varrho c$ represents the sound energy E_1 falling upon the construction from the free sound wave with amplitude p_i, while $p_d^2/2\varrho c$ is the energy E_2 emitted from the second panel of the construction (p_i and p_d are peak values of the incident and transmitted plane sound wave). As we are not interested in the phase shift between p_i and p_d but only the energy quotient E_1/E_2, we can take the real part from the left hand and right hand side, and the insulation is then

$$I_s = 10 \log \frac{E_1}{E_2} = 8{,}68\ A_o + 10 \log \frac{\omega m_1}{2\varrho c} + 10 \log \frac{\omega m_2}{2\varrho c} + 6\ \text{dB} \tag{5}$$

where I_s represents the insulation of the total construction and A_o the real part of the complex exponent g_o.

The second and third term in expression (5) right, represent half the insulation figure for the first and second panel alone, according to the known classical formula for the single wall's sound insulation. With the same mass for both panels we have simply

$$\boxed{I_s = 8{,}68\ A_o + I_{s_2 m}} \tag{6}$$

In other words, in the real part of the operational exponent we can immediately find the improvement or deterioration produced by the cavity, compared with the insulation of a single wall of mass $2\,m$, and as the operational exponent of a four-terminal network can be calculated with the result of two or three separate measurements on the four-terminal network alone, depending on whether the network is symmetrical or not. The insulation improvement or deterioration produced by the cavity can thus be calculated from measurements on the filling material (as sample of length equal to the panel spacing l) alone.

To imitate the conditions under which the material in the cavity transmits vibrations from the first to the second panel, the "acoustic network" is constructed as shown in fig. 4. The porous material is placed between two thin plastic membranes in a cylinder whose height is just equal to l and this is placed between two measuring tubes. The membranes, suspended between two rubber rings, are practically without stiffness.

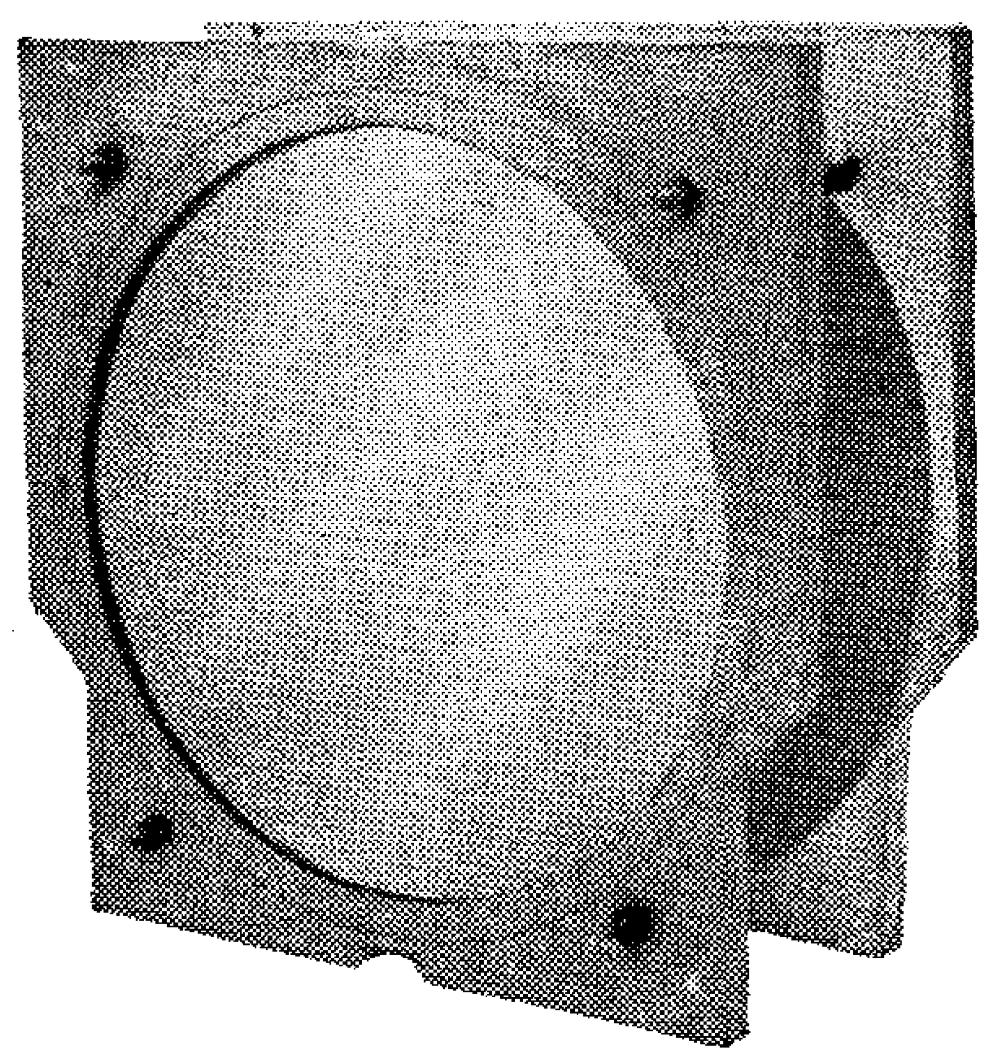

Fig. 4. Measuring unit with filling material between membranes used for the different impedance measurements. The whole unit is placed between two tubes as shown in fig. 5 and 6.

In the case of a symmetrical four-terminal network working between two equal impedances, i. e. in the acoustical case of a homogeneous filling between two equally heavy panels, it is useful for the calculation of the exponential exponent, to use Sterky's formula[2]), which can be worked out to

$$g_o = \ln \left\{ \cosh g_f + \frac{1}{2} \sinh g_f \left(\frac{Z_f}{Z_B} + \frac{Z_B}{Z_f} \right) \right\} \qquad (7)$$

where g_f is the network exponent and Z_f the network image impedance, or, in case the system can be regarded as a single transmission line, g_f is the propagation constant along the line and Z_f the characteristic impedance. Of the three magnitudes here appearing, $\cosh g_f$, $Z_f \sinh g_f$ and $\frac{\sinh g_f}{Z_f}$ the first two can be measured direct by a tube method described by Wüst[3]), and which is shown in principle in fig. 5. For a symmetrical four-terminal network the following relations between sound pressure p and velocity v are effective:

[2]) For the different formulae and derivations of operational exponents see:
Feldtkeller: »Vierpoltheorie«, (Hirzel, Leipzig).
Rybner: »Kredsløbsteori«, (Ingeniørfond, Copenhagen).

[3]) »Hochfrequenz und Elektro-Akustik«, 44 (1934), p. 73.

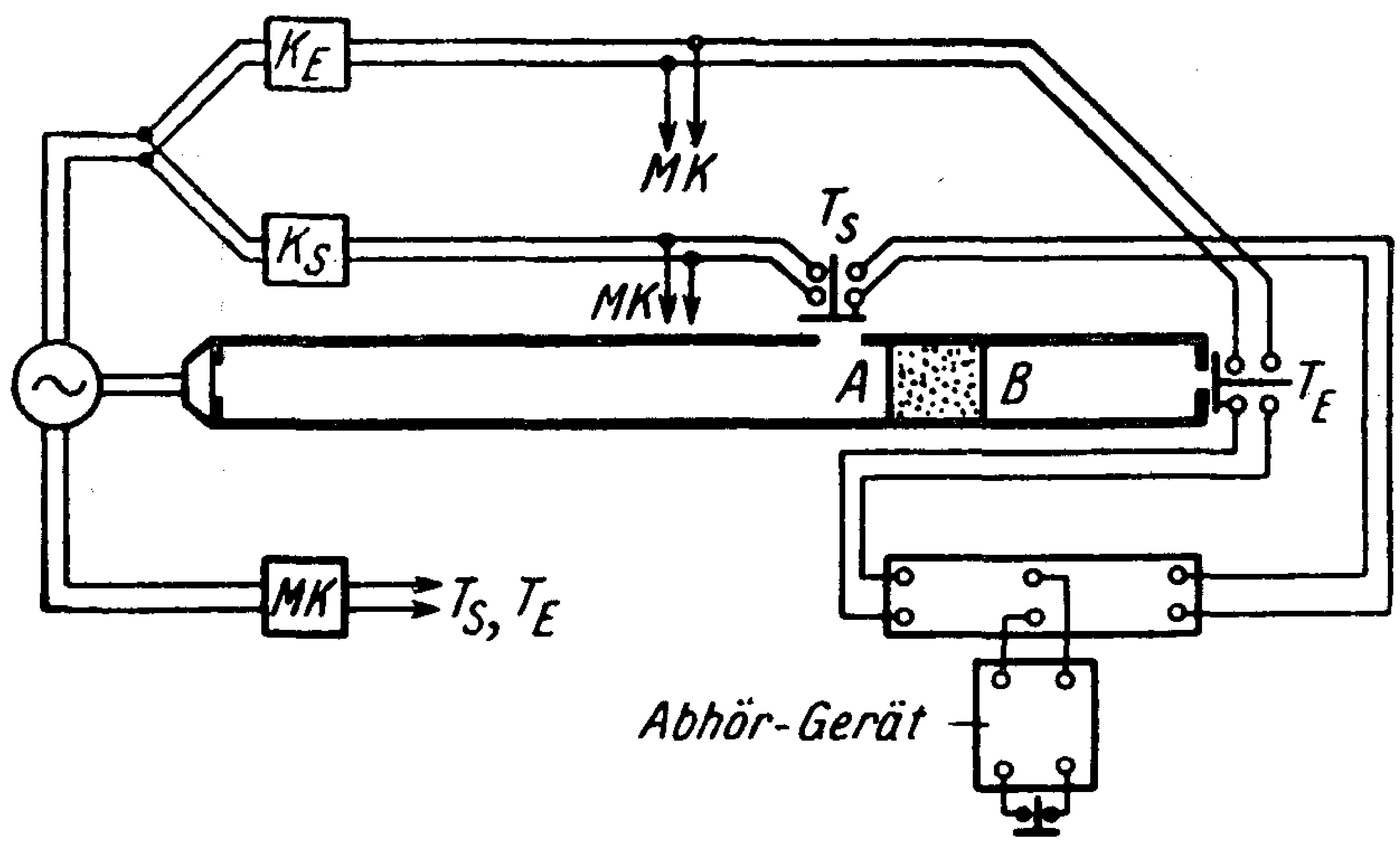

Fig. 5. Determination of the coefficients of an acoustical four-terminal network by means of a tube measurement and compensation microphones according to Wüst[3]).

$$p_A = \cosh g_f \cdot p_B + Z_f \sinh g_f \cdot v_B$$
$$v_A = \cosh g_f \cdot v_B + \frac{\sinh g_f}{Z_f} \cdot p_B \tag{8}$$

so that with $v_B = 0$ we get $\cosh g_f = \frac{p_A}{p_B}$ (9)

and with $p_B = 0$ $Z_f \sinh g_f = \frac{p_A}{v_B}$ (10)

$v_B = 0$ is obtained by giving the test sample a hard, thick back plate, and $p_B = 0$ by placing the whole sample at a distance of 1/4 wavelength λ from this plate. All pressures are measured in both modulus and phase by means of two telephones with two separated windings, one of which is fed by the same signal source as the loudspeaker mounted in the measuring tube, and the other led to a monitor. The equalizers K_S and K_E are then set to a minimum for the monitor, and compared with each other. Finally, v_B of formula (10) is measured from the pressure p_E in 1/4 wavelength distance as the relation exists $v_B = - \frac{j}{\varrho c} p_E$. From this, g_f and Z_f can be read off by the aid of tables, and then the third unknown follows, $\frac{\sinh g_f}{Z_f}$.

