B & K INSTRUMENTS:

ACOUSTICAL....
Condenser Microphones
Piezo-Electric Microphones
Microphone Preamplifiers
Microphone Calibration Equip.
Sound Level Meters
(general purpose-precision-
and impulse)
Standing Wave Apparatus
Tapping Machines
Noise Limit Indicators

ELECTROACOUSTICAL....
Artificial Ears
Artificial Mouths
Artificial Mastoids
Hearing Aid Test Boxes
Telephone Measuring Equipment
Audiometer Calibrators
Audio Reproduction Test Equip.

STRAIN....
Strain Gauge Apparatus
Multipoint Panels
Automatic Selectors
Balancing Units

VIBRATION....
Accelerometers
Accelerometer Preamplifiers
Accelerometer Calibrators
Vibration Meters
Magnetic Transducers
Capacitive Transducers
Vibration Exciter Controls
Vibration Programmers
Vibration Signal Selectors
Mini-Shakers
Complex Modulus Apparatus
Stroboscopes

GENERATING....
Beat Frequency Oscillators
Random Noise Generators
Sine-Random Generators

MEASURING....
Measuring Amplifiers
Voltmeters
Deviation Bridges
Megohmmeters

ANALYZING....
Band-Pass Filter Sets
Frequency Spectrometers
Frequency Analyzers
Real-Time Analyzers
Slave Filters
Psophometer Filters
Statistical Analyzers

RECORDING....
Level Recorders
(strip-chart and polar)
Frequency Response Tracers
Tape Recorders

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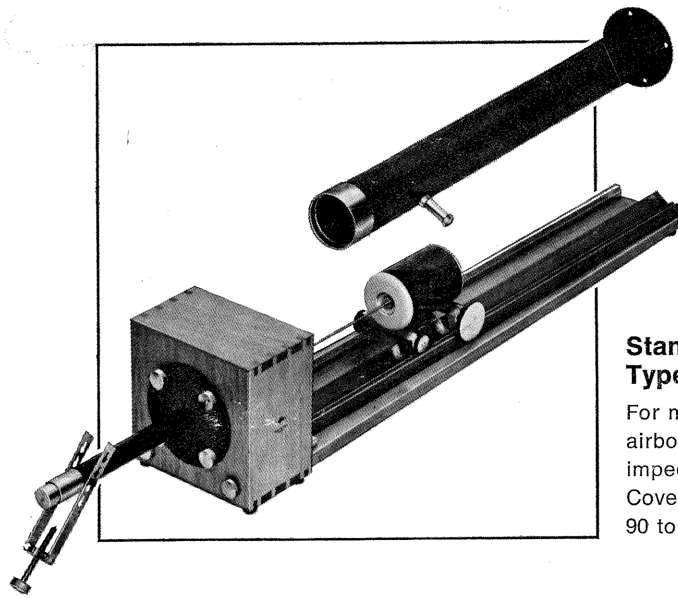
Instructions and Applications



Standing Wave Apparatus Type 4002

For measurements of specific airborne acoustic absorption and impedance of material samples. Covering a frequency range from 90 to 6500 Hz.

BRÜEL & KJÆR

STANDING WAVE APPARATUS TYPE 4002

September 1970

CONTENTS

1. INTRODUCTION AND DESCRIPTION

The Standing Wave Apparatus Type 4002 is designed for easy and quick determination of the absorption coefficients of acoustical materials by the standing wave method. The 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 reproducable. However, as the largest dimensions of the sample 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 whose absorption ability depends on resonance, as, for example, vibration panels or large slit resonators. The tube method is therefore best suited to measurements of porous materials, ordinary resonance absorbents, light membrane absorbents etc.

The complete tube apparatus comprises two measuring tubes, the larger one with an interior diameter of about 10 cm, which covers the frequency range from 90 to 1800 Hz and the smaller one with a diameter of about 3 cm, covering the frequency range from 800 to 6500 Hz. 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.

