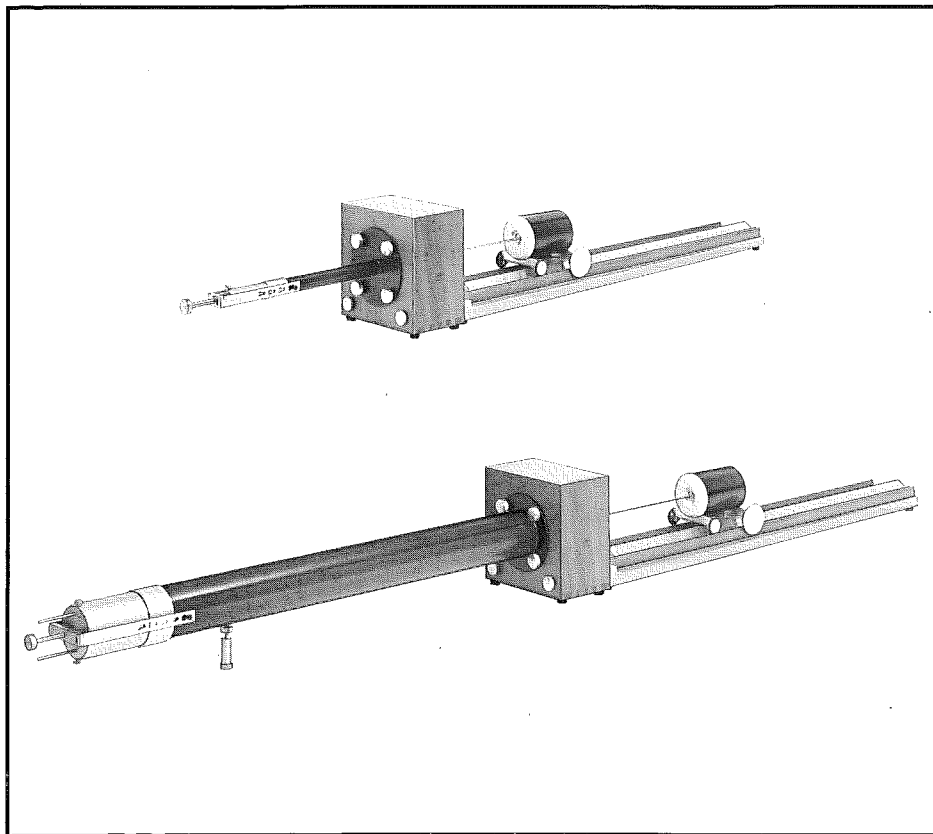




Standing Wave Apparatus Type 4002



For measurements of acoustic absorption coefficient and complex specific impedance of small samples over the frequency range of 90 Hz to 6500 Hz.

**STANDING WAVE APPARATUS
TYPE 4002**

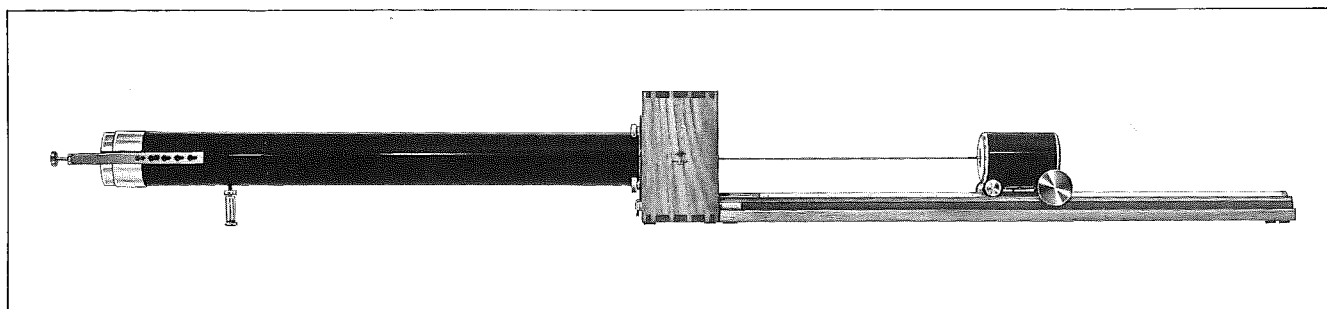
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type 4002

Standing Wave Apparatus



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 usable 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.

