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Measurement of transmission parameters of porous sound-absorbing materials. Part 3. How the test gear is applied

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Part 3. How the test gear is applied

Measurement of transmission parameters of porous sound-absorbing materials

by E. R. WIGAN

Duct tests on Fibreglass (8·4 lb/ft³)

Testing conditions have been described (*4*). Time-delay and attenuation were measured in a 30 ft (9 m) duct of considerable cross-section which had been filled with Fibreglass. Here these data are reduced to α and β per 2cm run. As there are on impedance measurements the quantity R in the equivalent network remains unknown, but as all the K-quantities have zero dimensions they can be derived from the dimensionless

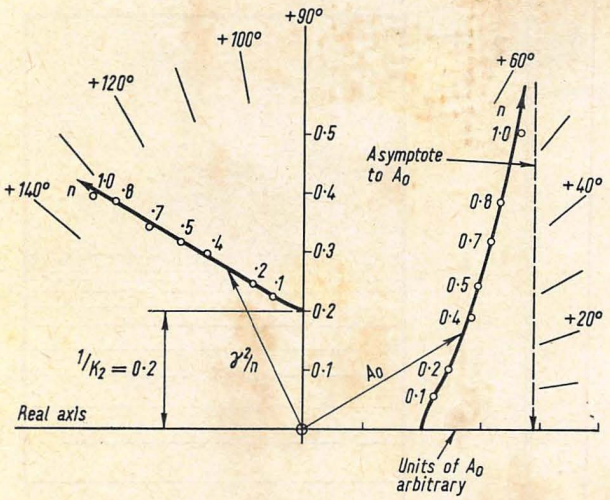


Fig. 8 Loci deduced from duct tests of (*4*) on Fibreglass (8·416 lb/ft³); converted to 2cm-run

term γ^2/n without reference to R; the process is straightforward but too elaborate to illustrate here. A simple approach is to give the term $K_4 . R$ a nominal value, say unity, and to write the others in proportion. It is then possible to construct the locus of $1/A_0$ and to confirm the validity of an equivalent network like fig. 6*b* once again; in any case the tilt of the locus of γ^2/n and the step in the A_0-locus of fig. 8 confirm not only the presence of a dual A_0-structure but also the existence of a term in K_4.

When measurements given in reference *4* on a lighter type of Fibreglass were treated in the same way, analysis proved difficult and for an interesting reason. To obtain information on the A_0-structure, published data had to be extrapolated below 100 c/s and this was done on the logarithmic basis that is the thesis of the cited paper. Although the paper shows this to be true at frequencies *higher* than 100 c/s it must fail as frequency falls.

In accordance with reference *4* log α and log β should fall on straight lines relative to log-frequency, the lines having different slopes. This necessarily implies an intersection at the frequency at which $\alpha=\beta$. The log-law forces this frequency to be finite. Now, once the equivalent network is accepted as having the form of either fig. 6*a* or 6*b* reference back to Part 1 (*Deductions from* N_∞) shows that $\alpha=\beta$ is possible only when $n=0$. Thus the only safe method of extrapolation is one which brings α and β to equality when $n=0$ and this the cited log relation can never achieve.

It has not been possible to recast the cited data on this basis in order to derive diagrams like fig. 8 for the lighter material, but there can be little doubt that they will take a similar form, for subsidiary tests, not reported here, have been made with the gear of fig. 2 on samples of density only 1 lb/ft³ (16 kg/m³) which confirm this.

Measurements on a composite test piece

The test piece consisted of fifteen sheets of rubberized cushion fabric.

The performance of the sample as measured in the test gear of fig. 2 is shown in figs. 9 and 10. The sheets of fabric were so thin [about 0·045 in (1·14 mm)] that they had to be held in place within the testing tube 1 by a subsidiary ring-clamp. This located but did not nip the samples sharply. Although the working area of the sample was slightly restricted, which, of course, increased the impedances measured, the clamp did not in any way modify the non-dimensional quantities K and γ.

No 'diaphragm' action was observed (a simple test is mentioned later), but there is clearly something wrong with the measurements as critical examination will show that co-ordinates of the two semicircles in fig. 10 do not sum to the co-ordinates of the locus of $1/A_0$. It is thought that this is because the sample is behaving like two transmission-lines in tandem, i.e. the rubberizing treatment and the fabric upon which it is imposed. In spite of this the presence of the element $R . K_4$ in the b_0-locus of fig. 9 is clearly demonstrated.

ment can still be mounted with its mercury level below the bottom of the vessel, it is possible to measure between the maximum level and the level of the vessel connexion point. Mounting the instrument with its mercury level above the vessel connexion point further restricts the level range over which it can operate.