In many instances, especially for higher frequencies, we have $Z_B (= j\omega m) \gg Z$ so that it is sufficient to take only the quantities $\cosh g_f$ and $\frac{\sinh g_f}{Z_f}$ into consideration in the calculation, simplifying the calculation of g_o to a great extent.

The more general formula for the operational exponent expressed in the four-terminal network, reflection- and reciprocal exponents

$$g_o = g_f + g_{r1} + g_{r2} + g_x \qquad (11\ a)$$

of which for our calculations we only need the real part of each exponent, so that

$$A_o = A_f + A_{r1} + A_{r2} + A_x \qquad (11\ b)$$

can be used for both symmetric and asymmetric four-terminal networks (that means filling samples of homogeneous material or layers of different materials) as well as for two different masses m_1 and m_2, for the two panels of the construction. For the calculation of the different terms in this formula both in the symmetrical and asymmetrical case, only 3 independent quantities have to be measured. Use can then be made of existing tables and nomograms as employed in telephone and network techniques. The simplest measuring technique consists of the orthodox tube method, exploring the sound field with a probe and measuring the short-circuit and open impedances of the test-sample Z_{1s}, Z_{2s} and Z_{1o}, Z_{2o}.

Only three impedances have to be measured as we have the relation

$$\frac{Z_1}{Z_{1o}} = \frac{Z_{2s}}{Z_{2o}}$$

and in the case of symmetry only two, Z_s and Z_o.

Shortcircuited and open "four-terminal networks" can be set with these impedance measurements in the same way as with the first method. The advantage here is a much simpler measuring procedure than working with the different compensators, which also require calibration. This method was worked out as part of an investigation to improve the insulation of "light weight structures" especially in the more critical frequency range from 100 to 1000 c/s.[4]) The measurements were carried out in a big standing wave tube of more than 5 m total length and diameter 28 cm, allowing measurements to be made up to 750 c/s (see fig. 6). A curve was plotted for the short circuit

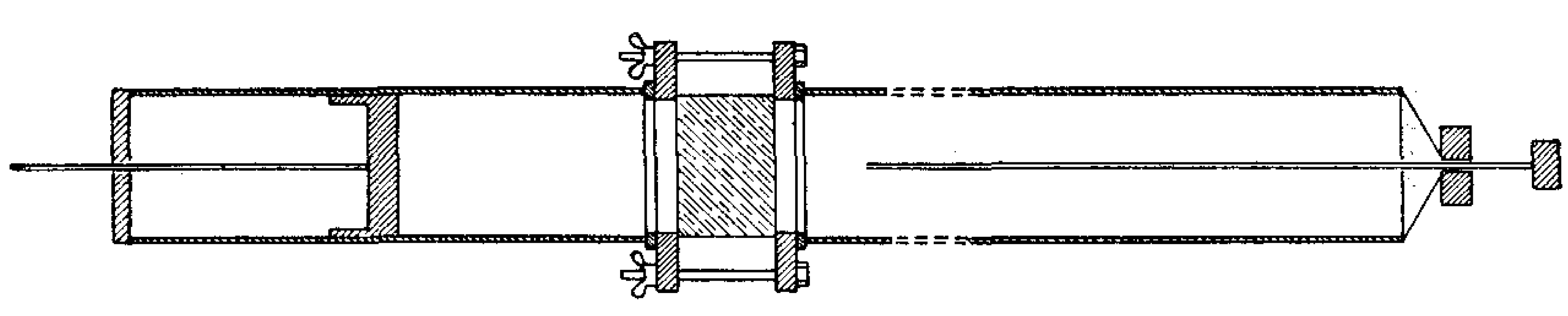

Fig. 6. Impedance measurements on test sample, with normal standing wave measurement. The conditions "open and short circuited quadripole" are fulfilled by placing the piston in the cylinder close to the sample and at a distance of ¼ wave length λ.

and open impedances of the different samples. With homogenous samples only two measurements were necessary for Z_s and Z_o of which an example

4) Carried out at Technical University, Delft.

is given in fig. 7. With asymmetrical filling samples the same two measurements gave Z_{1S} and Z_{1O} after which the sample was turned and the measure-

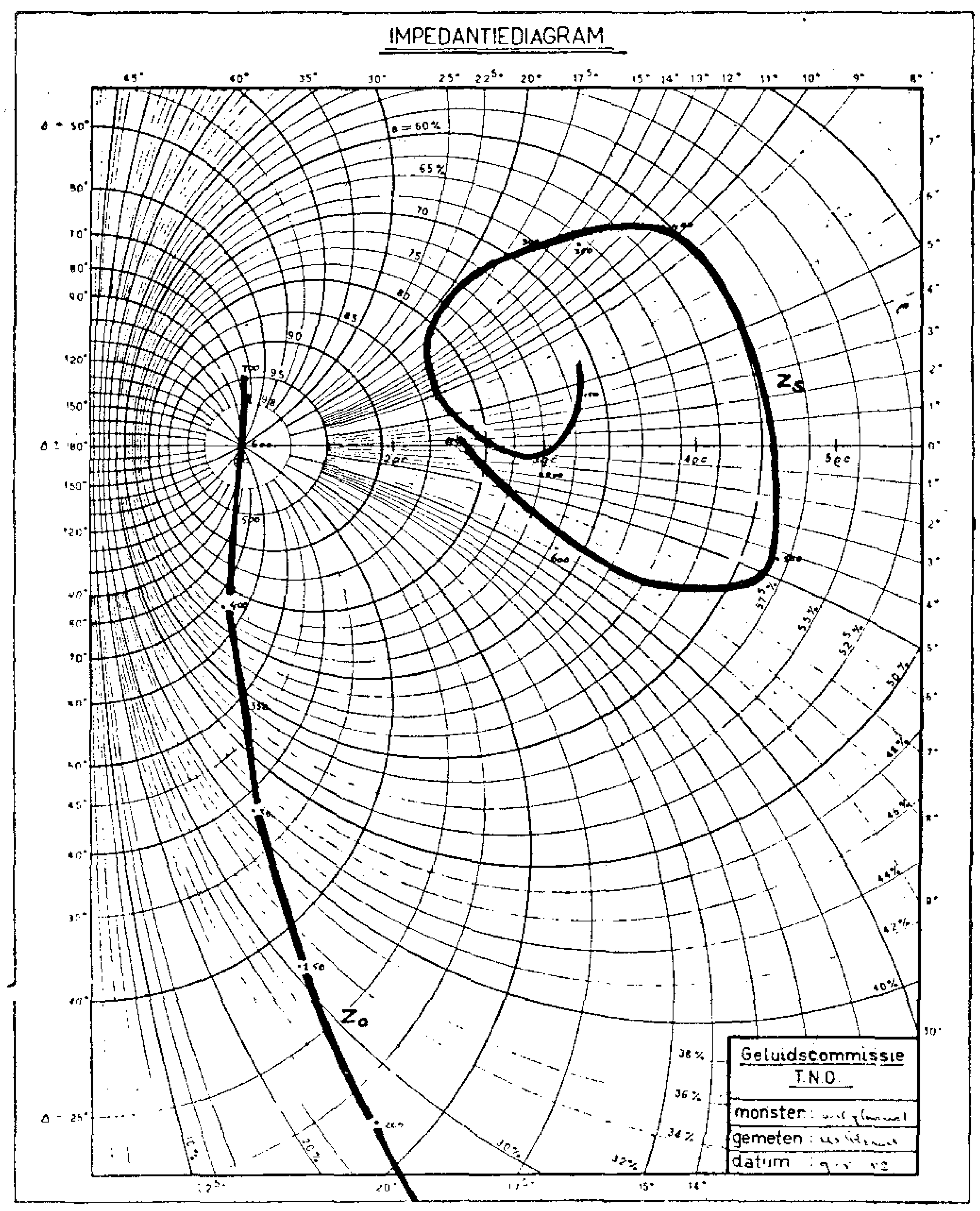

Fig. 7. Example of plotted impedance curves in a complex plane for the short circuit and open impedance of a homogenous sample of filling material of 4.5 cm length.

ments repeated, giving Z_{2S} and Z_{2O} The relation (12) when verified with the results, proved to be followed within the accuracy of the measuring procedure. With the impedance curves plotted the three network magnitudes: network exponent gf_2 and network image impedances Zf_1 and Zf_2 (or symmetrical Zf) follow from

$$\text{tgh } gf = \sqrt{\frac{Z_{1S}}{Z_{1O}}} = \sqrt{\frac{Z_{2S}}{Z_{2O}}} \qquad \left(\text{symmetrical } \sqrt{\frac{Z_S}{Z_O}}\right) \qquad (13)$$

$$Zf_1 = \sqrt{Z_{1S}\, Z_{1O}}$$
$$Zf_2 = \sqrt{Z_{2S}\, Z_{2O}} \qquad \left(\text{symmetrical } Zf = \sqrt{Z_S\, Z_O}\right) \qquad (14)$$

Only A_f, the real part of g_f, has to be read off from tables[5]), while A_r follows from

$$A_r = {}^1/_2 \ln \left\{ r + {}^1/r + 2 \cos \Phi \right\} \tag{15}$$

if $\frac{Z_f}{Z_B} = r \angle \Phi$ (Tabelized up to 10, see [5]))

A_X follows also from tables but is in many cases when $e^{-2A_f} < 1$ negligible compared with A_f and A_r.

The method showed itself satisfactory up to about 900 c/s. Above this frequency and with samples of greater lengths than 10 cm it appeared that for porous materials with very great stiffnes Z_S and Z_O were too near in the complex plane to estimate g_f with the aid of quotient $\frac{Z_S}{Z_O}$ with satisfactory exactitude.