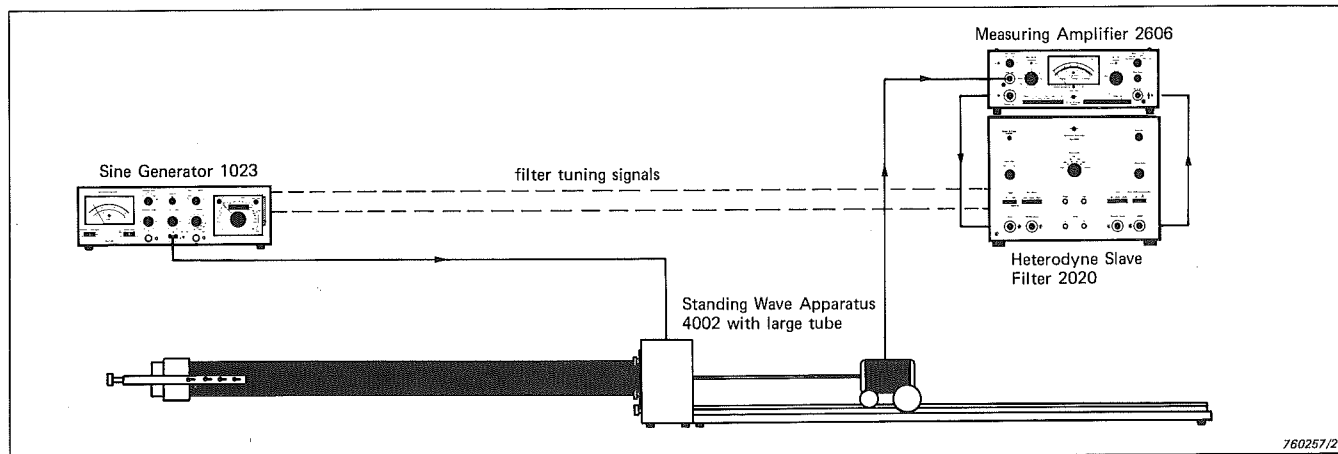


Fig.1. Measuring arrangement for measuring the acoustic absorption coefficient

Specifications 4002

<p>Frequency Range: Large Tube: 90 Hz to 1800 Hz Small Tube: 800 Hz to 6500 Hz</p> <p>Dimensions of Measuring Tubes: Large Tube: Diameter: 99 mm (3,9 in) Length: 1 m (39 in) Small Tube: Diameter: 29 mm (1,14 in) Length: 280 mm (11 in)</p> <p>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)</p>	<p>Loudspeaker: 7 in, 6 W, 4 Ω</p> <p>Microphone: (Crystal type)</p> <p>Sensitivity: 25 mV/Pa at 1000 Hz (without probe)</p> <p>Capacitance: 2 nF</p> <p>Min. Load Impedance: 1 MΩ (-3 dB at 90 Hz)</p> <p>Overall Dimensions: Total length with large tube: 2,4 m (95 in)</p>	<p>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 x 380 x 350 mm (55 x 15 x 14 in)</p> <p>Weight: 48 kg (106 lb)</p>
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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.