It is worth noting here that when the instrument is equalized the upstream chamber will contain a liquid level according to the height of the valve manifold above the mercury chamber. It is useful to make a reference point on the scale for this condition, for if any liquid found its way to the mercury in the downstream chamber the instrument would read low when operating normally (see fig. 4).

The method already discussed for level measurement in vented vessels may be applied to pressurized vessels. The low-pressure side of the instrument is connected to some point near the top of the tank as shown in fig. 5. The conditions for this arrangement are that (a) the level in the vessel, under

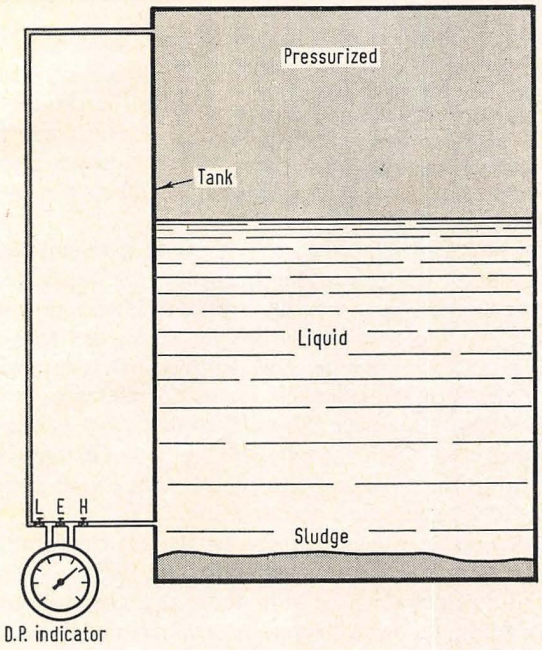


Fig. 5 Inference of level from differential pressure in tank pressurized with non-condensing vapour

operating conditions, must never reach the top connexion point (or the instrument will gradually return to zero level), and (b) there must be no danger of vapour condensing in the low-pressure connexion. It is helpful to provide a valve in the lowest point of this low-pressure connecting line to ensure from time to time that the line is liquid free.

If it is found that condensation does accumulate in the low-pressure pipe the system must be modified so that this pipe is always filled with the vessel liquid. *The leg, of course, then becomes the one of higher pressure and the connexions to the instrument must be crossed over*. It is usual to supply the filled leg with a condensation chamber on a level with the top connexion to the vessel. This filled leg is sometimes known as the 'wet leg' to distinguish it from the unfilled leg, known as the 'dry leg'. The capacity of the condensation chamber should be large compared with the capacity of the wet leg pipe, so that the liquid displaced by the mercury moving throughout its range makes little difference to the height of the wet leg column of liquid. A plug is usually fitted to the top of the chamber to enable the operator to fill it externally, and another plug opposite the connexion to the vessel makes it easy to check that the leg is completely full. A system I have used, with some success, is shown in fig. 6. A $\frac{1}{4}$ in (6·35 mm) bore pipe is taken from the main inlet vessel, to the chamber *via* a $\frac{1}{4}$ in valve. The valve can be cracked to ensure that, whilst the vessel is filling, a small flow of the liquid is fed to the chamber. This maintains a constant head on the wet leg by overflowing through the top vessel connexion.

For some high-temperature applications the wet leg may be considerably cooler than the vessel, and the difference in density between the vessel liquid and the wet leg liquid may be sufficient to cause significent errors in measurement. In such a case it has been known for the wet leg, including chamber, to be built inside the vessel, the leg coming out near the low-pressure connexion to the measuring instrument.

When it is necessary to measure the level of a corrosive liquid, and in certain other cases, a mercury manometer instrument can only be used in conjunction with liquid seal pots. The sealing liquid must be carefully chosen to ensure that it is not miscible with the measured liquid and should be at least 10% more dense. However, it is doubtful whether this method would be used by many engineers today. On top of the instrument price there is the cost for the seal pots and liquid. The seal pots would probably need to be made of stainless steel, or a better material, and there would be extra maintenance involved in checking the sealing liquid. It would be more economical, providing compressed air were available, to use a differential pressure transmitter and a local gauge