As an example, some results effective for the two previously mentioned double walls of mass respectively 5 and 12 kg per m^2 per panel can be given. The theoretical insulation of a single wall with mass $2m$ is shown in fig. 1 as a straight line, while the improvement 8.68 A_O for an unfilled double wall can be derived from formula (7) to be

$$I_{SC} = 8{,}68\ A_O = 20 \log \left\{ \cos \frac{\omega l}{c} - \sin \frac{\omega l}{c} \cdot \frac{\omega m}{2\varrho c} \right\} \tag{16}$$

(g_f for the "sample of air« of length l is equal $\frac{\omega l}{c}$ and Z_f the characteristic impedance ϱc)

The resonance frequencies for such a construction can be found as solutions of the transcendental equation $\operatorname{tg} \frac{\omega m}{c\ m/l} = \frac{2\ \varrho c}{\omega m}$ (17)

which for the first resonance frequency directly gives formula (3).

Different kinds of glass wool of varying stiffness and air resistance were measured as indicated above on samples of various thickness. Measurements show that with most porous materials, and with double wall constructions where the panel spacing l is greater than 20 cms, A_f i.e., the real part of the network exponent g_f is the predominent factor in the formula for the improvement in insulation $A_O = A_f + A_{r_1} + A_{r_2} + A_X$ (or with a homogenous filling sample between two walls of equal mass $A_O = A_f + 2A_r + A_X$) With l smaller, the reflection factors A_{r_1} and A_{r_2} become more significant,

5) Rybner: Nomograms of Complex Hyperbolic Functionc. (Gjellerup, Copenhagen.)

while last'y the factor A_x starts to become effective when A_f decreases so that e^{-2A_f} becomes comparable with 1
From formula (15) it follows, since it is always the case that $\omega m > Z_f$ that the image impedance must be as small as possible. It is therefore necessary to find materials which for a definite sample length provide the greatest damping A_f with small image impedance Z_f.

The insulation increase for a double wall according to fig. 1 (insert) compared with that of the single wall with mass $2m$, calculated from measured data on filling samples of 8.5 and 4.5 cm thickness, is shown finally in figs. 8, 9 and 10. In each figure the corresponding insulation curve for the unfilled double wall with same panel mass and spacing, is given as comparison, re-drawn from fig. 1.

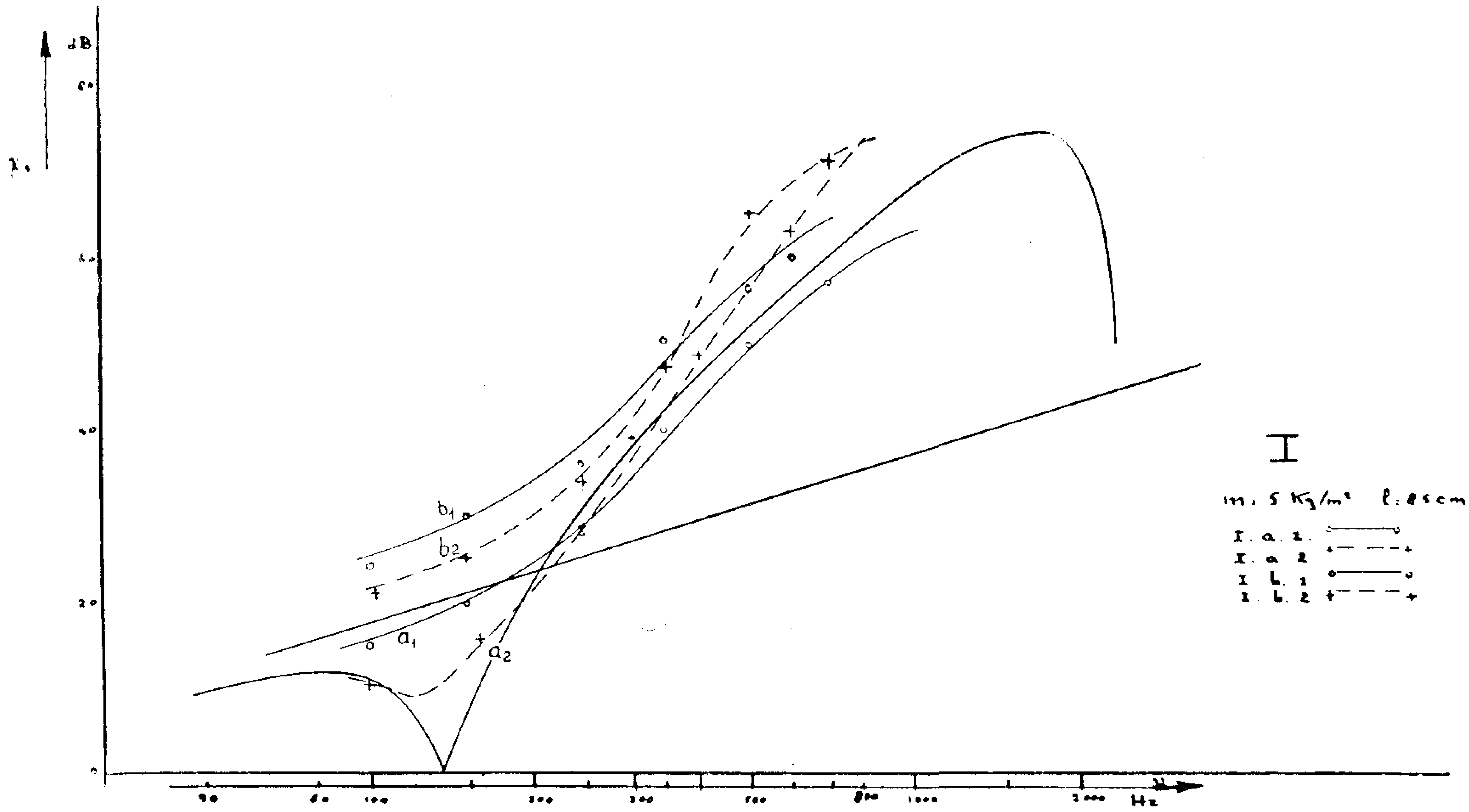

Fig. 8. Insulation curves for a double wall construction with mass m = 5 kg/m² and panel spacing l of 8.5 cm filled with two different kinds of glasswool a and b. The insulation curve for the unfilled double wall is given as comparison. The differences between curves a_1—a_2 and b_1—b_2 are caused by partitioning of the fillings by means of thin impermeable membranes in the sample.

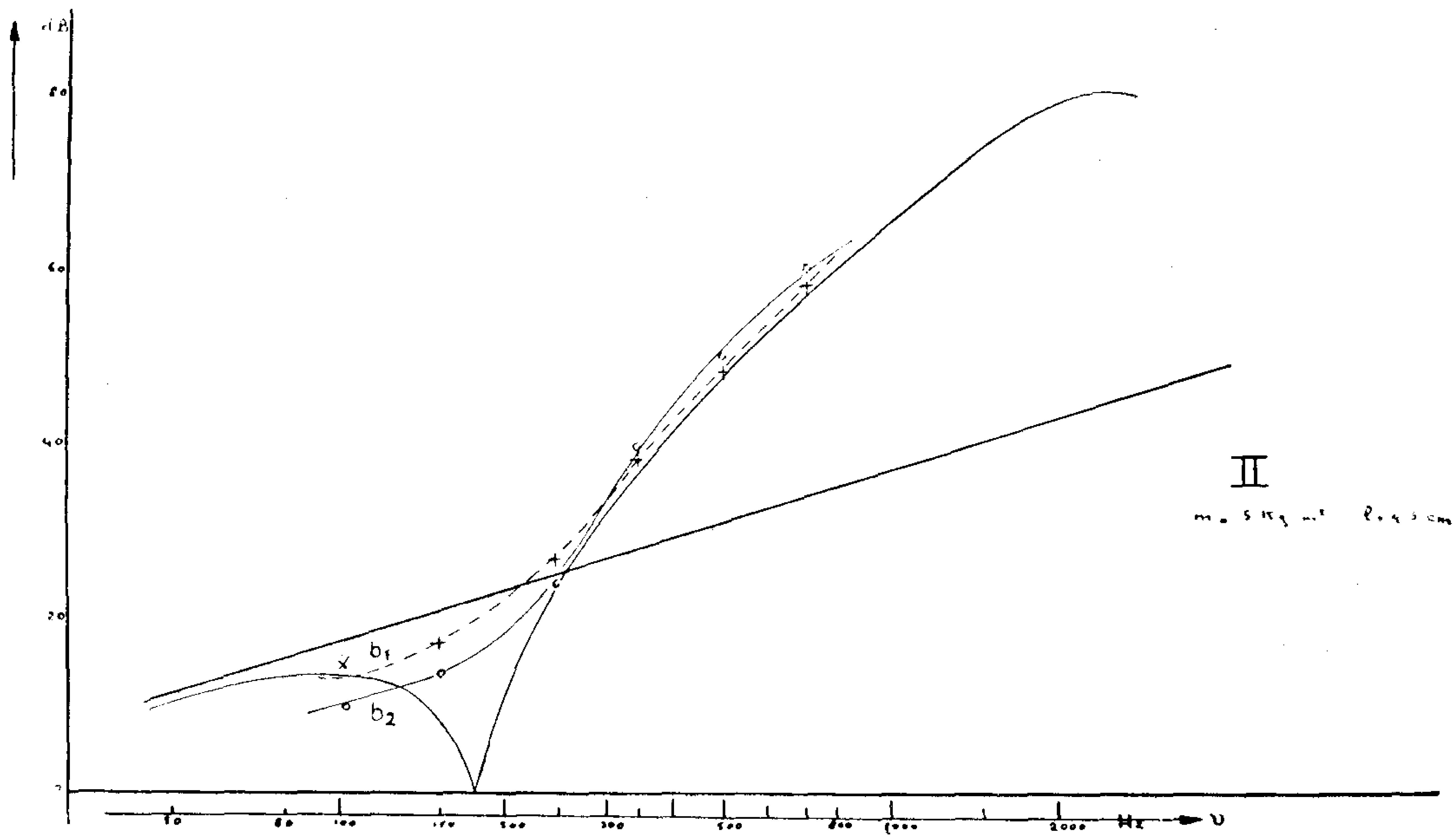

Fig. 9. Idem fig. 8 for a double wall construction with m = 5 kg/m² and l = 4.5 cm.