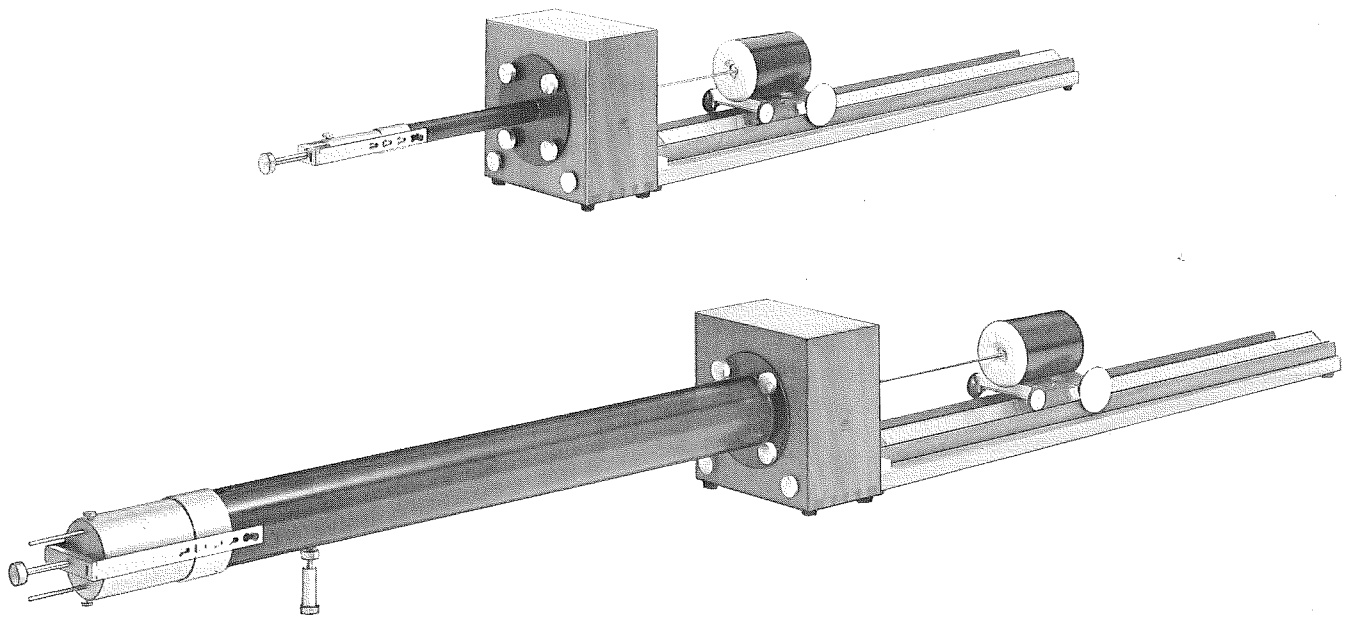
However, as the largest dimension of the sample must not be larger than about half the wavelength of the sound at the measuring frequency, it is impossible to obtain reliable results for materials whose ability to absorb depends upon resonance as, for example, damped vibrating panels or large slit resonators. 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:

$$p_i = A \cos 2\pi ft \quad (1)$$

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:

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

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:

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

By applying the Addition Theorem i.e.

$$\cos(\theta - \phi) = \cos\theta \cdot \cos\phi + \sin\theta \cdot \sin\phi \quad (4)$$

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 $\lambda = \text{wavelength} = c/f$. A microphone situated at a distance $\lambda/2$

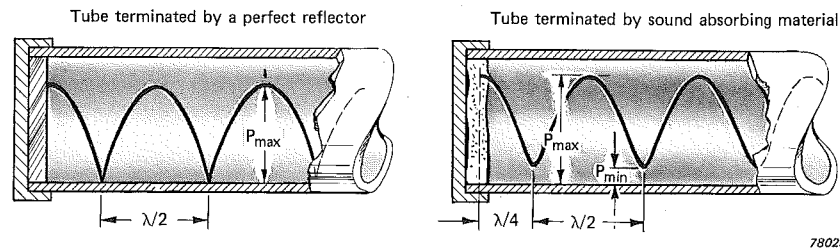


Fig.3.1. Cross section of the standing wave tube showing the standing wave pressure patterns and the effect of terminating the tube with sound absorbing material

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

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

This equation can be written

$$\alpha = 1 - r^2 \quad (6)$$

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

$$r = \frac{B}{A} \quad (7)$$

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:

$$n = \frac{P_{\max}}{P_{\min}} \quad (8)$$

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

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

Hence

$$\frac{B}{A} = \frac{n - 1}{n + 1} \quad (10)$$

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

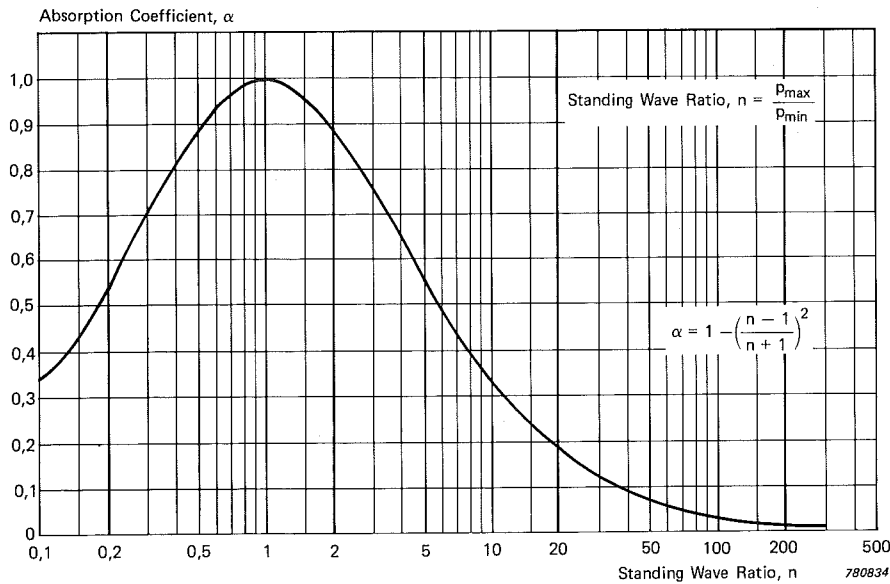


Fig.3.2. The relationship between the absorption coefficient, α , and the standing wave ratio, n

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

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

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:

$$Z_n = \frac{p_i + p_r}{v_i + v_r} \quad (14)$$

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/m³ and the speed of sound is 343 m/s, giving the standard acoustic characteristic impedance of air a value of 415 rayls.

Therefore,

$$p_i = \rho c v_i \quad (15)$$

$$p_r = \rho c (-v_r) \quad (16)$$

Hence,

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

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

Now p_r and p_i are related by:

$$p_r = p_i \cdot r \cdot \exp(j\Delta) \quad (19)$$

where

r = reflection coefficient

Δ = phase angle between the incident and reflected sound pressures

Therefore

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

This equation can be written as

$$Z_n = (R_e(Z_n) + j \text{Im}(Z_n)) \cdot \rho c \quad (21)$$

where it can be shown that

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

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

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

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

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

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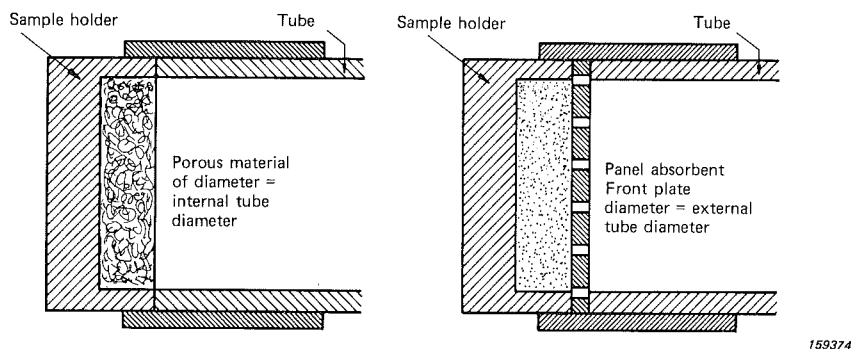
Leo L. Beranek: Acoustic Measurements. Wiley & Sons, New York.