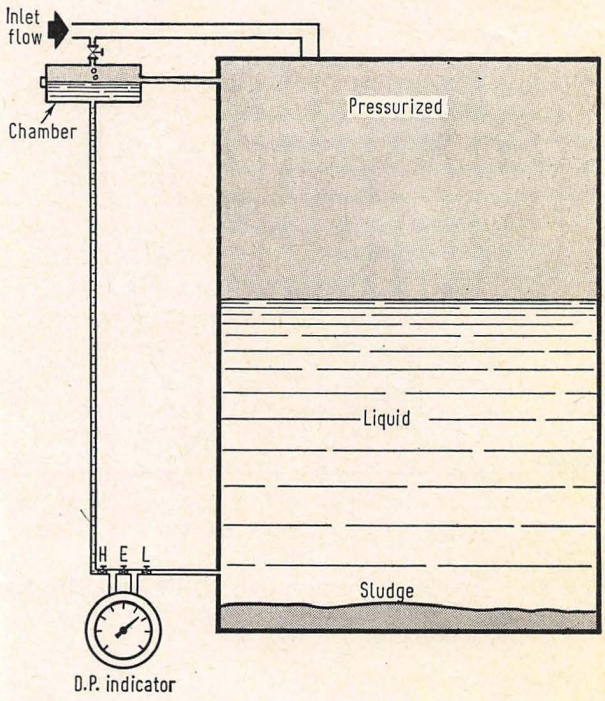


Fig. 6 Inference of level from differential pressure when there is some condensation from pressurizing vapour

connected to the transmitter output. Using the type of d.p. transmitter employing separate filled systems, would mean that the elements could each be connected directly to an isolating valve—one at the top, and one at the bottom of the tank. There would then be no need for pipe connexions, sealing chambers, or sealing liquids.

(To be continued)

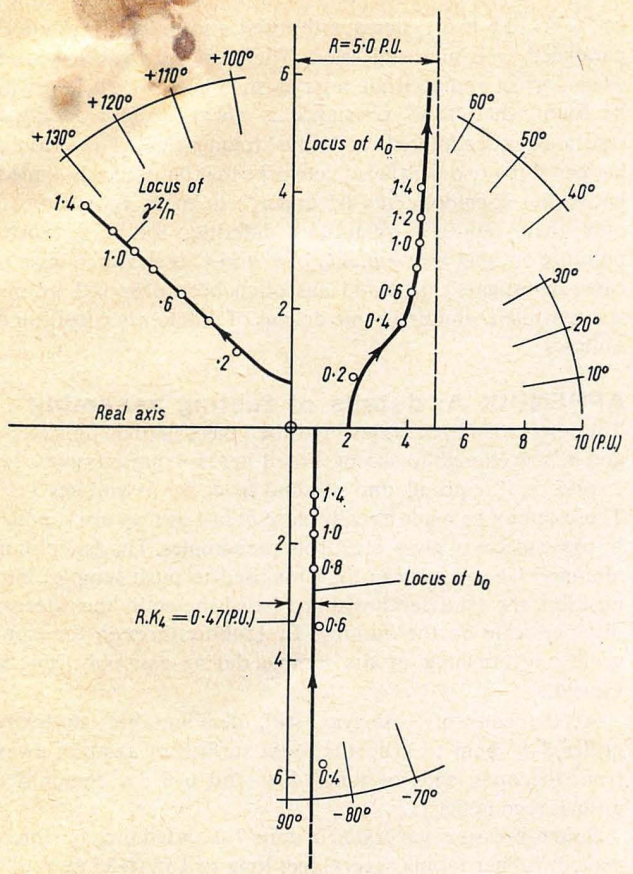


Fig. 9 Application of technique of fig. 2 to 15 sheets of rubberized cushion fabric

