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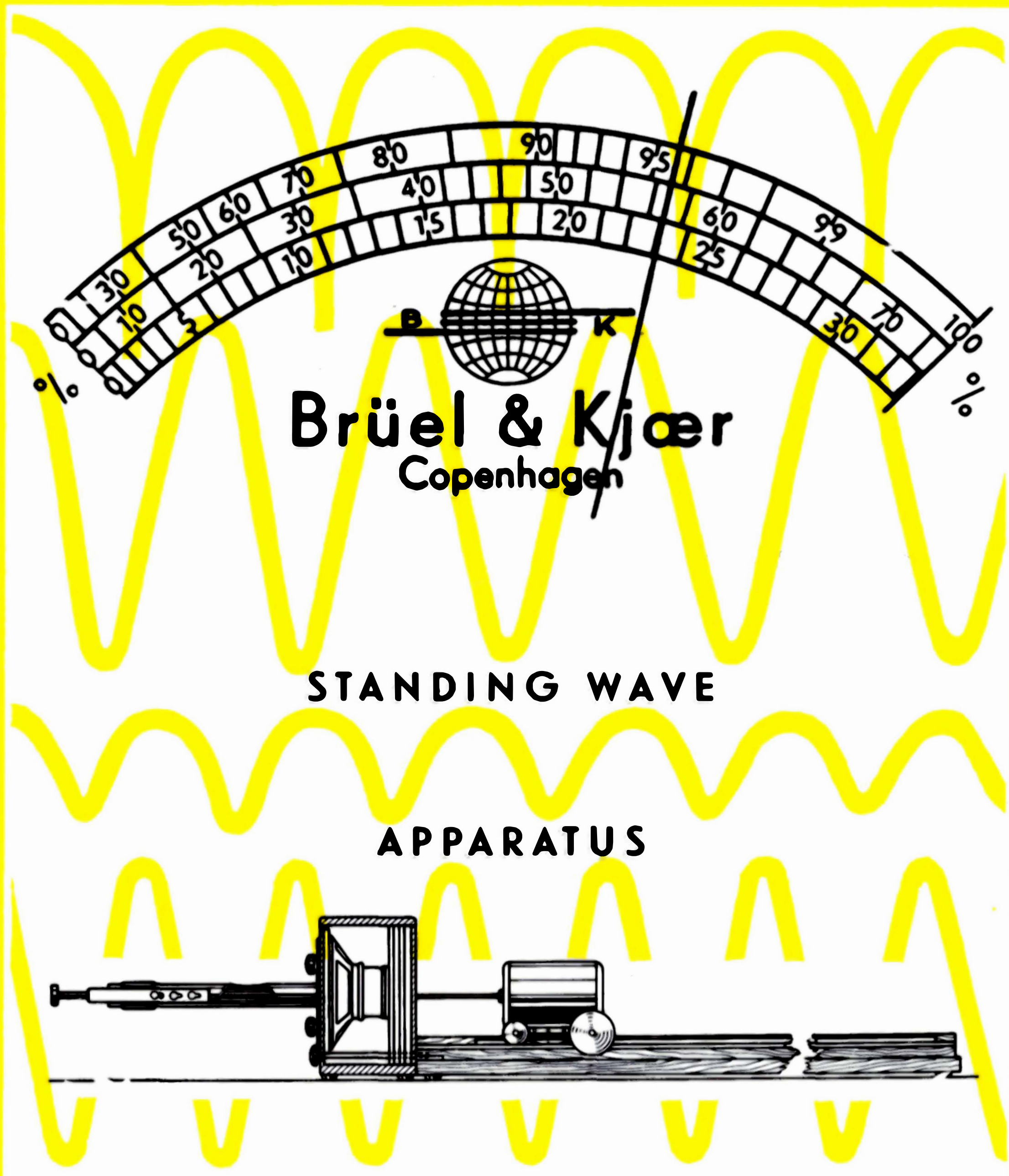

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The Standing Wave Apparatus

by

Per V. Brüel. D. Sc.

As early as 1902 Tuma*) gave a method for measuring acoustic absorption coefficients by means of standing waves in a tube. This standing wave method has been considerably developed in the course of time, and has contributed greatly to the development of effective acoustic absorbents, which are the most effective weapon at the command of modern building technique in its fight against noise.

In Fig. 1 a sketch of the principles of the apparatus is shown. Sound of pressure amplitude A is directed down the length of the tube by means of a loudspeaker at one end, to strike the sample placed at the other end. When the sound waves encounter the sample, part of the sound energy is absorbed and another part reflected back through the tube at an amplitude B. As a result of interference with the incident wave a partly stationary wave is formed in the tube, which can be measured by means of the microphone probe mounted in the small moveable microphone car. In Fig. 2 it is shown how the sound pressure develops as a function of position, both for complete reflection, that is to say, an absorption coefficient $\alpha = 0$, and for a partly absorbing sample. The maximum sound pressures (A+B) lie at distances of one-half wavelength from each other, and in between these maxima lie the minimum points with amplitudes equal to (A—B). At such maxima and minima the incident sound wave is in phase or anti-phase with the wave reflected from the sample.

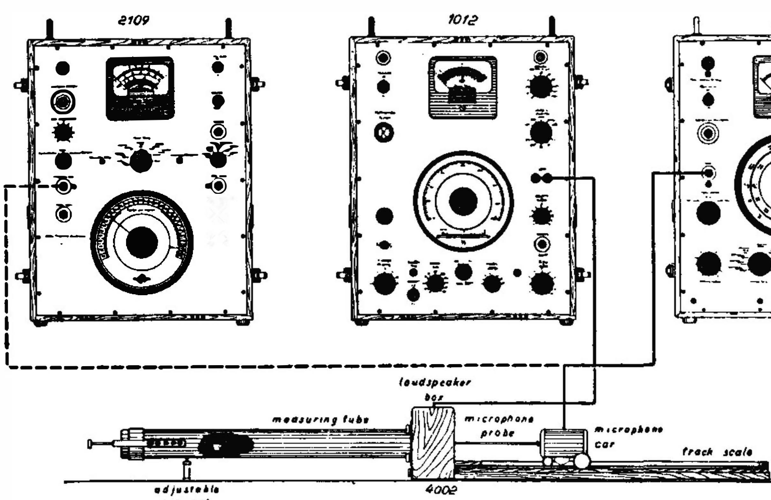

Fig. 1. Principle of the Standing Wave Apparatus for measuring acoustic absorption coefficients. The audio frequency generator used is the Brüel & Kjær B. F. O. type 1012, while as selective amplifier either Analyzer 2105 (adjustable to any frequency between 47 and 12,000 c/s) or Analyzer 2109 (for measurements at the standardized frequencies according to table 1) may be used.

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*) Tuma: Sitz. der Kais. Akad. der Wissenschaften, III 2 A, p. 402 (1902).

The measuring apparatus measures the relation n between the sound pressure maxima and minima in the tube

$$n = \frac{(A+B)}{(A-B)} = \frac{p_{max}}{p_{min}} \cdot$$

The absorption coefficient of the sample is defined as the ratio between the energy absorbed by the sample and the total energy striking the sample. As the energy is proportional to the square of the sound pressure, we have

$$a = 1 - \frac{B^2}{A^2} = 1 - \left(\frac{n-1}{n+1}\right)^2 = \frac{4}{n + \frac{1}{n} + 2}$$

It is thus particularly easy to find the absorption coefficient, provided one knows the ratio between the maximum and minimum sound pressures. By means of a suitable construction of the electronic amplifying equipment the absorption coefficient can be read directly as a percentage on the instrument scale.

When a sample of an acoustic absorbing material is investigated in a standing wave apparatus, the question arises as to what kind of absorption coefficient one is measuring. It is well known from the acoustic literature that different laboratories often measure widely different absorption coefficients for the same material, with the result that many manufacturers and users of acoustic material have a certain mistrust for acoustic absorption measurements. The usual method for measuring the acoustic absorption of a material is the room method, where the material is placed in an acoustically "hard" room. The reverberation time of the room is measured both before and after the material is placed in it, whereafter, by using the well known Sabine formula, one can calculate the absorption coefficient of the material by dividing the total absorption found, by the area of the test material: It must be pointed out that what is really being measured in this room method is the given material's **acoustic behaviour in the given room.** One can both theoretically and practically demonstrate that even with the very same test material the acoustic effect is different in different rooms, and again, in these rooms, is dependent on the placing of the material on the wall or ceiling. Furthermore, the acoustic effect (calculated as an absorption coefficient) is dependent on the superficial area of the test material in the room.

Thus, with the room method, it is in a way useless to speak of a definite absorption coefficient when, at the same time, one has not precisely specified the room's size and shape, and the material's superficial area and method of siting. The absorption coefficients measured by the room method are thus not only dependent on the physical constants of the absorption material, such as the mechanical construction, thickness, density, porosity, elasticity, homogeneity, etc., but also to a high degree influenced by the conditions under which the material is measured. This state of affairs is easily understood, when one considers that the absorption coefficients measured by the room method are not based directly on the definition of the absorption coefficient as the ratio between the energy absorbed by the sample and the total energy

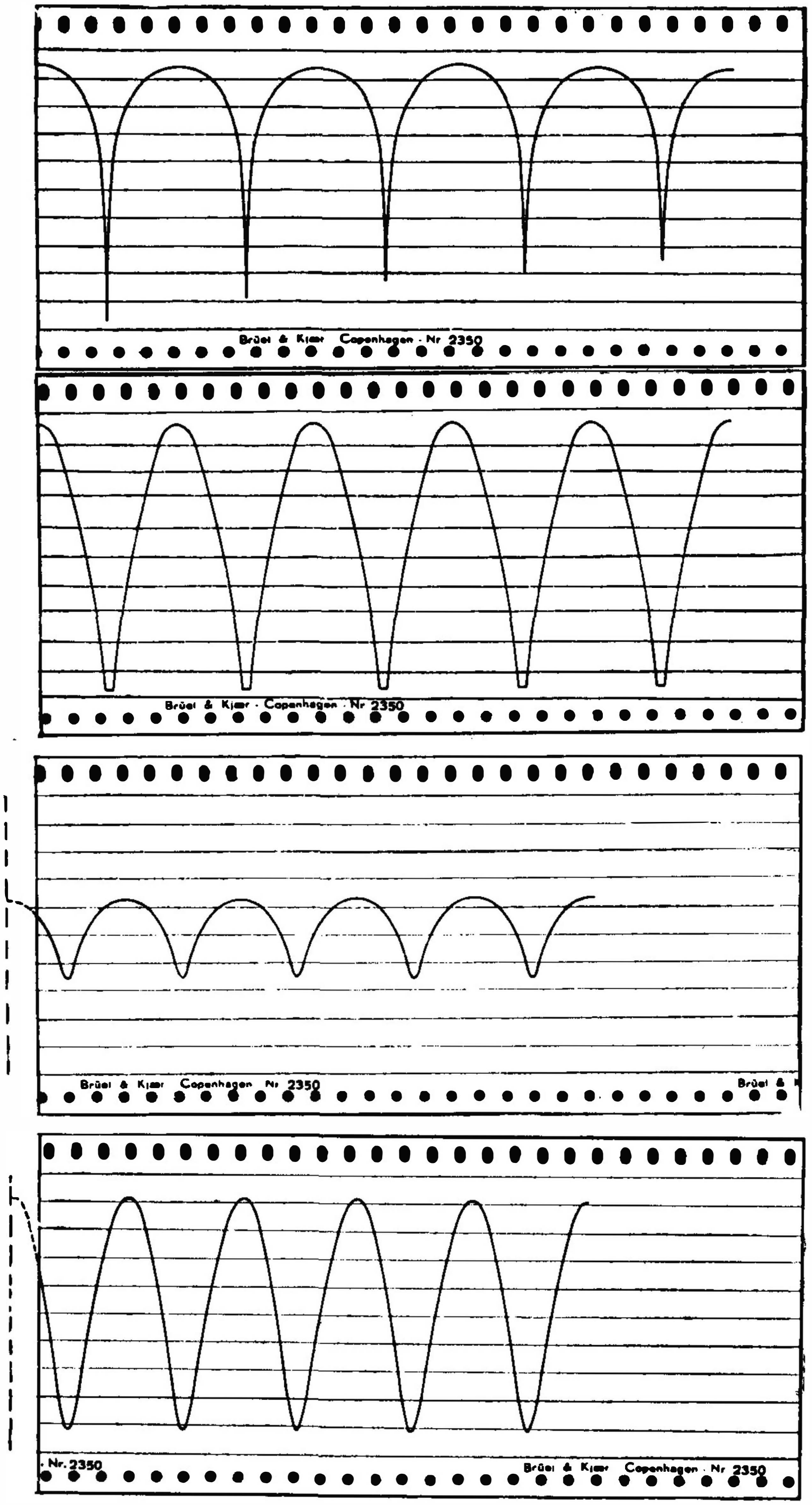


Fig. 2. Sound pressure as a function of the position of the microphone car, for different terminations. Test frequency 1000 c/s.

a) Hard termination. The sound pressure is depicted logarithmically. The difference between the 1st maximum and the 1st minimum is greater than 50 db, which corresponds to a zero absorption of the tube less than 1.3%

b) As a), with linear pressure scale.

c) With absorbent termination, logarithmic scale.

d) As c), with linear scale.

striking it, but only indirectly, in that, by means of Sabine's statistical reverberation formula (which postulates a series of conditions which no practical room can satisfy) a reverberation coefficient is *calculated*.

The matter is quite different when it comes to the Standing Wave Apparatus method. Here, the absorption coefficient is *measured* directly on the basis of its definition, so that it is only dependent on the physical constants of the material. This fact is again demonstrated if one sends different samples to different laboratories with the request that they be measured in a Standing Wave Apparatus. Provided the samples are uniform, and set up in the same way in the apparatus, the results obtained will be the same. The Standing Wave Apparatus is therefore eminently suited for the development of new absorption materials and for continuous production control.

In recent years, with various room acoustic problems, such as the investigation of troublesome flutter echoes and similar phenomena which can arise in radio studios, auditoria and so on, the sound waves in the room have been calculated by solving the so-called wave equation, in which, as a boundary condition for the room's limiting surfaces, the specific acoustic impedance of the wall coverings has been inserted. This is defined as the complex ratio between the sound pressure and particle velocity at the material's surface. The complex form of the impedance arises because there is a phase difference between the pressure and the particle velocity of the air at the surface. As a rule the impedance is expressed as a complex number $Z = R + jX = |Z| \angle \phi$ The unit is the *Rayl*, which in the CGS system is g $cm^{-2}s^{-1}$, and in the MKS system is kg $m^{-2}s^{-1}$. It is possible to measure this complex impedance of an absorption material by means of the Standing Wave Apparatus, as will be described later.

Manufacturers and users of absorption material very often have use for a method of working out an absorbent which has a special absorption curve as function of frequency. If, for example, the frequency spectrum of the noise in a factory has been measured and found to be particularly accentuated for certain frequency bands, it would be natural to try to produce an absorbent for placing on walls and roof whose most powerful absorption lay just in the frequency bands in question, whereby the most effective and economic damping would be obtained. Very often, changes in the acoustic material, such as changing the air spacing between material and supporting wall, changing the degree of perforation, changing the thickness of the plate and so on, can shift the absorption maximum within very wide limits. The Standing Wave Apparatus is indispensable for the working out and checking of such investigations.

However, the Standing Wave Apparatus has also very great limitations. Thus, it is only possible to take measurements on very small samples, as it is a condition for the mode of operation of the apparatus that the diameter D be less than about half the length λ of the sound. Theoretically one can deduce that the condition $\lambda > 1.7$ D must be satisfied in order that plane sound waves exist in the tube. It is thus not possible to take measurements in the Standing Wave Apparatus on absorbents whose absorptive effect is based on the vibration of large surfaces as a whole. Similarly, the conditions under which the samples are set up can often cause difficulty, as it is easy when inserting the samples in the tube to produce stresses in the different layers of the material, and thus either change the resonance or even produce resonances which do not appear in larger surface areas. These limitations are of a fundamental nature, and in using the Standing Wave Apparatus one must bear them in mind at all times, as otherwise one is liable to obtain quite meaningless results.

What demands may one make of a practical Standing Wave Apparatus? The greatest possible frequency range is of course desired, but one is limited as far as the lower frequency limit is concerned by reason that the apparatus shall be a little more than a quarter wavelength long. That is to say, that if the apparatus shall be held within a reasonable length, one can hardly measure under 90—100 c/s. Upwards, one is limited by the necessity that the diameter of the tube shall be less than 0.586 λ, in that there is a possibility for a first transverse resonance at this wavelength. As the tube method presupposes a flat sound field in the measuring tube's cross section, transverse resonances can naturally not be allowed, as these would give rise to a varying sound pressure in the tube's transverse direction. To extend the frequency range, the apparatus in its later form has two measuring tubes, one for the lower frequency range of 95—1600 c/s, and one for the higher frequency range from 800—6500 c/s. Measurements above approx. 5,000 c/s have no significance whatever for the absorbents used in practice, as at these higher frequencies most materials have a more than sufficient absorptive capacity. To make do with a tube length of a little more than 1/4 wavelength, it is a condition that the sound field be symmetrical throughout the whole length of the tube, i.e., that the sound source be placed quite symmetrically at one end of the tube. If this is not the case, it is necessary to extend the tube by at least a half wavelength, so as to give a sufficiently uniform transverse distribution of the sound pressure in that part of the tube in which the measurement is taking place. Another condition is that the measuring tube be sufficiently stiff that no appreciable, spurious damping effects diminish the generated sound waves reflecting end-to-end within it. In practice then, the measuring tube must be circular in cross-section, not square as is so often seen, as it is exceptionally difficult to fabricate a square section sufficiently stiff that no significant deflection/damping effects occur. With the tube terminated by means of a solid, wholly reflective end piece it should be possible to obtain a high ratio between the maximum and minimum sound pressures, a sign that no damping occurs in either the tube's walls or the end piece.

As both the 4002's loudspeaker and the audio oscillator often used to drive it exhibit a quite weak second harmonic, one whose maxima lays exactly over the minima of the fundamental of interest, it is recommended in practice to use a frequency selective amplifier to measure the maximum/minimum ratio.

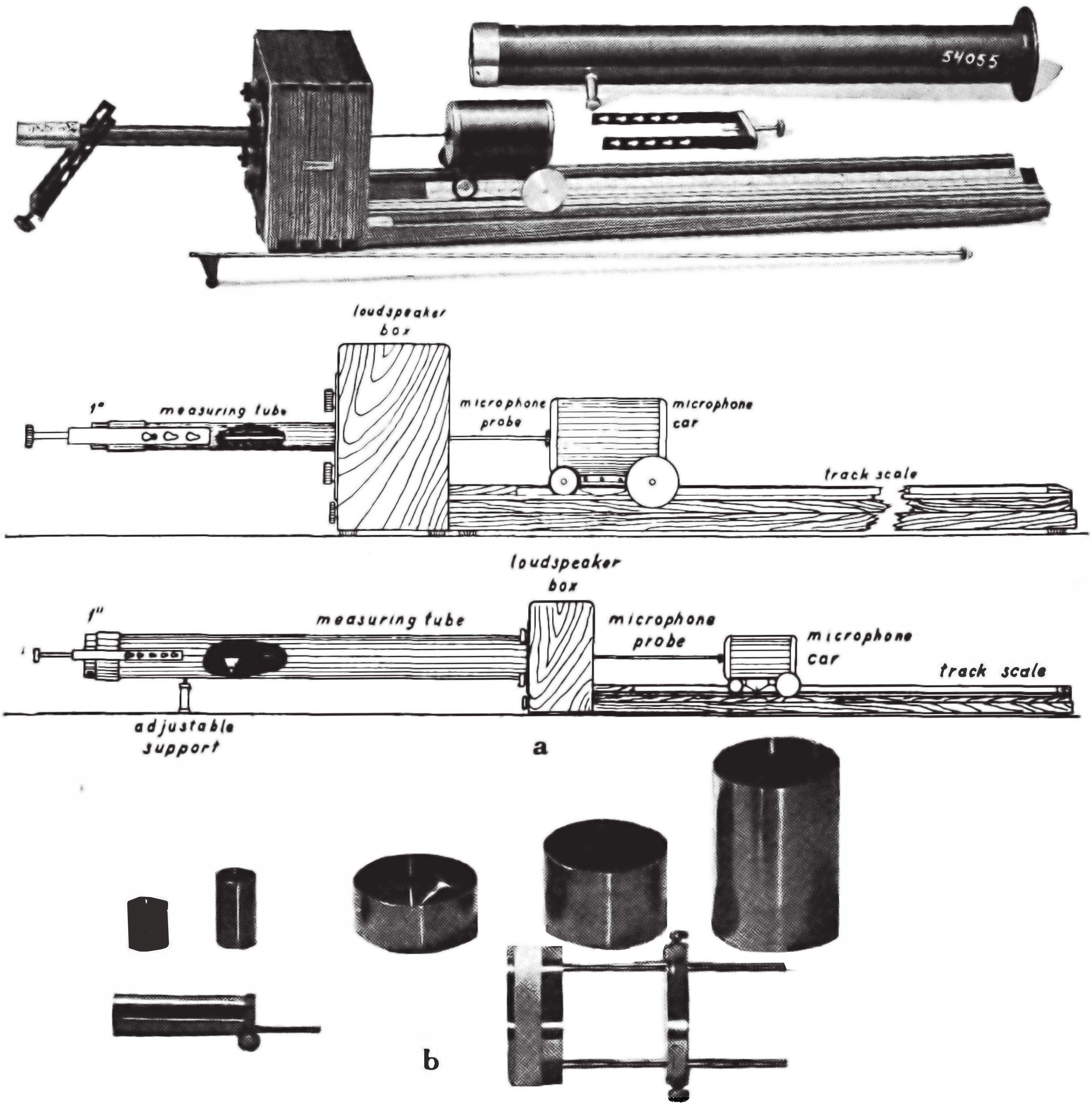
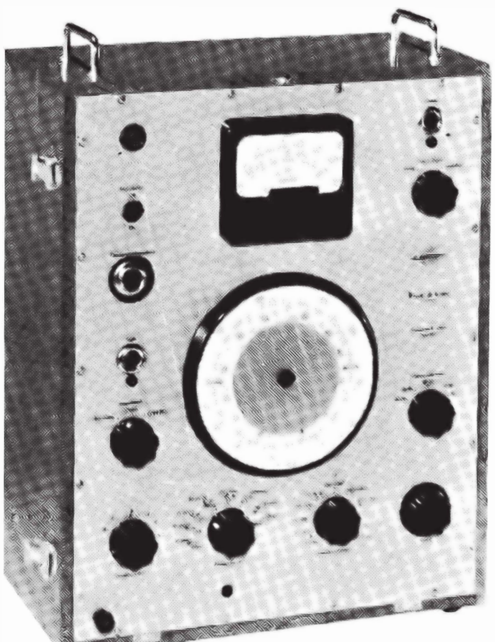


Fig. 3. a) Photograph and drawings of the Standing Wave Apparatus type 4002. b) Photograph of the six different sample holders belonging to the apparatus.

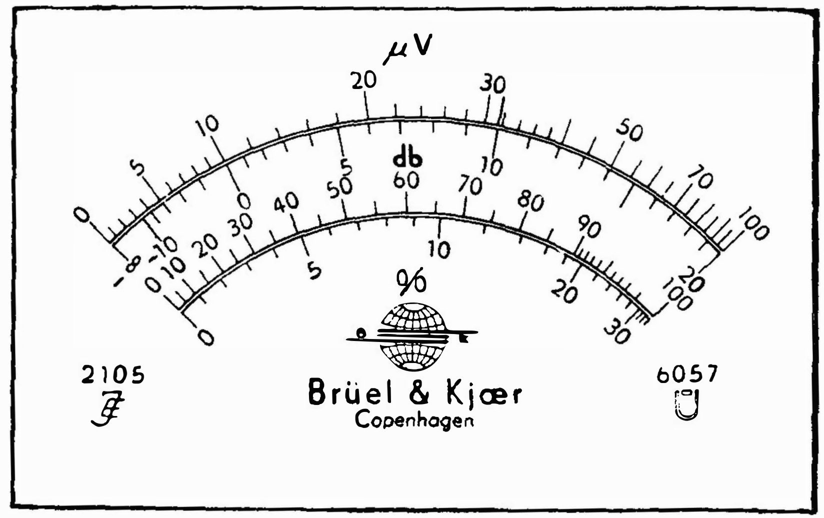
For the apparatus to be practicable in use it is important that test samples can be set up in a simple manner and that, whilst also terminating the tube, the holders containing them fit the tube in an airtight manner.

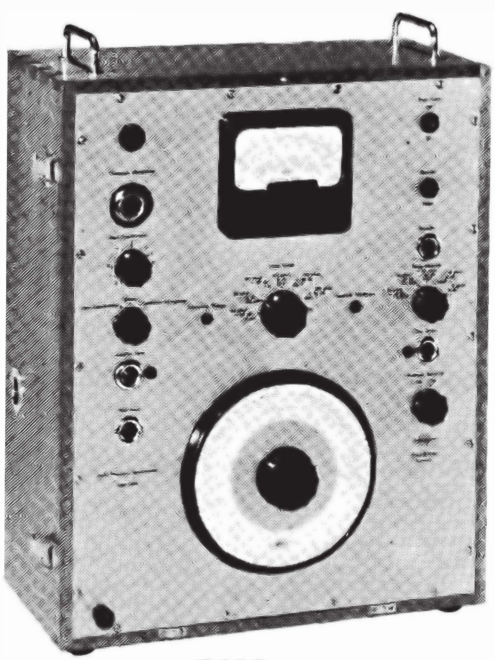
Description of the Standing Wave Apparatus type 4002.

Fig. 3 shows a photograph and drawings of the commercial form of the Standing Wave Apparatus; consisting of two measuring tubes with diameters of 3 and 10 cm and covering frequency ranges of 800 to 6,500 c/s and 95 to 1,600 c/s respectively. These tubes can be fastened to the loudspeaker enclosure such that they are coaxial with the loudspeaker, ensuring thereby the generated sound field within the tube is plane from the source. A microphone probe tube is inserted through a hole in the center-pole piece of the loudspeaker, with the microphone itself being mechanically well isolated within a moveable measuring carriage, running on rails. The position of the probe can be read off on a scale, parallel to the rails. The probe itself, which protrudes from the measuring carriage into the measuring tube, is a thin brass tube, running down the centre of the measuring tube and going through the loudspeaker's centre pole. There are two measuring probes, one for the small tube for the high frequencies and one for the large tube. There are three sample holders to each measuring tube. One has a depth of 25 mm (1"), the next has a depth of 50 mm (2"), and



2105





2109

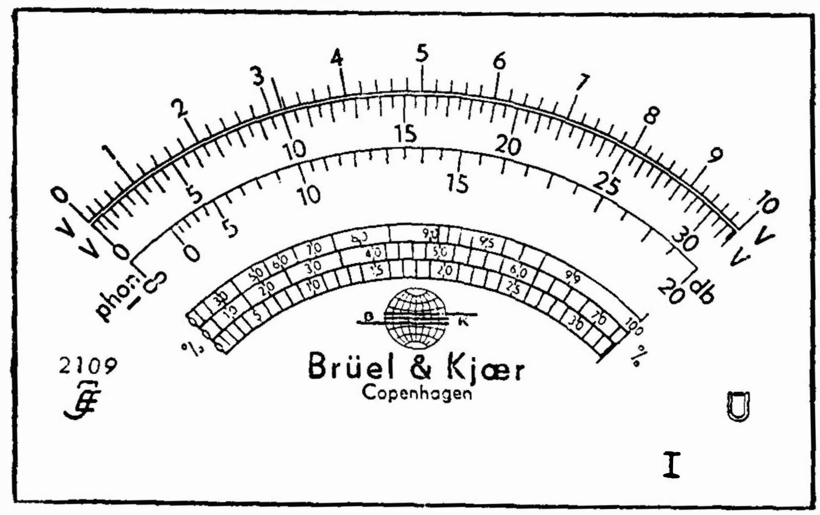


Fig. 4. Frequency Analyzer type 2105 and Audio Frequency Spectrometer type 2109, both suitable as amplifiers for the Standing Wave Apparatus type 4002. The meter scales of these instruments, showing the special calibration for reading absorption coefficients direct in %, are shown enlarged.

the third consists of a 15 cm tube with a sliding piston with airtight packing One can thus obtain any desired depth in the sample holders from 0—10 cm. The Standing Wave Apparatus type 4002 is intended for operation from an Audio Frequency Oscillator, for example the Beat Frequency Oscillator type 1012, and as measuring amplifier either the Frequency Analyzer type 2105 or Audio Frequency Spectrometer type 2109 should be used. Fig. 4 shows both these analyzers, with their meter scales. At the bottom of these scales the calibration, which allows the direct reading of absorption coefficients in percent, can be seen.

The procedure is as follows: The microphone measuring carriage is placed on a maximum as close to the sample as possible, which as far as the lowest frequencies are concerned is that maximum which lies in the immediate vicinity of the sample. For frequencies above 200 c/s that maximum which lies approx. 1/2 wavelength from the sample should be used. The analyzer is now adjusted in its selective position to the frequency of the BFO, and the BFO's output level and/or the analyzer's gain adjusted so that a full, 100%, deflection is obtained on the analyzer's meter. The microphone carriage is then moved to a minimum-reading position and the absorbption coefficient read directly off the analyzer meter scale. If the absorbtion coefficient is so small that this reading is not accurate enough

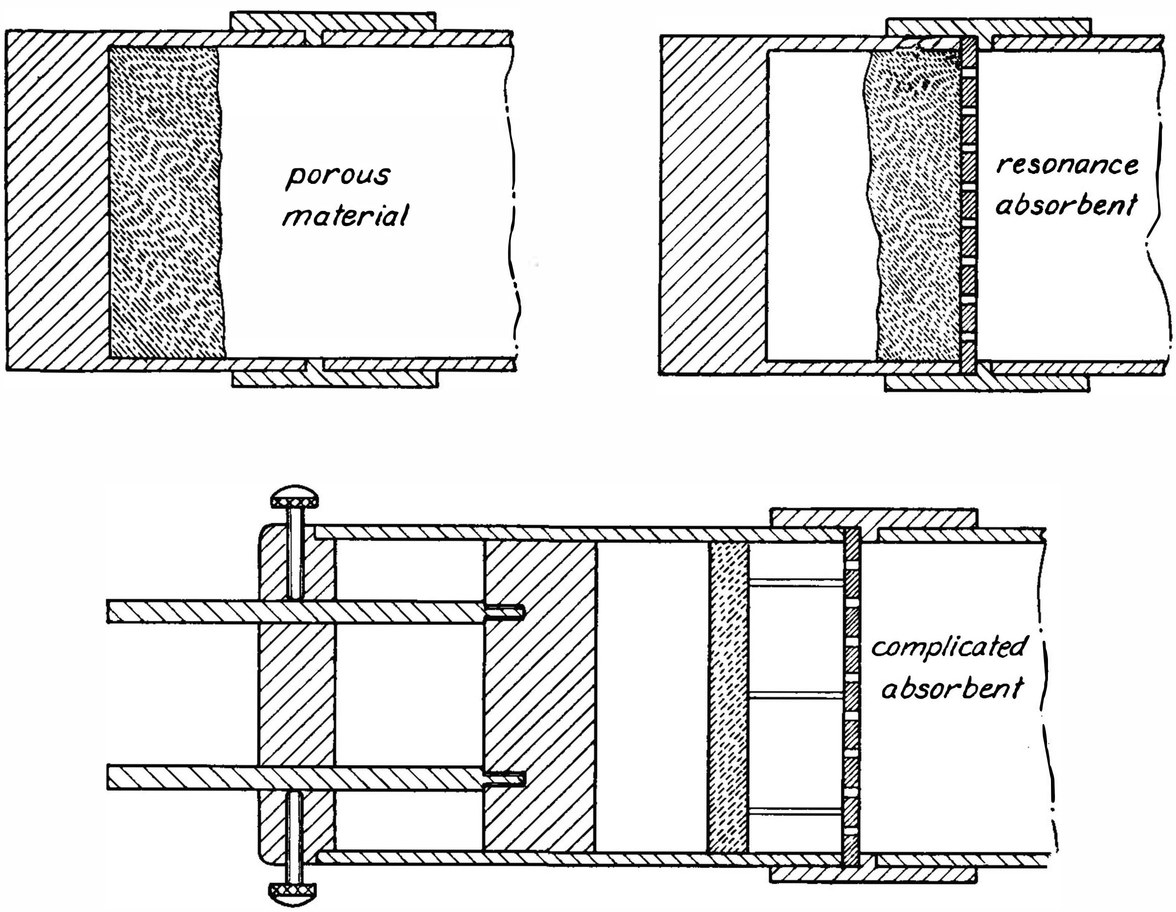
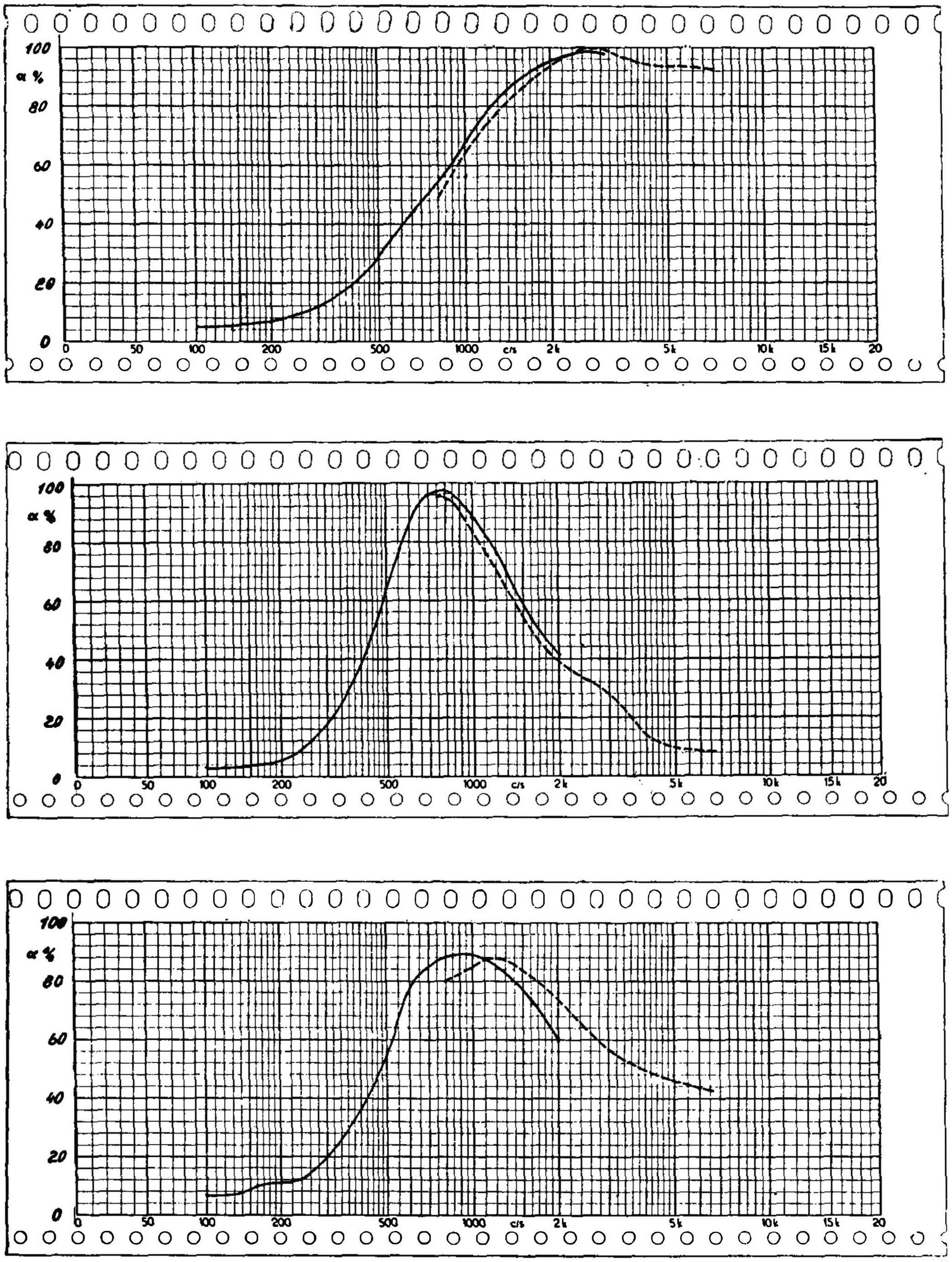


Fig. 5. Insertion of the samples in the apparatus. On the left, the insertion of a porous absorbent in the holder. On the right, the insertion of a resonance absorbent with perforated front plate, and below, a complex absorbent inserted in the variable holder.



a b c

Fig. 6. Absorption curves of three typical absorbents: **a)** *a porous material,* **b)** *a membrane absorbent and* **c)** *a resonance absorbent with damping material.*

the amplification can be increased by 20 db (x10) to achieve a sure reading of the minimum. The lowest absorption scale on the meter should then be used which ranges from 0—30 %. With type 2109 it is possible to increase the amplification $\sqrt{10}$ times, i. e., +10dB, and in that case the middle absorption scale on 2109 should be used, ranging from 0—70 %.