Assembly of the apparatus is shown in Figs. 2.1 and 2.2, on which are also marked component identification numbers for ordering replacement

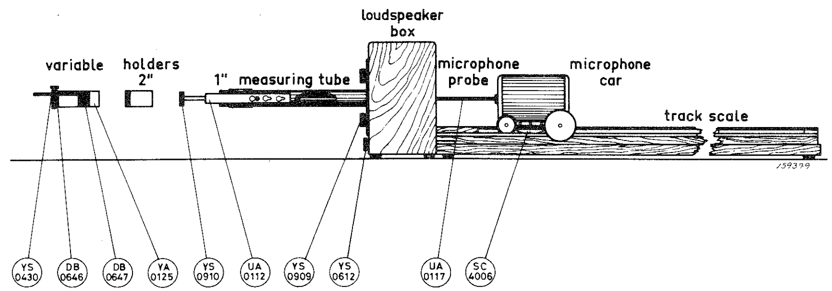


Fig. 1.1. Part Numbers of the Standing Wave Apparatus Type 4002. 3 cm tube.

parts should any item be mislaid. The measuring tube and the track scale are both screwed onto the loudspeaker box. The microphone probe tube passes through the centre of the loudspeaker core and one end screws into the microphone car while the open end is supported centrally in the measuring tube by a small trolley.

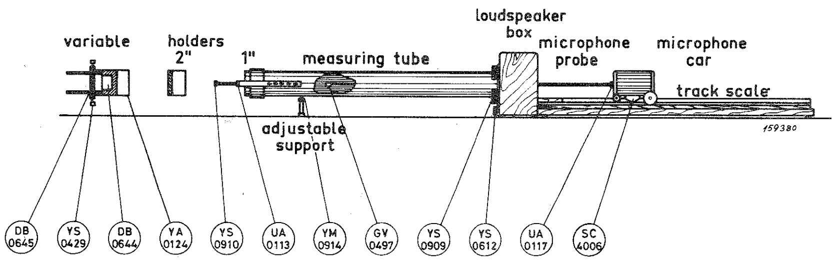


Fig. 1.2. Part Numbers of the Standing Wave Apparatus Type 4002. 10 cm tube.

The microphone built into the microphone car is a small dynamic microphone of adequate frequency range for the purposes of the standing wave tube method but of no other practical use for acoustic measurements. The microphone is mounted in elastic supports in the microphone car, well insulated from external airborne noise and impact sound or vibrations.

2. PRINCIPLE OF OPERATION

2.1 GENERAL

The standing wave tube method provides a convenient laboratory method of measuring acoustic absorption coefficient and acoustic impedance of small samples. In this chapter the theoretical basis of the method is described, while practical details are covered in later chapters.

The sample for measurement is mounted at one end of a stiff walled tube at the other end of which is mounted a loudspeaker with its axis coincident with that of the tube. A pure tone signal from the loudspeaker is therefore partially reflected from the sample and the reflected wave interferes with the incident wave to produce a standing wave. From measurement of the amplitude and phase characteristics of the standing wave we can determine the magnitude of absorption and impedance properties of the sample.

Results obtained from the standing wave tube are applicable for sound incidence normal to the surface of the sample and restrictions are placed on the use of the equipment to ensure that the theoretical conditions are closely approached in practical operation. The frequency range of the method is limited at its lower end by the length of the measuring tube, which must be at least 0.25 wavelength, and at the higher end by the diameter of the tube, which should theoretically be less than 0.586 wavelength in order to exclude the possibility of a transverse resonance.

2.2. ABSORPTION COEFFICIENT

Considering the wave incident on the sample, at a particular point the sound pressure will be of the form:

$$p_i = A \cos 2\pi ft \qquad 1.$$

and the reflected wave at the same point has the form

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

where f is the frequency of excitation
y is the distance from the sample surface
c is the velocity of sound in the tube.

The total sound pressure at this point will therefore be:

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

From this expression it can be seen that 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 $\lambda/2$ from the sample will therefore receive an alternating sound pressure of frequency f and amplitude $A + B$.