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

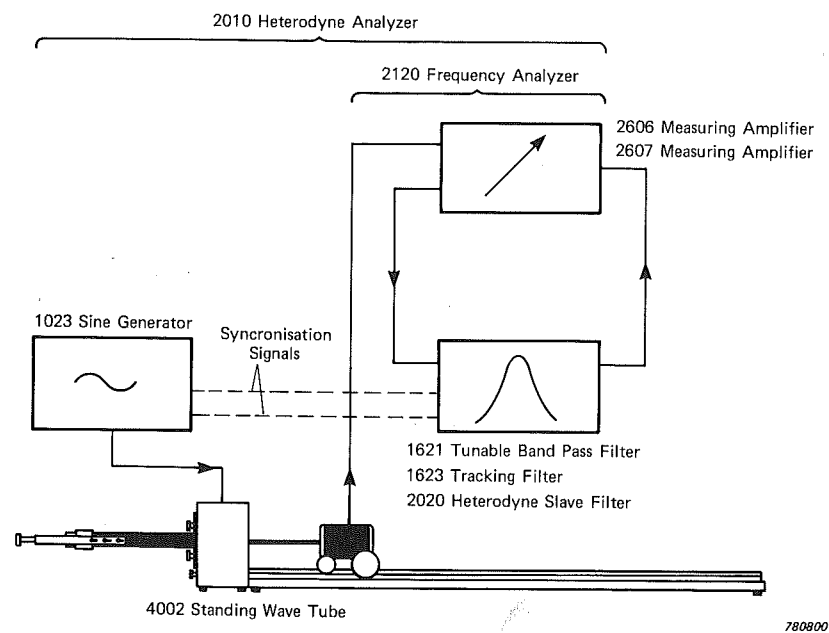


Fig.4.2. Possible arrangements of measuring instruments for use with the 4002

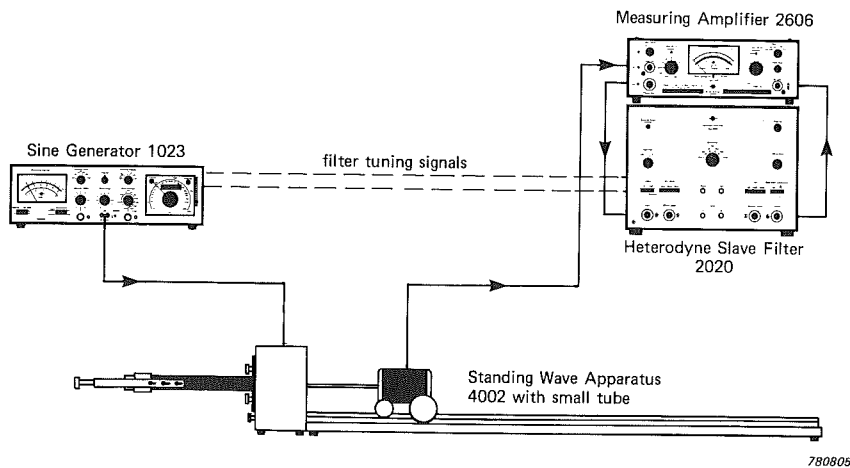


Fig.4.3. Typical measuring arrangement

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 loud-speaker
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 200Hz 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.

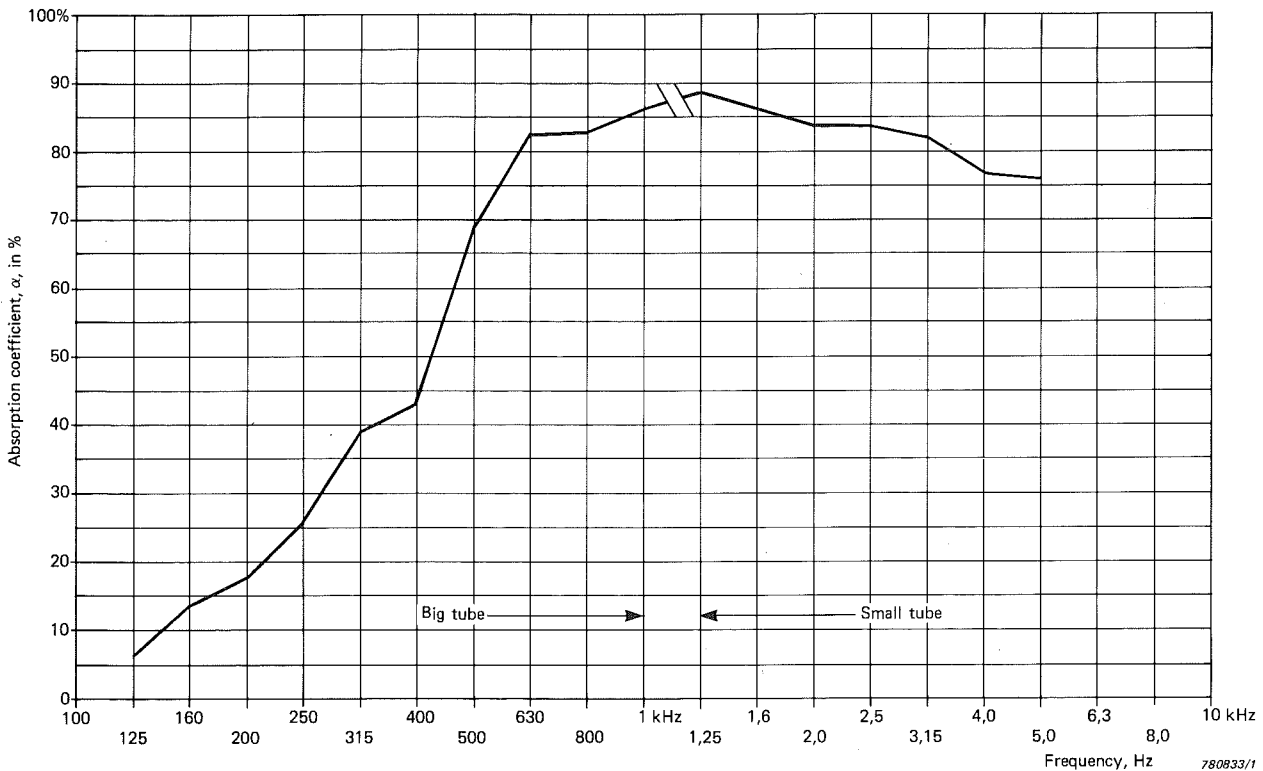
Frequency, Hz	100	125	160	200	250	315	400	500	630	800	1000	1250	1600
Test Sample α													
Minimum measurable α													

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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.