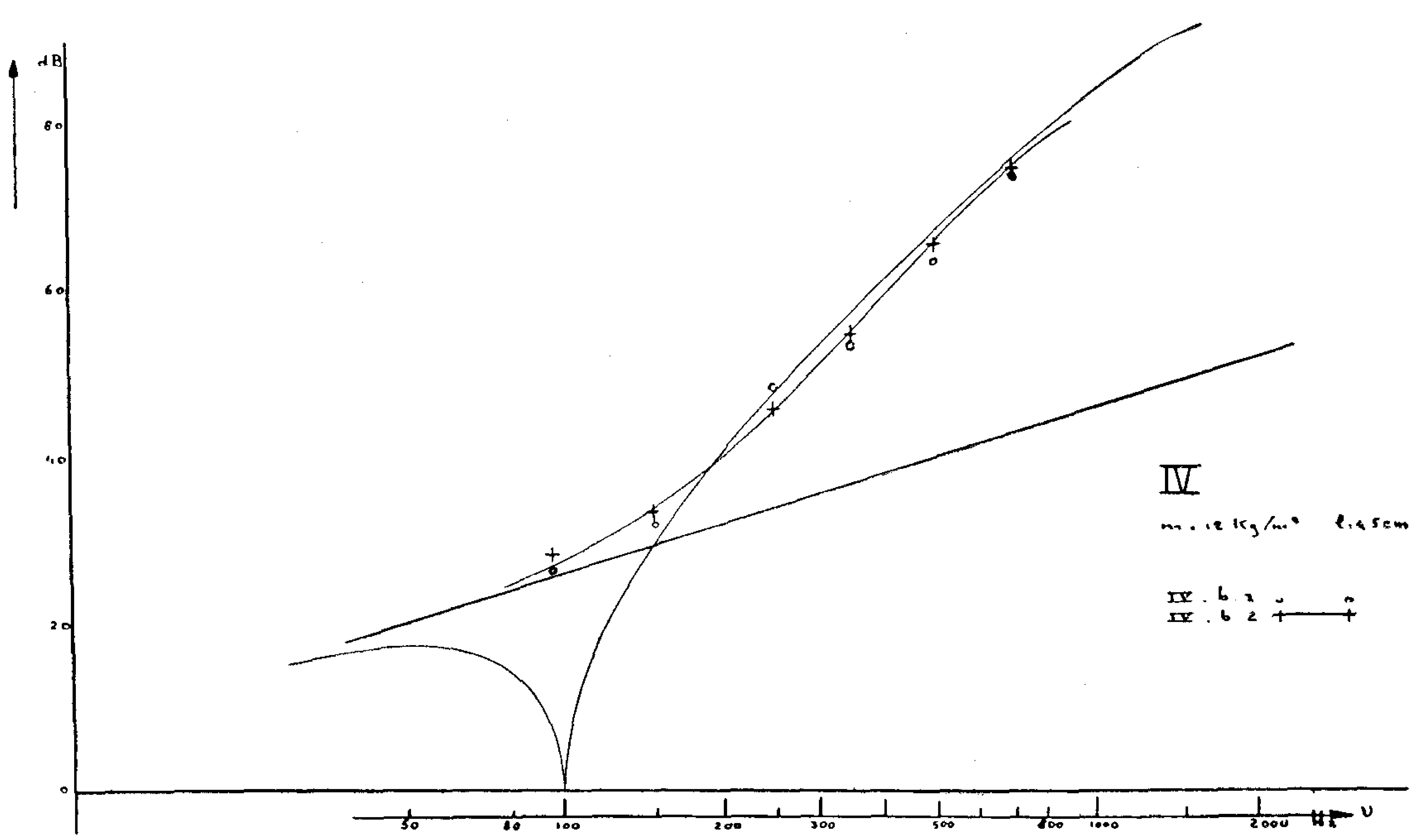

Fig. 10. Idem fig. 8 m = 12 kg/m² and l = 4.5 cm.

With 8.5 cm panel spacing and mass 5 kg/m^2 (see fig. 8), it appears that a good improvement in the resonance dip can be obtained, and *that the correct choice of filling material can then give a difference of 10 db* even with the lower frquencies. The curves a_1, a_2 and b_1, b_2 are valid for two glasswool samples with a considerable difference in specific stiffness (respectively 800 and 2400 N/m^2) and mass (16 and 38 kg/m^3). The differences between curves a_1—a_2 and b_1—b_2 arise from the fact that the values g_f and Z_f for a filling sample and thus also the insulation of a double wall with such a filling, differ depending on whether the sample consists of a homogeneous filling between the two terminating membranes or is partitioned by means of impermeable or permeable membranes. The wave phenomena and absorbing mechanisms appear to be different in both cases, as will be shown in a future number of Technical Review. Here only the result of the partitioning is given, showing with the given panel spacing for both filling materials an improvement in insulation for the higher frequencies but worsening for the lower ones using the partitioned samples.

With 4.5 cm panel spacing (see fig. 9), practically speaking one follows the curve for the empty double wall. Only at the resonance dip is there still some improvement.

Finally, it can be seen that with greater mass (12 kg) and 4.5 cms distance the filling material has no influence whatsoever outside the resonance dip, which was to be expected.

Moreover the insulation values for partitioned and unpartitioned samples now coincide as the influence of A_r and A_x n formula 11b is increased in this case with same damping A_f of the sample (this term only being dependent on the sample length *l*, which is the same in fig. 9 and 10).

CALIBRATION OF PROBE-TUBE MICROPHONES

by

Willem Brand M. Sc.

Accurate measurements of sound pressure levels carried out with probe-tube microphones find widespread use in many acoustical research programs whenever it is impossible to locate even a small microphone with or without preamplifier at the point of measurement. Measurements of the response of hearing aid receivers while inserted in the ear, impedance measurements of the external auditory meatus and tympanic membrane, and other psycho-acoustic measurements, belong to the more obvious uses of probe-tube microphones, where exact calibration of the combined probe-tube and microphone is necessary. However, in porous materials research, in measurements on small-scale test models of rooms and auditoria, and with standing wave methods for determination of absorption with varying frequency, the damping of the probe as a function of frequency should also be known. If an adequate accuracy is desirable in these measurements, it is necessary to turn to the category of condenser microphones, which are supplied with a calibrated frequency characteristic, and whose laboratory-controlled sensitivity may be assumed constant over a long period.

Condenser Microphone type 4111 can easily be employed as a probe microphone by removing the protective grid of the microphone cartridge and attaching a probe as shown in fig. 1. in its place. The dimensions of the probe itself are not given in this figure, as length and width of tube will be dependent on the type of work for which the probe is intended. The base should be flat and parallel to the membrane, and of sufficient thickness (about 4 mm brass) to avoid sound pick-up on its own accord. The distance "base to microphone membrane" should not exceed 1 mm. The outer ring should fit tightly around the cartridge, while the bearing portion of the accessory is formed by ring A which rests in its whole length on the cartridge surface, thus ensuring the parallelism of base and membrane.

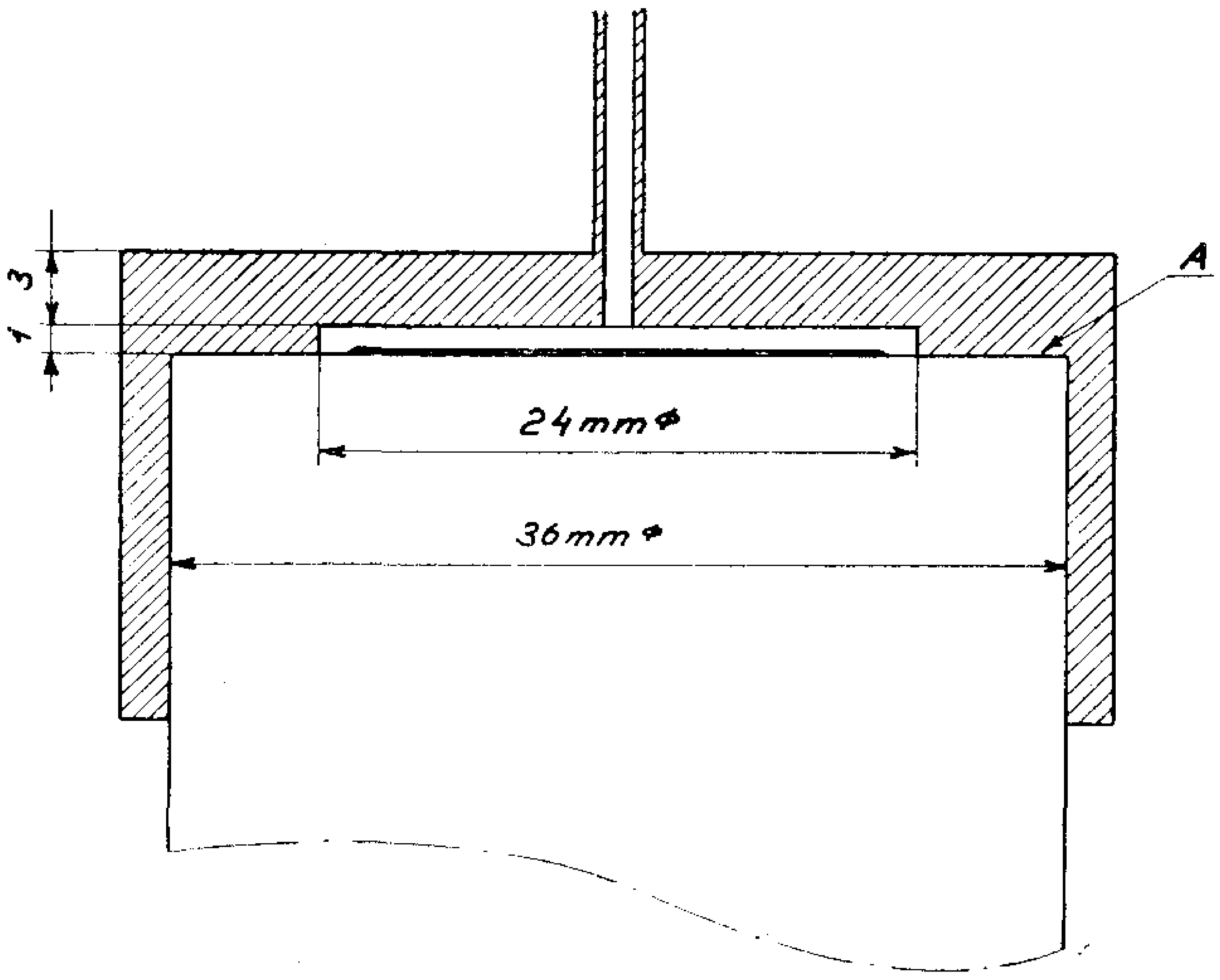

Fig. 1. Sketch of Condenser Microphone 4111 cartridge with probe-tube fitted.