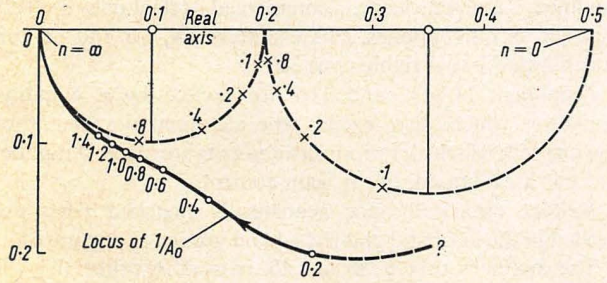


Fig. 10 Demonstration that the A_0 locus of fig. 9 is anomalous

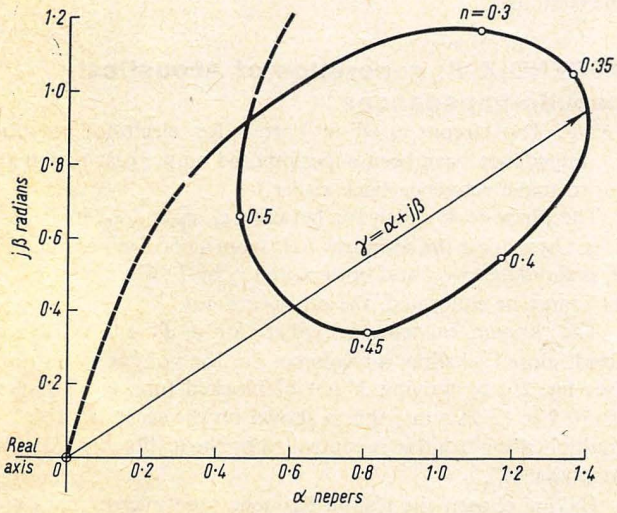


Fig. 11 Resonant loop in γ-locus measured by technique of fig. 2 on 1in sample of foamed rubber

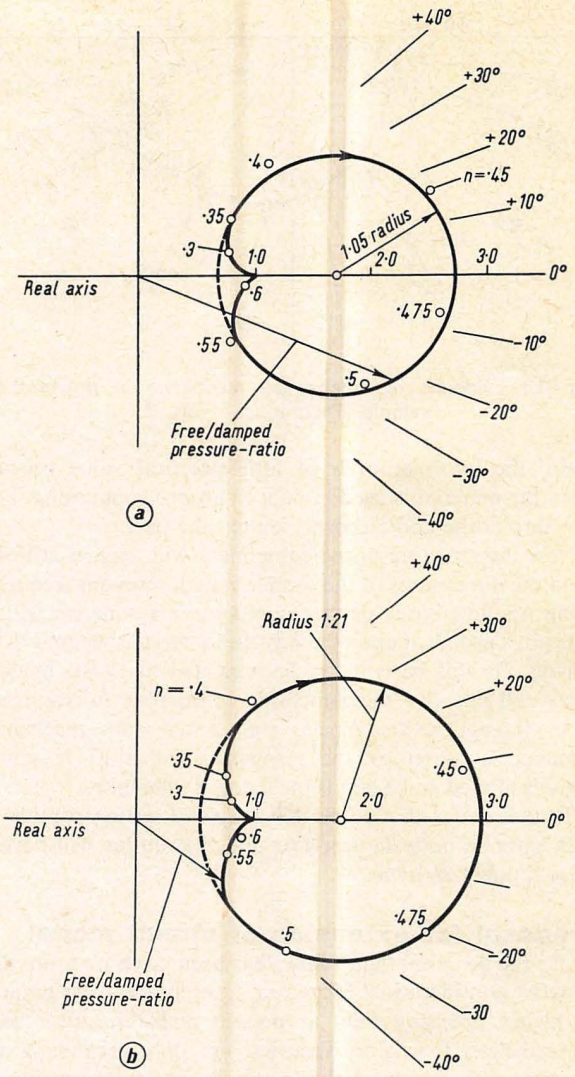


Fig. 12 Demonstration of mechanical resonance in samples of foamed rubber: **a** one 1in sample; **b** two 1in samples in tandem

Transmission through resilient materials

Materials such as 'foamed' rubber or plastics were used in an early stage of this investigation in order to explore the validity of the testing technique, for a sample that returned to shape after damage in a test could be expected to behave consistently. However, when transmission tests were made and the locus of γ drawn out (fig. 11) it was seen to imply a resonance of such high Q-factor that only physical vibration of the material could be responsible. To investigate this a blunt pin was arranged to pass axially through assembly 3′ so that a slight displacement would damp out any vibration. Results are shown in figs. 12*a* and 12*b* from which a Q-factor of about 10 can be deduced; even when two samples are tested in tandem Q-factor is hardly altered. (The increased circle radius in the second case is due to an unintentional change of test conditions.)