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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						
$y_2 - y_1 = \frac{\lambda}{2}$						
$\Delta = \left(\frac{2 y_1}{y_2 - y_1} - 1 \right) \pi$						
$\text{Re} \left(\frac{Z_n}{\rho c} \right) = \frac{1 - r^2}{1 + r^2 - 2 r \cos \Delta}$						
$\text{Im} \left(\frac{Z_n}{\rho c} \right) = \frac{2 r \sin \Delta}{1 + r^2 - 2 r \cos \Delta}$						
$\frac{Z}{\rho c} = \sqrt{\text{Re}^2 + \text{Im}^2}$						
$\phi = \tan^{-1} \left(\frac{\text{Im}}{\text{Re}} \right)$						

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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

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

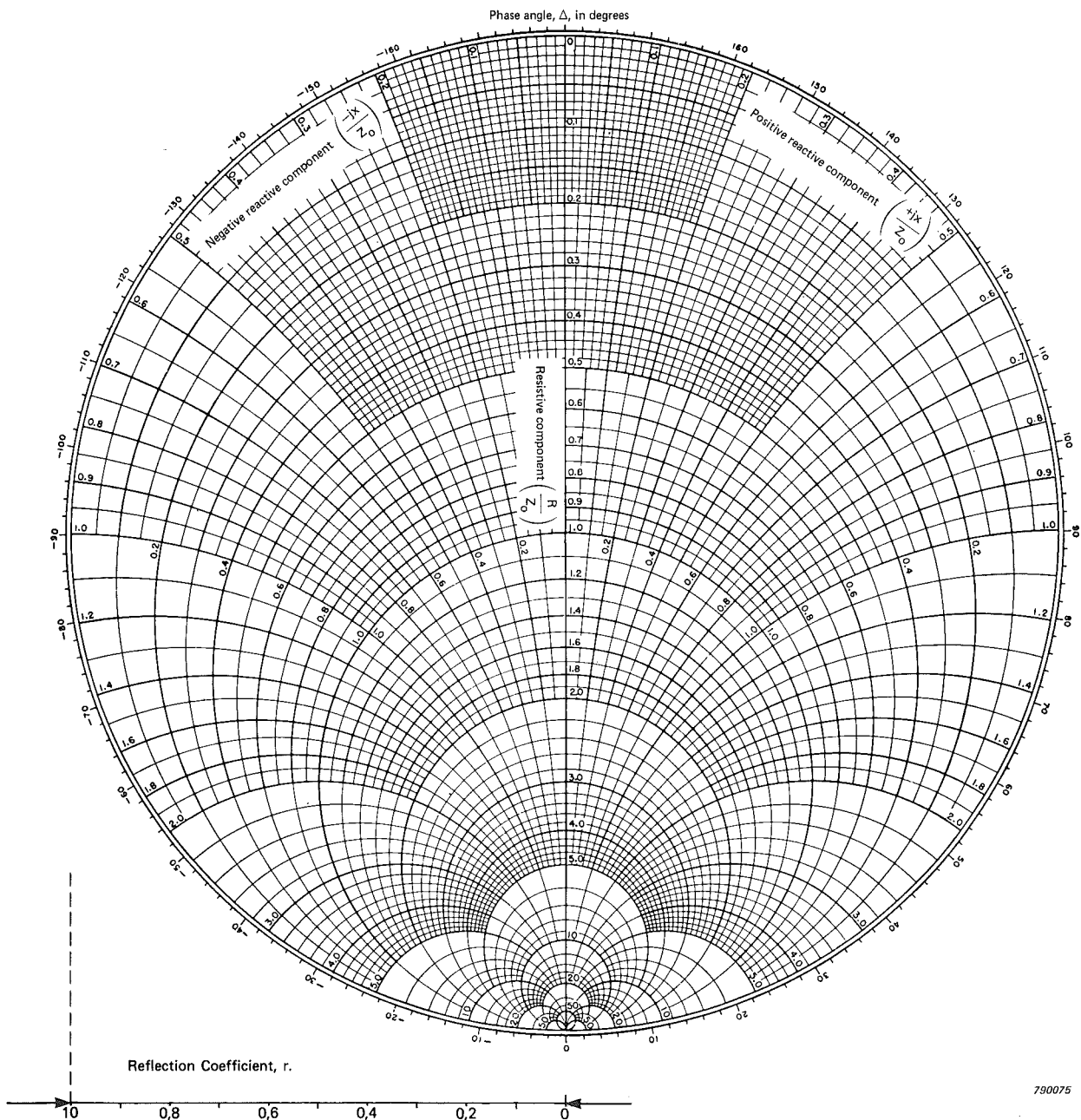


Fig.4.7. The Smith chart

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

Either by direct calculation using a pocket calculator from the equation

$$Z_n = (\text{Re}(Z_n) + j\text{Im}(Z_n)) \rho c$$

where

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

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

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 $\Delta = 30^\circ$. 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 $\text{Re}(Z_n/\rho c) = 1,4$ and $\text{Im}(Z_n/\rho c) = 3,1$. Therefore (see Fig.4.8)