From the definition of absorption coefficient (α) as the proportion of the incident energy which is not reflected from the surface it follows that:

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

or

$$\alpha = 1 - r^2$$

where

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

Using the standing wave tube, we can easily measure the ratio, n, of maximum to minimum sound pressure in the tube:

$$n = \frac{A + B}{A - B}$$

and hence

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

so that

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

Absorption coefficient can therefore be determined as:

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

$$= \frac{4n}{n^2 + 2n + 1}$$

The relationship is expressed graphically in Fig.2.1.

This measurement can be made particularly simple by a suitable calibration of an analyzing meter scale, and such a scale is provided on all the Brüel & Kjær measuring amplifiers which are suitable.

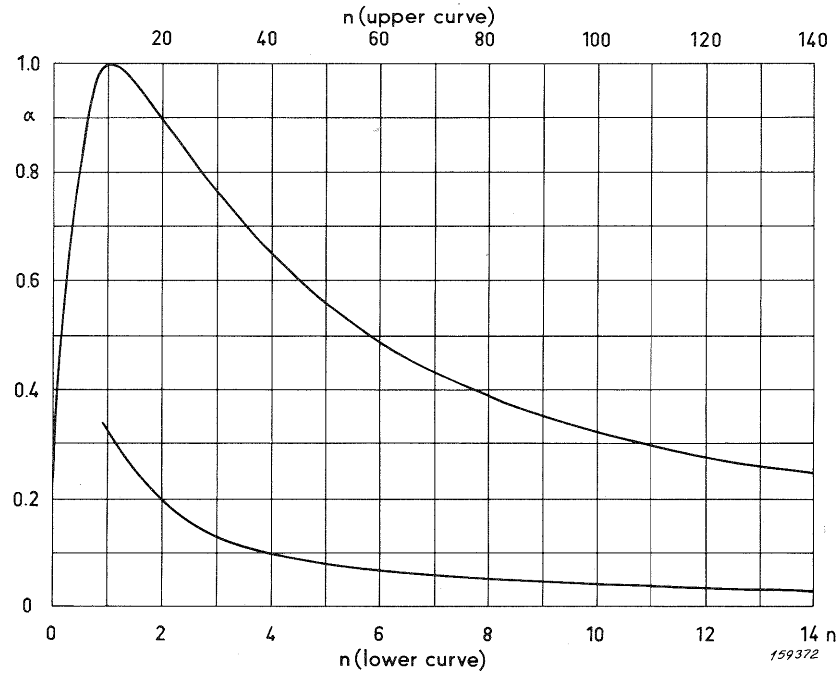


Fig.2.1. Absorption coefficient, α, as a function of $n = \frac{p\ max}{p\ min}$

2.3. ACOUSTIC IMPEDANCE

Acoustic Impedance, Z_A, is the complex ratio of the effective sound pressure at the surface of the medium to the effective particle velocity at that point. In the standing wave tube we have therefore:

$$Z_A = \frac{p_i + p_r}{v_i + v_r}$$

where p_i, p_r are the sound pressures of the incident and reflected waves and

v_i, v_r their respective particle velocities. p and v are related by the characteristic impedance of the air in the tube, so that:

$$p_i = \rho_c \, v_i$$

and

$$p_r = \rho_c \, (-v_r)$$

Hence,

$$\frac{Z_A}{\rho_c} = \frac{p_i + p_r}{p_i - p_r}$$

If we again consider the incident and reflected sound pressures, equations 1 and 2 can also be expressed:

$$p_i = A \exp\,(j\ 2\,\pi f\, t)$$

$$p_r = B \exp\left[j\ 2\,\pi\, f\ (t - \frac{2\,y}{c})\right]$$

so that

$$p_r = \frac{B}{A}\, p_i \exp\,(-\,j\ 4\,\pi \frac{y}{\lambda})$$

or

$$p_r = r\, p_i \exp\,(j\,\Delta)$$

where

$$\Delta = -\frac{4\,\pi\, f\, y}{c} = -\frac{4\,\pi\, y}{\lambda}$$

At a distance y in front of the sample, the incident wave has an angle of lead $2\,\pi\, y/\lambda$ relative to the phase angle at the sample surface, while the reflected wave acquires an angle of lag $2\,\pi\, y/\lambda$. Leaving the surface of the sample, therefore, the vectors of sound pressure rotate as indicated in Fig.2.2. The first maximum of sound pressure will occur when both vectors coincide: at a distance y_o from the sample, where $\Delta = 4\,\pi\, y_o/\lambda$. The first minimum, of magnitude $(1 - r)\, p_i$ will occur at $y = y_1$ when both vectors have rotated through a further $\pi/2$.