Though not so marked, vibration of this kind was also noted (fig. 13) in samples of polyurethane. The resonant loop in this locus of $1/T$ can be removed by the purely analytical subtraction of a similar loop imagined to be associated with mechanical resonance. When this is done correctly (a trial-and-error operation), the $1/T$ curve can be made smooth and from it the parameters associated with the airborne sound, alone, can be deduced. Although this tedious operation will show that the parameters agree with fig. 6*b* once

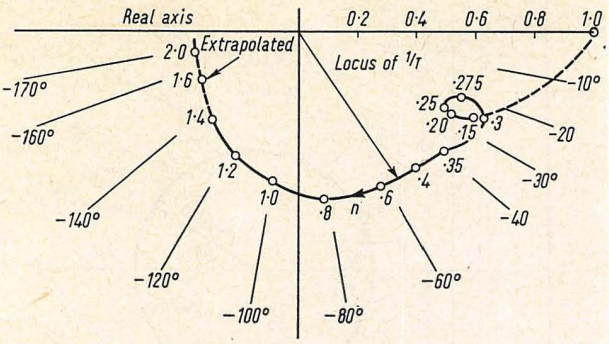


Fig. 13 Evidence of mechanical resonance in polyurethane sample. Technique of fig. 2

again, the information is of little practical value because, when the material is used in bulk to absorb room noise, both structure-borne and airborne sound take part.

Now the structure-borne component will depend critically upon the dimensions of the sample tested, resonant frequency rising as dimensions decrease; moreover resonance will be critically dependent upon the way the material is secured to the test-rig. On this basis it can be predicted that tests made in ducts will not give the same answers as tests in resonance-tubes (except at frequencies well away from mechanical resonance); moreover the resonance will shift if sample *shape* is altered and again if the fixing is indefinite.

Thus it seems that to establish a valid testing routine for such samples both the test-gear and the routine will have to be re-thought *ab initio*.

Proposal for extension of circuit model

So far the proposal that follows has been given no more than tentative consideration. Moreover, to support it measurements of higher precision than at present available are needed. Nevertheless, it will be discussed not only because it may discount readers' objections to certain earlier statements but also because it may even explain away apparent defects in some of the b_0-loci in this article.

The argument turns on the fact—now reasonably well established—that the A_0-element of the materials examined (and, by extension, possibly of all porous materials) has a dual form. It is now suspected that the b_0-element itself is essentially dual.

Duality of the b_0-element is described as 'essential' for purely formal reasons as follows: duality of the A_0-element has been established as an experimental fact; that is to say it is a representation—albeit, as we shall see in a moment, a slightly incorrect representation—of some physical micro-structure that exists in the material. Critical readers will have found it difficult to imagine, as did the writer, any physical structure that (in itself) could be responsible for the b_0 and dual A_0 circuit arrangement discussed here; however, the difficulty seems to be resolved when a separate (but analytically related) b_0-structure is imagined to be associated with each of the two inductive elements now recognized in the A_0 network.

When thus extended the equivalent network reveals itself as *two conventional transmission networks in parallel.* On such a basis there is no difficulty in imagining that a specific group of elements of the micro-structure is responsible for the one network and another group is concerned with the other.

Some of the methods of analysis adopted in this paper will have to be modified a little if it is true that the test-material performs like two systems with input and output 'terminals' paralleled as is now suggested. The idea is thrown out that when correct and accurate tests on such lines are made it will be found that 'flow' resistance is *always exactly half* the resistance encountered at finite frequencies. This would happen if the two paralleled networks that have been assumed had equal R-components (r' and r'') in their A_0-structures, only their inductive quantities differing, for it is worth pointing out that near-equality of r' and r'' is shown in several cases investigated here and has often been observed by the writer while examining some dozens of differently constituted samples.

APPENDIX A: details of testing assembly

The 5 in (130 mm) brass testing-tube 1 has $\frac{1}{4}$ in (6·35 mm) walls and is long enough to accept three 1 in (25·4 mm) samples, 2*a*, 2*b* and 2*c*, if required, and still find space for assemblies 3–3′. These cannot be made a really close fit in 1 or they are jammed by loose pieces of glass, etc., from the samples. The assembling 'dummy' (shown only in fig. 1) is used to push samples into position, the axial depth within 1 being shown by the external distance-scale on the dummy. By looking through the front grille any crushing of the sample during assembly can be viewed.

At the ends of 3–3′ two, stiff, demountable, steel-wire grilles 8–8′ help to keep the loose surface of samples away from the open ends of tubes 4–4′ and 6–6′; a demounted grille is seen in fig. 1.

Sound-pressure, generated in units 7–7′, is fed through thick-walled, rubber tubing several feet long to $\frac{1}{4}$ in (6·35 mm) diameter tubes 6–6′ that are fixed in 3–3′ with open ends just behind grilles 8–8′. Similar tubes 4–4′ pass the pressure existing at the test-planes (see diagram) through heavy rubber tubes to modified, high-efficiency, commercial telephone-receivers that act as microphones. Phase-shifters ϕA, ϕB and ϕC are uncalibrated but variable over 360°.