The calibration of such probe microphones is described by Veneklasen in J.A.S.A. **20** (1948) p. 812, and by Benson in J.A.S.A. **23** (1953) p. 128. The last article deals with measurements for the estimation of a "pressure response" carried out in a 4.7 cc cavity and a "free field response" carried out

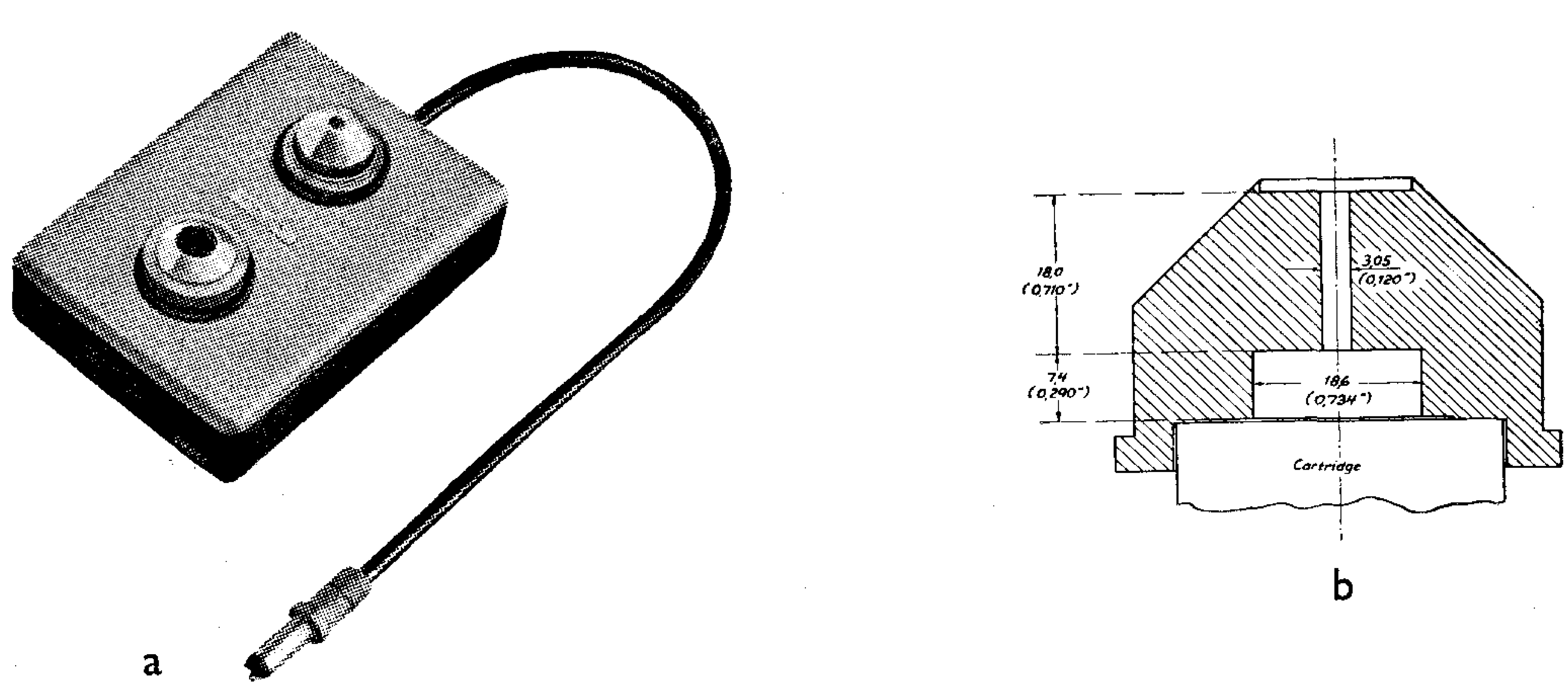

Fig. 2. Artificial Ear type 4109 constructed according to the American Standards Association Standard Z 24-9. The 2-cc coupler which can be used for these measurements is shown in fig. 2 b. On the instrument this coupler is visible at the right side and the National Bureau of Standards coupler (or possibly the 6 cc A. S. A. coupler) on the left. The apparatus is equipped with a T-type condenser microphone cartridge and built-in cathode follower, the necessary voltages for these being supplied via the 7-core cable from the Microphone Amplifier 2601 or Analyzer 2105.

in a well damped room. The differences between these two responses, the reasons for which are not self-evident as both measurements are carried out with the same sound pressure at the entrance to the probe tube, are then discussed. The following notes deal with automatic estimation of these probe microphone responses, making use of Artificial Ear 4109 (see fig. 2) for the pressure response and a damped duct with a "100 %" absorptive terminal unit for the free field response. From these responses the attenuation characteristic of the probe follows directly.

The two calibrations were carried out with a probe of 11.8 cm length, 1.9 mm outer diameter and 1.3 mm inner diameter, placed over a Condenser Microphone 4111 equipped with an F-type cartridge. The frequency response characteristics of this probe microphone, i.e., the electrical output, as a function of frequency of the probe and microphone in a free field, or cavity with constant sound pressure level, found as the ultimate result of these two tests, are given in fig. 8. For measurements at frequencies below 8 kc only, it is an advantage to fit the Cathode Follower 4111 with a T-type cartridge instead, in which case the characteristics of fig. 8 will be lifted up by from 0—10 db for frequencies higher than 1500 c/s. To explain this, it will be remembered that normally our Condenser Microphone is fitted with an F-type cartridge, of which the pressure response, i.e., the microphone output as a function of frequency when a constant sound pressure is applied to the membrane, is given in fig. 3 curve a. The response of the microphone mounted in a free sound field with the sound waves impinging normally on the diaphragm will be higher for frequencies higher than 1500 c/s on account of diffraction phenomena, and is shown in the same figure, curve b. The third curve c is the response of the cathode follower on which this particular cartridge was calibrated. This response is rectilinear from 20—20,000 c/s and does not vary for the individual cathode followers as the different condenser

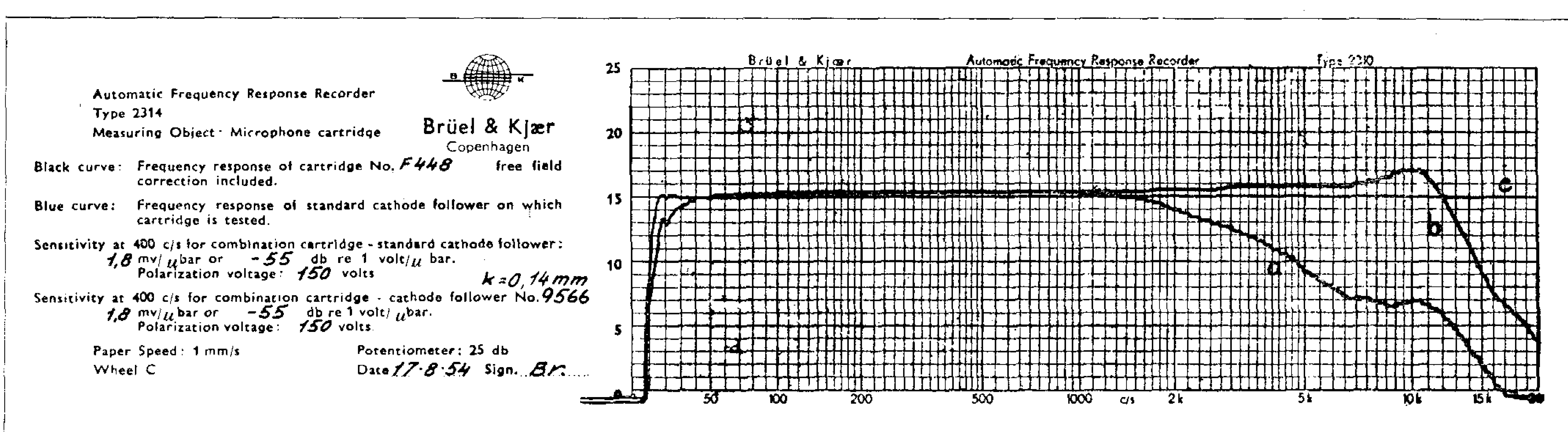

Fig. 3. Response of an F-type condenser microphone cartridge.
curve a: pressure response.
curve b: free-field response.
curve c: response of cathode follower.

microphone cartridges inevitably do, but only within the specified limits of ± 2 db in the frequency range from 80 c/s to 10 kc/s.

The T-type microphone cartridge is used in the Artificial Ear type 4109 and the Artificial Voice type 4210. For both instruments the response of the cartridge employed should be rectilinear for pressure conditions. For example in type 4109 for measuring a hearing aid receiver's output generated in a closed cavity, or in type 4210 to secure a constant sound pressure in front of the Artificial Voice, where the electrical output of the cartridge inserted in the aperture of the mouth as a control unit is held constant via an automatic volume regulator. Thus, the response of the T-type cartridge, when calibrated under constant pressure conditions, is linear from 30 c/s to 7—10 kc/s, as shown in fig. 4, curve a.

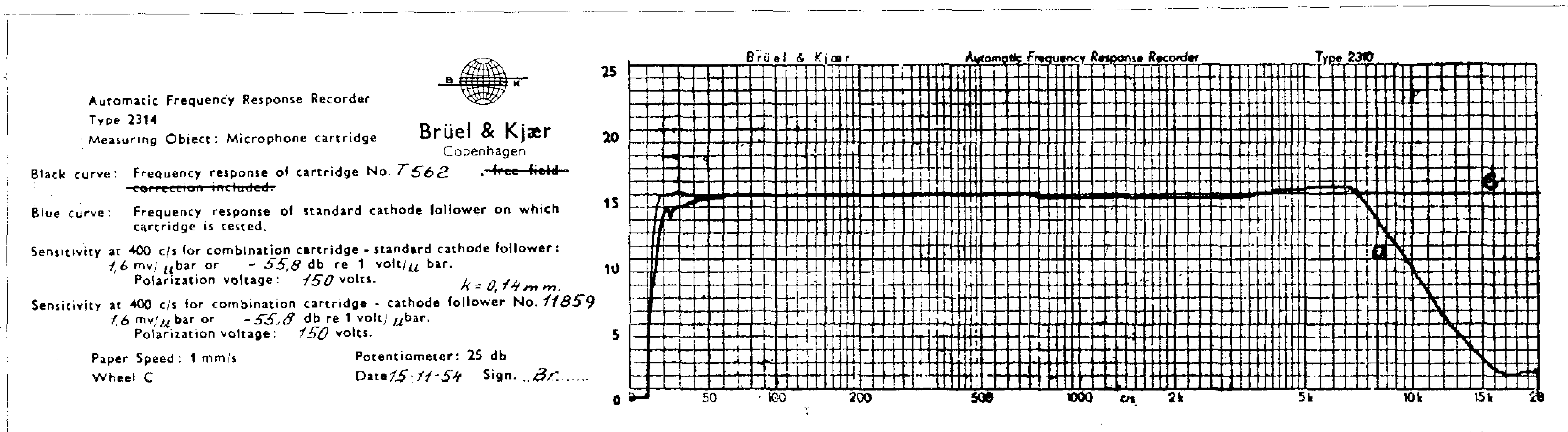

Fig. 4. Response of a T-type condenser microphone cartridge.
curve a: pressure response.
curve c: response of cathode follower.