Fig. 5 shows some typical set-ups of absorption material in the material holders. Porous materials such as rockwool, glass wool, wood fibre board, acoustic plaster and such like are placed in the base of the material holders, provided the materials are to be used normally set up directly in contact with a hard back wall. The holder with the porous material is placed in the Standing Wave Apparatus, taking great care that the edge of the container is quite clean, so that there is complete tightness between container and measuring tube. If the degree of airtightness is insufficient, possibly because the container edge is damaged, it should be made tight by means of a little vaseline. Leakages will give rise to measurements of too high absorption at the lowest frequencies.

An acoustic absorbent is often constructed of a perforated hard plate set up on wood laths, usually 1" or 2" thick, so that there is a space between the perforated hard front plate and the back wall. The space in between can then be partly filled with a porous material to increase the resistance part R of the impedance Z of the total construction. Such an absorbent is easiest inserted in the apparatus by cutting the hard plate to a diameter just equal to the holder's outer diameter. By using respectively the 1" or 2" holder the same result will be obtained as if the hard, perforated plate had a spacing of respectively 1" and 2" from the back wall. If a damping matting is used, inserted behind the perforated plate, it should be cut to a diameter corresponding to the holder's internal diameter and carefully inserted into the holder.

With more complicated constructions, for example when there are several layers in sequence, the variable holder is usually used. To obtain the correct measurements, it is important that the different sections fit tightly to the edge, so that the air particles cannot be set in motion in the space between the material and the inner side of the holder. Thus, the samples should be prepared with precision, and set up in the Standing Wave Apparatus without strains arising in them, or any considerable degree of packing in the case of soft materials.

Another important detail with measurements of materials where the surface is perforated, is that the sample should have the same percentage of perforations as is the average for a large area. Particular care should be taken when cutting out samples for the small measuring tube, where the area is small.

One often finds absorption material which is packed in paper or plastic. and in this case it is very important when taking tube measurements that the paper be not only cut precisely, but also glued internally to the holder, in such a way that it is impossible for air to get past the edge. The acoustic resistance of paper is often very great, so that even a very slight leak at the edge of the paper will cause considerable changes in the conditions of absorption.

Fig. 6 shows three typical absorbents, with their absorption curves measured as function of frequency. The different absorbents are: 1) Porous materials, which have poor absorption at low frequencies, but high at higher frequencies. 2) Membrane absorbents, consisting of the same porous material, but covered with a thin plastic membrane. Here it is seen that the absorption is

Standard frequenciec	American 1/3 - octave bandnumber
100 c/s	20
125	21
160	22
200	23
250	24
315	25
400	26
500	27
630	28
800	29
1000	30
1250	31
1600	32
2000	33
2500	34
3150	35
4000	36
5000	37
63C0	38

40-series	20-series	10-series	5-series	Exact Value	Mantissa
1	1	1	1	10000	000
1.06				10593	025
1.12	1.12			11220	050
1.18				11885	075
1.25	1.25	1.25		12589	100
1.32				13335	125
1.4	1.4			14125	150
1.5				14962	175
1.6	1.6	1.6	1.6	15849	200
1.7				16788	225
1.8	1.8			17783	250
1.9				18836	275
2	2	2		19953	300
2.12				21135	325
2.24	2.24			22387	350
2.36				23714	375
2.5	2.5	2.5	2.5	25119	400
2.65				26607	425
2.8	2.8			28184	450
3				29854	475
3.15	3.15	3.15		31623	500
3.35				33497	525
3.55	3.55			35481	550
3.75				37584	575
4	4	4	4	39811	600
4.25				42170	625
4.5	4.5			44668	650
4.75				47315	675
5	5	5		50119	700
5.3				53088	725
5.6	5.6			56234	750
6				59566	775
6.3	6.3	6.3	6.3	63096	800
6.7				66834	825
7.1	7.1			70795	850
7.5				74989	875
8	8	8		79433	900
8.5				84140	925
9	9			89125	950
9.5				94406	975

Table 1. Standard frequencies which should be chosen when taking measurements in the apparatus. The frequencies are based on the R_{10} series of the international "Preferred Numbers". A complete table of these socalled "standardized Renard numbers" dividing a decade into 10 equal logarithmic steps is shown at the right.

higher at the lower frequencies and lower at the higher frequencies. Finally, we have 3) resonance absorbents, built up of a perforated plate, simply placed in front of the porous material. Here one notes a peak on the absorption curve, so that there is powerful absorption at a medium frequency range and lesser absorption at both lower and higher frequencies. By changing the size of the holes, air separation behind the hard plate, distance between holes and the thickness of the hard plate, it is possible, within wide limits, to alter the frequency characteristic entirely as one desires.

In Figs. 6a, b & c the results of the absorption measurements carried out on both the big and the small tube are given. The continuous curve is valid between 100 and 1800 c/s, the dotted curve between 800 and 6500 c/s. With the glass wool sample of Fig. 6 a and the glass wool covered with plastic of Fig. 6 b, the overlapping of the two domains is quite satisfactory. This is however far less the case with Fig. 6 c, due to the fact that in order to obtain the same percentage perforation for the panel used in both measurements, only 3 holes were allowed in the small measuring tube sample. With a hole diameter of 4 mm and a rectangular spacing of 13 mm it was impossible in this case to give each hole the same kind of back volume as the average hole had in the bigger sample. However, even in this extreme case both measurements give an idea of the absorption qualities of the given material in the complete frequency range from 100 to 6500 c/s.

When making tube measurements, the absorption coefficient or impedance should be determined at a series of different frequencies. For ordinary routine investigations of absorbents, it is recommended to take readings at frequency intervals of $^1/_3$ octave. It is most convenient to use the so-called preferred numbers, which are now standardized in most countries. In normal cases the R10 series can be used (see Table I), for more exact measurements the R20 series or the R40 series. When the analyzer 2109 is used as a selective amplifier, the R10 series in fact corresponds to the middle frequencies of the $^1/_3$ octave filters in that analyzer.

An absorbent whose acoustic impedance is real, i.e., where there is no phase difference between the pressure and the particle velocity at the surface of the absorbent, will have a pressure maximum exactly at the surface of the material, and a pressure minimum exactly a quarter wavelength away.

If the sample provides a complex impedance, of which one wishes to find both the real and imaginary parts, one must first measure the ratio $n = \frac{p_{max}}{p_{min}}$. One then measures the distance Δ by which the minimum has been displaced with respect to that position it would have had if the measuring tube has been terminated by a hard surface. The distance Δ can be found in two ways. 1) First, find the minimum position with the absorption material in the holder, then removing the holder with absorption material, replace it by an empty holder, reversed in position and find the new minimum position, taking into account the difference in position which can arise between the surface of the absorption material and the hard surface of the holder. The difference between the minima positions gives Δ . 2) By measuring $\lambda/2$ between two minima and then calculating Δ as the difference between

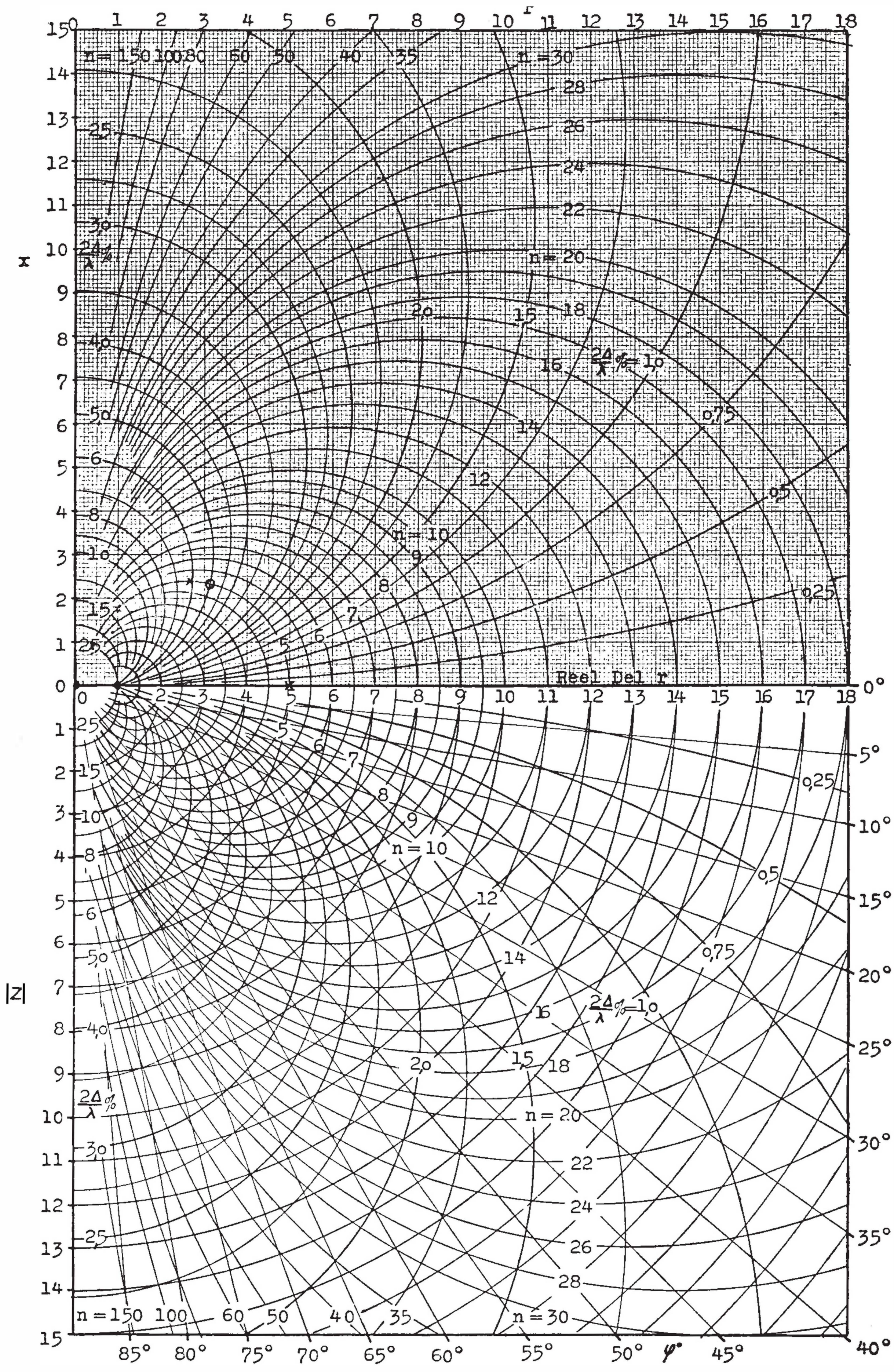
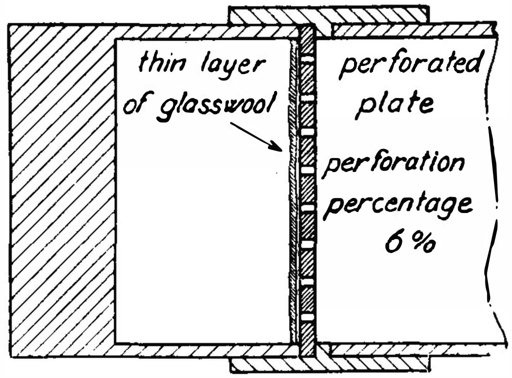


Fig. 7. Circle diagram for estimating the complex impedance Z = r + jx = /Z/φ from the measuring results n = max/pmin and 2Δ/λ 100% obtained in the Standing Wave Apparatus Type 4002.



v c/s	a %	n	Δ cm	$\lambda/2$ cm	$\frac{2\Delta}{\lambda}$ 100%	r	x	|z|	φ
100	$5^1/_2$	70	÷ 2,1	170,0	÷2,5	2,5	÷12,3	13,0	÷80°
125	4	100	÷ 4,9	136,8	÷ 3,6	0,7	÷8,9	9,0	÷85°
160	6	65	÷ 4,4	107,2	÷ 4,1	0,8	÷7,7	7,9	÷84°
200	8	48	÷ 5,0	86,8	÷ 5,8	0,4	÷5,6	5,7	÷84,5°
250	$10^1/_2$	36	÷ 6,0	68,7	÷ 7,3	0,4	÷4,3	4,3	÷84,5°
315	$17\frac{1}{2}$	21	÷ 5,5	53,7	÷10,2	0,3	÷3,0	3,0	÷83,5°
400	33	10	÷ 5,9	43,0	÷13,7	0.3	÷2,2	2,2	÷82°
500	57	4,8	÷ 6,5	34,7	÷18,8	0,7	÷1,2	1,5	÷54°
630	87	2,1	÷ 7,1	27,0	÷26,2	0,8	÷0,5	1,0	÷37°
800	96	1,5	+10,1	21,6	+46,5	0,8	+0,2	0,7	+ 5°
1000	88	2,0	+ 4,6	17,4	+26,2	0,7	+0,6	0,4	+40°
1250	69	3,5	+ 2,6	13,6	+19.0	0.8	+1,2	1,5	+56°
1600	47	6.3	+ 1,3	10,8	+12,0	0,8	+2,1	2,4	+69°
2000	32	10,4	+ 0,9	8,6	+ 9,5	1.8	+2,9	3,1	+72°

Fig. 8. A resonance absorbent with a table of standard frequencies, with the values of the absorption coefficient α, $n = \frac{p_{max}}{p_{min}}$ Δ' , $\lambda/2$ and r and x of the complex impedance $z = r + jx$, all at the standardized frequencies.

the distance from the absorption material to the first minimum and the value $\lambda/4$. For these measurements the millimeter scale placed on the microphone carriage track can be used. It is important, when inserting absorption material in the apparatus, to first adjust the microphone probe by screwing it further in or out of the microphone carriage, so that it is just touching the surface of the absorption material.

The real part R and the imaginary part X of the complex acoustic impedance can then both be calculated with the aid of n and Δ. The half wavelength $\lambda/2$ must also be known, and the ratio $\frac{2\Delta}{\lambda}$ expressed in percent. The upper half of the diagram shown in Fig. 7 will immediately give the impedances r and x if the values of n and $\frac{2\Delta}{\lambda}$ % are marked off. The lower half of the diagram gives the complex acoustic impedance expressed by the modulus /z/ and the angle $\varphi°$. The figures given in the diagram are the so-called reduced impedances, which are non-dimensional. To find the impedances expressed in Rayls ($gcm^{-2} s^{-1}$), the values found must be multiplied by the acoustic impedance of air. $\varrho c = 42$ Rayls.*) Lastly the positive or negative sign of x (i.e. whether the reactance of the impedance can be assumed to be a mass or a compliance) follows from the sign of Δ. With the distance sample to first minimum $>{}^1/_4\lambda$, Δ and x will be positive, when $<{}^1/_4\lambda$, Δ and x will be negative.

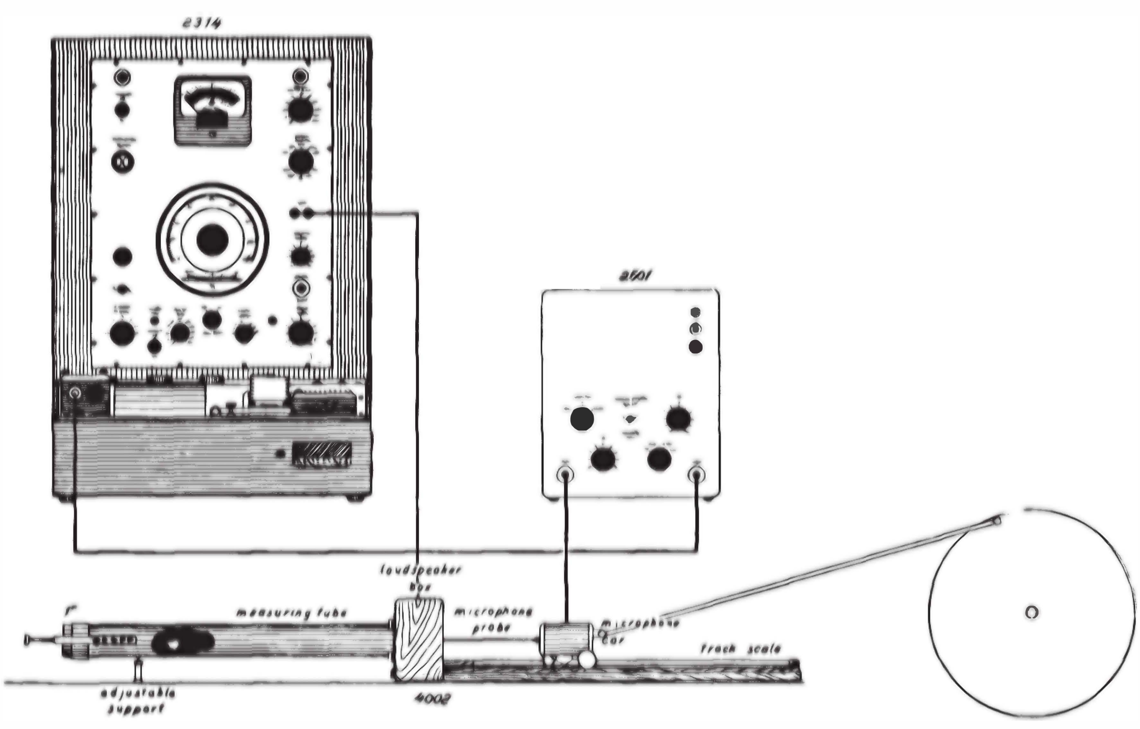


Fig. 9. Set up for the automatic measurement of the absorption coefficient with the aid of the Automatic Frequency Response Recorder type 2314, consisting of the BFO 1012 and the High Speed Level Recorder 2304. The Microphone Amplifier type 2601 has been used here as a linear amplifier. Frequency range 200—2000 c/s.

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*) For the derivation of Fig. 7 see Per V. Brüel: Sound Insulation and Room Acoustics, p. 56-63, Chapman & Hall, London 1951.

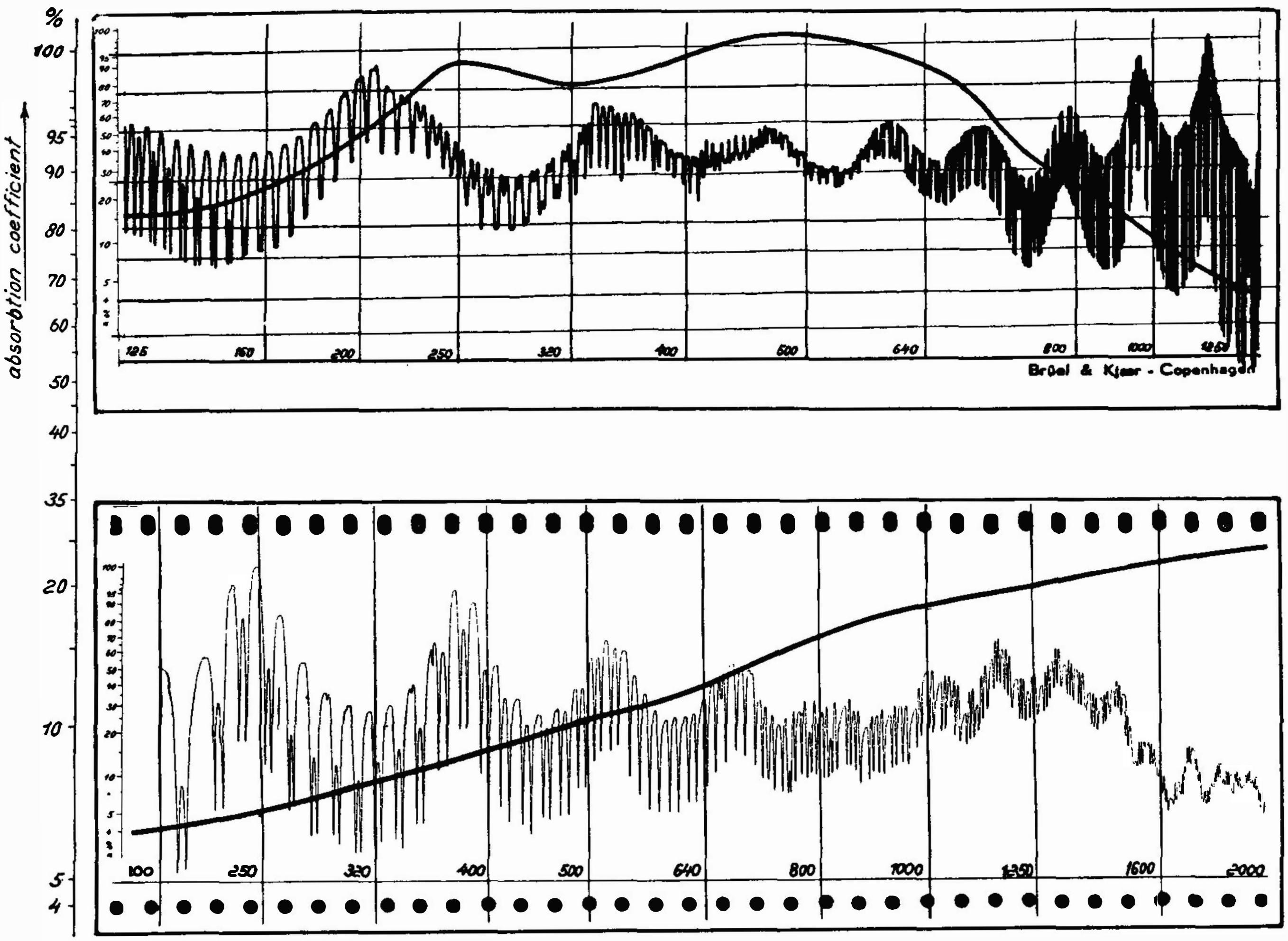

Fig. 10. The result of an automatic measurement-carried out on the set-up of fig. 9. The special scale for direct estimation of the absorption coefficient from the recording diagram is inserted in both diagrams and shown enlarged at the left side. The scale is effective for a 50 db potentiometer.

Fig. 8 shows a resonance absorbent as well as a table of the results measured at the standardized frequencies 100—125—160—200 etc., for the absorption coefficient α, n, Δ and $\lambda/2$ and acoustic impedance $z = r + jx$. Between 100 and 250 c/s the values of $\lambda/2$ and therefrom Δ followed with this measurement according to the first method described on p. 13; from 250 to 2000 c/s the values follow from the distance measurements of the first and second minima. The latter method should be regarded as the more accurate of the two, as one uses the same setting of the B.F.O., etc.

When developing new absorption materials one has often to carry out a long series of measurements, often within a certain frequency range only. If, in addition to a BFO 1012 and Analyzer 2105 or 2109, one has also access to a Level Recorder 2304, it is practicable to be able to carry out the measurements more or less automatically. Fig. 9 shows such a set-up, where a special motor slowly moves the microphone carriage back and forward by means of a simple connecting rod arrangement. The total range of movement of the microphone carriage is approx. 50 cm.

The Level Recorder is connected to the BFO, so that the BFO's frequency changes quite slowly at the same time as the paper moves on the Level Recorder in synchronism with the frequency traverse of the BFO. When the frequency has to change over a wide range, it is impossible to work with a selective amplifier, unless one uses type 2109, synchronized with the BFO and Level Recorder. In these measurements one therefore uses a linear amplifier, e.g. the Microphone Amplifier 2601 or uses the linear frequency range of Analyzer 2105 or 2109.

A logarithmic potentiometer of for example 50 db is used in the Level Recorder, whereby the ratio between pressure maxima and pressure minima can be read off directly from the recording paper. For these measurements it is possible to construct a scale as shown in Fig. 10, left, from which the absorption coefficient can be read off directly when the scale is placed over the recorded curve. On account of resonance phenomena in the measuring tube, loudspeaker and microphone, the absolute amplitude will naturally vary greatly, as can also be seen in the examples shawn in Fig. 10. It is therefore advantageous to use a 75 db potentiometer on the recorder when making this measurement, so as to be able, without changing the amplification, to carry out absorption measurements over a greater frequency range, with of course a consequent increased inaccuracy in the reading of the absorption coefficients from the special scale.

Another way of recording the absorption coefficient semi-automatically is shown in Fig. 11. Here, the Level Recorder with logarithmic potentiometer of 50 or 75 db is mechanically coupled to the 1/3-octave Analyzer 2109. Each time the Analyzer switches to a new filter the BFO is set manually to the mid-frequency value of that filter. The max./min. ratios are then recorded by moving the microphone carriage slowly by hand a few times up and down

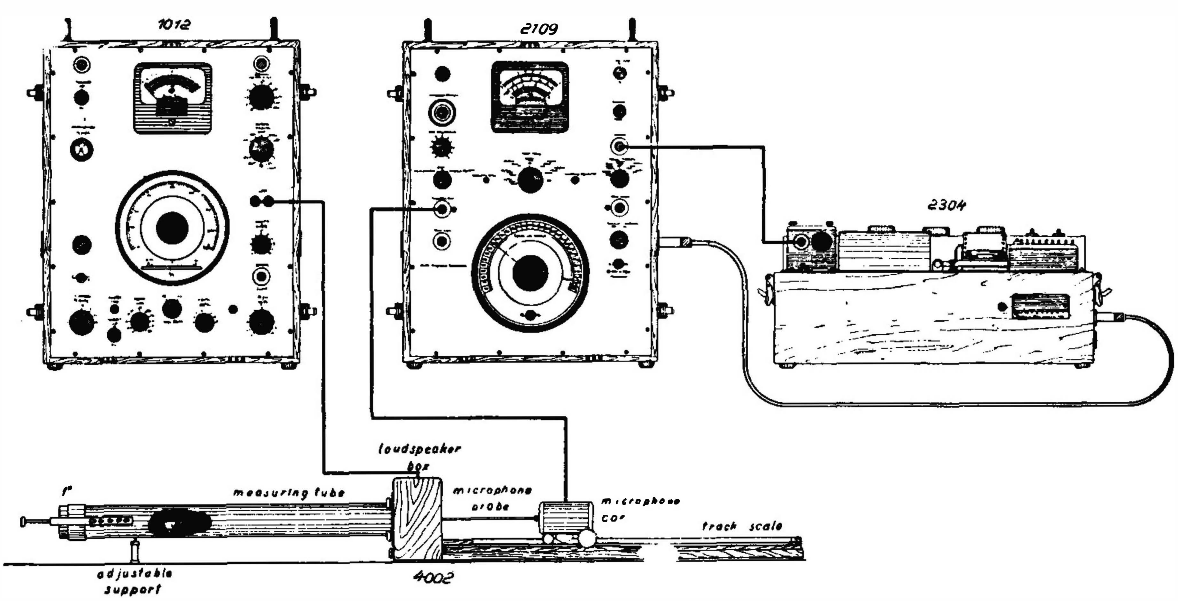

Fig. 11. Set-up for the semi-automatic measurement of the absorption coefficient with the aid of Level Recorder 2304 mechanically coupled to the 1/3-octave Analyzer 2109.

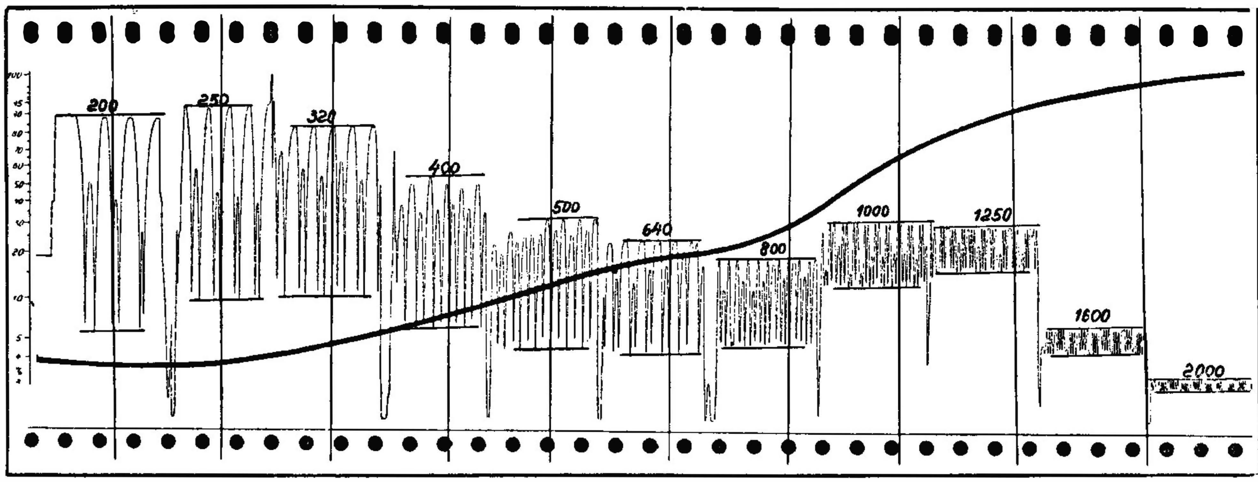

Fig. 12 Result of a semi-automatic measurement according to Fig. 11.

for each filter, while the paper passes through the recorder at an appropriate speed. The special scale of Fig. 10, left, can then again be used to determine the absorption coefficient at the standardized frequencies. The advantage, compared with the foregoing method is that the measurement is carried out selectively, which in principle is the only correct measuring procedure. However, for a preliminary investigation the difference between both procedures,

	Selective measurement with Analyzer 2109		Linear Measurement with Microphone Amplifier 2601 or Analyzer 2109 on "linear"	
v c/s	$\frac{p_{max}}{p_{min}}$	a	$\frac{p_{max}}{p_{min}}$	a
200 c/s	30 db	12,5 %	29 db	16 %
250 c/s	27 db	17 %	25 db	20 %
320 c/s	24 db	23 %	21 db	30 %
400 c/s	21 db	30 %	18 db	39 %
500 c/s	18 db	39 %	16 db	48 %
640 c/s	16 db	48 %	14 db	55 %
800 c/s	12 db	64 %	10 db	73 %
1000 c/s	9 db	77 %	8 db	82 %
1250 c/s	6 db	88 %	6 db	88 %
1600 c/s	4 db	95 %	4 db	95 %
2000 c/s	1,5 db	99 %	1,5 db	99 %

Table II. Comparison of measuring results of the two measurements of absorption coefficient according to Fig. 10 and 12.

especially with higher absorption coefficients, is rather small. The higher the absorption, the smaller the difference between max. and min. pressure in the tube, and the less the influence of the higher order modes which are also excited. The results, as shown in Figs. 10 and 12, of the measurements carried out according to Figs. 9 and 11 on the same sample of glass wool, are repeated below in tabular form to indicate the difference. Attention should be paid to having the right matching impedance (6 Ω) for the connection to the loudspeaker, so as to give minimum distortion, especially with the method of Fig. 9. Further, in both methods care should be taken that the writing speed of the level recorder is high enough, and the speed of rotation in the motor of Fig. 9 or the manual speed of the movement in Fig. 11 slow enough, to allow the correct recording of the pressure drop at the minima (see the logarithmic representation of pressure versus distance in the tube in Fig. 3 a). With the microphone car crossing the minima too quickly, the minima will be recorded too high, and an erroneous absorption coefficient will be obtained. A check at the lower frequencies that the minima are actually passed is the recording of the double minimum for only one maximum. This double tail (see Figs. 10 and 12) only results if the probe really passes a minimum twice in one up and down movement.