Amplifiers 11, 11′ and 11″ are excited by a common oscillator which also excites the a.c. potentiometer (not shown) with which all ratio-measurements are made. Amplifier 11″ has a calibrated, linear, gain-control.

Neither electrically nor acoustically matched parts are needed in the left-hand and right-hand groups of apparatus.

The auxiliary tube 9, in fig. 2*b*, is used in calibrating the pseudo-impedances. The temporary fibre packing in assembly 3′ in fig. 1 and the fine-bore tip on one tube, are explained in the main text.

APPENDIX B: generation of acoustical pseudo-impedances

(*Note:* The circuits used in Part 1 for electrical pseudo-impedance have been superimposed on the gear of fig. 2*a* to make reference back easier.)

The phase-lock called for between e_1, e_2 and e_3, in Part 1 is got by driving the sounders 7–7′ from a common oscillator; e_1 is simulated by 7 and both e_2 and e_3 by 7′. Gain control of 11″ must be calibrated, the others are not.

The 'known capacitance' called for in Part 1 is here a fixed, closed, shallow air-volume, *i.e.* the volume swept out (see fig. 2*b*) by moving 3′ out of blocked tube 9 a distance $D=0{\cdot}1$ in (2·54 mm); this is shown on the scale 10. The 'k-multiplication' routine is controlled by the (calibrated) dial on amplifier 11″.

Having chosen the testing frequency the microphones are adjusted (see Appendix C) and 3 is inserted into 1 as in fig. 2*a*. Then:

To measure N_∞ by terminating the test samples by a pseudo-impedance effectively infinite:

Stage 1: Insert 3′ into 9 (fig. 2*b*) and push home till blocked by the closed base of 9.
Set gain of 11″ to zero. Adjust 11′ til S/N ratio is adequate.
Lock control of 11′.
Store the voltage measured at P'. *Call this* P_0'.

Stage 2: Insert 3′ into 1 as in Fig. 2*a*.
Adjust ϕA and 11 until P_0' is restored.
(Load impedance is now effectively infinite.)
Measure P/P' which, following the main text, is $Pa/P'=N\infty$.
Q.E.F.

To measure N_1, N_2 etc., by terminating test sample with known acoustic capacitances:

Stage 3: With 3′ placed inside 9 as in stage-1 and leaving 11′ locked, as above, withdraw 3′ a distance $D=0{\cdot}1$ in (2·54 mm) out of 9.
Adjust ϕ_C and gain of amplifier 11″ to value k to restore P_0'. Note k. Lock ϕ_C.

Stage 4: Replace 3′ in 1.
Reverse input (or output) terminals of 11″ and adjust ϕ_A and 11 until P_0' is restored.
Measure P/P' which, following the main text is $(P_c/P')_1=N_1$.

Stage 5: Change gain of amplifier 11″ from k to $2k$.
Reset 11 and ϕ_A till P_0' is restored.
Measure P/P' which following the main text is $(P_c/P')_2=N_2$.
(Similarly for N_3 etc. raise k to $3k$.)
Q.E.F.

Note: When Stage 4 is complete the sample is (effectively) loaded by the acoustic capacitance of an air-volume (0·1) × (area of tube 9) in³; when k is doubled the effective volume is doubled, and so on. Multiplication is limited only by overloading of the sounders 11 and 11″. In certain test-conditions overloading can be avoided by omitting the reversal at the start of Stage 4. As a result the reactance of the terminal load changes sign (becomes inductive) but does not change magnitude—see Part 1.

APPENDIX C: inter-comparison of microphones

The objective is to make the voltage-outputs from the two microphone-systems alike in magnitude and phase when excited by a common sound pressure. The comparison is always made at the outset of a test at the testing-frequency proposed. Assemblies 3 and 3′ are removed from 1 and placed face-to-face on the test-bench, temporarily held in place by a small finger of Plasticene; a precise 'butt joint' is *not* essential. With 7 and/or 7′ excited, adjustments of the microphone-amplifiers and ϕ_B are made until microphone outputs match exactly. Amplifier gains and ϕ_B are then locked.

To avoid magnetic coupling between sounders 7–7′ and microphones 5–5′, crystal microphones were first tried but had so low an output and so high a temperature coefficient that they had to be abandoned. It was then found that the magnetic receivers worked well even through several feet of tubing and in this way magnetic coupling with 7–7′ was avoided.