With probes attached to Condenser Microphone 4111 it is advisable, for measurements below 8 kc/s, to equip the instrument with a T-type cartridge, as we do not make any use of the artificially attained sensitivity decrease of the F-type cartridge above 1500 c/s, either for cavity or free-field measurements carried out with this type of microphone cartridge. In any case, the probe itself will attenuate to an increasing degree, the higher the frequency becomes. The attenuation constant of tubes of not too small dimensions, as well as for small capillary tubes, can be written in the form $\beta = C \frac{\sqrt{\omega}}{d}$ where C is a constant, ω = the angular frequency and d = tube diameter in cm.[1]) Even though this formula does not describe the probe's behaviour correctly in practice (among other things it does not take into account any resonances arising in the tube), the general trend for probes is an increased attenuation at those frequencies where the sensitivity of the F-type cartridge

1) See Beranek: Acoustical Measurements, p. 188, Wiley & Sons, New York.

also decreases. The calibration curves given in fig. 9 show the attenuation of the test probe only, i.e,. 20 log p_i/p_d where p_i is the sound pressure at the entrance of the probe, and p_d the sound pressure at the microphone diaphragm, the probe being thus acoustically loaded with the compliance of the air above the diaphragm and the compliance of the cartridge itself. When this probe is employed with a T-type or F-type cartridge, this attenuation

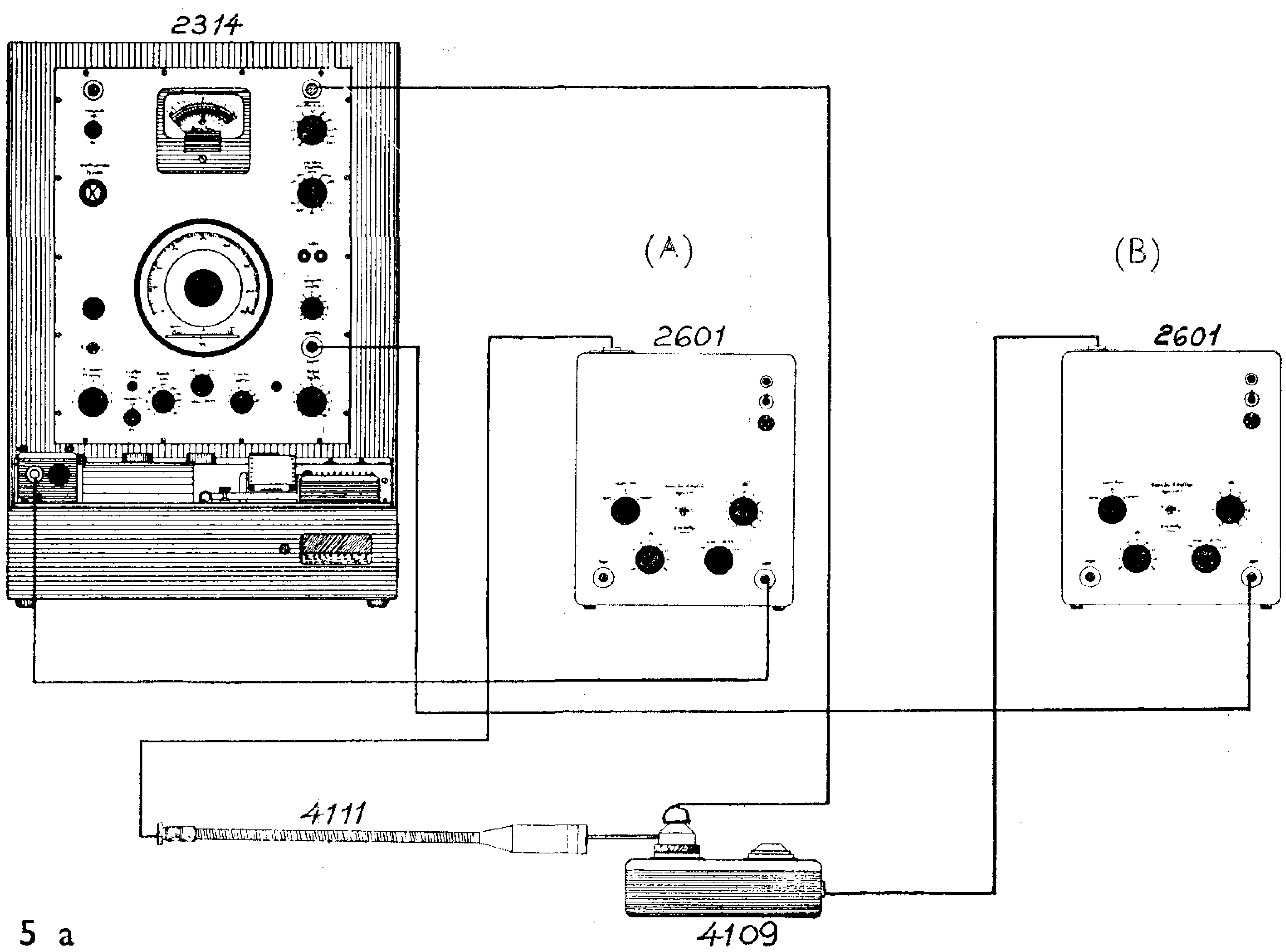

Fig. 5 a

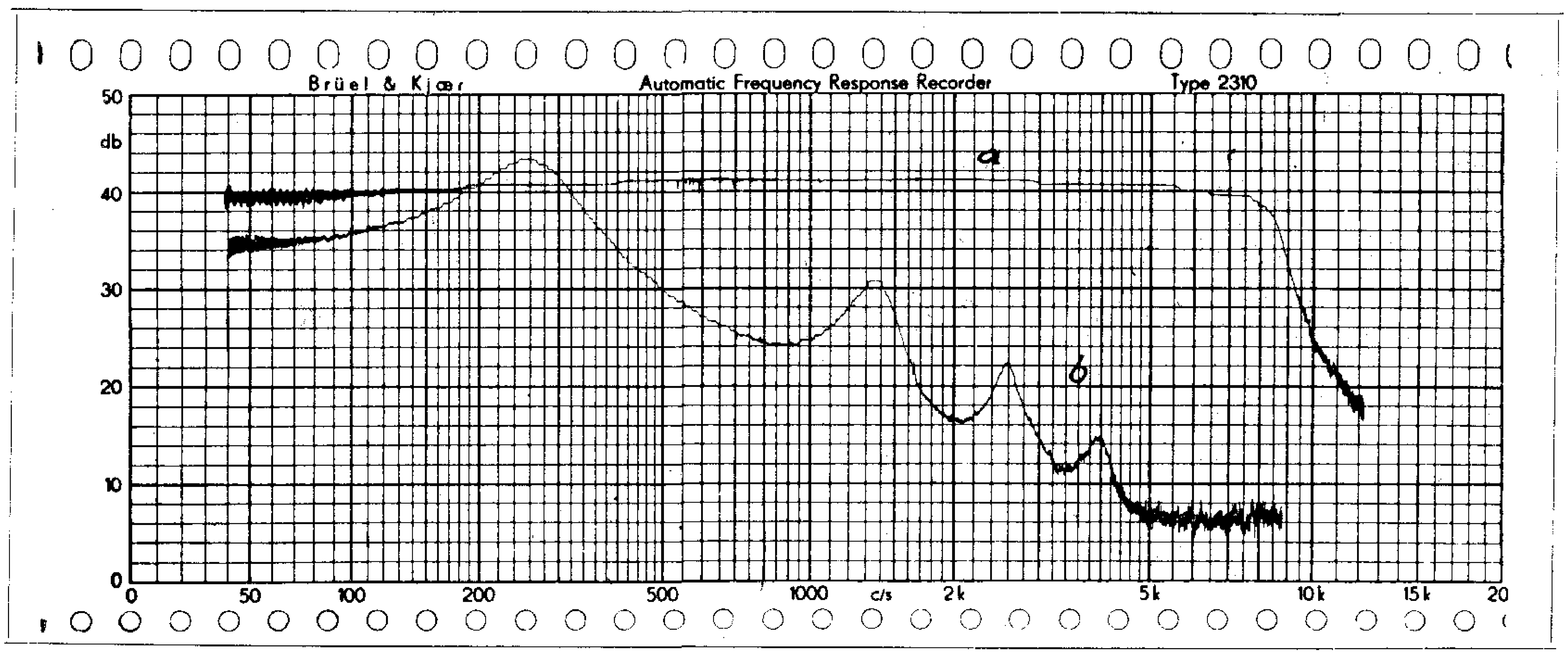

Fig. 5 b *Fig. 5. a: Pressure calibration of probe microphone.*

5 b: Result of pressure calibration.

curve a: compressor voltage.

curve b: probe-tube microphone response.

should be subtracted from the cartridge **pressure response** to yield the response of the combination of probe-microphone, in which we are interested (i.e., the probe-tube microphone sensitivity curves of fig. 8 may be obtained by subtracting the attenuation β of fig. 9 from the curve 3a). The advantage of using the T-type cartridge for measurements at frequencies up to 8 kc/s, is thus evident (i.e., subtracting β from curve 4a). Finally, it can be assumed that on interchanging cartridges the acoustical load does not vary, so that with the attenuation β for a certain probe being given, the sensitivity for a combination of this probe and an arbitrary microphone 4111 can be derived by means of the subtraction indicated.

Fig. 9 thus gives a permanent record of the probe attenuation to be used for all future combinations of probe and cartridge.

Pressure and Free-field Calibration.

The pressure calibration can be carried out as shown in fig. 5a, using the 2 cc coupler of the Artificial Ear 4109. A hearing aid earphone placed on top of the coupler is used as the sound source, fed from the BFO in the Automatic Frequency Response Recorder type 2314. A hole of diameter equal to the outer tube dimension is bored horizontally through the coupler at half the cavity height, and the probe inserted in the coupler wall so that the probe entrance is flush with the cavity. The sound pressure in the cavity is held constant during an automatic frequency traverse of the BFO via the T-cartridge and cathode follower of the Ear 4109, Microphone Amplifier 2601 and the compressor in the BFO. With the complete probe microphone mounted in the cavity a curve is registered of the compressor voltage. This curve (fig. 5b curve a) should be constant between 50 c/s and 5 kc/s to within $\pm$ 1 db. In the example, the compressor voltage is constant up to 7 kc/s, but this does not guarantee a constant sound pressure up to this frequency at the probe entrance, as above 5 kc/s the sound pressure is not constant throughout the whole cavity.

A curve is then recorded (fig 5b curve b) of the probe microphone response via a second Microphone Amplifier 2601, or an Analyzer type 2501. The relative position of the two curves on the recording paper does not matter, since the sound pressures are accurately measured at 400 c/s on each of the two channels, after the recording.