Brüel & Kjær

ADR.: BRÜEL & KJÆR
NÆRUM - DENMARK

TELEPHONE: 80 05 00
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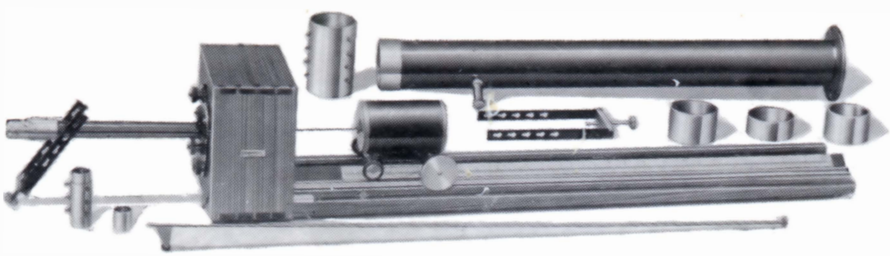
4002

INSTRUCTIONS AND APPLICATIONS

Standing Wave Apparatus
Type 4002



For measurements of absorption and specific acoustic impedance of absorption material samples. Covering a frequency range from 95 to 6500 c/s.

BRUSH ELECTRONICS CO.
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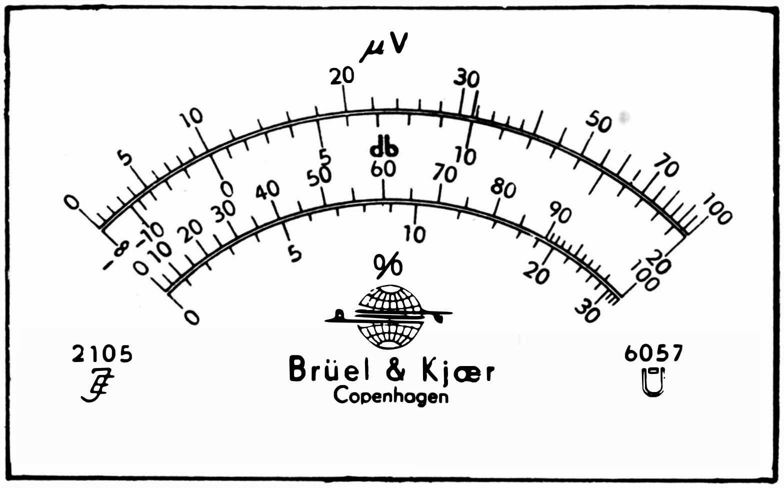
STANDING WAVE APPARATUS

Description

The tube apparatus is designed for easy and quick determination of the absorption coefficients of acoustical materials. The great advantages of the method are that only small circular samples, about 10 cm in diameter, are needed, and the measurements are easy to carry out and are perfectly reproduceable. However, as the largest dimension of the sample, according to the principle of the measuring method, which requires plane sound waves in the measuring tube, must not be larger than about half the wave length of the sound at the measuring frequency, it is impossible to obtain reliable results for materials, the absorption ability of which depends on their extent, as, for example, vibration panels, large slit resonators, etc. The tube method is therefore particularly suited to measurements of porous materials, ordinary resonance absorbents, light membrane absorbents, etc.

The principle of the measuring method is shown in figs. 1 and 2. The loudspeaker at one end of the tube is operated at the desired test frequency from an audio-frequency oscillator with 6 ohms output impedance and with a distortion of less than 1%. For this we recommend our B. F. Oscillator type 1012. The sound waves move through the tube



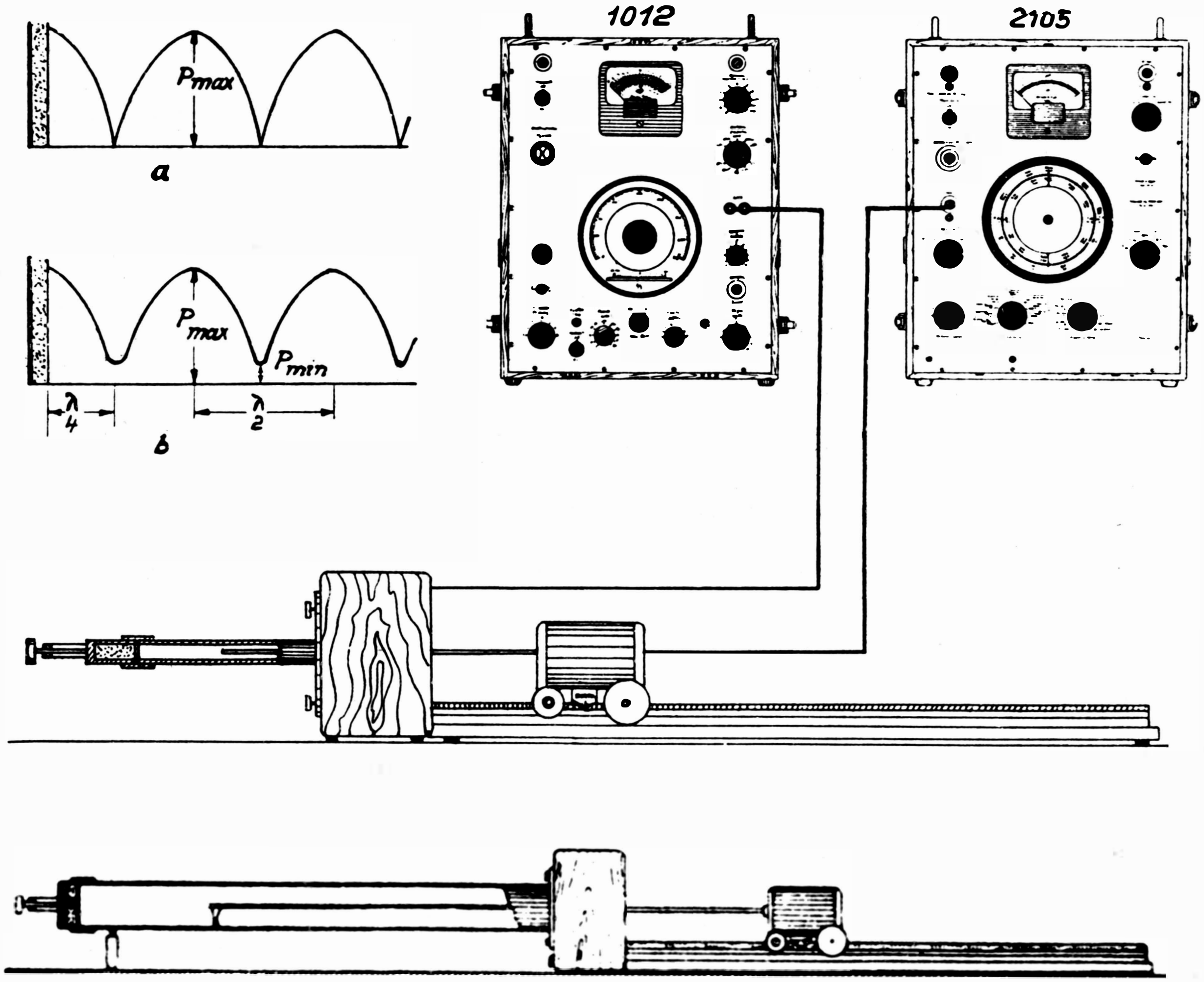


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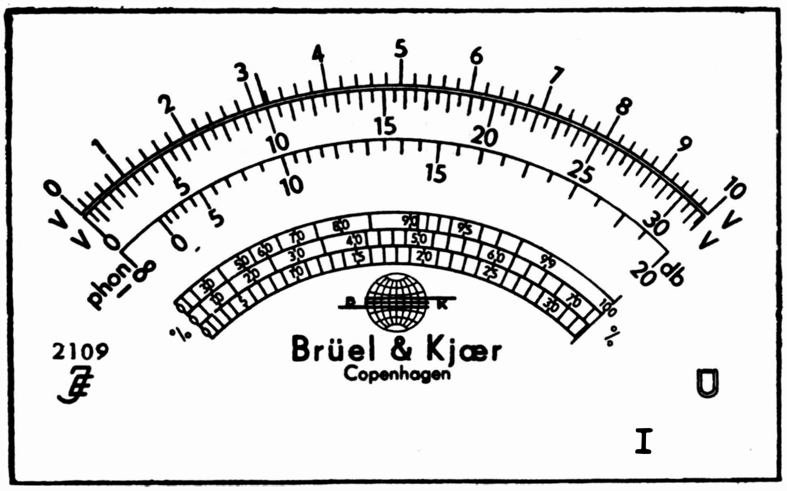
Fig. 1. Measurement of acoustic absorption coefficient with the aid of Frequency Analyzer 2105. (Constant Percentage Bandwidth Type).



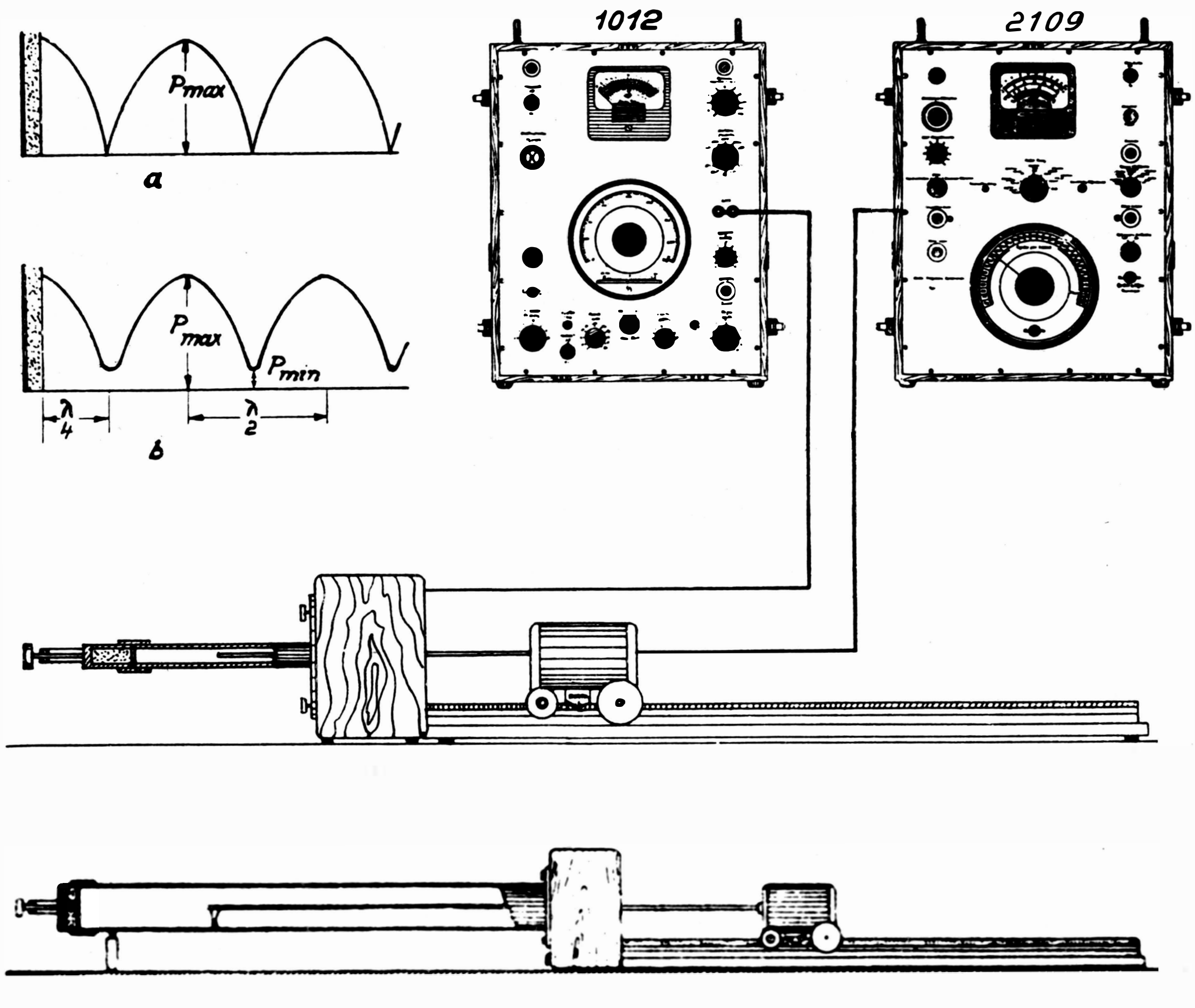


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Fig. 2. Measurement of acoustic absorption coefficient with the aid of 1/3 Octave Analyzer 2109.

and strike the sample which is placed in a sample holder with a thick back plate, to avoid all sound absorption by the apparatus itself. The sound waves are then partly reflected at the sample. The resultant of the incident wave with amplitude 1 and reflected wave with amplitude r is a standing wave pattern with alternate sound maxima 1 + r and minima 1 - r in the tube. From the ratio n of these sound pressure maxima and minima the reflection coefficient r follows directly,

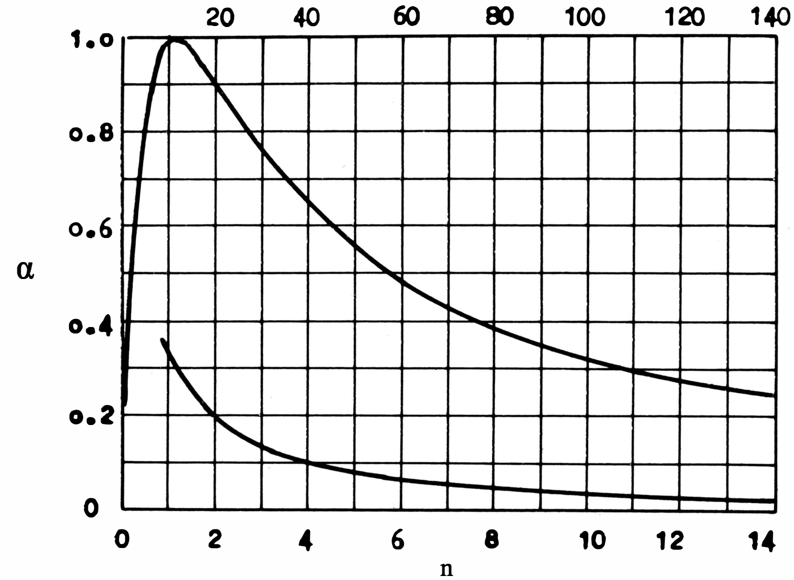
$$|r| = \frac{n - 1}{n + 1} \qquad (1)$$

However, we are more interested in the absorption coefficient α, i.e., the ratio of the energy absorbed by the sample to the incident energy. In other words $\alpha = 1 - |r|^2$, from which, with the aid of relation (1), follows directly,

$$\alpha = \frac{4}{n + \frac{1}{n} + 2} \qquad (2)$$

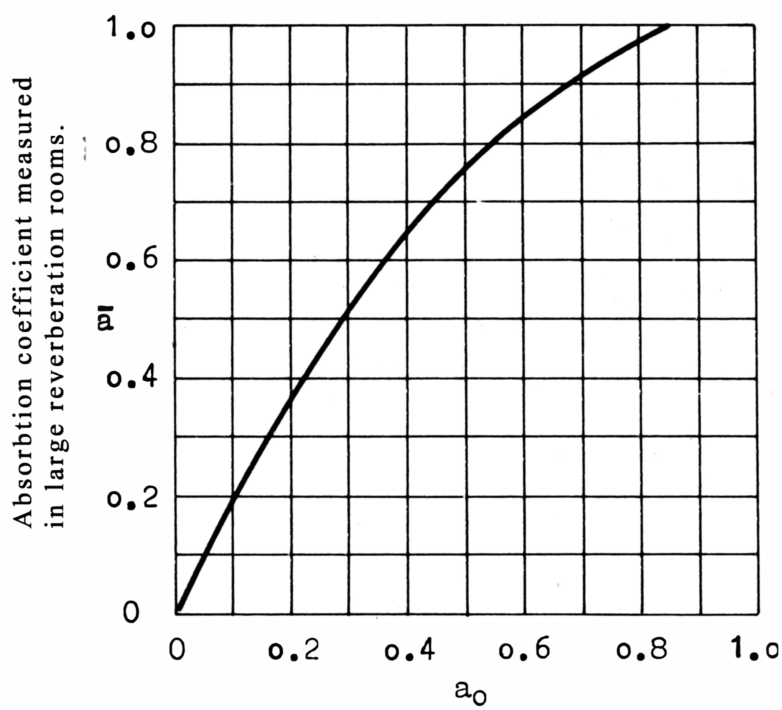
(see fig. 3)

The sound field is explored by means of a probe microphone, movable on a track equipped with a scale on which the exact distance between probe entrance and test sample can be read. The microphone voltage should be amplified by means of a selective amplifier to reduce the influence of hum and noise and higher harmonics, which are also inevitably generated by the loudspeaker in the tube.



$$\alpha = \frac{4}{(n+1) / (n+2)}$$

Fig. 3. Absorption coefficient as a function of n= p_{max} / p_{min}



Absorbtion coefficient measured with 4002 tube apparatus.

Fig. 4. Relation between absorption coefficient
of large reverberation rooms & tube apparatus.

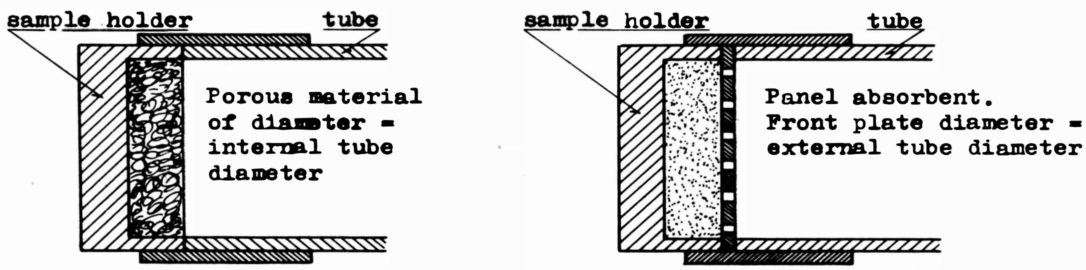


Fig.5 Mounting absorbents in tube apparatus

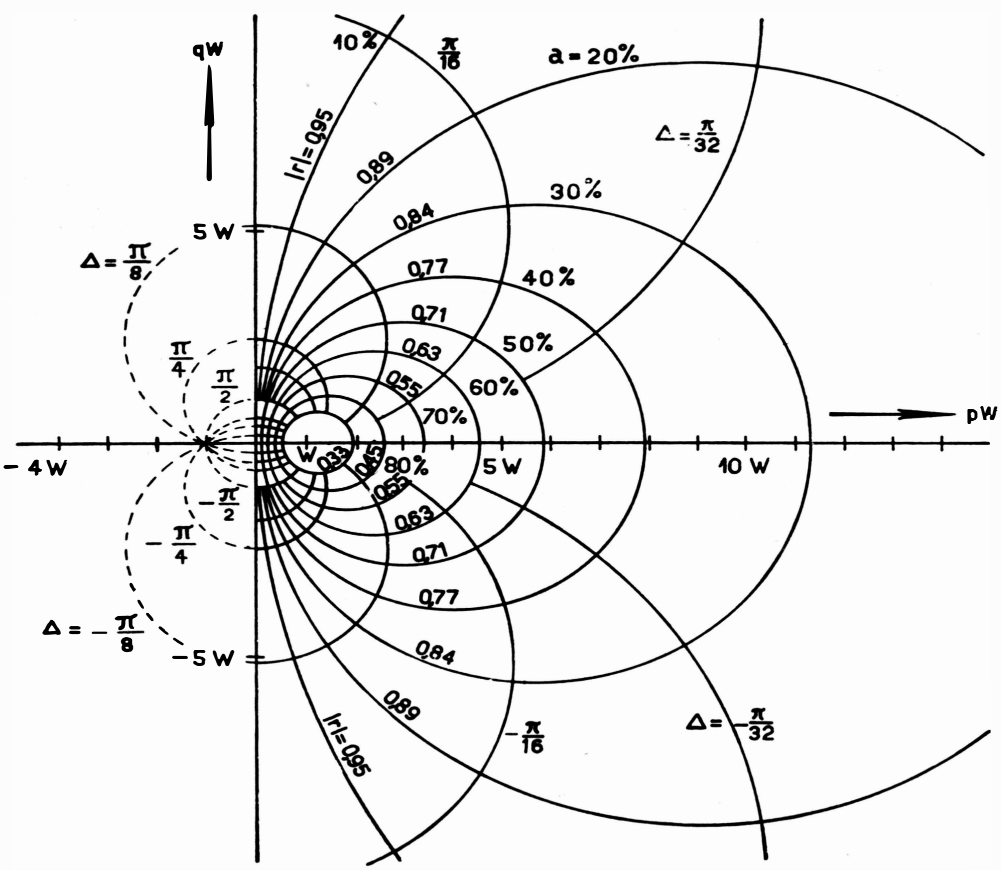


Fig.6 Graph to obtain resistive and reactive part of impedance Z with the aid of the measured α and Δ values

Particularly suitable for this purpose is the Frequency Analyzer 2105 (of the Constant Percentage Bandwidth type, fig. 1), which is continuously tunable in the frequency range from 47 c/s to 12000 c/s, or the 1/3 Octave Analyzer 2109 (fig. 2), with 27 fixed filters from 40 c/s to 16 kc/s. Both types are equipped with special scales on which the absorption coefficient can be read directly. Type 2105 has two absorption scales, 0-100% and 0-30% (when the instrument's amplification is increased by 20 db); type 2109 has three scales, 0-100%, 0-70%, and 0-30% (by increasing the amplification 10 db and 20 db).

The absorption coefficient is determined by the tube measurement method only at normal incidence, which is why the measured coefficients are generally somewhat smaller than those determined by the reverberation room method according to W. C. Sabine's formula. In fig. 4 a curve is shown which indicates the relation between the results of the tube method and the reverberation room method. This curve, though based on a theoretical foundation, must be taken with every possible reservation, as it is necessary that the reverberation room be very large, and the materials in the tube and reverberation room be placed perfectly identically. This last requirement is very difficult to meet to any sufficient degree of accuracy, so that deviations often occur. Below, some literature is given dealing with the measurement of acoustical impedance, and with a more detailed discussion of the tube method:

Per V. Brüel: Sound Insulation and Room Acoustics.
Chapman & Hall, London 1951. (1)

C. Zwikker, C. W. Kosten: Sound Absorbing Materials.
Elsvier, New York, London, 1949. (2)

Leo L. Beranek: Acoustic Measurements.
Wiley & Sons, New York 1949. (3)

Directions for Use

The complete tube measurement apparatus comprises two measuring tubes; a larger one with an interior diameter of about 10 cm, which covers the frequency range from 90 to 1800 c/s, and a smaller one with a diameter of about 3 cm, covering the frequency range from 800 to 6500 c/s. A set of holders for the samples is supplied for each tube. Two are fixed holders with depths of 1" and 2" respectively, and a third one has a variable depth. All the holders have a very thick base. The tube is screwed to the loudspeaker cabinet. The microphone probes are led through a hole in the loudspeaker, and are connected at the back of the cabinet with the microphone car, which runs on a track provided with a scale. The microphone lies in elastic mountings in the microphone car, well insulated from airborne noise and impact sound or vibrations.

An accurate circular sample of the material is placed in a suitable holder. (The sample is best cut with a band-saw). Porous material is cut so that it fits the inside diameter of the holder, while absorption material with a hard covering plate, for example common resonance absorbents and membrane absorbents, is cut so that the hard plate fits the outside diameter of the holder, the soft back plate fitting the inside diameter (see fig. 5). By mounting the material in this manner a very tight and effective fixing of the front plate is obtained. It is important that the bracing piece is screwed tightly to prevent vibrations arising in the bottom of the holder.

The oscillator is connected to the loudspeaker terminals (6 ohms output impedance), and the jack of the probe microphone is connected to the input of the Frequency Analyzer 2105 or 2109 with the input selector on "Input Potentiometer". The oscillator is adjusted to the desired frequency and a suitable power output selected. The analyzer is tuned to the same frequency, but the selectivity is not chosen greater than is necessary. The analyzer deflection is regulated by its range switch, calibrated in steps of 20 db. The fine adjustment is made by the input potentiometer. The measurement itself is carried out as follows.

The microphone is placed in a sound pressure maximum and the deflection of the instrument pointer adjusted to 100% by means of the input potentiometer. The microphone is then moved to a minimum and the absorption coefficient read directly in % on the one %-scale of the instrument. With absorption coefficients less than 30% the amplifier's gain can be increased by 20 db by means of the "Meter Range" switch on types 2105 and 2109. The absorption is then read off from the 0-30% scale. The extra 0-70% scale of type 2109 is used by increasing the gain only 10 db by means of the "Range Multiplier" switch.

At frequencies below 200 c/s the wave length is so great that it is impossible to find an isolated pressure maximum. It is then necessary to use the pressure immediately in front of the sample, which has practically the same value when the wave length is great. At higher frequencies it does not matter so much which maxima and minima are used, as the damping of the measuring tubes is very small. However, the highest accuracy is obtained by taking the maximum and minimum closest to the sample, but with perforated panels with big holes it is advisable to take the second maximum due to the inhomogeneity of the sound field close to the front of the sample.

In comparing the absorption coefficient of the same sample measured in the overlapping range 800-2000 c/s of the two tubes, the greater weight ought normally to be given to the results from the big tube, since small inhomogeneities in the sample have a bigger influence with the smaller diameter tube.

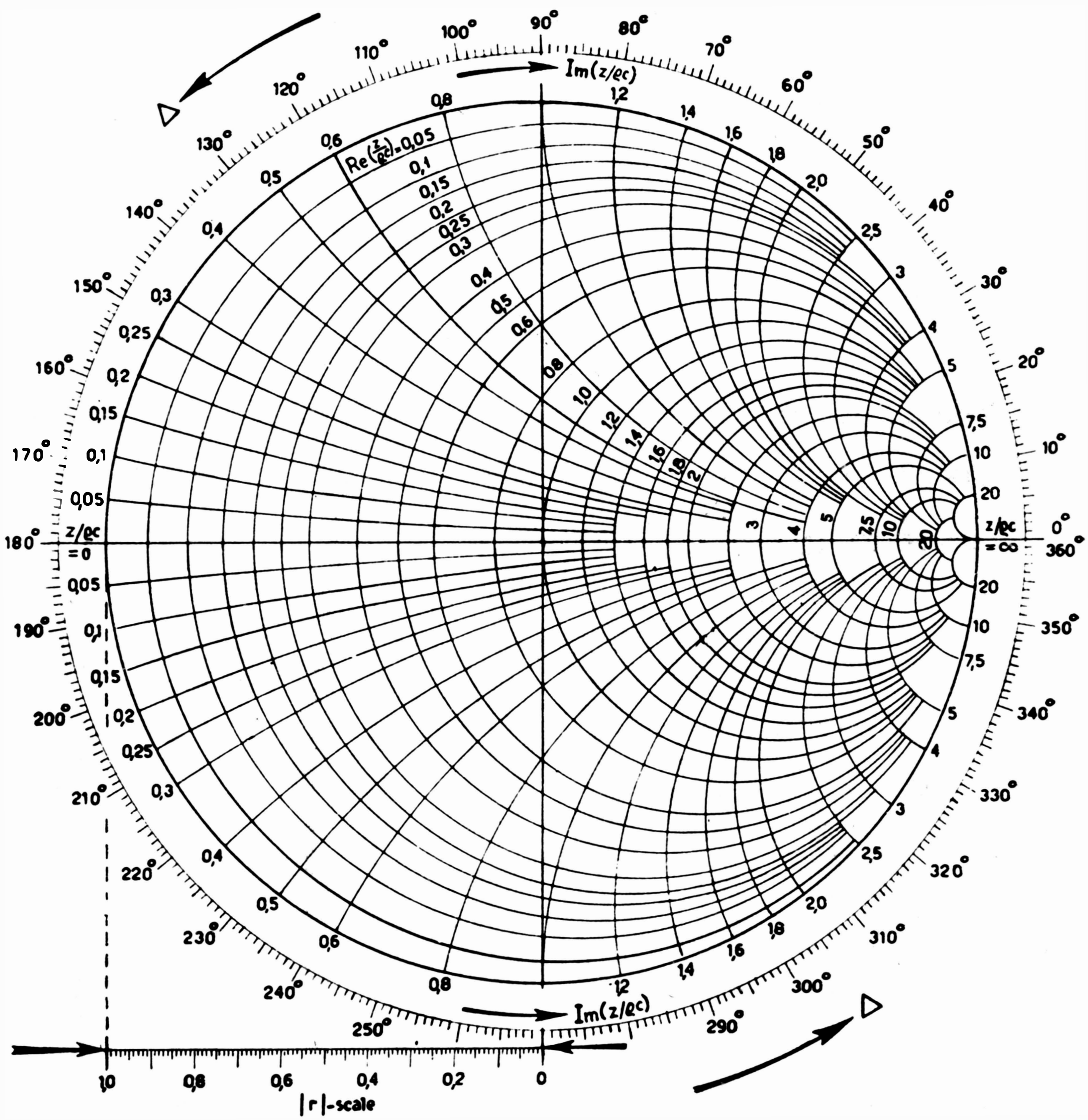


Fig.7 Idem graph 6. All values for |r| and Δ, which fill the whole right half plane in graph 6 are here represented in a circle with radius 1.

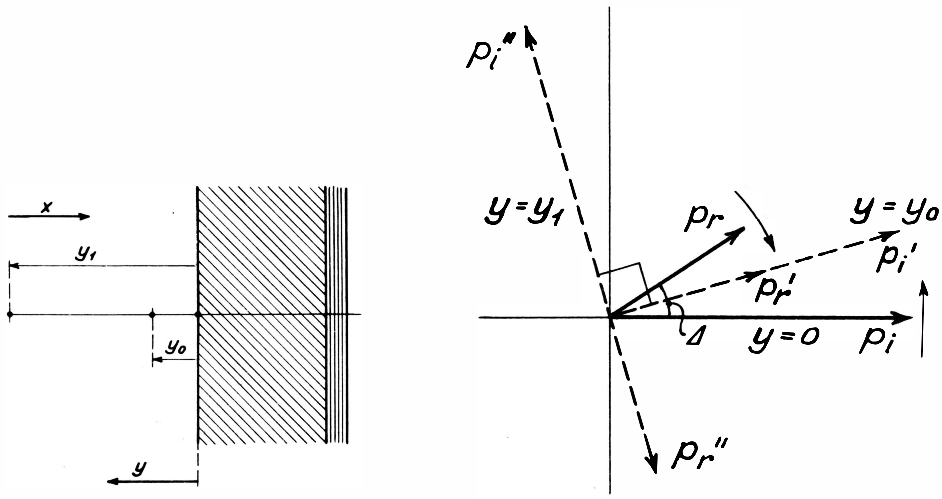


Fig. 8 Vector diagram indicating incident and reflected wave pressures p_i and p_r at sample surface $(y = 0)$, first maximum $(y = y_0)$ and first minimum $(y = y_1)$

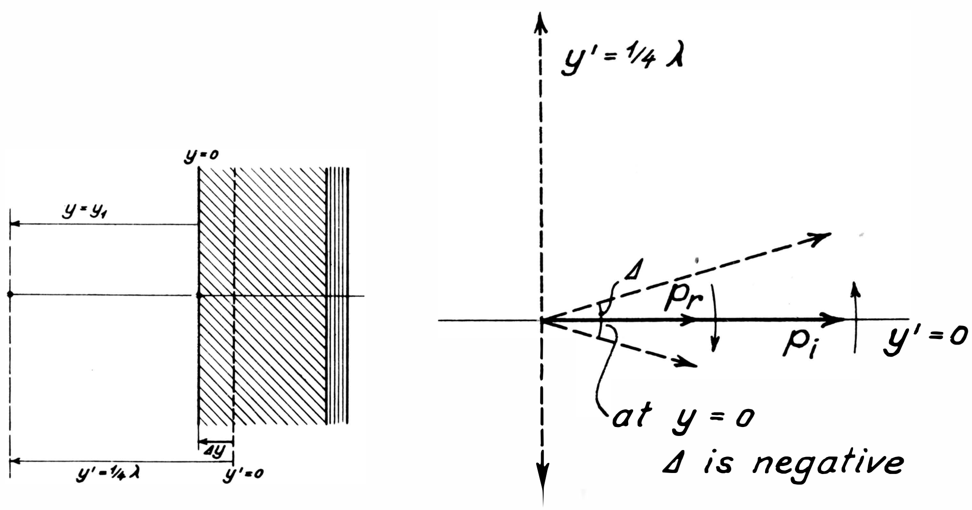


Fig. 9 Vector diagram indicating incident and reflected wave pressures p_i and p_r at fictive plane $y' = 0$, where the reflection appears to occur without any phase jump, and first minimum $y' = 1/4\lambda$, $y = y_1$

2109, the resistive and reactive parts of the impedance Z, expressed in the unit ρc or W, i.e. the characteristic impedance of air = 420 kg/m^{2}sec, are found with the aid of graphs 6 or 7.