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

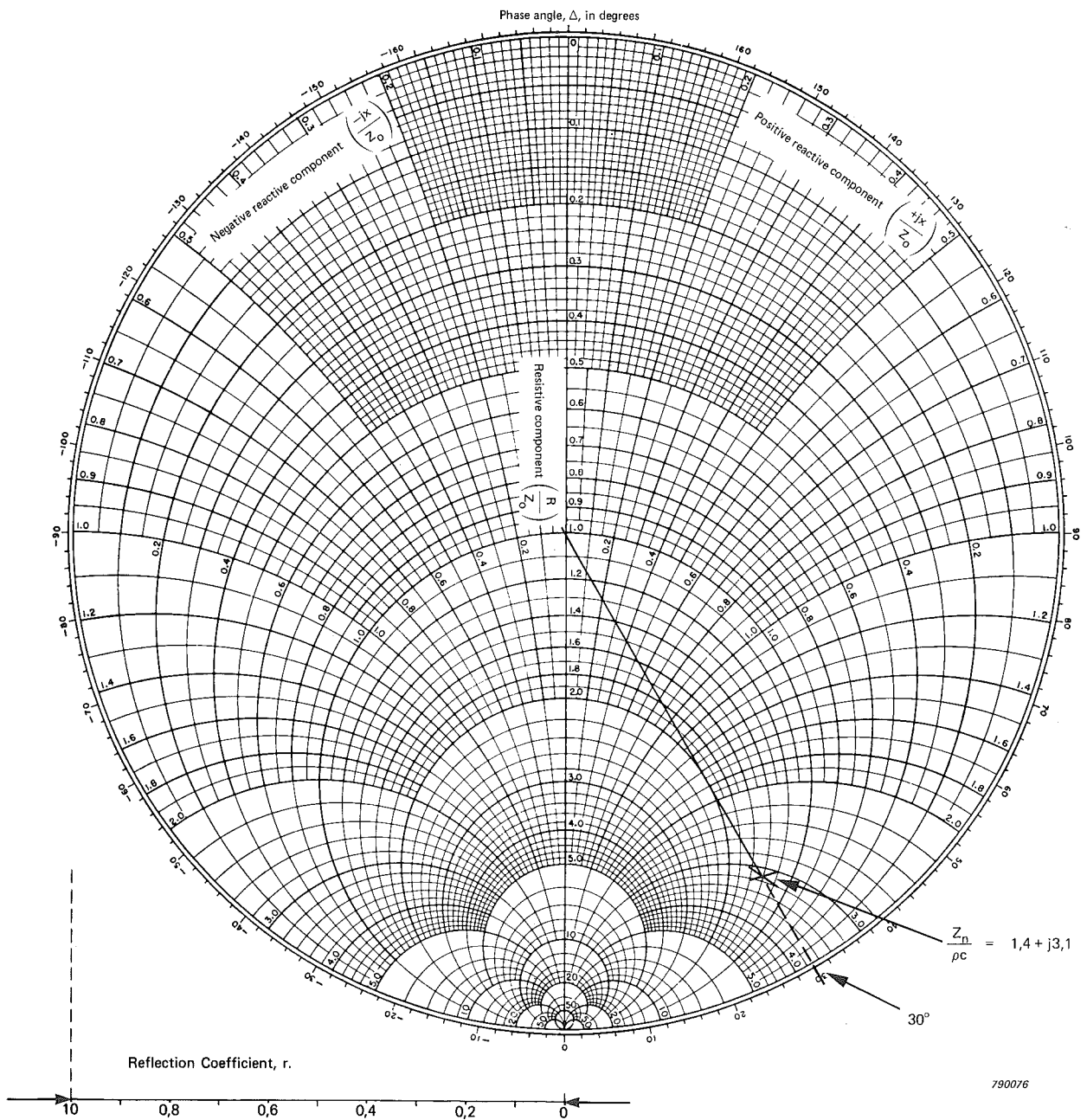
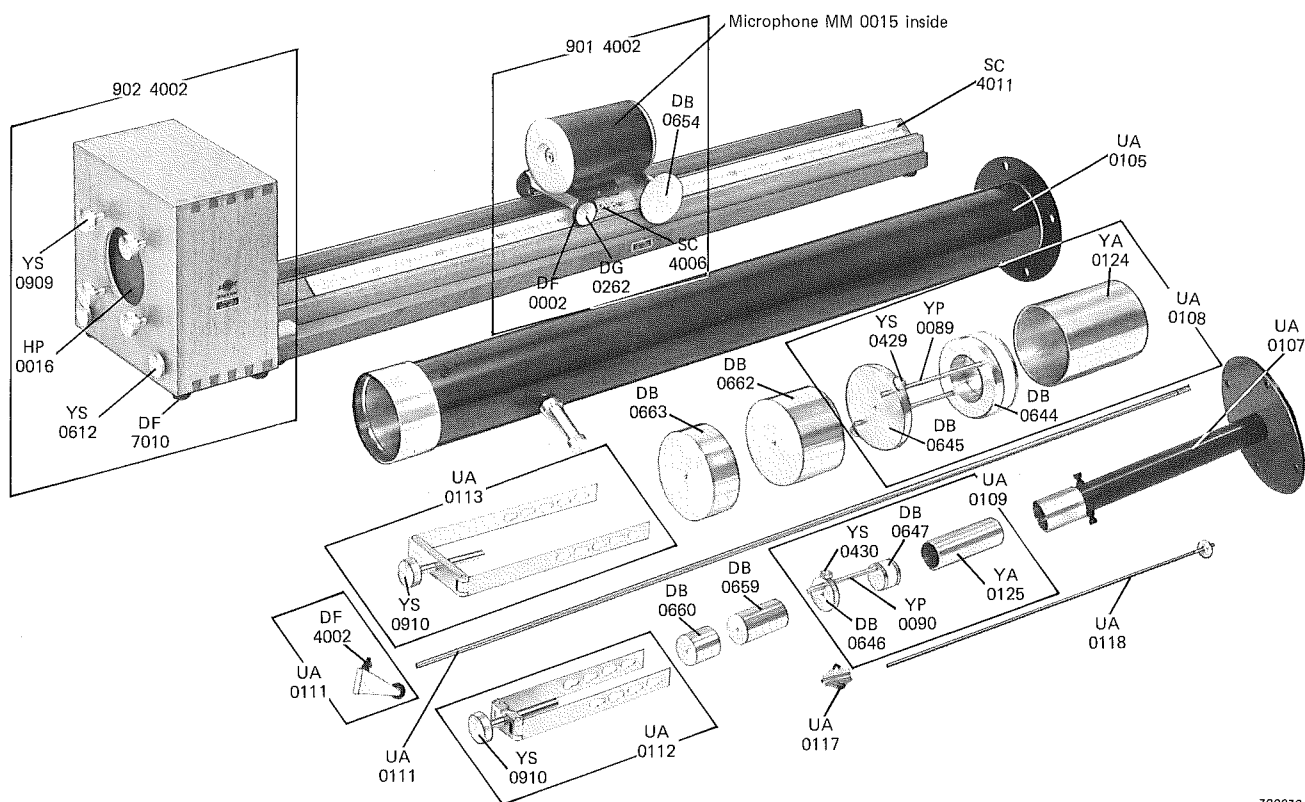


Fig.4.8. Example of use of Smith chart

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.



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