so that

$$\Delta + \pi = \frac{4\,\pi\, y_1}{\lambda}$$

Returning to the definition of Acoustic Impedance, we see that it is determined completely from a knowledge of reflection factor r and its phase angle Δ, since

$$\frac{Z_A}{\rho_c} = \frac{1 + r \exp j\,\Delta}{1 - r \exp j\,\Delta}$$

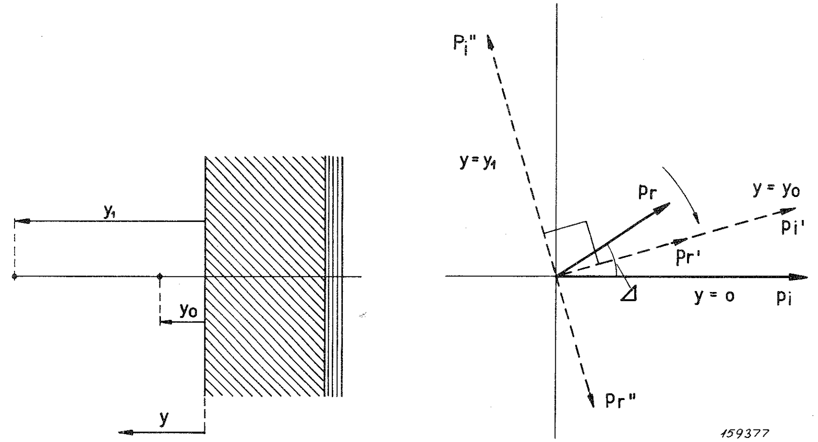


Fig.2.2. Vector diagram of incident and reflected wave pressures.

Using the standing wave tube, the phase angle Δ can be determined as:

$$\Delta = (\frac{4\, y_1}{\lambda} - 1)\ \pi$$

and r can be measured directly from the ratio of the maximum to minimum sound pressure, n, as:

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

The relationship between a, r, and Δ evolves graphically to a family of circles, while b is determined from a family of circles orthogonal to these. The most convenient method of determining acoustic impedance is from such a graphical solution, which is provided by the Smith chart of Fig.2.3.

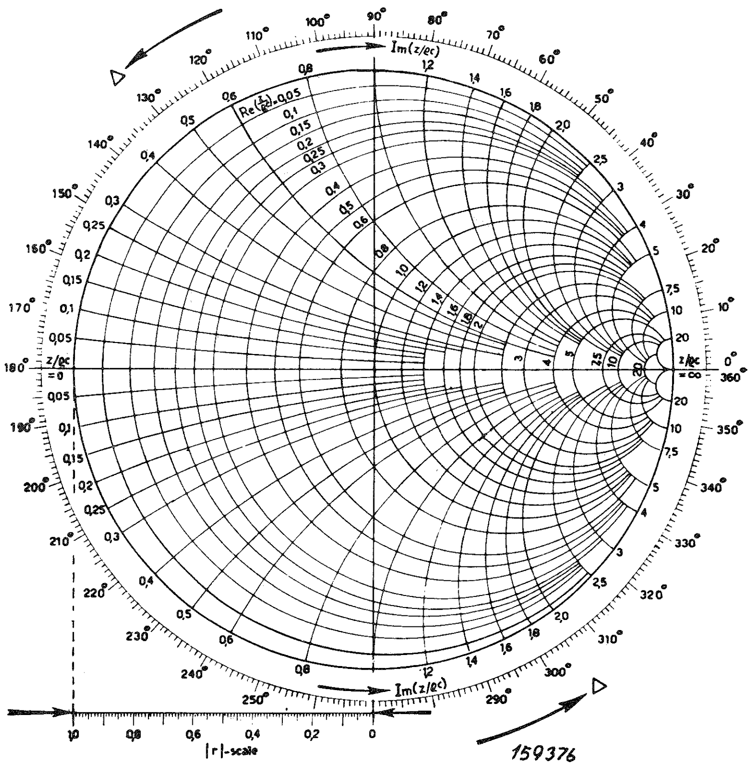


Fig.2.3. The Smith Chart.