In graph 6 the intersection of the two circles corresponding to the α and Δ value found in the measurement corresponds with the end point of the vector Z/W drawn from the origin of the orthogonal coordinate system $Z/W = p + jq$. In graph 7 the $|r|$ value ($|r|^2 = 1-\alpha$) is set out on a radius drawn from the centre of the big circle to the measured Δ value on the circumference. The two orthogonally intersecting circles here also yield directly the resistive and reactive parts of the impedance Z.

Short Derivation of Formulae used with Standing Wave Measurements

Formulae (1), (2) and (3) are easily derived with the help of a simple vector diagram (see fig. 8). We suppose that at $y = 0$ (i.e., the front surface of the sample) the sound pressure of the incident wave is p_i and the sound pressure of the reflected wave

$$p_r = |r| \cdot p_i e^{j\Delta} \qquad (5)$$

At a distance y in front of the sample the incident wave has an angle of lead $(2\pi y/\lambda$ (following the convention $p_i(y)$ =

$p_i e(-j\omega x/c)$ where $y = -x$ and $\omega/c = 2\pi/\lambda$). The reflected wave acquires an angle of lag $2\pi y/\lambda$. Leaving the sample surface, therefore, both vectors rotate in the indicated way. With positive argument of the complex reflection coefficient r there will be first a maximum sound pressure in the tube $(1 + |r|)p_i$, when both vectors coincide. This occurs at a distance y_o such that $\Delta = 4 y_o/\lambda$. Then, with both vectors rotated through an additional angle $\pi/2$, the vectors lie in opposite directions, and a minimum, $(1 - |r|)p_i$, will be the result. This occurs at a distance y_1 such that $\Delta + \pi = 4\pi y_1/\lambda$, which yields formula (3) directly. The quotient $\frac{p_{max}}{p_{min}}$ thus follows as

$$n = \frac{p_{max}}{p_{min}} = \frac{1 + |r|}{1 - |r|} \qquad (6)$$

from which follows (1) and (2).

If we define Z as the impedance at the surface of the sample, we have

$$Z = \frac{p_i + p_r}{v_i + v_r} \qquad (7)$$

with v_i and v_r as the particle velocities of the incident and reflected wave. For the incident wave the relation between pressure and particle velocity is $p_i = \rho c . v_i$, for the reflected wave $p_r = -\rho c . v_r$. These, substituted in (7), give

$$\frac{Z}{W} = \frac{1 + r}{1 - r} \qquad (8)$$

This relation between the two complex qualities $r = |r| \cdot \angle\Delta$ and $Z/W = p + jq$ is represented in the two graphs of figs. 6 and 7. Thus, by measuring the modulus and argument of the reflection factor we can directly read off the resistive and reactive parts of the impedance Z.

True Impendance

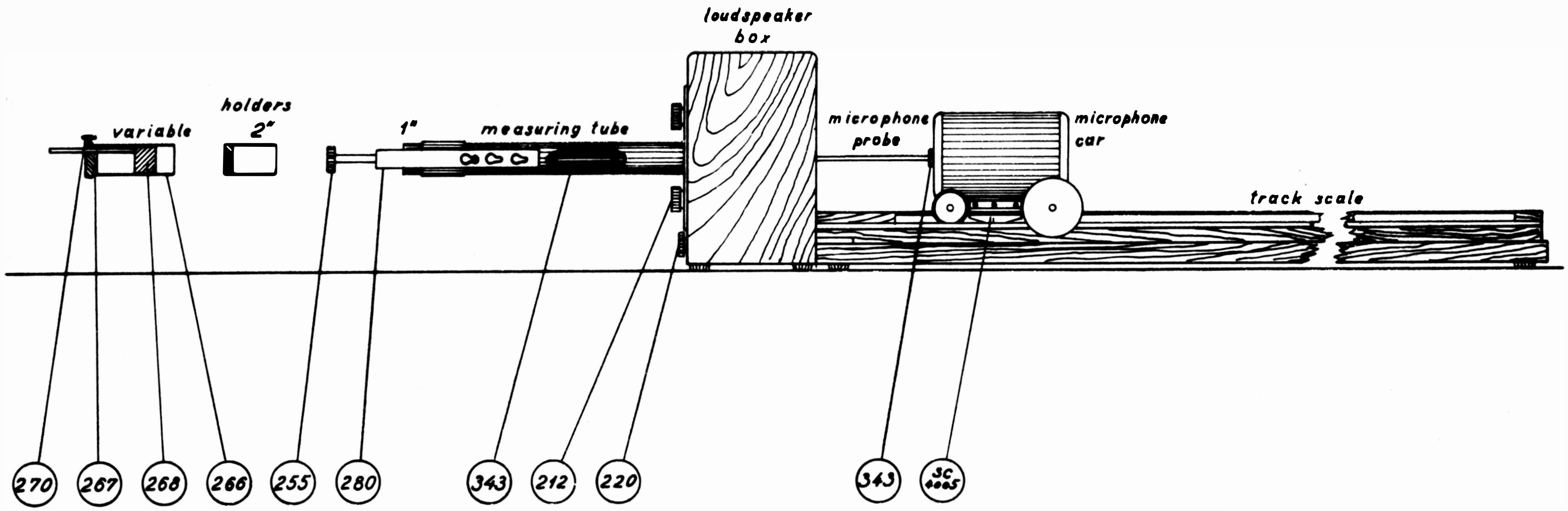
The measurement of n itself is of importance, as it is equal to the "true impedance" N of a material, divided by the characteristic impedance ρc of air (see ref. 3 p. 66).

The measurement of n follows by moving the microphone car first to a minimum. The meter indication is now regulated by means of the input potentiometer to a deflection of 10 μV (on Analyzer 2105) or 1 volt (on Analyzer 2109). The car is then moved to a maximum, after which n values lying between 1 - 10 can be read off directly from the meter scale, and n values lying between 10 - 100 by decreasing the amplifier's gain 20 db with the "Meter Range" switch.

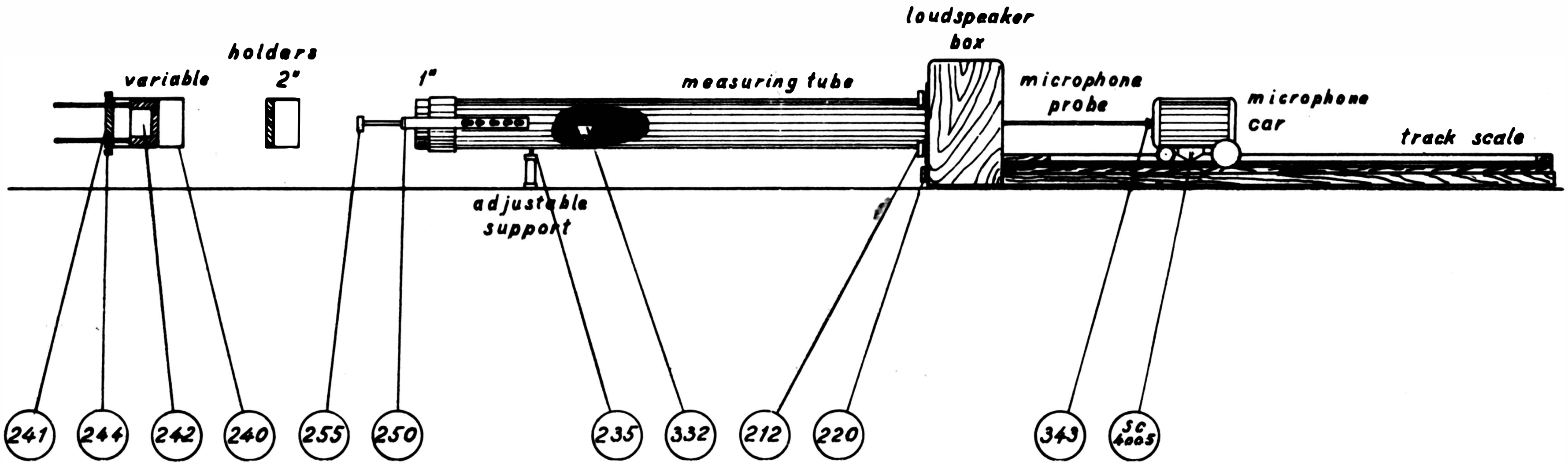
The true impedance of an absorbing material is the impedance at a fictitious plane in the material where the reflection can be assumed to take place. The incident sound wave with pressure p_i penetrates into the material and is reflected at the fictitious plane so that no phase jump occurs, so that we have only $p_r = r . p_i$, where all three quantities are real. This also simplifies the complex equation (8) to

$$\frac{N}{W} = \frac{1 + r}{1 - r},$$

now a relation between real quantities only. As r is real this is also equal to the measured value n according to (6). Thus, the measuring result n yields directly the true impedance $N = n . \rho c$ without the employment of any graphs, which largely helps to simplify the calculations of most acoustical problems, for example, damping in ducts (see ref. 3 p. 159). The distance Δy between the "reflection plane" and the sample surface follows directly from fig. 9. Δy + the distance "sample surface to the first minimum", should equal $1/4\lambda$. (The distance y_1 is now smaller than $1/4\lambda$, which gives a negative angle Δ for the normal impedance at $y = 0$ according to formula (3). This follows also from fig. 9b. At $y = 0$ there will be a negative angle Δ between p_i and p_r).



Standing wave Apparatus type 4002
3 cm tube



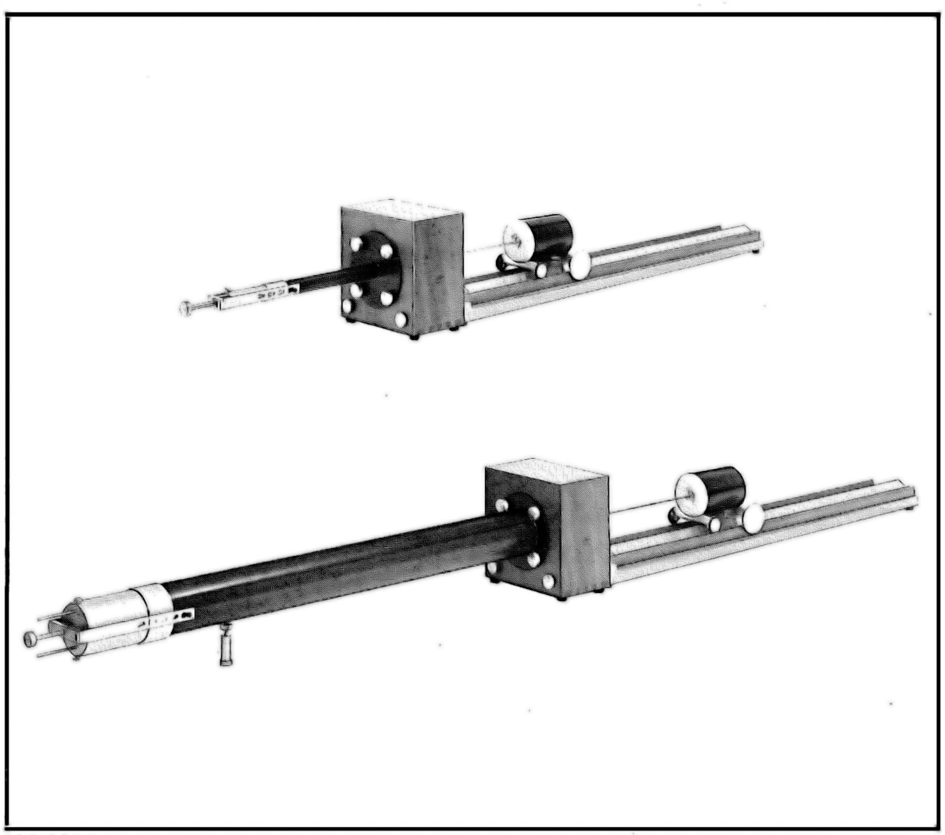
Standing wave Apparatus type 4002
10 cm tube

SPARES LIST

No.		Stock Number	Mark
1	loudspeaker	HP 0006	
4	loudspeaker box	4002	211
4	nut for loudspeaker	4002	213
1	track scale		216
2	bolt for track		220
1	large tube		231
1	adjustable support		234
1	nut for do.		235
1	large 1" holder		238
1	large 2" holder		239
1	tube for large variable holder		240
1	clamp cover for do.		241
1	piston for do.		242
2	thumb screw for do.		244
1	large variable holder, complete		245
1	large bracket		250
1	screw for do.		255
1	small tube		261
1	small 1" holder		264
1	" 2" "		265
1	tube for small variable holder		266
1	clamp cover for do.		267
1	piston for do.		268
1	thumb screw for do.		270
1	small variable holder, complete		271
1	small bracker		280
1	screw for do.		255
1	microphone car		300
1	index	SC 4005	
1	long probe assembley	4002	330
1	support for do.	4002	332
1	locking nut for do.		336
1	short probe assembly		340
1	support for do.		343
1	locking nut for do.		336

Instruction Manual 4002

Standing Wave Apparatus Type 4002



033-0511

For measurements of acoustic absorption coefficient and complex specific impedance of small samples over the frequency range of 90 to 6,500Hz.

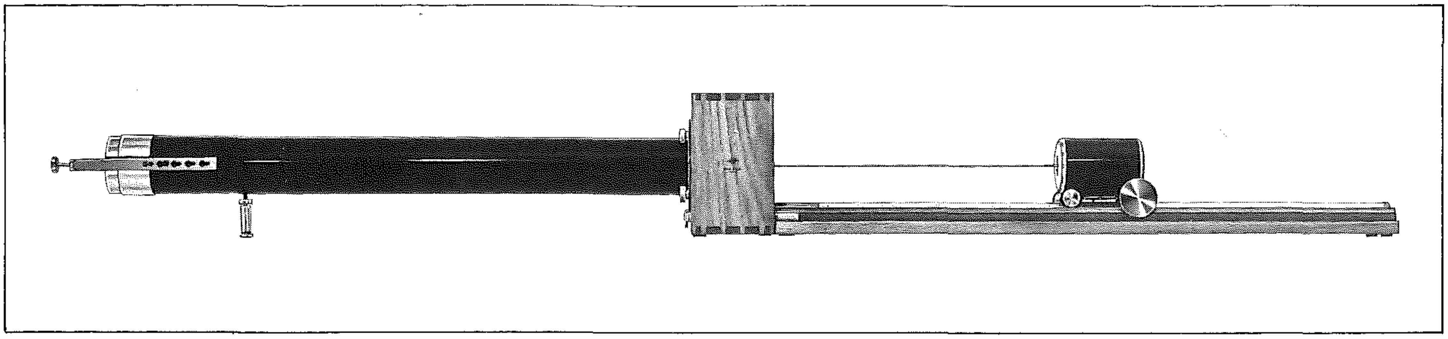
Brüel & Kjær

STANDING WAVE APPARATUS
TYPE 4002

Revision March 1979

CONTENTS

Standing Wave Apparatus type 4002



FEATURES:

- Easy measurement on small samples
- Wide frequency range 90 Hz to 6,500 Hz
- Direct reading of absorption coefficient

USES:

- Measurement of acoustic absorption coefficient of materials
- Measurement of specific acoustic impedance of materials

The Standing Wave Apparatus Type 4002 is designed for measurements of absorption coefficients and specific acoustic impedance of circular cut samples of sound absorbing materials in the frequency range from 90 Hz to 6,500 Hz.

The Apparatus should be used with the Sine Generator Type 1023 and the Frequency Analyzer Type 2120 or the combination of Measuring Amplifier Type 2606 and Heterodyne Slave Filter Type 2020, with scales for direct reading of absorption coefficient.

Basic Measurements

Measurements are carried out according to the standing wave method in which a loudspeaker sets up a sound field in a tube terminated by the sample to be investigated. Because of reflection from the sample, standing waves are produced in the tube. By measuring the ratio between the maximum and minimum sound pressure, the absorption coefficient of the sample for zero degree incident sound can be calculated. By measuring the distance between the surface of the sample and the minima and maxima pressure, the complex acoustic impedance of the sample is also easily calculated. Since the only absorbing material is the sample, the numerical figures obtained are very closely related to its sound absorbing properties. By designing the measuring tube with a circular cross section and making the sample holders heavy, only a small amount of sound energy is absorbed by the apparatus. Thus, comparison of results of sound absorption measurements made at various laboratories may be safely made.

As the measuring method requires plane sound waves in the measuring tube, the diameter of the sample must not be greater than about half the wave length of the sound. To enable measurements to be carried out in a relatively wide frequency range, the Standing Wave Apparatus is supplied with two measuring tubes with different diameters. The larger one (with a tube diameter of 100 mm) is useable in the frequency range from 90 Hz to 1800 Hz and the smaller one (with a diameter of 30 mm) should be used from 800 Hz to 6500 Hz. Both tubes are supplied with three sample holders.

To set up the arrangement a circular disc is cut out of the absorbing material and placed in one of the three sample holders supplied with each tube. One holder is designed with adjustable depth while the other two have fixed depths. By means of a clamping device the sample holder is fastened to one end of the measuring tube; the other end of which is screwed onto the box containing the loudspeaker. Through an axial hole in the loudspeaker a probe tube type microphone is led. The probe microphone is supported at one end (inside the measuring tube) by a small gliding carriage and at the other by a microphone car containing the microphone. The microphone car is guided by brass rails and its position is indicated on a rule.

Measuring Arrangement

Fig.1 shows a complete measuring arrangement for measurement of acoustic absorption coefficients and, if required, complex impedance. The loudspeaker of the Standing Wave Apparatus Type 4002 is fed from the Sine Generator Type 1023, covering the frequency range 10 Hz to 20 kHz. The microphone output voltage is indicated on the Measuring Amplifier Type 2606 which is made selective by the addition of the Heterodyne Slave Filter Type 2020, the frequency range of which is 10 Hz to 20 kHz and with bandwidths down to 3,16 Hz. The filter is tuned automatically from the Generator 1023, to follow the frequency of this. The advantage of this set-up is that disturbing effects of noise and harmonic distortion from the loudspeaker are minimized, and that the determination of the pressure minima can be made more accurately. This is of special interest where measurements are carried out on materials with small absorption coefficients. In this case the amplitude of the reflected wave is almost equal to the incident wave, hence the sound pressure in the minima becomes very small. A similar set-up can be made employing the Heterodyne Analyzer Type 2010 which includes both a generator, a measuring amplifier and a constant bandwidth filter. It should be noted however that Type 2010 can only supply 100 mA and the SPL will be 17 dB below that which can be obtained with a 1023 generator.

The meter scales of the B & K Frequency Analyzers and Measuring Amplifiers enable the absorption coefficient α to be read off directly, and information concerning the positions of minima can be obtained using the rule mounted on the 4002.

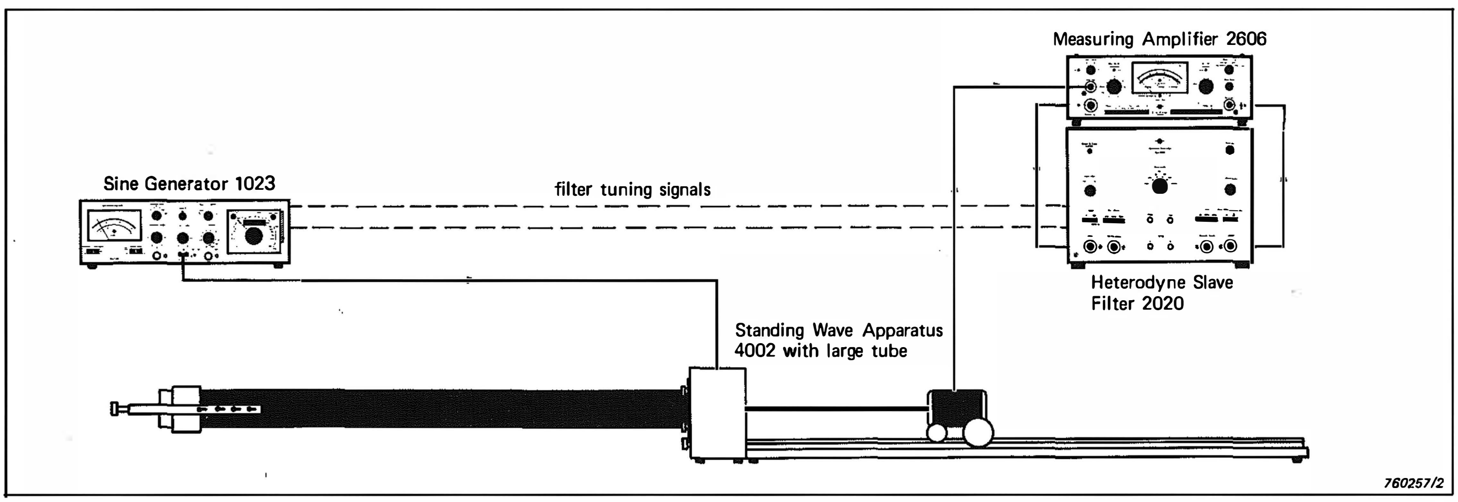


Fig.1. Measuring arrangement for measuring the acoustic absorption coefficient

Specifications 4002

Frequency Range:
Large Tube: 90 Hz to 1800 Hz
Small Tube: 800 Hz to 6500 Hz

Dimensions of Measuring Tubes:
Large Tube:
Diameter: 99 mm (3,9 in)
Length: 1 m (39 in)
Small Tube:
Diameter: 29 mm (1,14
Length: 280 mm (11 in)

Sample Holders:
Each tube is provided with two sample holders with fixed depths of 25 mm (1 in) and 50 mm (2 in) and one sample holder with variable depth from 0 to 95 mm (3,75 in)

Loudspeaker:
7 in, 6 W, 4 Ω

Microphone:
(Crystal type)

Sensitivity: 25 mV/Pa at 1000 Hz (without probe)

Capacitance: 2 nF

Min. Load Impedance: 1 MΩ (—3 dB at 90 Hz)

Overall Dimensions:
Total length with large tube: 2,4 m (95 in)
Total length with small tube: 1,66 m (65 in)
Maximum width: 260 mm (10 in)
Maximum height: 250 mm (10 in)
When dismantled the Apparatus is compactly stored in the shipping container, the outer dimensions of which are:
1400 × 380 × 350 mm
(55 × 15 × 14 in)
in)

Weight:
48 kg (106 lb)

2. CONSTRUCTION AND PRINCIPLE OF OPERATION

The Standing Wave Apparatus Type 4002 is designed for the quick and easy determination of absorption coefficients of acoustical materials by the standing wave method. The advantages of this method compared with measurements in a reverberation room, are that

a. only small circular samples (either 100 mm or 30 mm in diameter) are required,
b. the measurements are quick and easy to perform,
c. the measurements are reproducible.

However, as the largest dimension of the sample must not be larger than about half the wavelength of the sound at the measuring frequency, it is impossible to obtain reliable results for materials whose ability to absorb depends upon resonance as, for example, damped vibrating panels or large slit resonators. The tube method is therefore best suited for measurements on porous materials, ordinary acoustic tiling, brick etc.

The principle of operation of the Standing Wave Tube is based on the interference of two plane waves. A loudspeaker is situated at one end of an acoustically rigid tube and a sample of the material to be tested at the other with its axis coincident with that of the tube. A pure tone signal is supplied to the loudspeaker and a plane wave is generated in the tube in the direction of the sample. The wave is partially reflected from the sample and the interference between the incident and reflected wave gives rise to a standing wave pattern. From measurements of the levels and positions of the sound pressure maxima and minima of the standing wave pattern the acoustic absorption and impedance of the sample can be determined.

The complete tube apparatus comprises two measuring tubes, the larger one with an internal diameter of 100 mm used for measurements in the frequency range from 90 Hz to 1800 Hz and the smaller one with an internal diameter of 30 mm covering the frequency range from 800 Hz to 6500 Hz. A set of three metal holders for the samples is supplied for each tube. Two of the holders have fixed depths of 25,4 mm and 50,8 mm respectively while the third has a variable depth. All six holders have a very thick base in order to reduce sound absorption by the apparatus itself. For each tube a compatible microphone probe and support is supplied.

The main components of the 4002 are:

Two Measuring Tubes
Loudspeaker and cabinet
Graduated measuring track
Microphone Carriage with cable
Microphone probe (one per tube)
Probe Supports (1 Sliding Support, 1 Support Trolley)
Sample Holders (3 for each tube of which one has a variable depth)
Retaining Clamp (1 per tube)

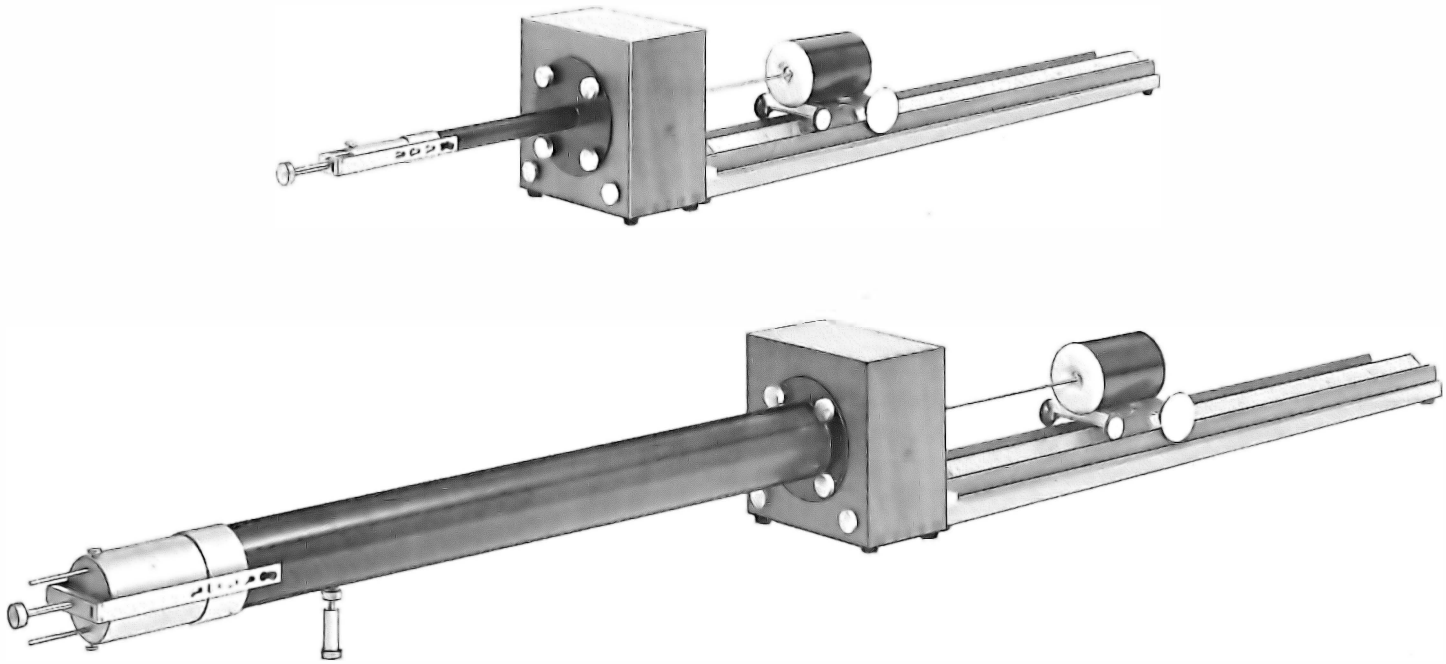


Fig.2.1. (Upper photo) The 4002 fitted with the short tube
(Lower photo) The 4002 fitted with the long tube

Fig.2.1 shows the 4002 assembled ready for use with both the short and the long tube. In the Microphone Carriage, which can run back and forth along the Graduated Track, is a small crystal microphone of adequate frequency range for the purposes of the standing wave tube method but which is not intended for other acoustic measurements. The microphone is mounted in elastic supports in the Microphone Carriage and is thus well insulated from external noise and vibration.

3. THEORETICAL BASIS FOR MEASUREMENTS

Results obtained from the standing wave apparatus are applicable for sound incident normally to the surface of the sample and restrictions are placed on the use of the equipment to ensure that the theoretical conditions are closely approximate during the practical operation. The frequency range of the method is limited at the lower frequencies by the length of the measuring tube which must be at least 0,25 of the wavelength under consideration and at the higher frequencies by the diameter of the tube which theoretically should be less than 0,586 of the wavelength under consideration in order to exclude the possibility of transverse resonances with the tube.

3.1. ABSORPTION COEFFICIENT

Consider an acoustic plane wave incident normally on the sample in the standing wave tube. At a particular point, the sound pressure due to the incident wave at a particular instant of time is given by the equation:

$$p_i = A \cos 2\pi ft \tag{1}$$

and the sound pressure due to the reflected wave at the same point at the same instant of time disregarding the phase angle between the incident and the reflected wave is given by:

$$p_r = B \cos 2\pi f \left(t - \frac{2y}{c} \right) \tag{2}$$

where

p_i = sound pressure of the incident sound wave in Pa
p_r = sound pressure of the reflected sound wave in Pa
f = frequency of excitation in Hz
y = distance of observed point from the surface of the sample in m
c = velocity of sound within the tube in $m.s^{-1}$
t = time in s

The total sound pressure at this point, p_y, will therefore be:

$$p_y = p_i + p_r = A \cos 2\pi ft + B \cos 2\pi f \left(t - \frac{2y}{c} \right) \tag{3}$$

By applying the Addition Theorem i.e.

$$\cos (\theta - \phi) = \cos \theta \cdot \cos \phi + \sin \theta \cdot \sin \phi \tag{4}$$

to the ultimate term in Eqn.3, it can be seen that the sound pressure will have a maximum value of $(A + B)\cos 2\pi ft$ when $y = \lambda/2$ and a minimum value of $(A - B)\cos 2\pi ft$ when $y = \lambda/4$ where λ = wavelength = c/f. A microphone situated at a distance $\lambda/2$

Tube terminated by a perfect reflector

Tube terminated by sound absorbing material

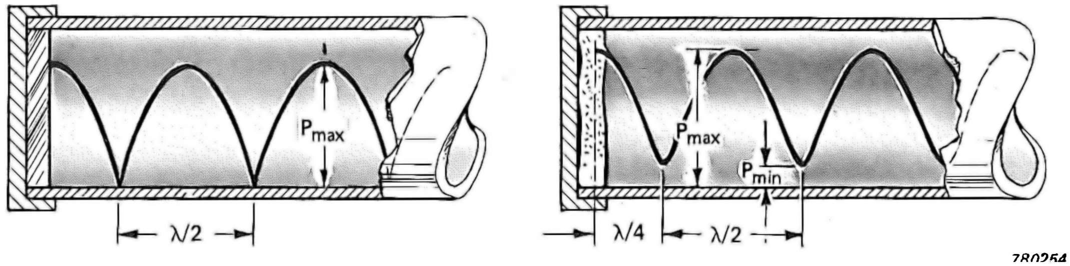


Fig.3.1. Cross section of the standing wave tube showing the standing wave pressure patterns and the effect of terminating the tube with sound absorbing material

from the sample will therefore receive an alternating sound pressure of frequency f and amplitude (A + B).

The absorption coefficient of the sample is defined as the ratio between the energy absorbed by the sample to the total energy incident on the sample and as energy is proportional to the square of the sound pressure then

$$\alpha = 1 - \left(\frac{B}{A}\right)^2 \tag{5}$$

This equation can be written

$$\alpha = 1 - r^2 \tag{6}$$

where r is the ratio between the reflected and the incident wave amplitudes i.e.

$$r = \frac{B}{A} \tag{7}$$

Using the standing wave apparatus, it is an easy matter to measure the ratio, n, of the maximum to minimum sound pressure in the tube that is the so called standing wave ratio:

$$n = \frac{p_{max}}{p_{min}} \tag{8}$$

$$\therefore \quad n = \frac{A + B}{A - B} \tag{9}$$

An analogy can be drawn between this acoustic standing wave ratio and the standing wave ratio measured in electromagnetic wave guides.