With a given sensitivity for the Artificial Voice of s_1 mV/μbar, the easiest procedure for finding the sensitivity of the probe-tube microphone and the attenuation of the probe itself is as follows: the BFO output is adjusted at 400 c/s until the output of Amplifier A with 60 db amplification is s_1 volt, read off from VT voltmeter 2407 on the output, *and with the output disconnected from the BFO compressor input*. The sound pressure in the cavity and at the probe entrance will now be 1 μbar. Let us suppose the sensitivity of the Condenser Microphone 4111 is s_2 mV/μbar without probe attachment.

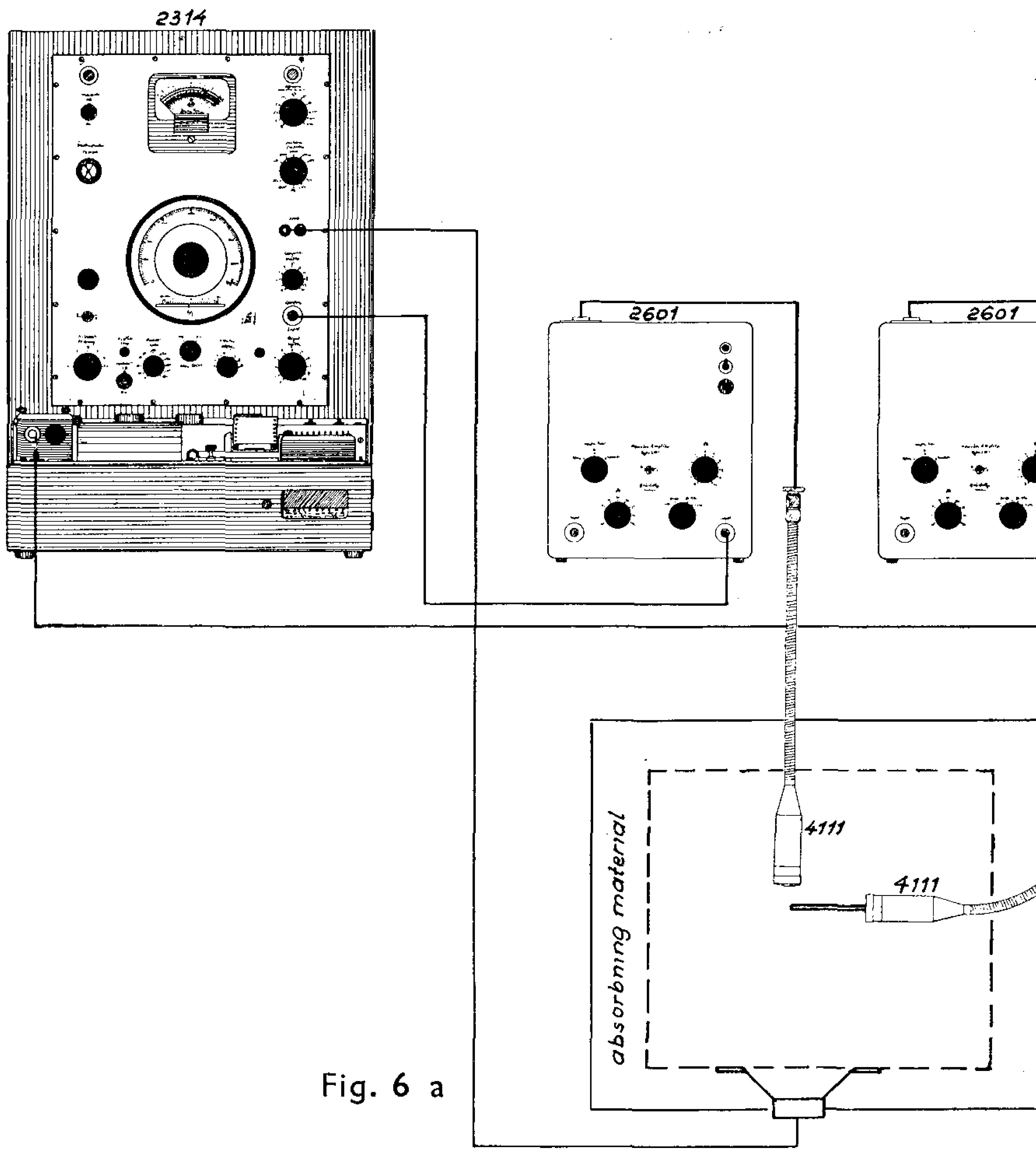

Fig. 6 a

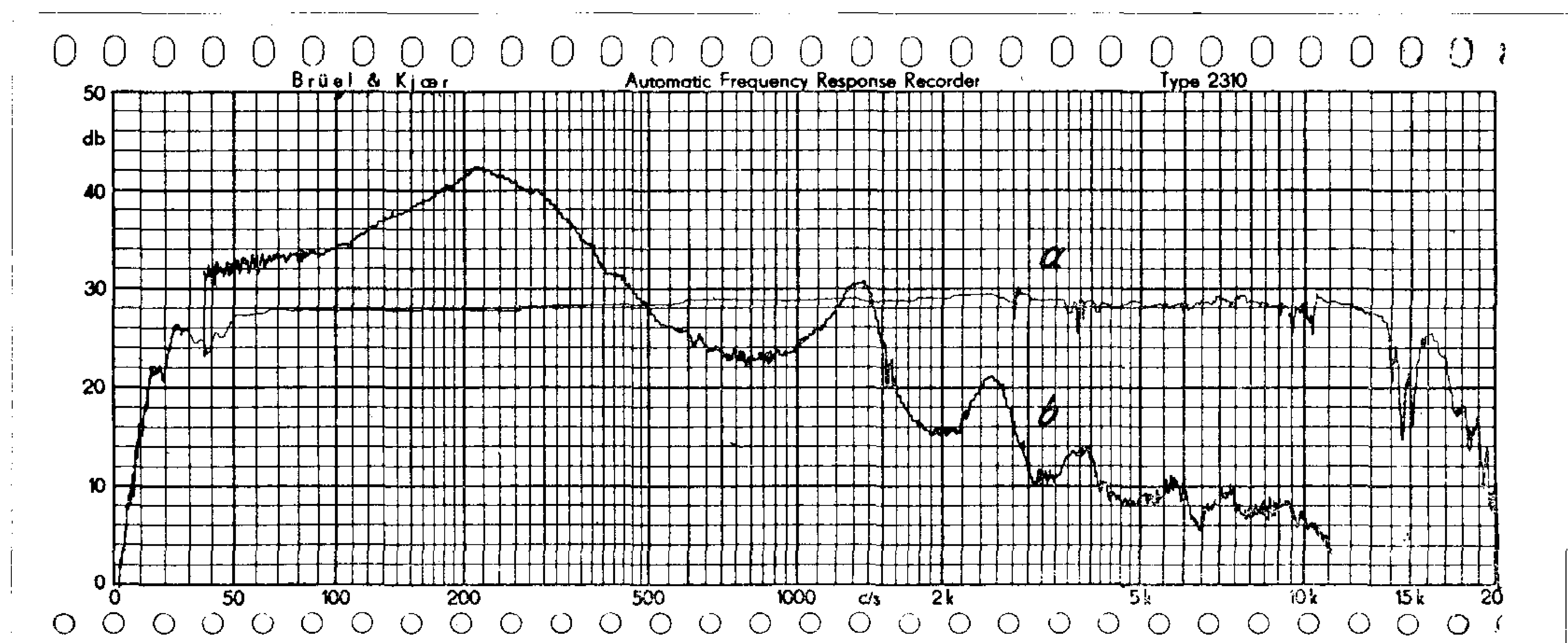

Fig. 6 b

Fig. 6 a. Free field calibration of probe microphone.
6 b: Result of freefield calibration.
curve a: compressor voltage.
curve b: probe-tube microphone response.

The gain of Amplifier B is now set to a value A db by means of the two attenuators of 10 db and 1 db steps, such that the output is s_2 volts. The attenuation of the probe alone at the frequency 400 c/s is consequently A—60 db. Once the attenuation is determined for one frequency, the total sensitivity characteristic for the microphone and the attenuation characteristic for the probe alone follows with the aid of the recorded difference between the compressor and probe response, plus the responses of the two condenser cartridges provided with the Artificial Ear and Microphone. In the event that the first response is perfectly linear in the frequency range under consideration, a variance in the recorded compressor voltage is identical with a variance in the sound pressure in the cavity, and the sensitivity curve follows simply as the difference between this sound pressure and the probe response curve moved in its totality up or down so that the attenuation at 400 c/s is A—60 db.

If the sensitivity of the Ear cartridge response for a certain frequency is a db above its sensitivity at 400 c/s, a db should be added to this sensitivity, as the sound pressure level in the cavity will be a db less for that frequency (compared with the level at 400 c/s, as the microphone output is the electrical parameter which is held constant by the automatic volume regulator in the BFO during the frequency traverse). The curve drawn in fig. 8 is obtained in this way from the two recording of fig. 5b. The ordinate — 55 db is the original sensitivity of the Condenser Microphone at 400 c/s. Lastly, the attenuation characteristic of the probe-tube alone is obtained as the difference between the sensitivity of the cartridge employed under pressure conditions (fig. 3, curve a), and the total sensitivity. In fig. 8 the pressure response of fig. 3a is redrawn, and in fig. 9 the probe-tube attenuation is given plotted downwards for the sake of comparison.