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3. PRACTICAL OPERATION

3.1. ASSEMBLY OF EQUIPMENT

Select the tube appropriate to the frequency range of measurements required. The 10 cm diameter tube is suitable for the range 90 to 1800 Hz and the 3 cm diameter tube is suited to the range 800 to 6500 Hz. The Standing Wave Apparatus is assembled and connected to a sine generator and measuring amplifier as suggested in Figs.3.1 or 3.2. Particularly suitable for supplying the loudspeaker signal are either the Beat Frequency Oscillator Type 1022, or the Sine-Random Generator Type 1024 operated in its Sine mode. However, any low distortion sine signal generator with 6 ohm output impedance can be used with the Apparatus. The microphone voltage should be amplified by a frequency selective amplifier to reduce the influence of hum and noise and higher harmonics, which are inevitably generated by the loudspeaker. For this purpose, any of the Brüel & Kjær analyzers is

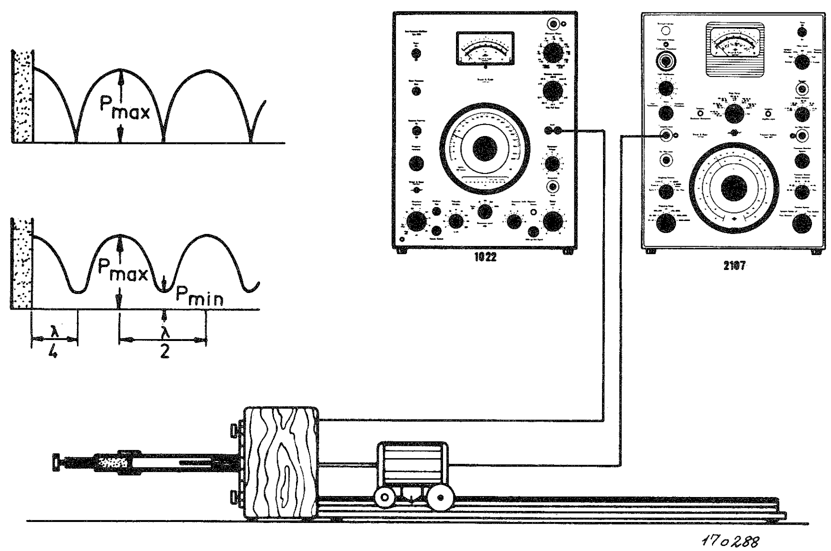

Fig.3.1. Measurement of Absorption Coefficient with Frequency Analyzer Type 2107.

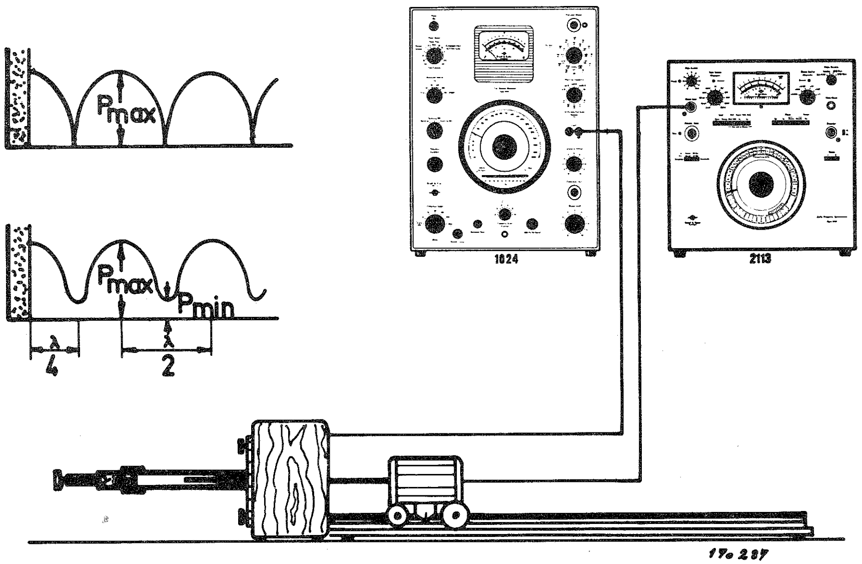

Fig.3.2. Measurement of Absorption Coefficient with Frequency Spectrometer Type 2113.