Hence

$$\frac{B}{A} = \frac{n - 1}{n + 1} \tag{10}$$

Therefore the absorption coefficient can be expressed in terms of the standing wave ratio by substituting Eqn.10 in Eqn.5 yielding:

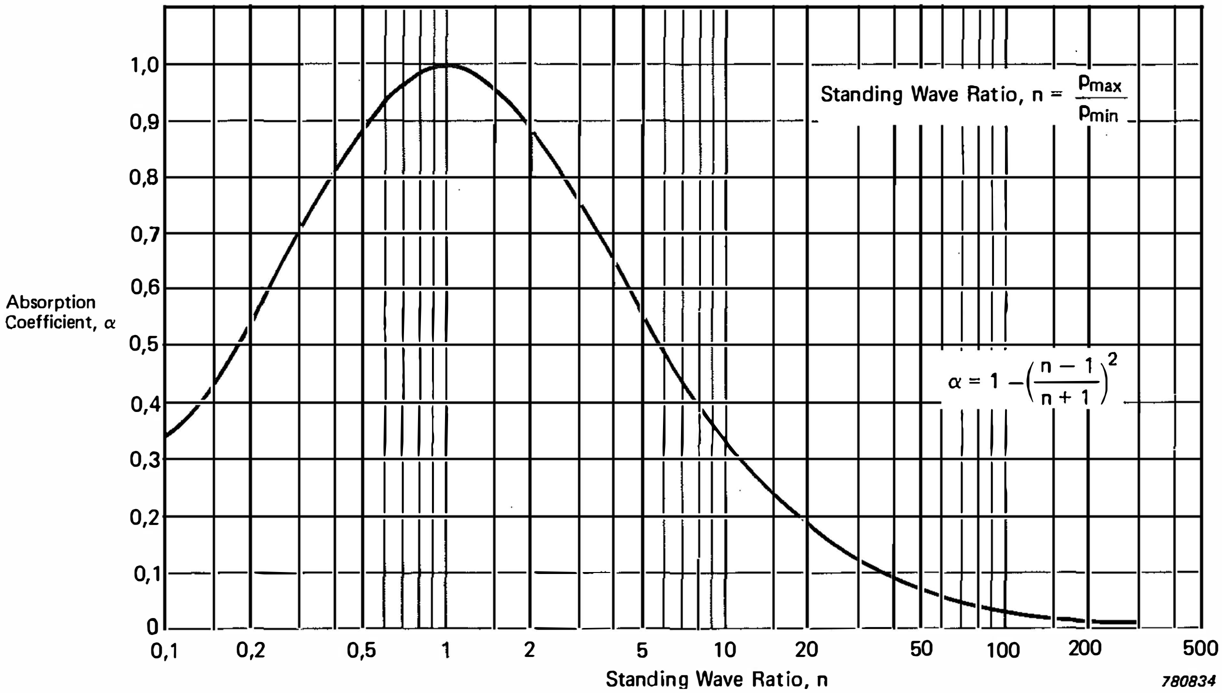


Fig.3.2. The relationship between the absorption coefficient, α, and the standing wave ratio, n

$$\alpha = 1 - \left(\frac{n-1}{n+1}\right)^2 \tag{11}$$

$$\therefore \quad \alpha = \frac{4n}{n^2 + 2n + 1} \tag{12}$$

This relationship between the absorption coefficient and the standing wave ratio is expressed graphically in Fig.3.2.

This measurement is made especially easy when a suitably calibrated scale is employed thus enabling the absorption coefficient to be read directly from the meter of the measuring amplifier. Such scales are available for all suitable B & K measuring amplifiers.

3.2. ACOUSTIC IMPEDANCE

When a sound wave impinges normally on an acoustic absorber, some energy is absorbed and some is reflected. The reflection, however, does not take place at the surface of the absorber, as is light, for example, when reflected from the surface of a mirror. The sound wave penetrates a certain distance into the absorber and reflection occurs at a hypothetical plane within the absorber. It is obviously impractical to make measurements within the absorber but fortunately the behaviour of the sound wave can be characterised by the normal acoustic impedance of the sample, z_n. The normal acoustic impedance of a sample is defined as the ratio of sound pressure acting on the surface of the sample to the associated particle velocity normal to the surface. Since the sound pressure and the particle velocity are not always in phase at the surface of a sample then the normal acoustic impedance may be complex and can thus be written as a sum of real and imaginary parts corresponding to the resistive and reactive components respectively, i.e.

$$z_n = (\text{resistive component}) + j(\text{reactive component})$$

For the standing wave tube we have therefore:

$$Z_n = \frac{p_i + p_r}{v_i + v_r} \tag{14}$$

where p_i and p_r are the sound pressures of the incident and reflected waves and v_i and v_r are their respective particle velocities. Now p and v are related to the characteristic impedance of air, ρc, within the tube. This quantity, sometimes referred to as the specific acoustic impedance of air, is a real quantity for plane waves and is the product of the density of air, ρ, and the speed of sound, c. For an air temperature of 20°C and at standard atmospheric pressure of 1013 mbar, the density of air is 1,21 kg/m^3 and the speed of sound is 343 m/s, giving the standard acoustic characteristic impedance of air a value of 415 rayls.

Therefore,

$$p_i = \rho c v_i \tag{15}$$

$$p_r = \rho c \ (-v_r) \tag{16}$$

Hence,

$$Z_n = \left(\frac{p_i + p_r}{p_i - p_r}\right) \cdot \rho c \tag{17}$$

$$Z_n = \left(\frac{1 + \frac{p_r}{p_i}}{1 - \frac{p_r}{p_i}}\right) \cdot \rho c \tag{18}$$

Now p_r and p_i are related by:

$$p_r = p_i \cdot r \cdot \exp \ (j \Delta) \tag{19}$$

where

r = reflection coefficient
Δ = phase angle between the incident and reflected sound pressures

Therefore

$$Z_n = \left(\frac{1 + r \cdot \exp \ (j\Delta)}{1 - r \cdot \exp \ (j\Delta)}\right) \cdot \rho c \tag{20}$$

This equation can be written as

$$Z_n = \left(R_e \ (Z_n) + j \, Im \ (Z_n)\right) \cdot \rho c \tag{21}$$

where it can be shown that

$$R_e \ (Z_n) = \frac{1 - r^2}{1 + r^2 - 2r \cos \Delta} \tag{22}$$

$$Im \ (Z_n) = \frac{2r \sin \Delta}{1 + r^2 - 2r \cos \Delta} \tag{23}$$

The normal acoustic impedance can therefore be completely determined from a knowledge of the reflection factor, r, and the phase angle, Δ. The reflection factor, as we saw in the previous section, can be determined from the standing wave ratio, n, i.e.

$$r = \frac{n-1}{n+1}$$

To determine the phase angle, it is useful to consider the quantities p_i and p_r as vectors rotating in the directions indicated on Fig.3.3, the phase angle between the vectors being Δ.

Writing p_i and p_r respectively as:

$$p_i = A \exp(j2\pi\, ft) \tag{24}$$

$$p_r = B \exp\left[j\left(2\pi ft - 2\pi f \frac{2y}{c} + \Delta\right)\right] \tag{25}$$

where $c = f\lambda$.

then dividing Eqn.25 by Eqn.24 yields:

$$p_r = \frac{B}{A}\, p_i \exp\left[-j\left(4\pi \frac{y}{\lambda} - \Delta\right)\right] \tag{26}$$

p_r is a minimum for

$$\frac{4\pi y_1}{\lambda} - \Delta = \pi \tag{27}$$

$$\therefore \Delta = \left(\frac{4y_1}{\lambda} - 1\right)\pi \tag{28}$$

At a distance, y_o, in front of the sample the phase angle between the incident and reflected wave is nought. As shown in Fig.3.3, y_o is positive for Δ positive and negative for Δ negative. At this point a pressure maximum occurs. A negative value of y_o means that the pressure maximum is situated within the sample, between the surface of the sample and the hard metal end of the tube. A mimimum of sound pressure occurs at a distance, y_1, where the two vectors in Fig.3.3 are 180° or π radians out of phase.

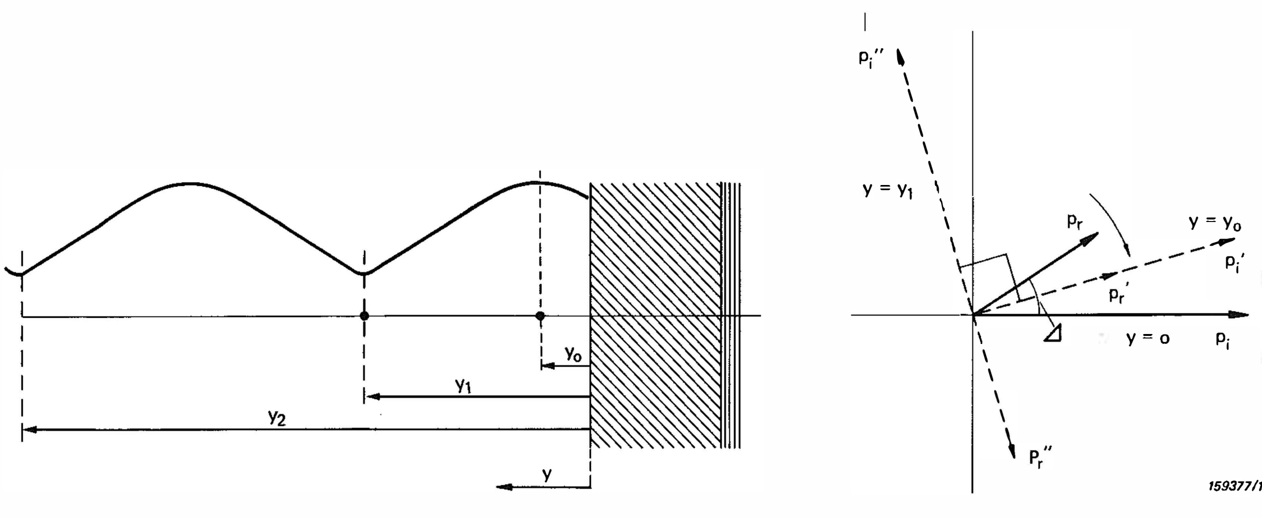


Fig.3.3. Vector diagram showing the phase relationship between the incident, p_i, and the reflected, p_r, wave pressures

The wavelength, λ, can be measured, instead of deriving this quantity, from the frequency set on the oscillator. In the cases where a second minimum can be measured at a distance y_2 (for the big tube this means for frequencies above about 250 Hz), the distance $y_2 - y_1$ yields the half wavelength so that Eqn.28 becomes

$$\Delta = \left(\frac{2y_1}{y_2 - y_1} - 1 \right) \pi \tag{29}$$

Knowing Δ and the absorption coefficient, α, the resistive and reactive parts of the normal acoustic impedance can be found with the aid of the Smith chart Fig.4.7, (see section 4.5) or by calculating the real and imaginary parts from Eqns.22 and 23.

3.3. BIBLIOGRAPHY

Per V. Brüel: Sound Insulation and Room Acoustics. Chapman & Hall, London.

C. Zwikker, C. W. Kosten: Sound Absorbing Materials. Elsvier, New York, London.

Leo L. Beranek: Acoustic Measurements. Wiley & Sons, New York.

Brüel & Kjær Technical Review, No.1, 1955.

4. PRACTICAL OPERATION

4.1. PREPARATION AND POSITIONING OF SAMPLE

The 4002 possesses two tubes of different lengths and each tube is provided with three sample holders. The test material has to be carefully cut, by employing a band saw, and the circular sample placed snugly into the sample holder. Porous material is cut so that it fits the internal diameter of the holder while absorption material with a hard covering plate, for example, acoustic tiling, is cut so that the hard plate fits the external diameter of the holder and the soft backing fits the internal diameter of the holder as seen in Fig.4.1.

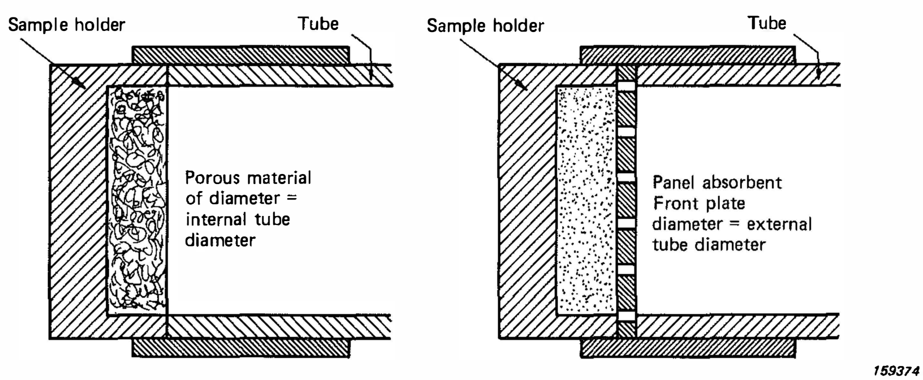


Fig.4.1. Mounting of absorptive material in the tube
On the left: porous material
On the right: porous material faced with hard plate

By mounting the material in this manner, the front plate is held very firmly. The securing clamp which braces the holder against the tube should be screwed on tightly in order to prevent vibrations occurring.

4.2. ASSEMBLING THE 4002

The Standing Wave Tube Type 4002 is assembled in the following manner:

1. The graduated measuring track is screwed firmly onto the loudspeaker cabinet by means of the knurled screws.

2. Either the long or the short tube, depending on the frequency range of interest is screwed firmly onto the loudspeaker cabinet by means of the four remaining knurled screws. The long tube should be orientated so that the supporting pin is on the underside of the tube.

3. The supporting pin is adjusted (only necessary for the long tube).

4. The microphone probe (either the long or the short depending on the tube) is carefully passed through the hole provided in the loudspeaker and into the tube itself.

5. The microphone carriage is placed on the track on the graduated measuring scale. Note that the vernier scale on the microphone carriage must be positioned over the graduated scale.

6. The microphone carriage is then wheeled up to the probe and the two parts are screwed firmly together. The long thread on the probe can be used to adjust the length of the probe thus altering the zero position of the microphone carriage (see step 9).

7. Wheel the probe as far as possible into the tube and slide either the supporting trolley or the sliding trolley (depending on the tube) over the end of the probe via the opening in the end of the tube. Wheel the microphone carriage back again.

8. The sample holder equipped with the sample material is placed in the tube and held in position by the retaining clamp. The slots in the arms of the clamp fit over the pins set on the side of the tube. The screw of the clamp is placed in the hollow on the rear of the sample holder and screwed down tightly. Note that if the clamp is not securely fastened then the measurements will be disrupted by the ensuing vibrations.

9. The microphone carriage is carefully wheeled up to the test sample. When the tip of the probe just touches the surface of the sample then the microphone carriage should be in the zero position. If not, then the probe position can be adjusted relative to the microphone carriage by means of the screw thread on the probe.

The 4002 is now ready for use. The connection of measuring instruments to the 4002 is described in the following section. Dismantling the 4002 is performed in the reverse order to that described above.

4.3. CONNECTION OF MEASURING INSTRUMENTS

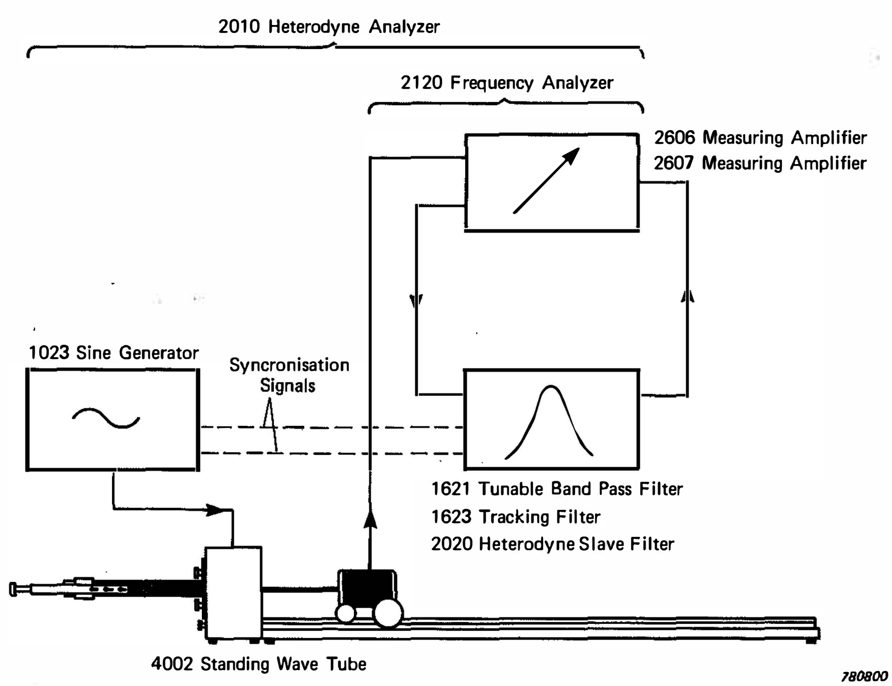


Fig.4.2. Possible arrangements of measuring instruments for use with the 4002

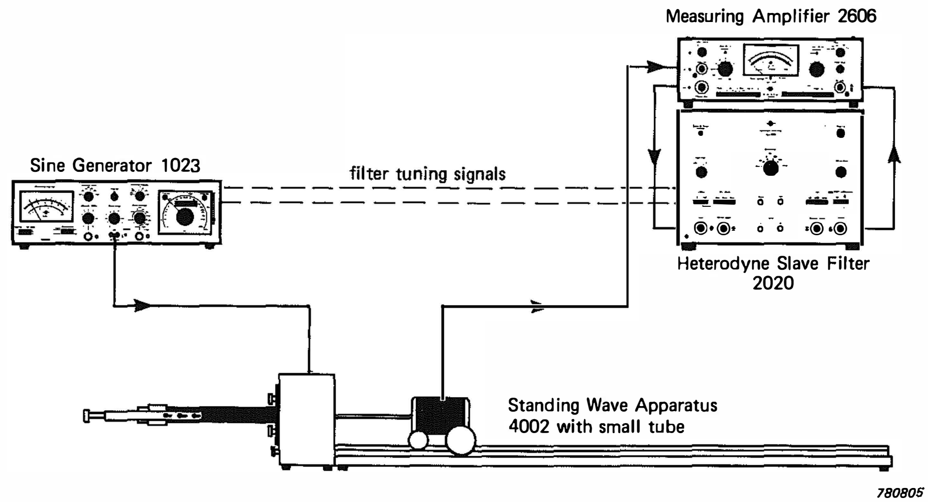


Fig.4.3. Typical measuring arrangement

The 4002 can be used with various measuring instruments. Fig.4.2 shows some possibilities. It should be noted that instead of using two or three measuring instruments, the Type 2010 can be connected to the 4002 giving a system which can probably be considered as the easiest to use. However, other laboratory instruments are often employed e.g. amplifiers and generators. The measuring arrangement shown in Fig.4.3 will be taken as an example and its use will be carefully described. Further information about how to employ the other measuring instruments will be found in the relevant Instruction Manuals. A filter such as the Type 2020 is used to improve the signal to noise ratio.

To connect the instruments shown in Fig.4.3, proceed as follows:

1. Connect the instruments to the mains.

2. Connect the instruments as given in Table 4.1.

Type No.	Socket	Cable	Socket	Type No.
4002	Loudspeaker Cabinet	AQ 0100 (2)	LOAD	1023
4002	Microphone Carriage	conn. to 4002	DIRECT INPUT	2606
2606	EXT. FILTER INPUT	AO 0014	OUTPUT	2020
2606	EXT. FILTER OUTPUT	AO 0014	INPUT	2020
1023	VARIABLE OSC.	AO 0064	"100 kHz - 120 kHz"	2020
1023	FIXED OSC.	AO 0064	"120 kHz"	2020

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Table 4.1. Cables and connections for the measuring arrangement shown in Fig.4.3

3. The controls of the 1023 are set as follows:

GENERATOR:	"On"
REF. SIGNAL:	"Off"
SWEEP CONTROL:	"Manual/Ext. Mech." and "Log."
COMPRESSOR SPEED:	"Off"
MODULATION FREQUENCY:	"Mod. Off"
COUNTING TIME:	"0,1 s"
POWER:	"On"
OUTPUT VOLTAGE:	As high as possible without overloading the loudspeaker
FREQUENCY SELECTION KNOB AND FINE ADJUSTMENT:	Set to the desired frequency. This frequency is the frequency of the standing wave in the tube.

4. Set the 2020 controls:

BANDWIDTH Hz:	"Auto"
B.F.O. MODE:	"Sine"
BANDWIDTH COMPENSATION:	"Off"
GAIN:	"0 dB"
POWER:	"On"

5. Insert Scale SA 0045 into the 2606.

   N.B. If instead of the 2606 another Measuring Amplifier be used such as the 2607, 2010 or the 2120 then Scale SA 0054 must be employed.

   Set the controls of the 2606:

Gain CONTROL:	"Cal."
FILTERS:	"Ext."
OUTPUT SECTION ATTENUATOR:	"x 1"
METER FUNCTION:	"RMS Fast"
INPUT:	"Direct"
POWER:	"On"
INPUT SECTION ATTENUATOR:	At a conveniently high level, without producing overloading

4.4. MEASUREMENT OF SOUND ABSORPTION COEFFICIENT

To measure the sound absorption coefficient one first completes the preparatory operations in sections 4.1, 4.2 and 4.3 then:

1. Set the FREQUENCY DIAL of the Sine Generator so that the FREQUENCY DISPLAY indicates the frequency of interest. Turn up the OUTPUT VOLTAGE until the DISTORTION lamp lights then slightly reduce the OUTPUT VOLTAGE. A suitably high sound pressure level should then be present in the tube.

2. Move the microphone carriage up and down until a pressure maximum is detected within the tube i.e. the probe microphone is positioned at a pressure maximum.

3. Adjust the meter deflection on the 2606 by means of the INPUT SECTION ATTENUATOR and the DIRECT INPUT "sens." to 100% on the scale. N.B. At frequencies below 200 Hz it may not be possible to find an isolated pressure maximum. In this case the pressure just in front of the sample should be used as a maximum.

Frequency, Hz	100	125	160	200	250	315	400	500	630	800	1000	1250	1600
Test Sample α													
Minimum measurable α													

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Frequency, Hz	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
Test Sample α										
Minimum measurable α										

Fig.4.4. Tabulation of absorption coefficient

4. Move the microphone carriage until the minimum nearest to the sample is indicated. The reason for measuring at this point is to minimise a possible error caused by sound attenuation along the tube. The absorption coefficient can then be read directly from the scale of the Measuring Amplifier. If the absorption be less than 70%, the gain on the amplifier can be increased by 10 dB and the absorption read from the 0 to 70% scale. If the absorption be less than 30% then the gain should be increased a further 10 dB and the absorption read from the 0 to 30 dB scale.

5. Repeat steps 1 to 4 for the other frequencies of interest and tabulate the results in tables as shown in Fig.4.4.

6. Remove the sample from the sample holder, reverse the sample holder and measure the absorption coefficient of the metal surface to determine the minimum measurable absorption coefficient.

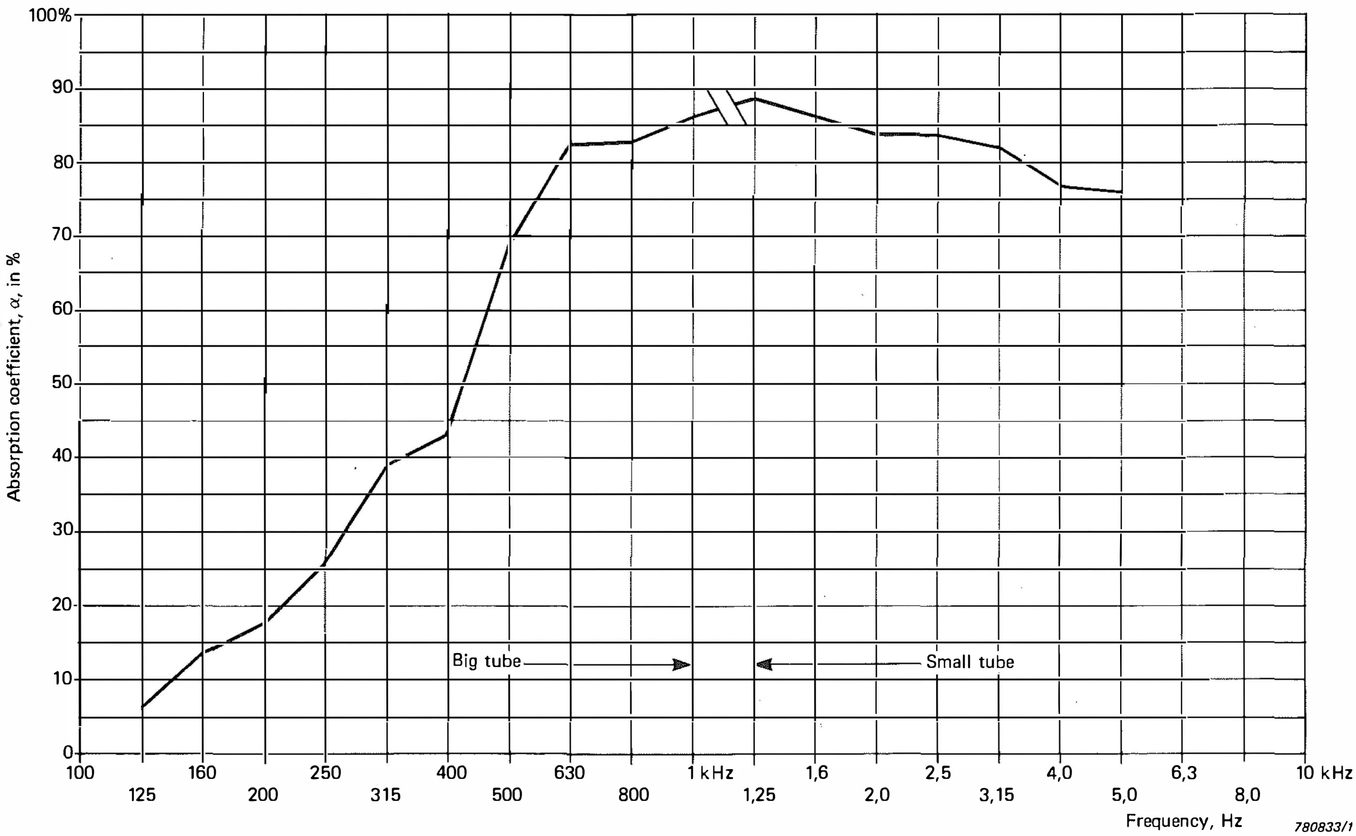

Fig.4.5. Absorption coefficient as a function of frequency for a fissured acoustic tile with a backing of mineral wool.

It is often useful to plot the absorption coefficient as a function of frequency. Fig. 4.5 shows the results obtained for a sample of fissured acoustic tile with a backing of mineral wool.

It should be remembered that the absorption coefficients as measured by the standing wave method are for normal incidence only which is why the measured coefficients are generally smaller than those determined by the reverberation room method and by employing Sabine's formula. In the diffuse field of the reverberation room, sound is incident on the test sample from all angles. As of yet no reliable way has been devised for relating the results obtained from the two methods.

4.5. MEASUREMENT OF ACOUSTIC IMPEDANCE

To measure the acoustic impedance of the sample, first carry out the preliminary adjustments described in sections 4.1, 4.2 and 4.3 then:

1. Determine the absorption coefficient of the sample as described in section 4.4. Tabulate the results in Fig. 4.6 and determine the ratio of reflected to incident sound pressure from the relationship

$$r = \sqrt{1-\alpha}$$

	Frequency					
	125	250	500	1000	2000	4000
α						
$r = \sqrt{1-\alpha}$						
y_1						
y_2						
$y_2 - y_1 = \frac{\lambda}{2}$						
$\Delta = \left(\frac{2\,y_1}{y_2 - y_1} - 1\right)\pi$						
$\mathrm{Re}\left(\frac{Zn}{\rho c}\right) = \frac{1 - r^2}{1 + r^2 - 2\,r\cos\Delta}$						
$\mathrm{Im}\left(\frac{Zn}{\rho c}\right) = \frac{2\,r\sin\Delta}{1 + r^2 - 2\,r\cos\Delta}$						
$\frac{Z}{\rho\,c} = \sqrt{\mathrm{Re}^2 + \mathrm{Im}^2}$						
$\phi = \tan^{-1}\left(\frac{\mathrm{Im}}{\mathrm{Re}}\right)$						

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Fig. 4.6. Calculation of acoustic impedance

2. Measure the distance between the sample and the first minimum of sound pressure in the tube and tabulate this value as y_1 in Fig.4. The specific acoustic impedance or characteristic impedance of air, ρc, appearing in Fig.4.6 may be taken as having a value of 415 rayls (see section 3.2).

3. Measure the distance between the sample and the second minimum of sound pressure in the tube and tabulate as y_2 in Fig.4. $y_2 - y_1$ therefore gives the half wavelength of the sound. The phase angle, Δ, of the reflection factor can then be evaluated from

$$\Delta = \left(\frac{2\,y_1}{y_2 - y_1} - 1 \right) \pi$$

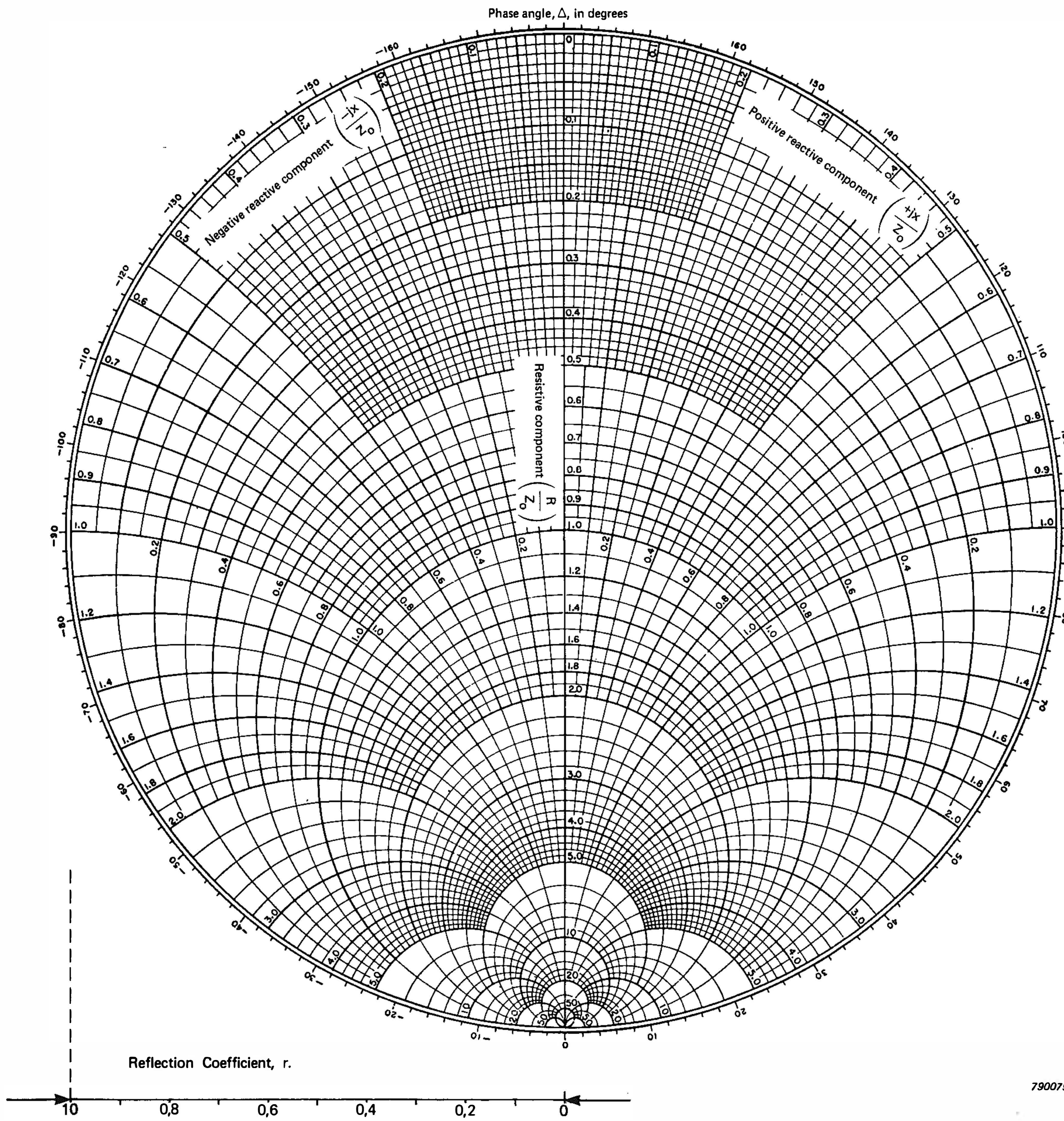


Fig.4.7. The Smith chart

4. The acoustic impedance is obtained from these values of r and Δ:

Either by direct calculation using a pocket calculator from the equation

$$Z_n = \left(\mathrm{Re}\,(Z_n) + j\mathrm{Im}\,(Z_n)\right)\,\rho c$$

where

$$R_e\,(Z_n) = \frac{1 - r^2}{1 + r^2 - 2r\cos\Delta}$$

$$\mathrm{Im}\,(Z_n) = \frac{2r\sin\Delta}{1 + r^2 - 2r\cos\Delta}$$

or by inserting the values of r and Δ into the Smith chart of Fig.4.7.