The free field calibration (see fig. 6) requires the same set-up, with an Automatic Frequency Response Recorder type 2314, 2 Amplifiers type 2601,

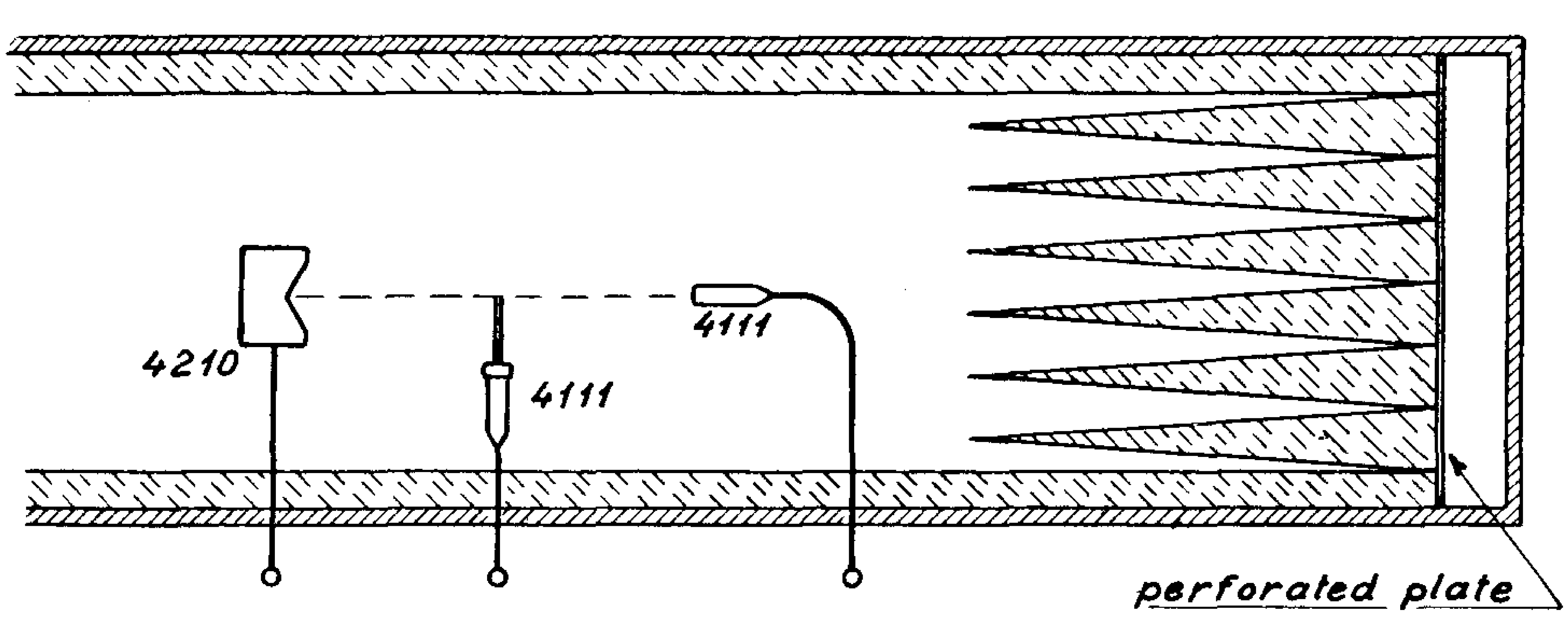

Fig. 7. Free field calibration in a lined duct terminated with "100 %" absorptive unit.

one controlling Condenser Microphone type 4111 equipped with the normal F-type microphone cartridge, and the probe-tube microphone to be tested (either with T- or F-type cartridge). The measurement can be carried out as shown in fig. 6, in a well-damped box, with thick acoustical lining, but even here the measuring results will be obscured by the persisting reflections from the walls. To fulfil more faithfully the condition that the microphone output is proportional to the sound pressure level at the point of measurement prior to the introduction of the controlling microphone in the sound

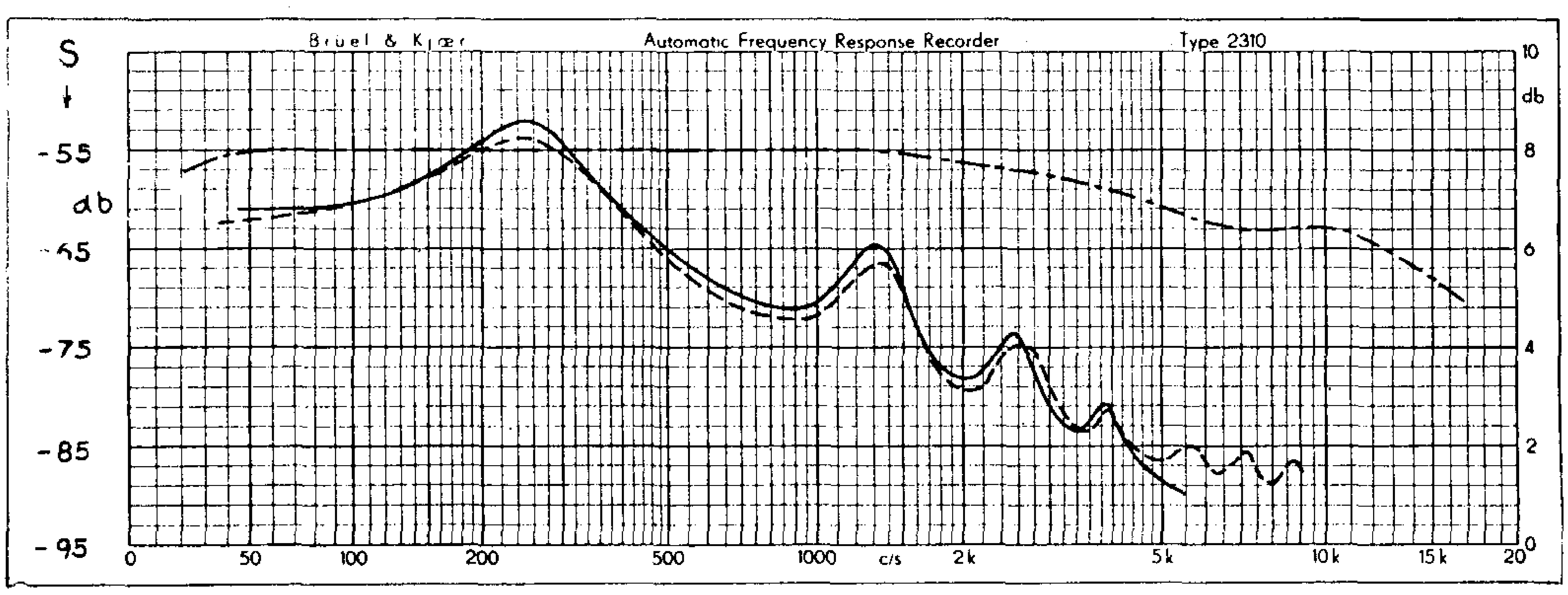

Fig. 8. Frequency response characteristics of probe-tube microphone. The ordinate — 55 db corresponds to the original sensitivity at 400 c/s of the Condenser Microphone 4111, equipped with cartridge F 448.
Continuous line: sensitivity for cavity measurements.
Dotted line: sensitivity for free field measurements.

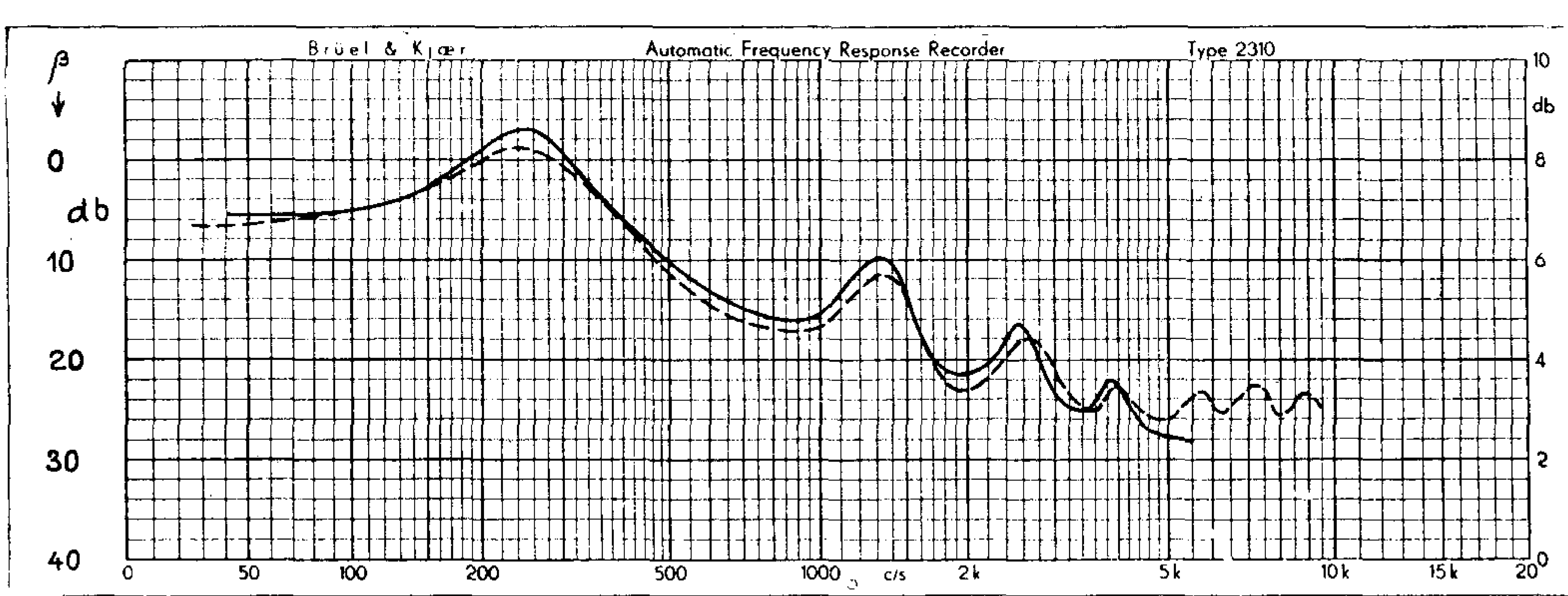

Fig. 9. The attenuation characteristics of the probe itself, under constant pressure and free field conditions, and acoustically loaded with the termination of the condenser microphone cartridge.
Continuous curve: attenuation for pressure conditions.
Dotted curve: attenuation for free field conditions.

field, the actual calibration was carried out in a lined duct terminated by a "100 %" absorptive unit consisting of a set of long wedges of rock wool placed before a perforated panel acting as a resonant absorber (see fig. 7). The controlling Condenser Microphone 4111 was placed in the centre of this duct in the plane, free sound wave generated by the loudspeaker of 4120. (This speaker was only used because it was well damped, in order that the BFO compressor should not have to cope with too sharp resonances from the sound source). The probe microphone was placed vertically with the probe entrance in the line of the loudspeaker and controlling microphone, and at such a distance in front of the latter instrument that in the frequency range under consideration the influence of the scattered wave at the probe entrance was negligible. (This distance can be calculated with the aid of diffraction formulæ or found by moving the probe microphone from the position of the controlling microphone towards the loudspeaker, in which case the variances even for frequencies up to 10 kc, should not exceed ± 0.5 db. With Microphone 4111 this requires about 10 cm distance). The compressor voltage, that is, the controlling microphone output, which is again held constant by means of the BFO compressor, thus secures a constant free field sound pressure at the probe entrance. This voltage is first recorded, and then the response of the probe tube microphone. See fig. 6b. The sensitivity and attenuation characteristics then follow in the same way as for the pressure responses, with the aid of the recorded curves a and b. A correction for the sound field is now made with the free field response of the control microphone, by adding the difference in sensitivity from that at 400 c/s to the probe microphone sensitivity. The dotted line in fig. 8 is the result. The difference between this curve and the pressure response of the microphone type employed (depending on whether it is equipped with an F-type or T-type cartridge) yields the "free field attenuation" of the probe alone (dotted line in fig. 9).

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