suitable, and particularly the Frequency Analyzer Type 2107, which is continuously tunable in the frequency range 20 Hz to 20 kHz, with variable effective bandwidth down to 6% of centre frequency.

A carefully cut circular sample of the material is placed in a suitable holder. (The sample is best cut with a bandsaw). Porous material should be cut so that it fits the inside diameter of the holder, while 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.3.3). 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 on tightly to prevent vibration arising in the bottom of the holder.

Referring to the equipment shown in Fig.3.2, the output of the Sine Random Generator (6 ohms output impedance) is connected to the loudspeaker terminals. The output from the probe microphone of the Standing Wave Apparatus is taken to the DIRECT input of the Frequency Spectrometer. The oscillator and the analyzer are tuned to the same frequency and a suitable output level set. The analyzer indication is regulated by its main

attenuators and its GAIN CONTROL, which can be switched to an "Uncal." position for fine adjustments. The measurement itself is carried out as follows:

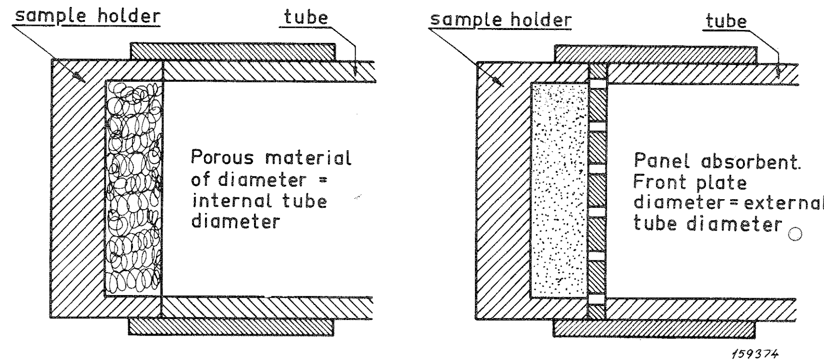

Fig.3.3. Mounting absorbents in the Standing Wave Apparatus.

3.2. MEASUREMENT OF ABSORPTION COEFFICIENT

(a) Connect the instrumentation as in Fig.3.1 or 3.2. Procedure is described for the instrumentation of Fig.3.2.

(b) Fit scale number SA 0054 to the Audio Frequency Spectrometer Type 2113.

(c) Frequency calibrate the Oscillator and tune the Oscillator and Spectrometer to the measurement frequency required.

(d) Set up a suitable sound pressure in the Standing Wave Apparatus. Check that the sound pressure level at a minimum of the standing wave is at least 10 dB above the ambient noise level.

(e) Place the microphone probe at the first maximum point of the standing wave away from the sample. At the lowest frequencies it may not be possible to find an isolated sound pressure maximum, and in this case the sound pressure close to the sample should be used.

(f) Using the INPUT SECTION ATTENUATOR and the GAIN CONTROL of the Analyzer, adjust the meter deflection of the Spectrometer to 100%.

(g) Without altering any controls on the Oscillator or Spectrometer, move the microphone probe to the closest sound pressure minimum.

(h) The absorption coefficient can now be read directly from the top line of the "%" scale of the Spectrometer. If the meter deflection is below 70%, a more accurate reading can be obtained by switching the INPUT SECTION ATTENUATOR of the Spectrometer 10 dB anticlockwise and reading the absorption coefficient from the centre "%" scale. If the meter deflection is below 30%, the INPUT SECTION ATTENUATOR should be switched a further 10 dB anticlockwise and the coefficient read from the bottom "%" scale.