Practical use of the Smith chart is best illustrated by an example. Suppose the results of the measurements and calculation produce a value for the phase angle of $\Delta = 0{,}17\,\pi$ radians = 30° and a reflection coefficient of r = 0,80. First draw on the chart, the radius of the major circle to the point $\Delta = 30°$. Then measure from the centre of the circle along this radius a length corresponding to the value of r = 0,80 from the scale at the bottom of the chart. The point thus located on the chart determines the values of the real and imaginary parts of the normal acoustic impedance giving $\mathrm{Re}(Z_n/\rho c)$ = 1,4 and $\mathrm{Im}(Z_n/\rho c)$ = 3,1. Therefore (see Fig.4.8)

$$\frac{Z_n}{\rho c} = 1{,}4 + j\,3{,}1$$

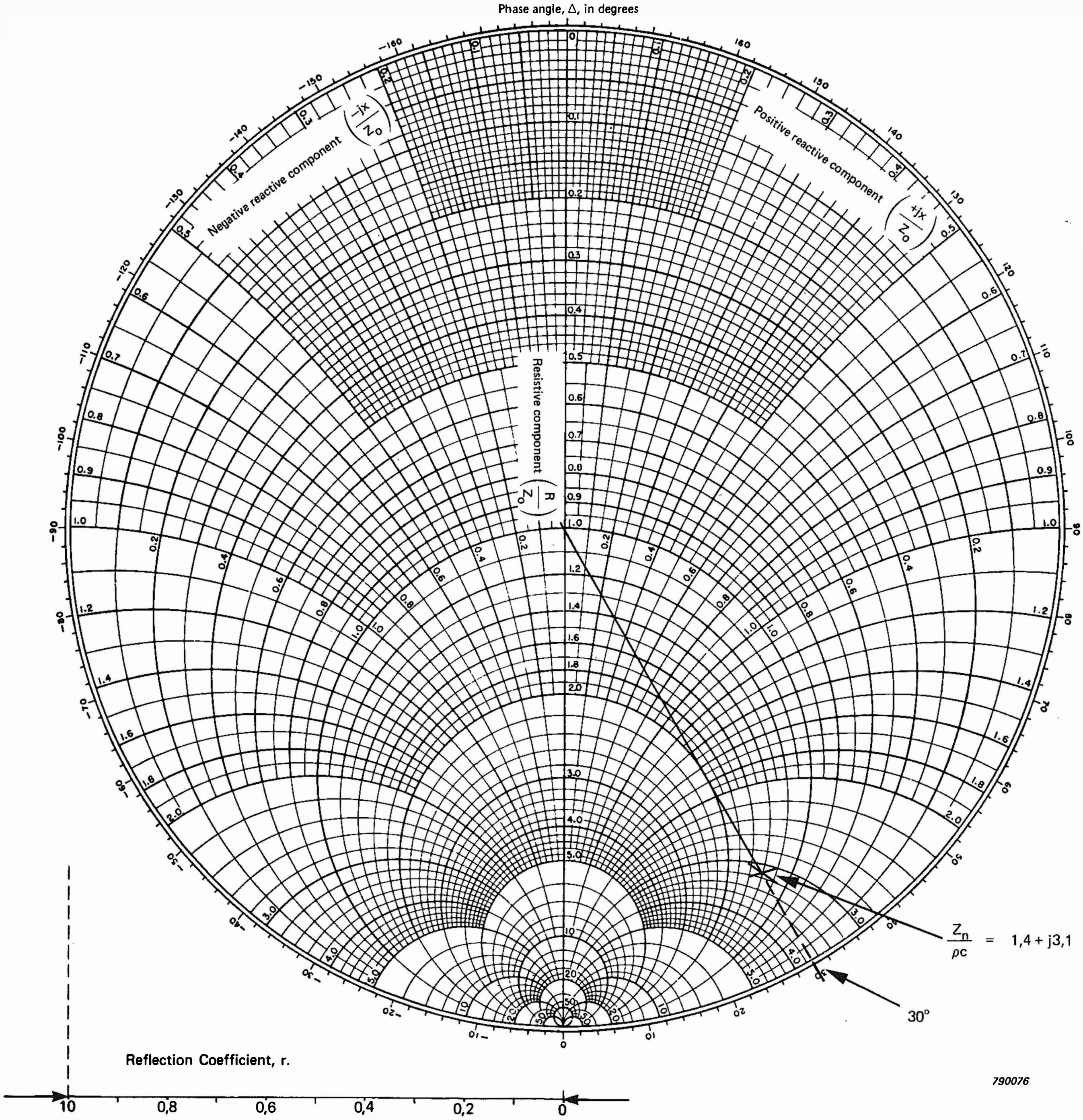
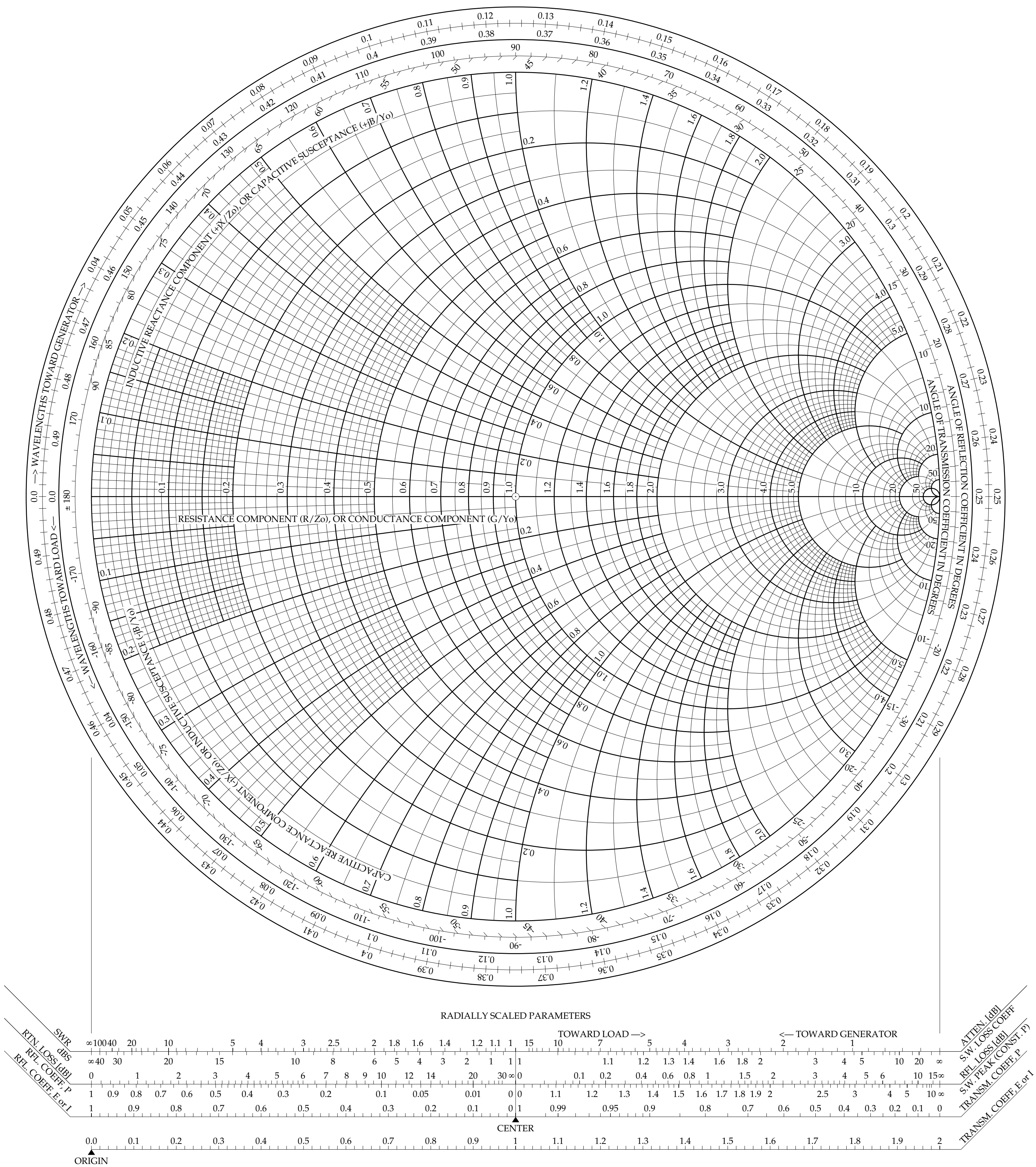


Fig.4.8. Example of use of Smith chart

The Complete Smith Chart

Black Magic Design



5. SERVICE AND REPAIR

The part numbers to the Standing Wave Apparatus Type 4002 are given in Fig.5.1 below, so that should any item be mislaid, a replacement can be ordered.

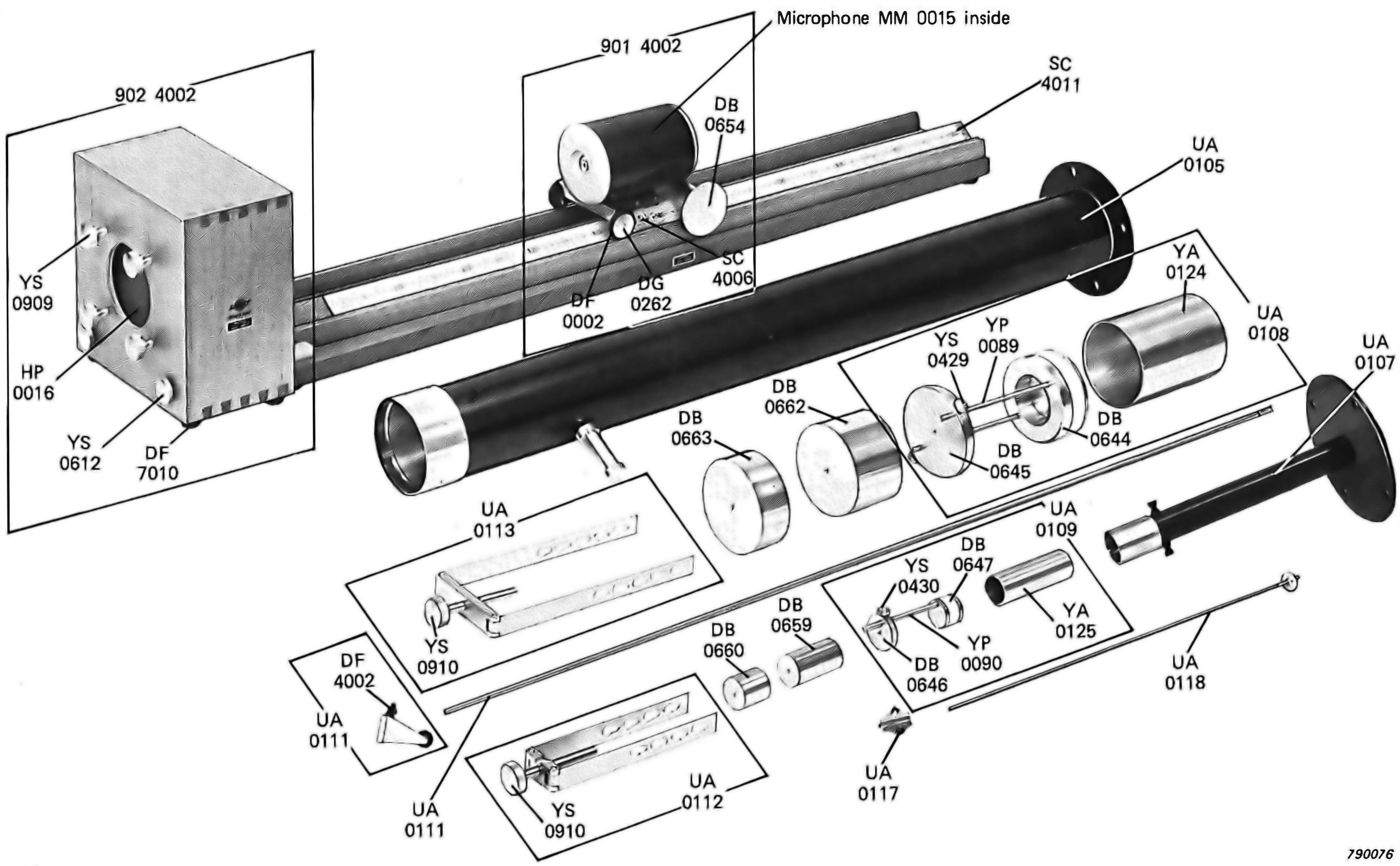
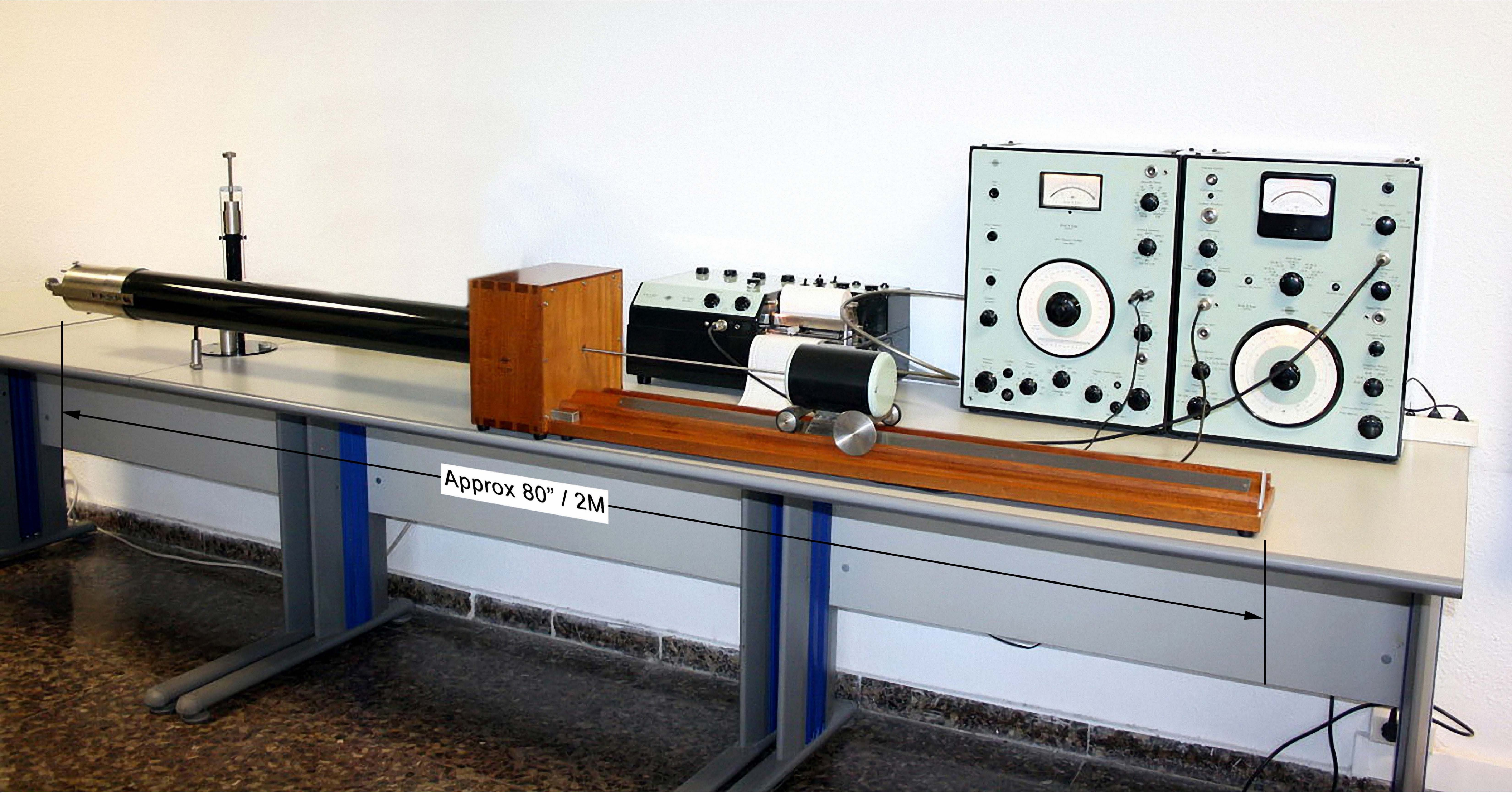


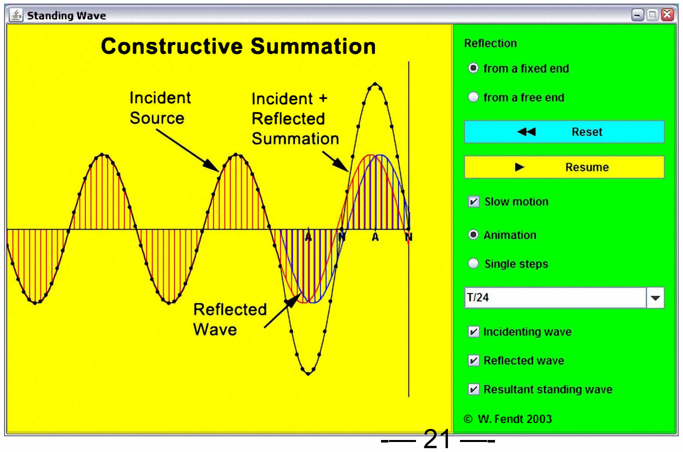
Fig.5.1. Part numbers of the Standing Wave Tube Type 4002

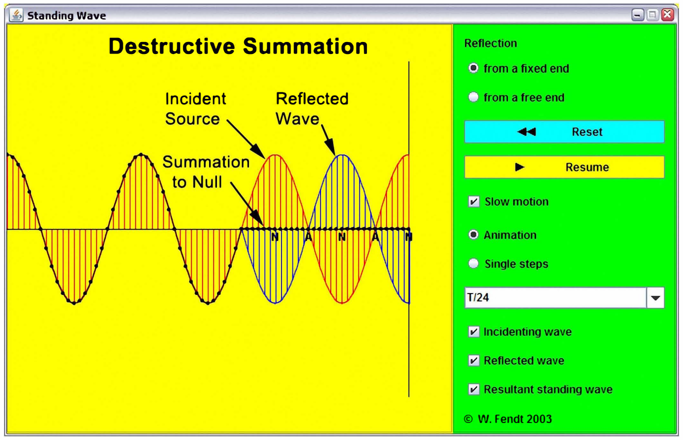


Java Standing Wave Applet

The outputs seen to the right were produced using a Java applet illustrating superposition of the reflected wave from a perfectly reflective surface.

Written by W. Fendt, the applet can be run on this page and downloaded for installation here; while a page with many other of his apps is seen here.





Absorption Coefficients and Impedance

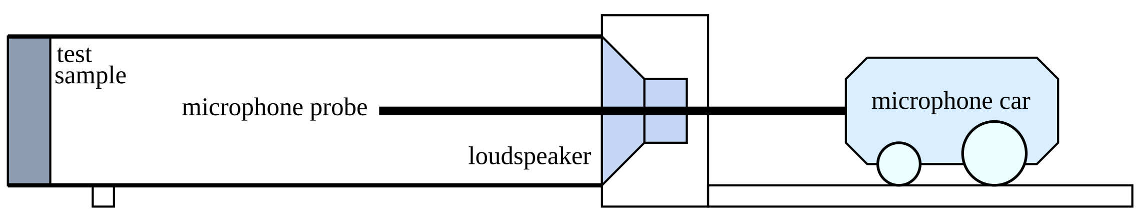
Daniel A. Russell
Science and Mathematics Department, Kettering University, Flint, MI, 48504

I. Introduction and Background

In this laboratory exercise you will measure the absorption coefficients and acoustic impedance of samples of acoustic absorbing materials using the Brüel & Kjær Standing Wave Apparatus Type 4002. Absorbing materials play an important role in architectural acoustics, the design of recording studios and listening rooms, and automobile interiors (seat material is responsible for almost 50% of sound absorption inside an automobile).

The reverberation time of a room is a very important acoustic quantity of concern to both architects and musicians. The growth and decay of the reverberant sound field in a room depends on the absorbing properties of the materials which cover the surfaces of the room under analysis. The Standing Wave Apparatus Type 4002, one of Brüel & Kjær's first products (almost 50 years ago), was developed primarily to measure the sound absorbing properties of building materials, and is still widely used today. The standing wave tube (also called an impedance tube) method allows one to make quick and easy, yet perfectly reproducible, measurements of absorption coefficients. The impedance tube also allows for accurate measurement of the normally incident acoustic impedance, and requires only small samples of the absorbing material.

A sketch of the B&K Standing Wave Apparatus is shown in the figure below. A loudspeaker produces an acoustic wave which travels down the pipe and reflects from the test sample. The phase interference between the waves in the pipe which are incident upon and reflected from the test sample will result in the formation of a standing wave pattern in the pipe. If 100% of the incident wave is reflected, then the incident and reflected waves have the same amplitude; the nodes in the pipe have zero pressure and the antinodes have double the pressure. If some of the incident sound energy is absorbed by the sample, then the incident and reflected waves have different amplitudes; the nodes in the pipe no longer have zero pressure. The pressure amplitudes at nodes and antinodes are measured with a microphone probe attached to a car which slides along a graduated ruler. The ratio of the pressure maximum (antinode) to the pressure minimum (node) is called the standing wave ratio SWR. This ratio, which always has a value greater than or equal to unity, is used to determine the sample's reflection coefficient amplitude R, its absorption coefficient α, and its impedance $\mathbf{Z}(\omega)$.



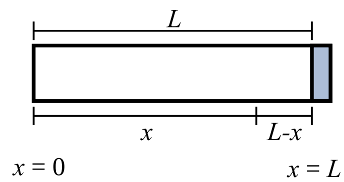
An alternate method for determining the absorbing properties of a material, also in wide use today, involves placing a unit-area piece of material (say one meter squared) in a special reverberation room. The difference in the reverberation time with and without the material yields the absorbing properties of the material. This method is generally more expensive, requiring precisely calibrated sensors and a specially designed reverberation chamber, and is much less convenient. Although this method does not yield normally incident acoustic impedance data, it is superior for measuring absorption characteristics for randomly incident sound waves, and is preferable for determination of absorbing properties that depend on the size of the material.

On a historical note, water-filled impedance tubes became critically important to the development of absorptive coating for submarines during World War II. Such coatings, developed first by Germany, were used (and still are) to protect submarines from sonar detection.

II. Theory

Assume that a pipe of cross-sectional area S and length L is driven by a piston at $x'=0$. The pipe is terminated at $x'=L$ by a mechanical impedance $\mathbf{Z}_{mL}$. If the piston vibrates harmonically at a frequency sufficiently low that only plane waves propagate[†] then the pressure wave in the pipe will be the sum of two waves travelling in the positive and negative x-directions,

$$\mathbf{p}\left(x,t\right)=\mathbf{A}e^{i\left[\omega t-kx\right]}+\mathbf{B}e^{i\left[\omega t+kx\right]} \tag{1}$$



To simplify the math, we specify the position in the pipe in terms of $L-x$, rather than x, as shown at right. The quantity $(L-x)$ measures the distance from the termination towards the driver. With this variable change the pressure equation becomes

$$\mathbf{p}\left(x,t\right)=\mathbf{A}e^{i\left[\omega t+k(L-x)\right]}+\mathbf{B}e^{i\left[\omega t-k(L-x)\right]} \tag{2}$$

where $\mathbf{A}$ and $\mathbf{B}$ are determined by the boundary conditions at $x=0$ and $x=L$. Using Euler's Equation $[\rho\partial\vec{u}/\partial t=-\partial p/\partial x]$, one may obtain the particle velocity in the pipe,

$$\vec{\mathbf{u}}\left(x,t\right)=\frac{1}{\rho c}\left(\mathbf{A}e^{i\left[\omega t+k(L-x)\right]}-\mathbf{B}e^{i\left[\omega t-k(L-x)\right]}\right) \tag{3}$$

The mechanical impedance of the plane waves in the pipe may be expressed as

$$\mathbf{Z}_m\left(x\right)=\frac{\mathbf{p}S}{\vec{\mathbf{u}}}=\rho cS\left[\frac{\mathbf{A}e^{i\,k(L-x)}+\mathbf{B}e^{-i\,k(L-x)}}{\mathbf{A}e^{i\,k(L-x)}-\mathbf{B}e^{-i\,k(L-x)}}\right] \tag{4}$$

The wave mechanical impedance at $x=L$ must equal the mechanical impedance of the termination,

$$\mathbf{Z}_{mL}=\rho cS\left[\frac{\mathbf{A}+\mathbf{B}}{\mathbf{A}-\mathbf{B}}\right]=\rho cS\left[\frac{1+\frac{\mathbf{B}}{\mathbf{A}}}{1-\frac{\mathbf{B}}{\mathbf{A}}}\right]\;. \tag{5}$$

If we choose to write $\mathbf{A}=A$ and $\mathbf{B}=Be^{i\,\theta}$ then

$$\mathbf{Z}_{mL}=\rho cS\left[\frac{1+\frac{B}{A}e^{i\,\theta}}{1-\frac{B}{A}e^{i\,\theta}}\right]\;. \tag{6}$$

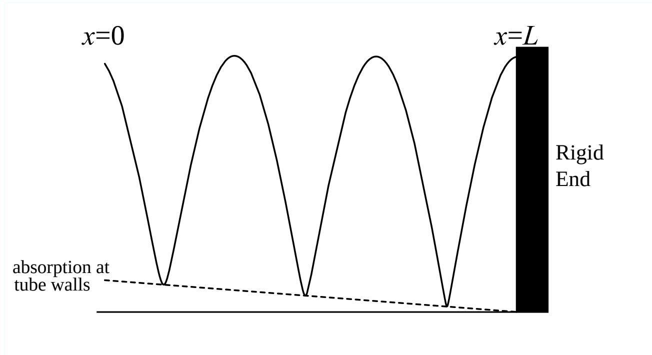
Thus, given the ratio of incident to reflected amplitudes, and the phase shift θ, the mechanical impedance of the sample may be determined.

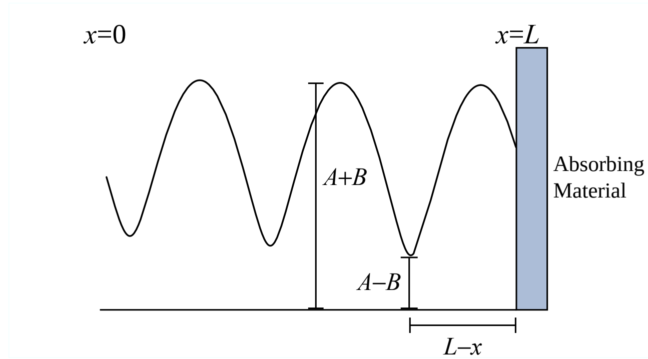
After a little algebraic manipulation, the pressure amplitude $P=|\mathbf{p}|$ of the wave from Eq. (2) may be written as

$$P=|\mathbf{p}|=\left\{\left(A+B\right)^2\cos^2\left[k\left(L-x\right)-\theta/2\right]+\left(A-B\right)^2\sin^2\left[k\left(L-x\right)-\theta/2\right]\right\}^{1/2} \tag{7}$$

This pressure amplitude is shown in the figures at the top of the next page. The figure on the left shows the pressure amplitude in the pipe with a rigid termination at $x=L$. All of the sound energy incident upon the termination is reflected with the same amplitude. However, there may be some absorption along the walls as the waves travel back and forth along the pipe. The figure on the right represents the case when the pipe is terminated at $x=L$ with some acoustic absorbing material. Now some of the incident sound energy is absorbed by the material so that the reflected waves do

[†] For a circular waveguide (pipe) filled with air, the highest frequency at which only plane waves will propagate is given by $f_{\text{max}}\approx 101/a$ where a is the radius of the waveguide. For the 10 cm diameter pipe used in this experiment $f_{\text{max}}\approx 2000\,\text{Hz}$.





not have the same amplitude as incident waves. In addition the absorbing material introduces a phase shift upon reflection. The amplitude at a pressure antinode (maximum pressure) is $(A+B)$, and the amplitude at a pressure node (minimum pressure) is $(A-B)$. It is not possible to measure A or B directly. However, we can measure $(A+B)$ and $(A-B)$ using the standing wave tube.

We define the ratio of pressure maximum to pressure minimum as the *standing wave ratio*

$$SWR = \frac{A+B}{A-B} \tag{8}$$

which may be arranged to provide the reflection coefficient B/A and the sound power reflection coefficient R_Π

$$\frac{B}{A} = \frac{SWR-1}{SWR+1}, \qquad R_\Pi = \left|\frac{B}{A}\right|^2 = \left(\frac{SWR-1}{SWR+1}\right)^2. \tag{9}$$

A pressure minimum occurs when

$$\cos\left[k\left(L-x\right)-\theta/2\right]=0 \qquad \text{and} \qquad \sin\left[k\left(L-x\right)-\theta/2\right]=1 \tag{10}$$

which requires that

$$k\left(L-x\right)-\theta/2 = \left(n-\frac{1}{2}\right)\pi \tag{11}$$

or

$$\theta = 2\,\frac{\omega}{c}\left(L-x\right)-\left(2n-1\right)\pi \tag{12}$$

where the quantity $(L-x)$ equals the distance from the test sample to the first pressure minimum $(n=1)$ as shown in the figure. The B&K Standing Wave Tube Apparatus allows for measurement of the maximum pressure, $(A+B)$, the minimum pressure, $(A-B)$, and the distance from the sample of the first minimum, $(L-x)$.

The complex mechanical impedance of the test sample may then obtained by substituting (12) and (9) into (6). The mechanical impedance of the test sample may be a complicated function of frequency, and it may be necessary to repeat the above measurements over the range of frequencies of interest. When a large number of frequencies are measured, it is inconvenient and unnecessary to carry out all the calculations as outlined above. Instead, use of a Smith calculator, (see reference 5) a nomographic chart, enables rapid determination of the real and imaginary parts of the impedance directly from measurements of the standing wave ratio and the position of the node nearest the sample.

The sound power absorption coefficient α for the test sample at a given frequency is given by

$$\alpha = 1 - R_\Pi^2 = 1 - \frac{\left(SWR-1\right)^2}{\left(SWR+1\right)^2} = \frac{4}{SWR+\frac{1}{SWR}+2}. \tag{13}$$

As was the case for the impedance, the absorption coefficient may be a function of frequency, and measurements over the frequency range of interest may be required.

Example Calculation of Impedance and Absorption Coefficient

When the standing wave tube is driven at a frequency of 1000 Hz with some test sample at the end of the impedance tube, the standing wave ratio is $SWR = 2$ and the first node is 0.129m from the sample end. Then $(L - x) = 0.129\,\mathrm{m}$ and $\theta = 2(2\pi 1000/343)(0.129) - \pi = 1.58 \approx \pi/2$. Furthermore, $B/A = (2-1)/(2+1) = 1/3$ so that

$$\frac{\mathbf{Z}_{mL}}{\rho c S} = \left[\frac{1+\frac{1}{3}e^{i\,\pi/2}}{1-\frac{1}{3}e^{i\,\pi/2}}\right] = 0.80 + i\,0.60 \qquad \text{and} \qquad \alpha = 1 - \left(\frac{B}{A}\right)^2 = 1 - \frac{1}{9} = 0.89,$$

which means that 89% of the incident sound power is absorbed by the sample.

III. Equipment

- Function/Waveform Generator (Hewlett-Packard 33120)
- Audio amplifier
- Several samples of acoustic absorbing material
- B&K Real-Time Frequency Analyzer Type 2133 (or equivalent 1/3 Octave Band Analyzer)
- B&K Frequency Analyzer Type 2107.
- Brüel & Kjær Standing Wave Apparatus Type 4002

The complete impedance tube measurement apparatus consists of two measuring tubes: a large one with an interior diameter of 10 cm, covering the frequency range from 90 to 2000 Hz, and a smaller tube with a diameter of 3 cm, covering the frequency range from 800 to 6500 Hz. A set of three sample holders is supplied for each tube. The tube is screwed to the loudspeaker cabinet. The microphone probes are led through a hold in the loudspeaker, and are connected at the back of the cabinet with the microphone carriage, which runs on a track provided with a scale. The actual microphone lies in elastic mountings within the microphone carriage, well insulated from airborne noise and impact sound or vibrations.

IV. Procedure and Analysis

A. Calculating α and Z_{mL} using an octave band frequency analyzer

- Place a sample of acoustic absorbing material in the cap of the impedance tube, and clamp the cap down tight. **Be sure to record the type of absorbing material**.
- Power up the frequency analyzer and set it up for octave band measurements.
- Connect the microphone jack to the Direct input on the Frequency Analyzer. You will have to use alligator clips and banana plugs to make this connection. Connect the HP function generator through the amplifier to the loudspeaker. Turn on the function generator and set the amplifier volume to about 3.

□ Set the function generator to produce a 125 Hz sine wave.

- Press the [Start] key on the frequency analyzer to begin taking a measurement.
- Set the cursor on the Frequency Analyzer to the 125 Hz band.
- Starting with the microphone car close to the loudspeaker (this positions the microphone probe close to the sample — *be careful not to push the microphone probe into the sample*), move the car to the right until the cursor on the frequency analyzer indicates a minimum level for the 125 Hz band. Record the minimum level (in dB) for the 125 Hz band.
- Locate and record (using the ruled scale under the microphone car) the position of the first minimum from the sample end of the tube.
- Move the microphone car until the cursor reading indicates a maximum level for the 125 Hz band. Record the maximum level (in dB) for the 125 Hz band.
- Return to step □ and repeat for the 250 Hz, 500 Hz, 1000 Hz and 2000 Hz octave bands.

B. Analysis of α and Z_{mL} calculations

For each octave band (making a table might be a good idea):

- ○ Calculate the maximum and minimum rms pressures from the recorded decibel levels using

$$Level_{\mathrm{dB}} = 20 \log p_{\mathrm{rms}} \qquad \Longrightarrow \qquad p_{\mathrm{rms}} = 10^{(Level_{\mathrm{dB}}/20)}$$

- ○ Calculate the standing wave ratio SWR using

$$SWR = \frac{p_{\mathrm{rms,max}}}{p_{\mathrm{rms,min}}}$$

- ○ Calculate the sound power reflection (B/A) coefficient using Eq. (9).
- ○ Calculate the sound power absorption coefficient α using Eq. (13).
- ○ Calculate the phase θ from Eq. (12) with $n = 1$ and with the quantity $(L - x)$ equal to the position of the first minimum.
- ○ Calculate the normalized mechanical impedance $Z_{mL}/\rho c S$ of the test sample using Eq. (6)
- ○ Calculate the mechanical impedance using the Smith Chart.