Really thick-walled 'pressure' tubing is needed or sound transmission varies when assemblies 3–3′ are moved to new positions in the course of a test.

APPENDIX D: Z_0 measurement; the *P*-unit

Compare fig. D with fig. 3, Part 1, and associated text. For clarity the detailed vectors of fig. 3 are not shown in fig. D; it represents an actual Z_0-measurement made at 300 c/s; the

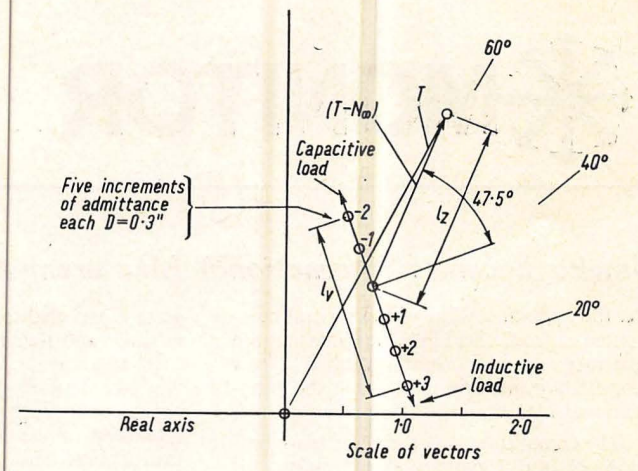


Fig. D Derivation of Z_0 by technique of fig. 2, illustrating advantage of inductive load.

argument of $1/Z_0$ is seen to be near 47°. Because frequency is low and D/λ less than 0·1, the 'reference' air volume has been increased to $D=0{\cdot}3$ in (7·62 mm) from $D=0{\cdot}1$ in (2·54 mm) (as mentioned in Appendix B) without introducing wavelength corrections; this increase also helps to improve diagram accuracy by loading the test-piece more heavily.

The sloping load-line is marked-off to show the location of the five N-vectors that were measured when two pseudo-capacitances (marked *negative*) and three pseudo-inductances (marked *positive*) were generated. For the positive points the reversal at Stage 4 of Appendix B was omitted; notice that this allows the load-line to be lengthened without calling on the sound generators for excessive sound-pressure.

Intervals on the load-line are due to the five equal steps by which the pseudo-load admittance has been increased using the K-routine of Appendix B. The linear distance l_v corresponds to five-times the acoustic admittance of the air volume associated with $D=0{\cdot}3$ in (7·62 mm). On the other hand the distance l_z corresponds to the admittance $1/Z_0$. (See Part 1.)

Since acoustic admittance of the reference air-space will be proportional to frequency, 'absolute' values of admittance can conveniently be ignored and replaced by pseudo-air-volume expressed in D-inches and multiplied by n, the frequency in kc/s. The units (frequency)$^{-1}$ × (inches)$^{-1}$, in which the inverse quantity, *i.e.* impedance, is expressed are arbitrarily defined as P-units.

In fig. D we have—

$n=0{\cdot}03$; $l_v=1{\cdot}5$; $l_z=1{\cdot}57$ and $\Sigma=1{\cdot}5$, the last being the total pseudo-air-volume in D-inches that has produced the vector-interval λ_v.

Whence:

$$|Z_0|, \text{ (in } P\text{-units)} = (l_v)/(n \,.\, l_z \,.\, \Sigma_v) = 2{\cdot}12$$

Acknowledgement

The major part of this article is based on several years' work done while the writer was with the Research Department of the B.B.C. at Kingswood Warren and acknowledgement is made for permission to use this material and the photograph; the broad conclusions reached have been the result of subsequent inter-comparison of all the data available.

References—*continued*

4. Z. Esmail-Begui and T. K. Maylor; *Journ. Ac. Soc. America.* **25**, *page* 87. 1953.

End

MONITOR . . . an instrumental eye on the world

Imeko becomes International Measurement Confederation

At the seventh session of the general committee of Imeko held in Warsaw last month the member organizations* ratified a new constitution making Imeko into the International Measurement Confederation.

The committee also accepted the application of the Egyptian Organization for Standardization (representing measurement and instrument specialists in the United Arab Republic), and in this way the first organization from the African continent was included as the fifteenth member of the general committee.

The structure and scientific program of the fourth Imeko congress to be held in Warsaw in July, 1967, was outlined. Prof. Dr György Striker, secretary general of Imeko, stated at the press conference held at the closing session, that the fourth congress is expected to surpass its predecessors in scope and significance.