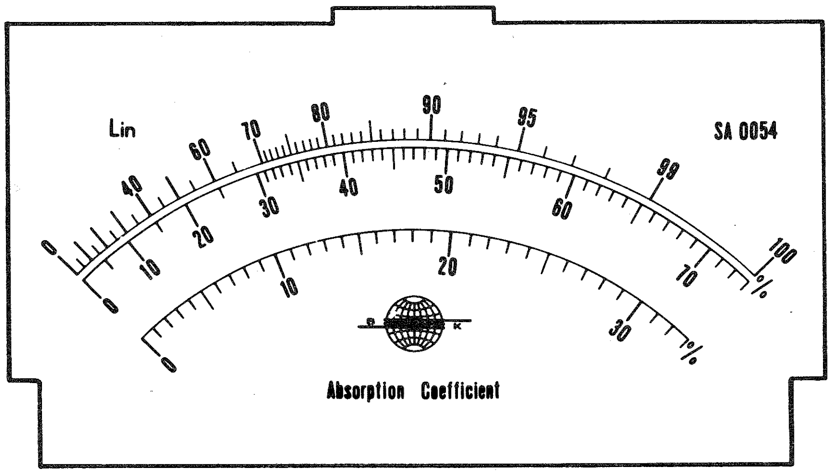

Fig.3.4. Meter Scales of B & K Types 2113, 2114, 2606, 2607.

3.3. MEASUREMENTS OF ACOUSTIC IMPEDANCE

(a) Adjust the length of the microphone probe until it just touches the surface of the sample when the microphone car stands at the zero position of the track scale.

(b) Measure the absorption coefficient of the sample as described in section 3.2.

(c) Measure the distance between the sample and the first minimum of sound pressure. Identify this distance as y_1.

(d) Measure also the distance between the two minima nearest to the sample. Identify as $y_2 - y_1$.

(e) Calculate the values of $r = \sqrt{1-\alpha}$

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

(see section 2.2 of this book for their derivation).

(f) From the Smith chart of Fig.2.3 read off the real and imaginary parts of the Acoustic Impedance. Practical use of the Smith chart is best illustrated by an example. Suppose the results of measurements and calculation produced values of $\Delta = 0.515$ radians $= 30^o$, and $r = 0.80$. First draw in the radius of the major circle of the chart to $\Delta = 30^o$. Then measure off from the centre of the circle the length corresponding to the value of r from the scale at the bottom of the chart. The point thus determined locates the values of the real and imaginary components of the impedance, giving $Re\,(Z_A/\rho_c) = 1.3$ and $Im\,(Z_A/\rho_c) = 3.2$. See also Fig.3.5.

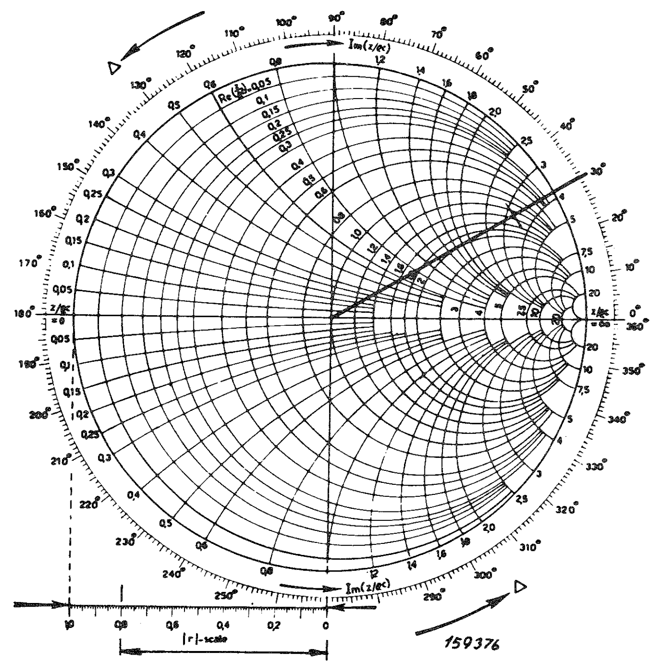

Fig.3.5. Use of the Smith Chart.