C. Direct Measurement of α using the B&K Frequency Analyzer Type 2107

The B&K Frequency Analyzer Type 2107 is designed especially for use with the Standing Wave Apparatus Type 4002, so that the sound power absorption coefficients may be measured directly without calculation.

- • Keep the same test sample in the impedance tube.
- • Disconnect the microphone from the B&K Real-Time Frequency Analyzer Type 2133 and turn the analyzer off.
- • Connect the microphone to the "Amplifier Input" jack on the Frequency Analyzer Type 2107.
- □ Set the function generator to produce a 125 Hz sine wave.
- • Using the "Frequency Tuning" dial and the "Frequency Range" knob, set the frequency of the analyzer to 125 Hz.
- • Set the "Input Potentiometer" knob to about 5, and adjust the "Meter Range" and "Range Multiplier" knobs until the needle on the "Indicating Meter" shows a response somewhere in the middle of the scale.
- • While watching the needle, move the microphone car until you find a pressure maximum (don't worry about the exact value indicated by the needle on the scale).
- • Adjust the "Input Potentiometer" knob so that the needle reads 100% on the top line of the bottom scale.
- • Move the microphone car until you find the pressure minimum closest to the sample.
- ○ Read off the percent from the top line of the bottom scale as indicated by the needle. This percent (converted to a decimal: 86%→0.86) is the sound power absorption coefficient.
- ○ For this sample, compare these measured values of the sound power absorption coefficient to the calculations previously obtained. Except for the lowest frequency band (125 Hz), the measured and calculated values should agree closely.
- △ Return to step □ and repeat for the 250 Hz, 500 Hz, 1000 Hz and 2000 Hz octave bands..
- • Repeat steps □ through △ for TWO additional samples. Be sure to record a description of the samples you are measuring.

D. Analysis of α measurements

- ⇒ Compare calculated and measured values for the absorption coefficient of your first sample.
- ⇒ Plot the absorption coefficient as a function of frequency for each of the three different samples. You can plot results of all three measurements on the same graph for comparison.
- ⇒ Some suggestions for analysis of your results: How does the absorption vary with frequency? Which samples provide the greatest amount of absorption? Over what frequency ranges are the samples most effective?

V. References

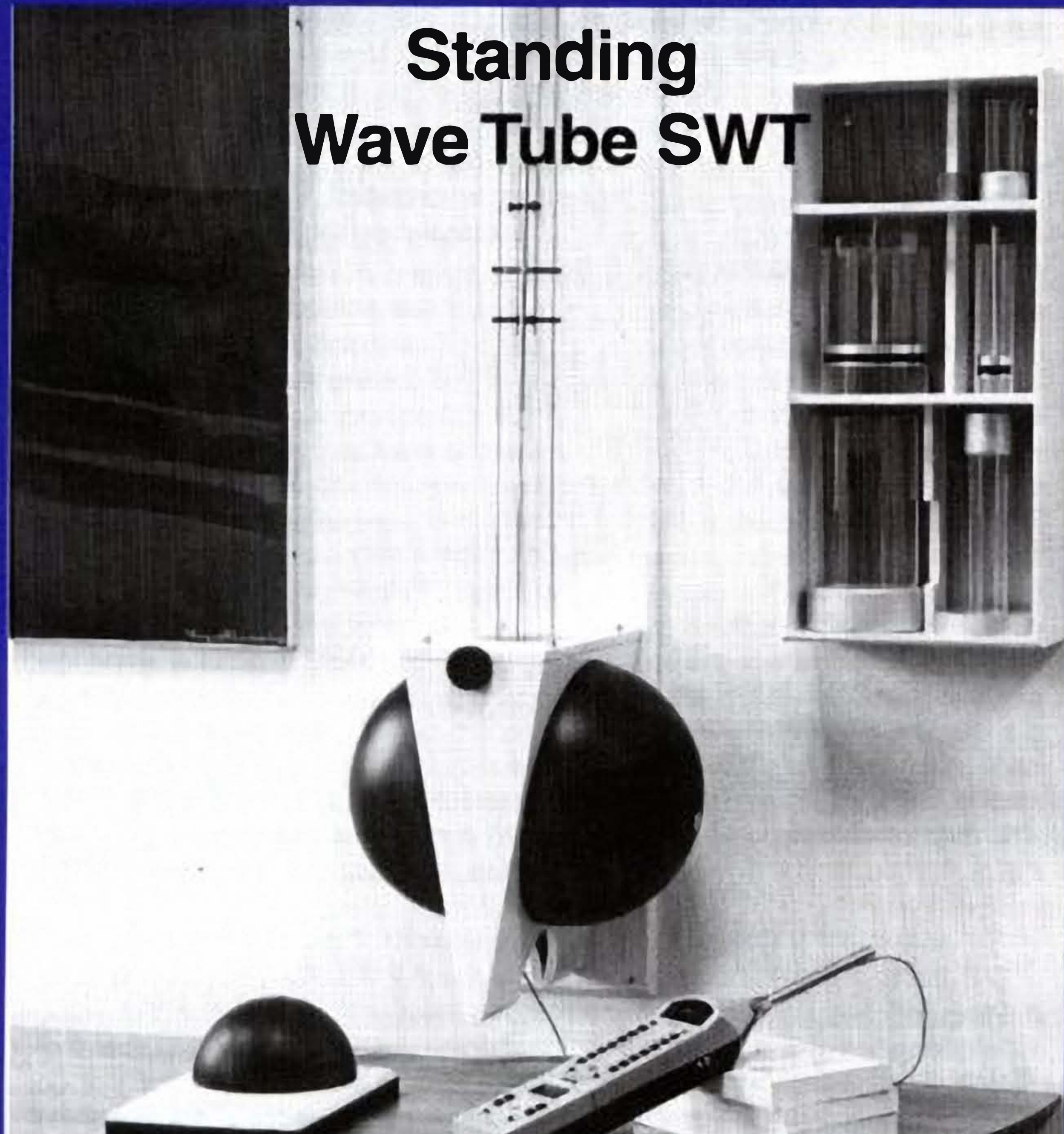
1. "Instructions and Applications" for Standing Wave Apparatus Type 4002 and Frequency Analyzer Type 2107, (Brüel & Kjær, 1967).
3. Kinsler, Frey, Coppens, and Sanders, *Fundamentals of Acoustics*, Third Edition, (John Wiley & Sons, 1982), Chapter 9.
2. Reynolds, *Engineering Principles of Acoustics: Noise and Vibration Control*, (Allyn & Bacon, 1981).
4. Bies and Hansen, *Engineering Noise Control: Theory and Practice*, Second Edition, (Chapman & Hall, 1996), Appendix D.
5. Elmore and Heald, *Physics of Waves*, (Dover reprint, 1985), Appendix B.
6. A very nice PostScript copy of a Smith Chart may be downloaded from the WWW URL: `http://marconi.uakron.edu/ wtm/smith.html`

Brüel Acoustics

97-01

Technical Review

To Advance Techniques in Acoustical and Noise Abatement Services



Acoustical Research - Sound Absorbers - Distributors - Instrument Services

Brüel Acoustics

Transparent Standing Wave Tube SWT 40BA

Transparent Standing Wave Tube SWT 40BA

For more than 65 years we have measured a material's acoustic absorption effectiveness in a Standing Wave Tube (SWT) (fig.l).
The probe is installed at the end of a long tube.
At the other end of the tube a loudspeaker radiates a pure tone along the tube to the sample under examination.
The sound is partly reflected from the sample and interference is generated which produces sound pressure maxima (p,,x) and minima (p min) along the tube.
The ratio between the maximum and the minimum is defined using a microphone or a microphone probe and through this the acoustical absorption co-efficient (d) is found.
Normally the SWT will be used in a horizontal position to allow the microphone or the probe to move.
Although this method is easy and accurate it has only limited use as the SWT is in the horizontal position and the probe is sitting vertically. **Most acoustical absorbing material is used on ceilings and is consequently used horizontally.**
As the SWT's probe is in a vertical position, the porous material in the sample will often separate from the front plate (fig.2).
As a consequence, a completely different sample is tested.
In addition, as the SWT is usually made of metal it is not even possible to check if the sample has been displaced.
To keep the sample in position a sample holder has been constructed.
As the sample is held vertically the holder is often complicated in design and uses heavy brackets and screws to avoid vibrations.
To achieve the correct sound field, the loudspeaker has been mounted centrally in the tube (fig.l).
This application is acoustically excellent but has the disadvantage that the probe or the microphone has to penetrate through a small hole in the LS-magnet which, from a practical perspective, is difficult.
Acoustical power level measurements using intensity technique will be increasingly common.
ISO recently published an Intemational Standard ISO 9614-1 for measuring sound power levels using the intensity method for checking the two microphone (2-Mic) intensity probe.
IEC has described in the draft paper TC 29/ 6631.91 a procedure where a special tube should be used. It would be advantageous if the SWT could be used for this checking procedure.
Unfortunately, with the SWTs known today, this is not possible (fig.l) as the intensity probe cannot be installed in the tube because of the central position of the loudspeaker.

It would also be useful if the SWT could be used for measuling acoustical absorption by using the 2-Mic intensity method i.e. described by Chang and Blazer in the Acoustic Society of America Joumal 68 914-921 (1980).
This method is very fast because the loudspeaker delivers white noise and the energy flow is analysed in such a way that the absorption is presented as a function of the frequency.
To date, in all the instruments which work according to the intensity principle, the 2-Mics are placed flush with the side of the tube, which is the worst possible position .
The microphones should be in the middle of the tube but this is not possible because of the centrally positioned loudspeaker.

This Brüel Acoustics invention eliminates all previously mentioned difficulties:
a) The SWT is turned 90 and is used in the vertical position. By this means the sample can be tested in its natural horizontal position (fig.3).
As only gravity is used to hold the sample and the sample holder the construction is simple and economical.

b) By having the SWT vertical, a lot of laboratory space can be saved.
Also, in this position the cables from the microphones or the intensity probes can move more freely.

c) By making the SWT of a transparent material it is possible to see if the sample is in the right position and to see if the microphone can be moved without hitting the sample or the tube wall.

d) By using two symetrically placed loudspeakers, as shown in fig.4, it is possible to insert an intensity probe in the measuring tube. The loudspeakers should only deliver sound to the tube and the loudspeakers should be mounted in such a way that the sound radiating backwards should be absorbed.
The loudspeakers should be energized in phase so that a symmetrical sound field will be produced in the tube.

e) By having two or more symetrically placed loudspeakers the whole construction is more versatile so it can be used for calibrating intensity probes and for measuring absorption co-efficients using the intensity methods.
This makes it possible to measure whole frequency bands at once instead of discreet pure tones.

Claims:
1) The SWT is intended for measuring absorption co-efficients from acoustical material and is characterized by being used in the vertical position.
Until now all SWTs have been used in the horizontal position.

2) The sample and the sample holder are kept in position by gravity alone.

3) The SWT is made of transparent material.

4) The SWT according to Claims 1, 2, and 3 uses two or more symmetrical loudspeakers.

5) The SWT according to Claims 1,2,3, and 4 can be used for checking intensity probes with reference to IEC Standards.

6) The SWT according to Claims 1,2,3, and 4 can be used for measuring absorption co-efficients and acoustic impedence by determining the energy flow with a centrally placed intensity probe.

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HOME

Brüel Acoustics

Technical Review 97-01

Front page

Renaissance of SWT

Dr. techn. Per V. Brüel

Today we have to develop and construct new acoustical absorbers without using mineral fibres as many people do not want this material used. We also need special absorbers which can stand high temperatures, heavy rain, and rough handling for sound damping in all kinds of machinery, airplane engines, cars, buses, railway cars, cold storage, operating theatres, etc. Testing of all the new absorbing material would normally be done in a certified laboratory where a standardised reverberation room is used in accordance with ISO standard 354. The standard requires a sample of around 10 m^2 placed on the floor. To test absorption material in a reverberation room in this way is somewhat doubtful, because it is not the physical constant, the absorption coefficient " which is tested, but the acoustical effect of the material placed in that particular room at a particular place. The result of the measurements depends on the size and form of the area of the test sample. The measurement also depends on the degree of diffusion of the sound waves in the room. The shape of the test room also has an important influence. The ISO standard therefore requires a specific size and form of the room. The room should have either non-parallel walls or large sound diffusers. The result is also influenced by the location in the room of the loudspeakers and microphones. It is recommended that the loudspeakers are placed in a corner, and that the microphones are moved or rotated during the measurement. As it is the acoustical effect of the material in the room which is measured, it is not surprising that a very effective absorbing material can show more than 100% absorption. This is natural as the material absorbs some energy from the hard walls close to the edge of the material. It is common to find 120- 140% absorption at some frequencies.

The new edition of the ISO standard 354 requires that if more than 100% absorption is measured, the result should be recorded in the report as 100%. This has been decided because people cannot understand that it is possible to absorb more energy than that impinging the surface. Ordinary people do not believe in *perpetuum mobile.* It is in fact incorrect to call what is measured in a reverberation room: absorption coefficient. Absorption coefficient is the physical ratio related to the material and defined as:

a = **(absorbed energy) / (energy impinging the surface)**

In accordance with this definition, the absorption coefficient can never exceed 100%. On the other hand, a measurement in a reverberation room cannot measure the absorption according to the above correct definition as there is no real control of either the energy absorbed or the impinged energy. The energy is estimated from Sabine's or Eyring's statistical formulas. As the reverberation room technique will always give results with an uncertainty of at best $\pm$ 10%, it is not practical to use it for the development of new absorbers.

Small improvements of a few percent are often very common at the many stages in the process of such development. Another disadvantage is that the reverberation process needs a large area of the sample material, which is both expensive and time consuming to make.

The right answer is to use the Standing Wave Tube (SWT), Fig. 1 shows a new convenient instrument which is used in the vertical position. A description of this instrument, **type 40 BA**, is given in BA Technical Information.

The SWT will always measure a physically correct absorption coefficient a_0 for sound incident perpendicular to the surface of the sample. a_0 is **only** dependent on the absorption material and not on other things such as the absorption measured in a reverberation room.

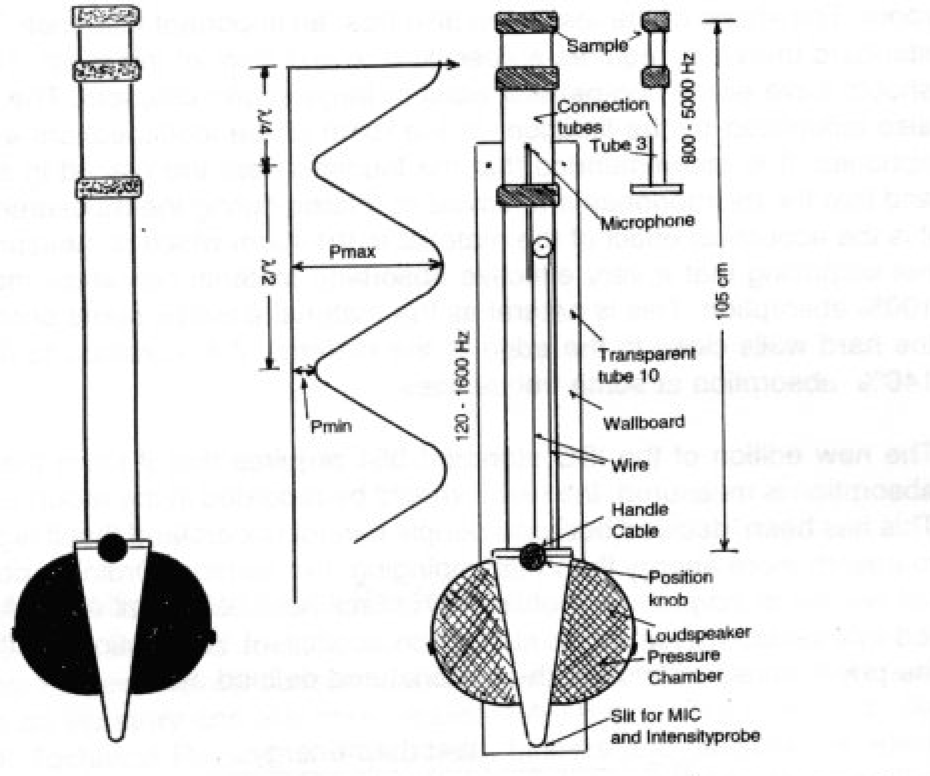


Fig. 1: Standing Wave Tube operating in vertical position. The tube is transparent and open between the two loudspeakers. Frequency range is 150-1600 Hz and 800-5000 Hz.

There are, however, some limitations, difficulties and psychological barriers to take care of.

Limitations: the SWT can only be used when the tube diameter D is less than given by the formula:

$$1{,}71\ \mathbf{D} = l$$

where l is the wavelength. But in practice a reliable measurement can only be made up to 20% from the lowest cross resonance. Fig. 2 shows some practical configurations for both circular and quadratic cross-sections.

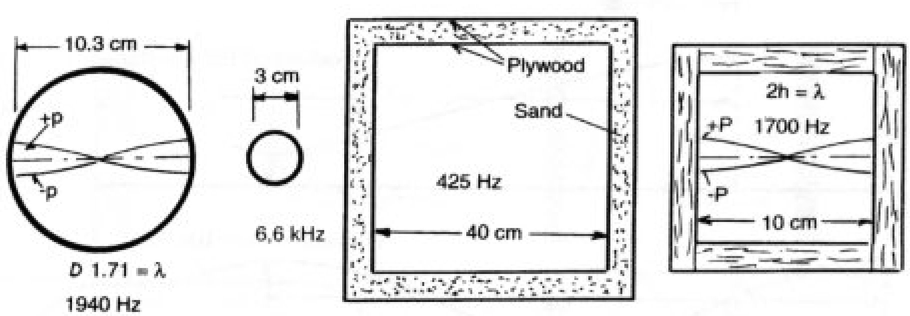


Fig. 2: Two cylindrical and two quadratic cross-sections of measuring tubes. The 40×40 cm tube wall is filled with sand. Max. error signal at the tube wall.

When a sound wave is travelling along a tube, it should maintain its amplitude. That is to say, no damping from the tube walls can be tolerated. With circular tubes there is no problem as all forces produced by the sound pressure are working tangential to the wall surface. As a consequence, the wall in a circular tube can be made of thin material and even transparent material. A quadratic or rectangular tube must be very stiff and strong to avoid energy absorption due to vibration. For a 10 cm quadratic tube, 20 mm glass or steel is normally sufficient. If vibration can be prevented, a thinner material can be used. For a 40x40 cm tube we have used a sand filling between two layers of glossy lacquered 6 mm plywood (see Fig. 2).

It is important that the microphone is placed in the middle of the tube as even two octaves below the cross resonance a pressure difference can occur over the tube cross-section. In Fig. 2 this is indicated for both a circular and a quadratic tube. It is also seen that if the microphone is placed in the centre, then a slight beginning of a cross resonance can be tolerated. But if the microphone is placed on the wall, it can be a disaster.

The length of the tube should be such that the ratio $\mathbf{p_{max}/p_{min}}$, can be measured with reasonable accuracy. This gives the limit for the lowest frequency which can be measured in a SWT. Fig. 3 shows the low frequency situation where the first part of the tube, close to the speaker, is not useful. At point C the sound wave is plane and the section of the tube after C is normally all right. At the other end of the tube, at points A-B, two things can happen:

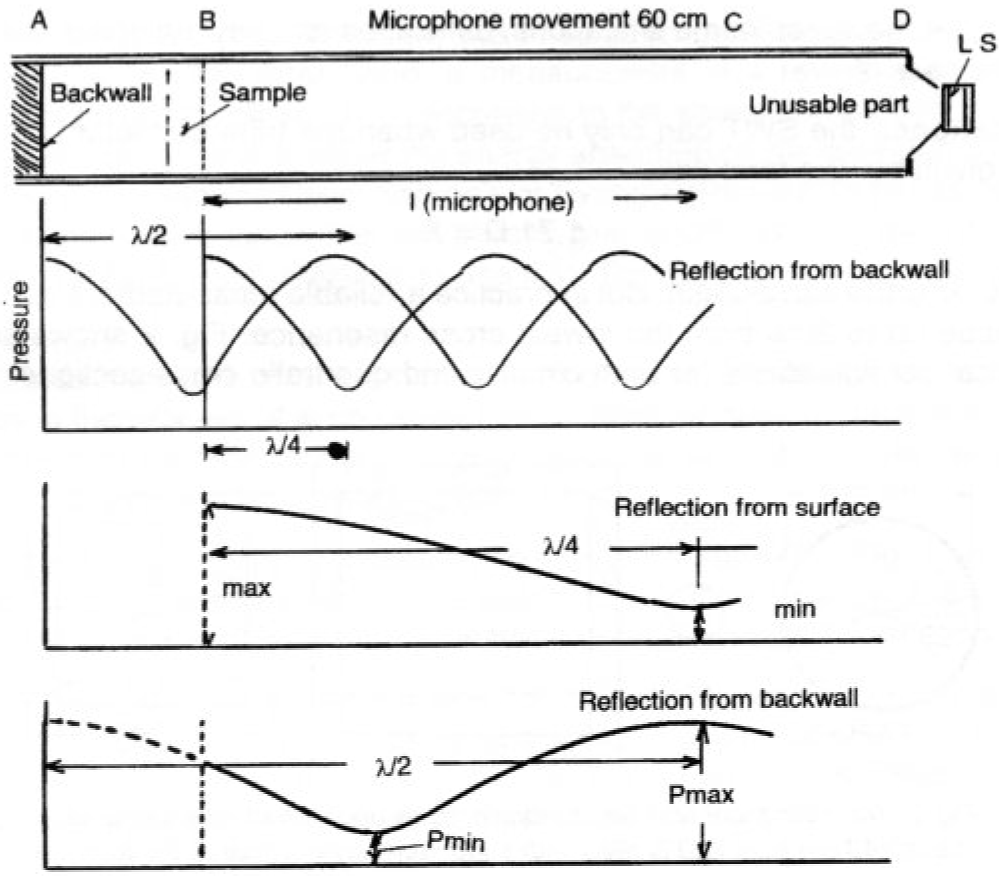


Fig. 3: Determining the lowest frequency for which a SWT can be used.

either the absorbing material B is very open and the sound passes through to point A before being reflected back. Or the material can be rather hard and the reflection takes place at B. In the latter case, the total measuring length B-C = l , can correspond to only l /4 as it is possible to measure maximum pressure at B and P_{min} at C. If the reflection takes place at A, the measurable length l , has to include the second maximum, so A-C has to be more than l /2. For the SWT shown in Fig. 1, the movable length of the microphone is 60 cm which for the hard absorbing material, where the maximum pressure is at the sample and the minimum is l /4 60 cm away, corresponds to 142 Hz. If the material is soft, the lowest frequency is determined by A-C = l /2 corresponding to 250 Hz. But when the wavelength is long and the thickness of the sample is small (less than 8 cm), it is still possible to use the pressure at the sample as max. p and then it is possible to measure down to l /4 = 60+8 = 68 cm corresponding to 130 Hz. When the absorbing material is textile or a perforated plate with mineral-wool behind, the absorber is stiffness-controlled at lower frequencies. In this case the absorption will decrease by 6 dB/octave, and the absorption can be estimated with a good approximation down to a very low frequency (see Fig. 4).

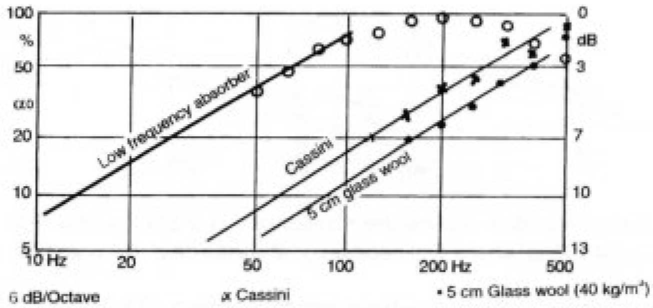


Fig. 4: Extrapolation of stiffness-controlled absorber. 6 dB/octave.

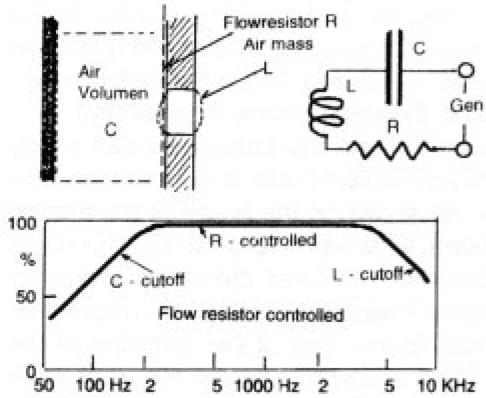


Fig. 5: Flow-resistor controlled absorber with high absorption over a broad frequency band.

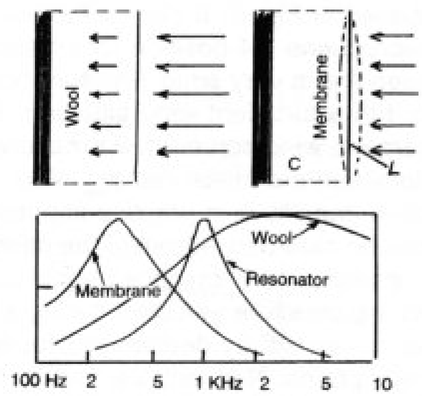


Fig. 6: Mass-stiffness (membrane) absorber has only a limited useable frequency band. Textile on a wall has only absorption at high frequency.

Absorbers of the membrane type, where the absorption is due to vibration in a plate or membrane, cannot be measured in a SWT. In any case, membrane-type absorbers have only limited applications as it can be proven that they cover only a narrow frequency band. Practically all effective absorbers are constructed as shown in Fig. 5. To obtain a broad frequency band, the flow-resistor (R) must have values of the same order of magnitude as the internal resistance of the generator. L must be small, which means a thin plate with small holes placed closely together. C should be large and this means the airspace behind the absorber also has to be large. It can been seen in Fig. 6 that a mass- stiffness controlled absorber can work only in a limited frequency band around a resonance. The best absorber is resistor controlled where the flow resistor make the impedance of air. So the most practical and efficient absorbers can be developed and tested in a SWT, thereby avoiding expensive and doubtful reverberation room tests.

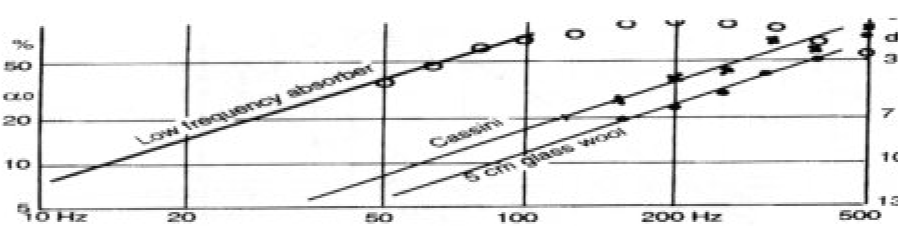


Fig. 7: Turbulent airflow around the microphone in a SWT where high velocity (λ/4) exists where it is necessary to measure a low pressure.

There are, however, still limitations to the lowest absorption which can be measured. Any material with less than 10% absorption has to be treated carefully, and material with an absorption coefficient less than 5% is impossible to measure. Not only is a very good seal between the sample and tube required, but also the cross-section at the microphone and transport system has to be less than 1-2 % of the tube cross-section. The friction between the moving air particles and the tube wall produces a slight damping which has to be compensated for. But the most important factor is a S/N problem illustrated in Fig. 7. It shows the sound pressure and particle velocity. At the microphone l /4 position for an absorption of 4% at the end of the tube, it is seen that a very small pressure has to be measured with a microphone placed in a turbulent wind situation. Even if the microphone is protected by a ceramic wind-screen, the pressure variation from the turbulence can easily dominate the measured p_{min}. With 10% absorption there is normally no problem, but 2% is in practice impossible. As shown in the figure, a nose-cone can be mounted in front of the microphone. This will help 8-10 dB. The noise from the wind turbulence cannot be filtered out as it has the same frequency as the pressure variation. Using a smaller microphone does not help much as the sensitivity decreases proportional to the area of the diameter of the microphone. Normally it is very seldom that absorption below 10% if of interest and since a cone makes it impossible to move the microphone all the way up to the surface of the sample, it is better not to use a turbulence cone.

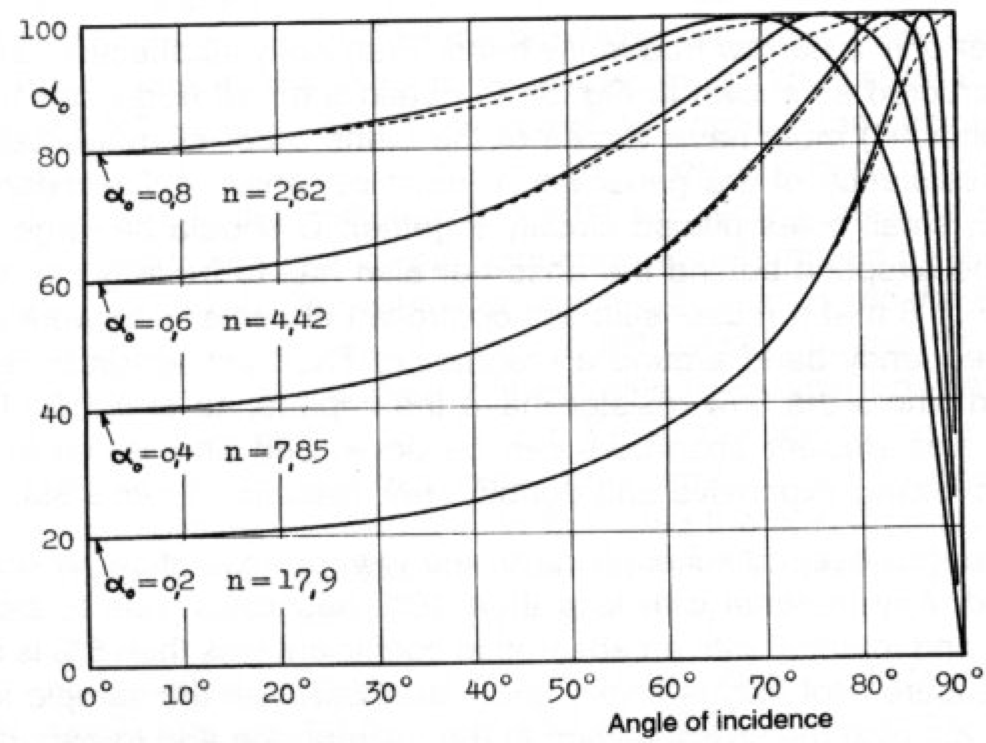


Fig. 8: Theory for absorption for different angle of incidence.

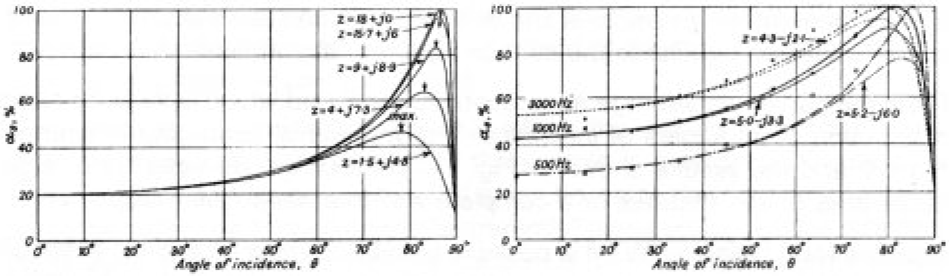
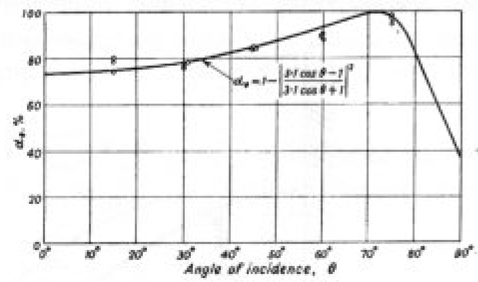


Fig. 9: Absorption as a function of angle of incidence. Curves for both real and complex acoustical impedance are shown. The dots are experimental verification.



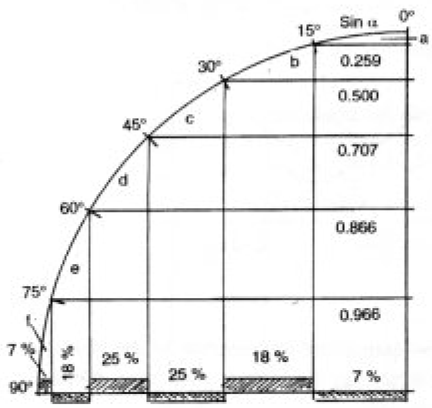


Fig. 10: Scheme for determining the contribution for each area of the sphere when sound is diffusely oriented.

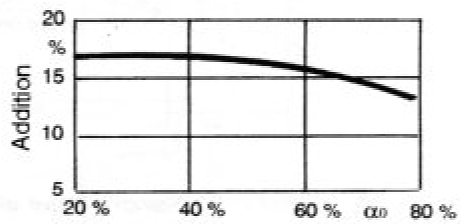


Fig. 11: The addition in percentage has to be added to the measured α_0 to get the average absorption α. Valid for diffuse field and large areas.