In addition to the fields covered at previous conferences the next congress is to appeal to a much greater degree to those interested in the industrial application of instruments. This is intended to bring to light new solutions to the problems of applying instruments for measurements in space, research and industry in difficult situations, for example flow measurement of slurries or very viscous fluids; temperature measurement in oxygen blown steel making furnaces or inside food cans being processed; measurements in conditions of high or low temperature; in presence of dirty atmosphere or high vibration; or measurement of fast moving objects.

New procedures will be considered for on-stream automatic inspection or quality testing in, for example, metallurgy and metal working industries. Special attention might be given to instrument applications in medical and biological engineering and other areas.

Participation in the congress is to be broadened in such a manner that papers entered from various countries but found to be dealing with closely associated subjects shall be covered by expert rapporteurs so as to give the participating authors more time for a plenary discussion.

Entries will be solicited on the widest range covered by the subject matter listed above in order to give the papers committee a good chance to select and arrange the papers into most interesting groupings. Some of these groups will also be discussed in workshop-session or round table meetings, a technique which proved very successful in Stockholm in 1964.

Upon recommendation of member organizations, a number of lectures on single specific topics will also be presented as was done at the previous conference.

The committee decided to shorten considerably the reviewing procedure of the submitted lectures. Synopses will have to be submitted by authors to the member organizations by July, 1966.

*Bulgaria, the Chinese People's Republic, Czechoslovakia, the Federal Republic of Germany, the German Democratic Republic, Hungary, Italy, Japan, Poland, Roumania, the Soviet Union, Sweden, the United Kingdom and the United States of America.

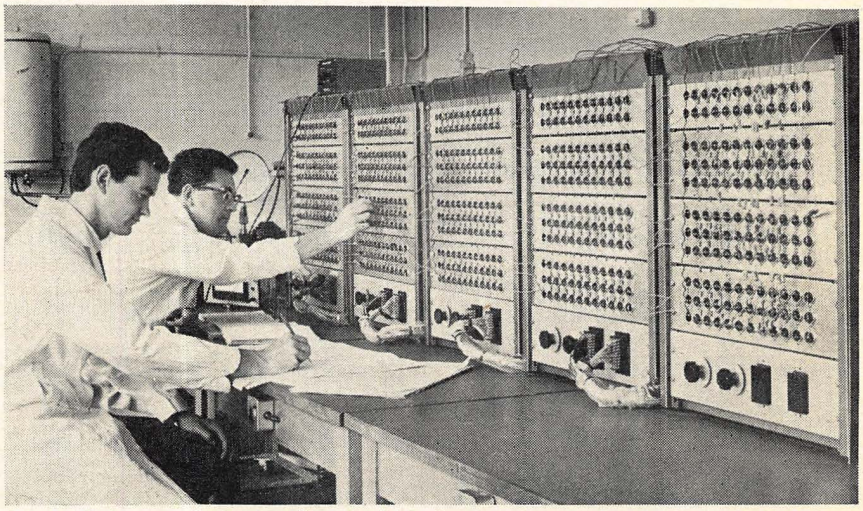
Instrumentation techniques aid water supply

Inexpensive neutron-scattering equipment developed for the Water Research Association by the United Kingdom Atomic Energy Authority, and now in use for the measurement of soil moisture, is described in the recently published report of the Association for the year ended 31 December, 1964. The work is being carried out in several experimental water catchments to permit the relationship between meteorological records and actual water available to be predicted with greater accuracy.

Other instruments developed include a recording self-emptying rain gauge which is now under trial by a number of Association members, and an antecedent precipitation index computer, a device which takes information from such instruments and gives a remote continuous indication of the soil moisture conditions in a catchment.

The W.R.A. is the central research organization for the United Kingdom water supply industry. It also serves organizations with ancillary interests, university departments and industrial water users for example, and bodies outside this country. There is no Government control, although the Association does receive a Government grant. Expenditure is divided fairly evenly between basic research work, development, and applications and services to members.

During the year under review, the Association has had a considerable amount of success in various aspects of design and maintenance of water distribution systems. The distribution analogue centre which has been established at the Medmenham (Bucks) research station has so far provided ten water undertakings with analyses of their mains networks in a detail that would be impracticable to achieve by conventional computation. The centre is able, for example, to determine where in a mains system difficulties will occur as consumption increases, and to decide the most



The W.R.A. ground water analogue, which simulates practical problems in the techniques of abstracting water from underground sources, or of recharging them