Angle of Incidence: In a SWT it is only possible to measure the absorption of the sample for perpendicular incidence with great precision. The results are only dependent on the sample. It is a real physical characteristic of the material, without any influence due to the size and form of the room or the placing of the material in the room. For other sound incidence you normally get a higher absorption than *u* for any other angle of incidence. In 1938 there were several theories explaining this increase in absorption. In a later BA Review we shall describe and show the background and verification of these theories. The practical results are shown in Fig. 8, and are valid for absorbers which are resistive controlled such as porous material, and porous material covered with a hard plate with holes. In other words, the acoustical impedance at the reflecting plane should be real. If the impedance in this plane is complex with an appreciable imaginary component, the curves are slightly different. An example is shown in Fig. 9. It can been seen that sound waves travelling parallel to the surface have an "absorption" which is $a_0/2$.

From the curves an average absorption can be found which is valid for even distribution of all angles of incidence. The method of averaging is seen in Fig. 10 and the results shown in Fig. 11. The curves are valid for a large plane area of the material or a complete wall in a rectangular room.

Penetration: Using a SWT it is possible to evaluate how far into the material the sound wave penetrates or in other words what part of the absorbing material is active in the mechanism of sound absorption. In this way it can be determined where the efficiency of an absorber reaches its maximum and unnecessary material can be omitted.

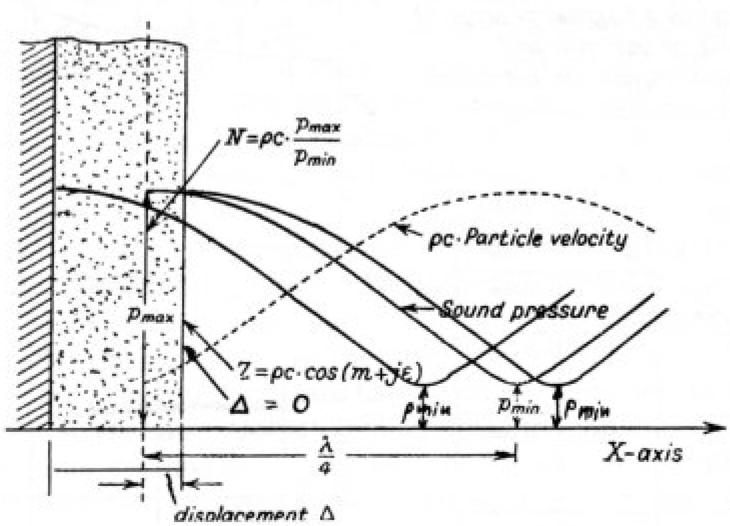


Fig. 12: Position of the Standing Wave when the acoustical impedance of the material is complex. An absorber is shown which is controlled by flow-resistance and stiffness (no mass is involved).

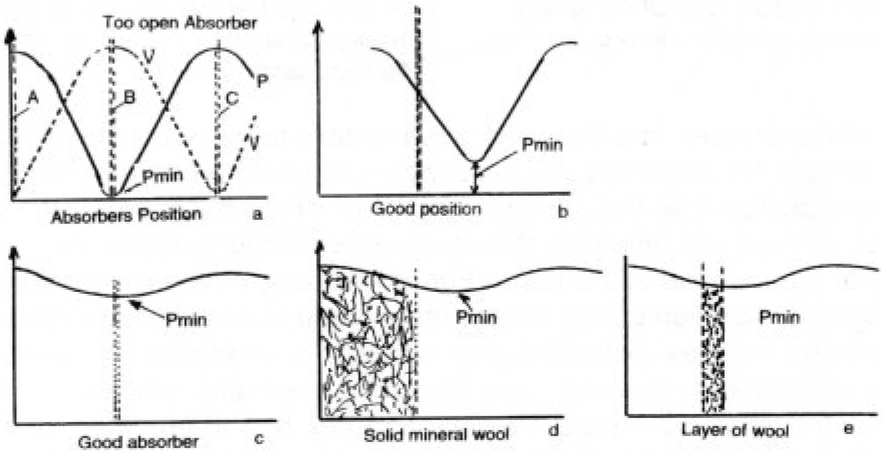


Fig. 13: Pressure standing wave for different absorption material. B is the position of surface of material, a: the thin material is too open, b: better flow resistance, c: close to optimal, d: high absorption mineral wool, e: economical high absorption of thin layer of wool.

The technique is simple, see Fig. 12, where the distance from the sound pressure minimum to the surface of the sample is measured. Knowing the frequency, l /4 can be calculated and it can be determined where the position of the reflection in the sample "apparently" takes place. If the reflection takes place at the surface, then the material is too hard and does not absorb any energy. If the reflection occurs at the "back wall", then the material is too soft or open. The optimum is when the reflection takes place between the surface and the back wall. A few examples in Fig. 13 show both p and the penetration.

In Fig. 14 it is seen that the hard rockwool does not absorb as much as the only 5 cm thick glasswool for frequencies over 600 Hz; for lower frequencies it is the other way round. The **AcoustiCassini**, which is a thin 0.3 mm resistor behind an Al-net, has a resonance around 500 Hz where the absorption is high. When both mass and stiffness are involved, the "reflection" can occur both behind the back wall and outside the surface of the sample. To facilitate the position of the microphone, it is necessary to have a fairly accurate and simple way to check the distance between the microphone and the surface of the sample. It is convenient to use only the standardised preferred frequencies, where the wavelength or l /4 for every frequency can be taken from a table.

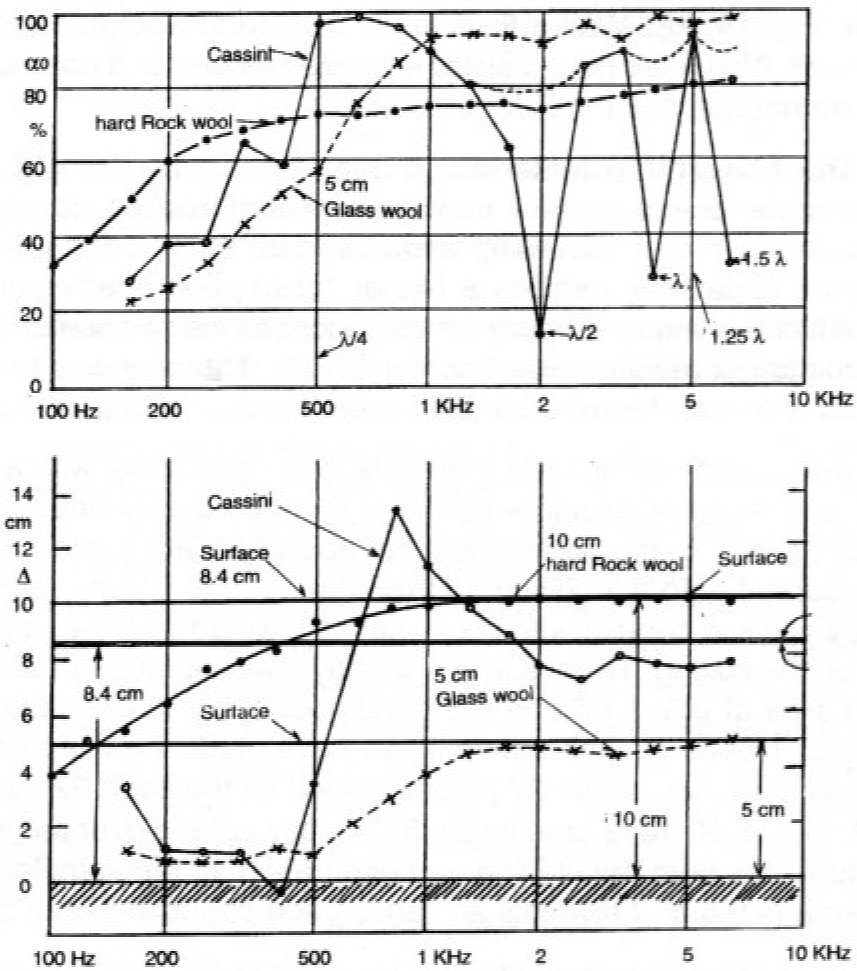


Fig. 14: Top: Absorption α_0 for hard Rockwool, Glasswool and the flow-resistor Cassini as a function of frequency. Below the corresponding distance from the surface where the "reflection takes place".

In Fig. 14 some pronounced minima in absorption for the **Cassini** are seen. The lack of absorption occur at l /2, l, and 1.51 . These minima occur when the flow-resistor is very thin and placed in a pressure maximum, where the particle velocity is small. When the velocity is nearly 0, no energy can be absorbed. This phenomenon only happens when the flow-resistor is perpendicular to the particle velocity direction. When the angle is different from 0° the phenomenon is blurred and the absorption is as indicated with the dotted lines in Fig. 14, top. With a thick layer of mineral-wool the phenomenon does not exist. Also if the flow-resistor is curved as part of a cone or cylinder, there are no notable minima.

Dividing the Absorption Material: It is a fact that by dividing acoustical absorption material into smaller parts one gets increased absorption. It is easy to understand that absorbing material can "suck" energy from the sides and thus apparently exhibits a higher *"absorption coefficient"*. It is not only very difficult to make a theory which describes the phenomenon, but it is also difficult to get reliable experimental results. The only way to rnake measurements is to use the reverberation room method with all its uncertainty.

We have measured two different materials: 5 cm glasswool with a density of 60 kg/m^3 and AcoustiCassini which is a half-cylinder Al-net supporting a flow-resistor sheet. In this experiment the absorbers are placed on the floor and not mounted onto the ceiling. In this case, due to gravity, the flow-resistor is not always in contact with the AI-net as it would be if the absorber was mounted on the ceiling. The result is a slightly lower absorption. The Cassini covers an area of 0.3x1 m^2 and the glasswool is cut to the same size. We have used 32 pieces of each material. We have made measurements with 6 different configurations of the 32 pieces placed on the floor: 32 pieces together, 2x16, 4x8, 8x4, 16x2, and finally 32 equally spread over the entire floor. Fig. 15 illustrates both the placing and orientation of the samples. The total covered area is 9.6m^2. From this an *"absorption coefficient"* can be defined.

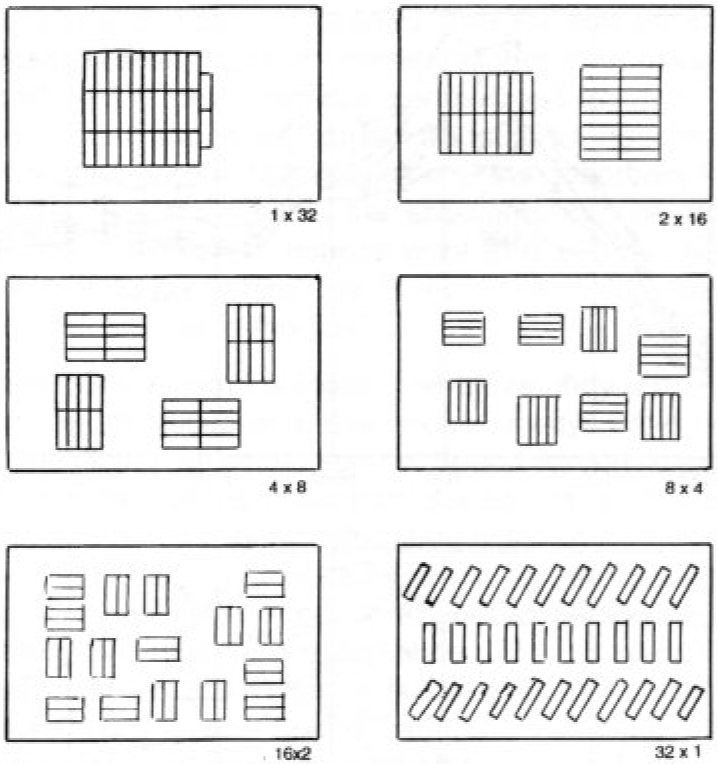


Fig. 15: Floor of a reverberation room where 32 pieces of glasswool and Cassinis are placed in various configurations. Optimum is when all pieces are spread out as much as possible (32×1).

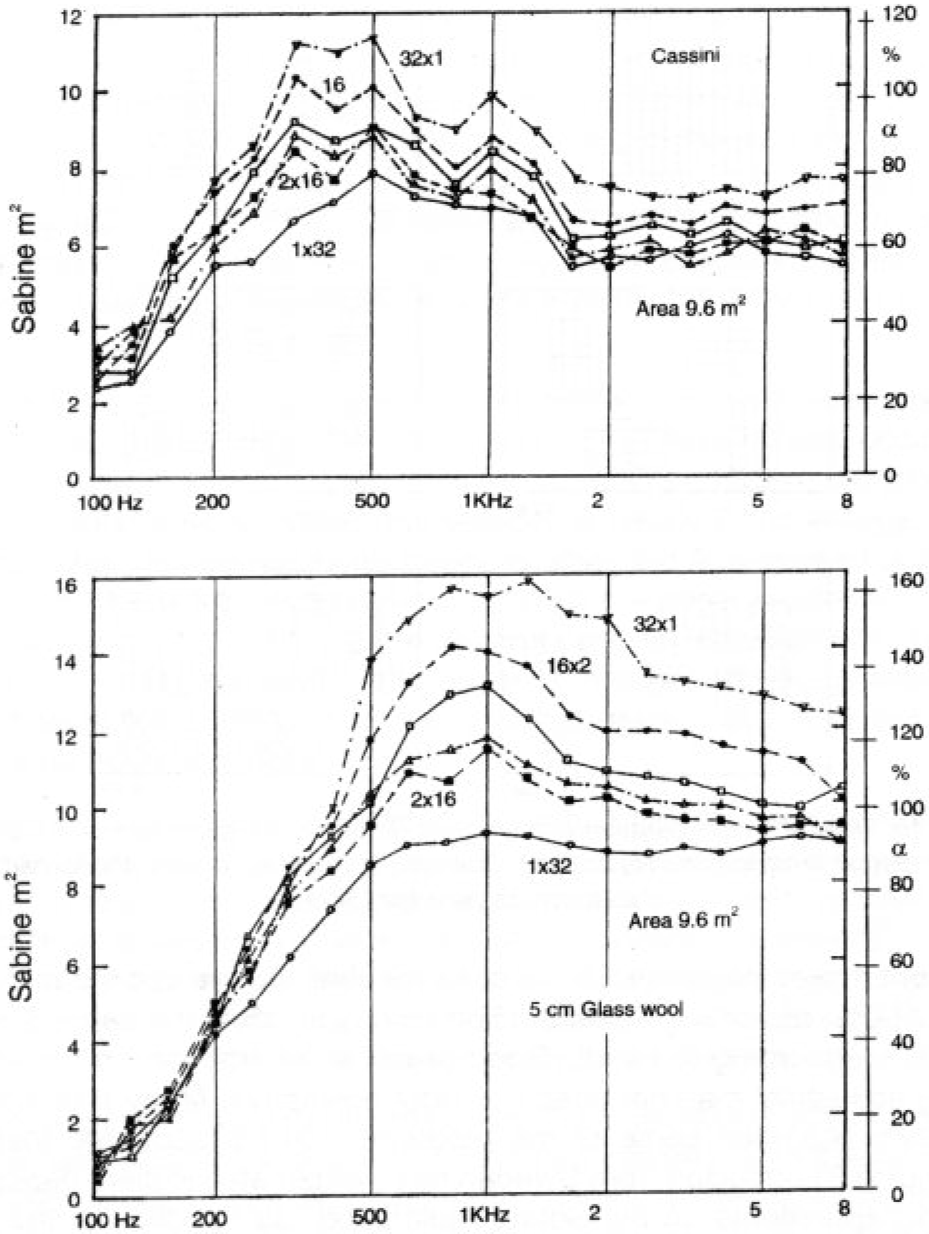


Fig. 16: Absorption expressed in Sabines (1m² 100% absorption) for the different configurations shown in Fig. 15.

The results of the measurements can be seen in Fig. 16. It is clear that a spreading of the material increases the absorption of the material. Over a large frequency range the *"absorption coefficient"* is far in excess of 100%. It is therefore economical to use single absorbers in workshops, offices, schoolrooms etc. To evaluate these single units with regard to absorption coefficient makes no sense. In this case we shall always use the unit Sabine = 1 m^2 100% absorbing surface. (Sometimes in USA the sab = 1 square- foot 100% absorbing is used). Good practical information on the effect of dividing acoustical material does not exist nowadays. Many theoretical papers have explained some of the problems. In his doctorate thesis, Dr. Sven-Ingvar Thomasson from Sweden has written an excellent paper "Theory and Experiments on the Sound Absorption as Function of the Area", (Report Trita-Tak-8201, Stockholrn, May 1982), which contains a comprehensive list of earlier work. We have tested some of the theories, but none fit our measurements. So we recommend you to use the information given in Fig. 16. One must bear in mind that the results are dependent on both the actual acoustical impedance, room size, location in room, sound distribution, and the actual form and area of the absorber. Which part of the reverberation curve is used for determination of the reverberation time (RT) also has great influence. The ISO standard requires the use of the part of the reverberation curve from -5dB to -35 dB and this has been done for the measurements in Fig. 16. In general we prefer the early decay (EDT) which is most important for both speech intelligibility and music.

The curves given in Fig. 16 are from a major research project concerning material division made in collaboration with Florence University and financed by the EU under the M.O.N.I.C.A. project.

Practical Determination of RT in Rooms: We now have everything we need to estimate the reverberation time for every single frequency in auditoria, theatres, concert halls, studios, schoolrooms, offices, and sports- halls. We have measured a_0 and from the drawing of the room in question the first reflection of the direct sound is determined for angle of incidence. From Fig. 8 and Fig. 9 the absorption coefficient a is found. Knowing the size of the absorber a correction of a can be estimated from Fig.16. Now simply multiply a with the surface area S of the absorber and we have the product a**S**. Adding it all together the total product Sa**S** for all walls, ceiling, furniture and persons is obtained. The RT can be estimated from Sabine's formula. The accuracy is normally higher than using the average absorption coefficient a measured in a standardised reverberation room. If a detailed calculation shows that certain frequency ranges do not have the desired RT, it is often easy to change some of the absorbers so that the RT can be corrected. The changes in the absorbers can be done by using another perforation, a different mineral-wool and another flow-resistor or using a different airspace behind the flow-resistor. Each change can be checked on a small sample in the SWT.

Sound Barriers: Good sound screens - whatever they are - along motorways, railway lines, in offices or banks, should always have absorbing elements on the side facing the sound source. Sound screens cannot give more than a few dB reduction of the noise from the source, so it is extremely important that the screens are both sufficiently high, have the best form and absorb as much as possible of the sound at the right frequencies. Therefore start by making an A-weighted spectrogram not at the source of the sound, but at the place where people are disturbed. Then construct an absorber with the highest possible absorption at the frequencies where the spectrogram shows maximum levels. Sound barriers for outdoor use should be made of weather-proof material. Under these conditions it is still more important to use the SWT instrumentation for optimum performance.

Ray Tracing: Computer models of concert halls, sports-halls, auditoriums and theatres are today made by tracking sound rays around in the room. Each ray may reflect from walls and obstacles several times and each time some sound energy is lost due to absorption and sound spreading. Often the absorption coefficient for wall material is determined as an average figure from a reverberation room test. As the rays impinge at many different angles of incidence, it would be far more accurate to use *u,* with corrections as shown in Fig. 8. Correction for the size of the material should be made according to Fig. 16. In this way, a ray tracing program can be made correctly.

Sound Intensity Probe Calibration: Intensity measuring systems must be tested and calibrated in a SWT according to IEC standard 1043 from 1996. The probe must be moved inside a SWT which is terminated with an absorber with 22,3% absorption. This gives a pressure ratio from p_{min} to p_{max} of 24 dB. In this reverberant field the intensity meter must give a constant value within ± 0.5 dB for all probe positions. You can now check any opening behind the microphone membranes, any holes in a membrane and if the multiplier in the electronics does not calculate correctly. Fig. 17 shows the set-up which all laboratories working with intensity should be able to perform.

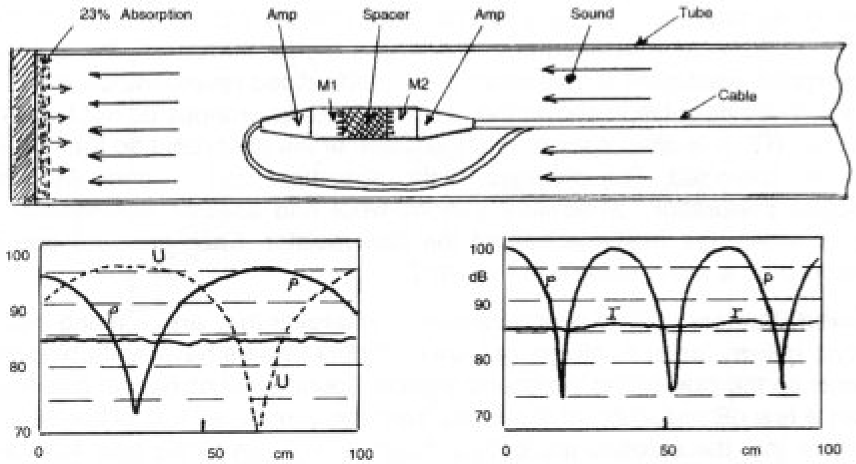


Fig. 17:: Intensity probe calibration according to IEC 1043, p_{max}/p_{min} should be 24 dB.

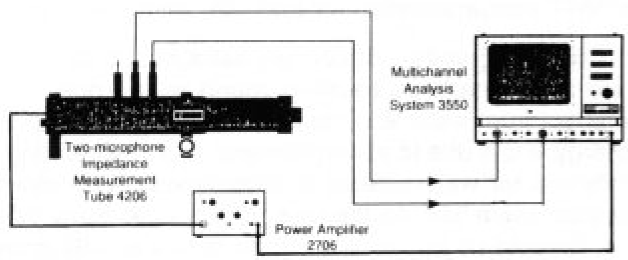


Fig. 18: Measurement of α_0 and impedance with the two microphone tubes.

Two Microphone Test: Some people prefer to test absorption material with broad-band noise. This is done using two microphones. See Fig. 18. This method is very fast to work with, but has some disadvantages. The microphone has a fixed location and for some frequencies, where the pressure is near 0, it is difficult to get reasonable results. A problem is also that an error signal always has a maximum at the tube wall, see Fig. 2.

The standard SWT as shown in Fig. 1 also has the possibility, besides calibration of intensity probes, to be used as the basis for a two microphone system (Fig. 19). An intensity probe simply replaces the two wall-mounted microphones.

By placing an intensity probe in the middle of the tube, it is possible to use the Two Microphone System over a larger frequency range. If the probe can be moved, it is possible to check the system only by moving the probe. Therefore the third microphone position shown in Fig. 18 is not necessary.

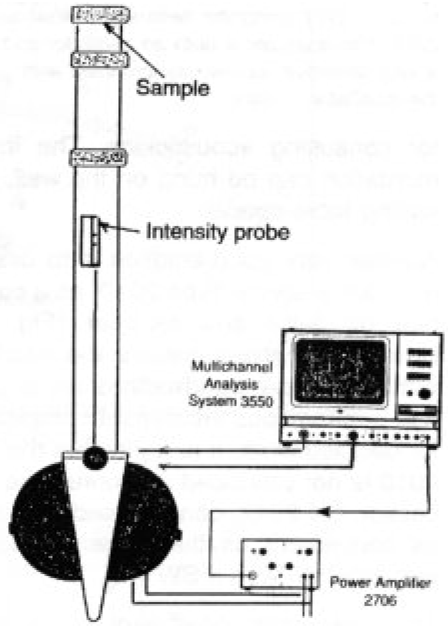


Fig. 19: Using an intensity probe in a standard SWT together with a multi-channel analyzer for measuring impedance with the two microphone method.

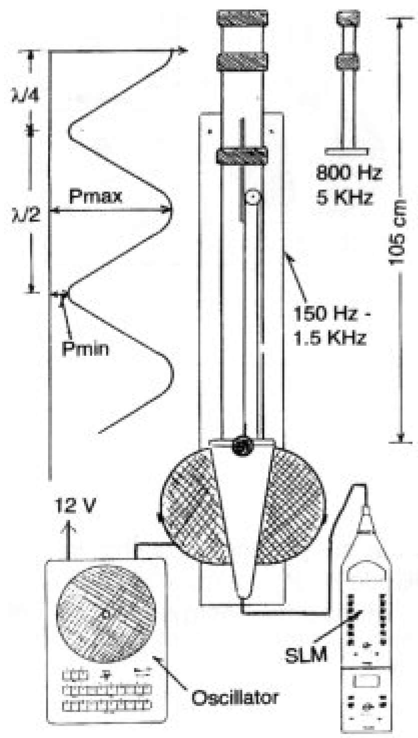


Fig. 20: Normal setup for SWT for measuring absorption α_0. Shows an oscillator producing sinetones at preferred frequencies. SLM with 1/3 octave filter as receiver .

Oscillator and Receiver: A SWT can be driven by any oscillator which can produce 0.5 W pure tone. The signal should be fairly clean, with better than 0.5% distortion. In particular, the second harmonic is very disturbing as it occurs where the pressure minimum is located. For absorption measurements it is an advantage to use an oscillator with fixed preferred frequencies according to IEC standard R 266. It is then easy to find A and the "apparent" reflection point. A sound level meter, SLM, with 1/3-octave filter can be used as a receiver. The set-up can be seen in Fig. 20. This is a very simple instrumentation set-up which can manage practically all measurement problems for consulting acousticians. The instrumentation can be hung on the wall, thus saving table-space.

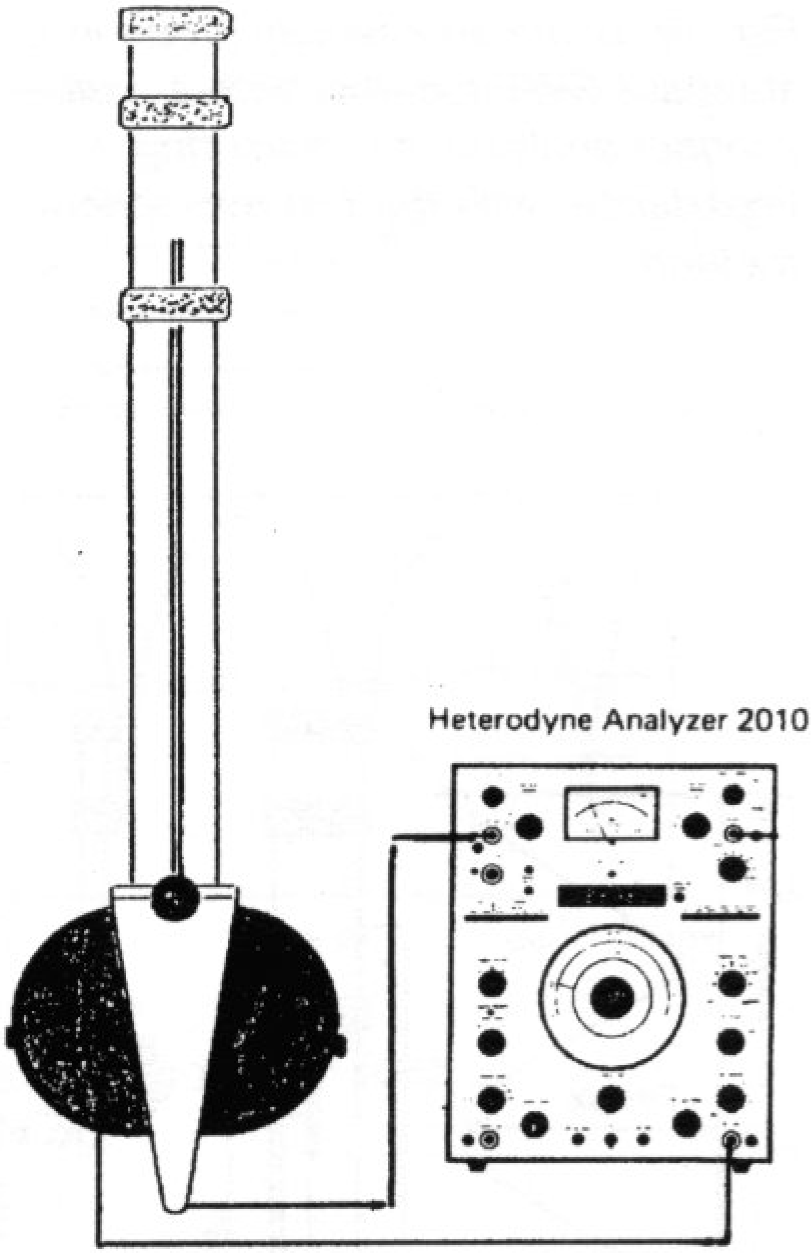


Fig.21: SWT using the heterodyne Analyser 2010. The analyser is both an oscillator and a very selective receiver synchronised with the oscillator

Another very good solution is to use the old B&K analyser Type 2010 as a combined oscillator and receiver (Fig. 21). Here the analyser follows the oscillator with a selective bandwidth down to 3 Hz. It is a marvellous instrument combination for detailed work. It is a pity that the B&K 2010 is not produced anymore. The successor, B&K 2012, can be used, but is not as convenient as the earlier model for use together with a SWT a_0.

The absorption coefficient a_0 is found from the ratio n between p_{max} and p_{min} (see Fig. 1 or 12).

$$n = \frac{p_{max}}{p_{min}} = \frac{A+B}{A-B}$$

This formula is derived from p_{max} and is the sum of the incoming waves' amplitude A plus the reflected waves' amplitude B. p_{min} is naturally A-B. The absorption coefficient a_0, is the proportion of incident energy which is not reflected from the sample.

The absorption coefficient is therefore:

$$\alpha_0 = 1 - \frac{B^2}{A^2} = \frac{A^2 - B^2}{A^2} = \frac{4}{n + \frac{1}{n} + 2}$$

With an instrument with a linear voltage scale, it is simple to determine n by setting the pointer at 100 with the microphone at a pressure maximum. Then roll the microphone to a minimum and read the minimum voltage. Find n and by the above-mentioned formula find a_0. In earlier instruments, B&K made this procedure even more simple. The analyser was supplied with a special scale (Fig. 22) where p_{max} was set to 100. Hereafter roll the microphone to p_{min} and read the absorption directly from the same scale. If amplification is increased 10 dB at minimum position, then the scale below is valid. With an increase of a further 10 dB, the lowest scale should be used.

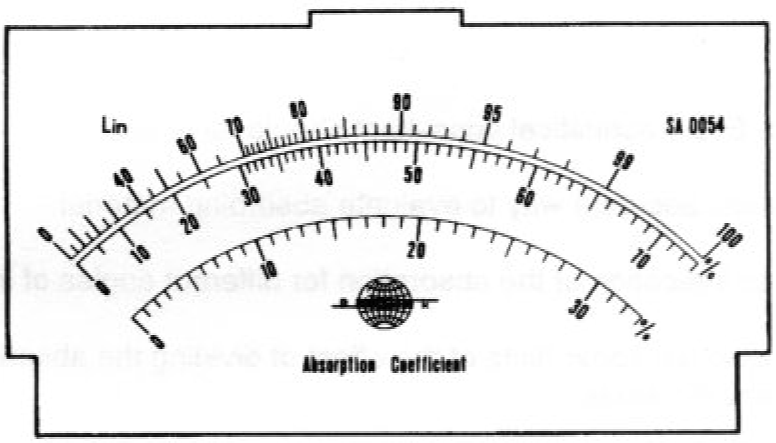


Fig. 22: Meter scale for selective amplifier where the absorption coefficient can be found directly.

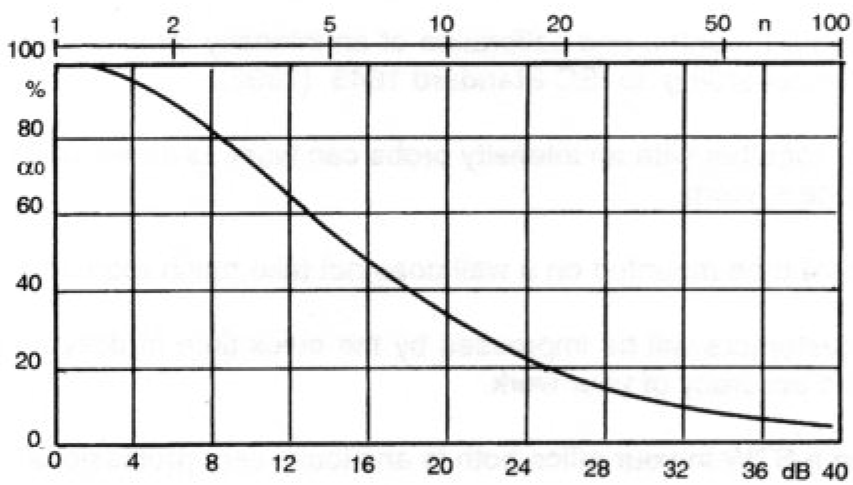


Fig. 23: Scale for determining the absorption coefficient α from the difference in DB between p_{max}/p_{min}.

If the receiver is a SLM or an instrument with a dB scale, it can be used directly by using the curve given in Fig. 23. Take the difference in dB between p_{max} and p_{min} and find either a_0 in % or the ratio n.

Conclusion: Every acoustical consultant should have and use a SWT.

It is the most accurate way to evaluate absorbing material.

1. **You get an indication of the absorption for different angles of incidence.**
2. **You can also get some hints of the effect of dividing the absorbing material into smaller areas.**
3. **It is easy, economical, and accurate to develop the most suitable absorber for different jobs.**
4. **With a vertical position the sample is kept in place naturally by gravity.**
5. **With a SWT, control and calibration of an intensity measuring system is possible according to IEC Standard 1043 (1996).**
6. **A SWT together with an intensity probe can work as an accurate two microphone system.**
7. **A vertical tube mounted on a wall does not take much room in the office.**
8. **Your customers will be impressed by the quick time of delivery and the detailed accuracy of your work.**
9. **Having a STW in your office both is and looks very professional.**

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