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Summary

The mechanical properties of timber, wood products and other materials potentially suitable for the construction of loudspeaker cabinets have been measured and details of the results are given. Various commercially available damping materials have also been assessed and their relative efficiencies are listed. A new method of test for the cabinets of completed loudspeakers has been devised and a tentative performance specification has been produced

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1. Introduction

In order to obtain good quality reproduction from a moving-coil type of loudspeaker unit it is necessary to mount it in an enclosure and it has long been recognised by designers that the materials from which a loudspeaker enclosure is made can substantially affect the sound quality produced. The cause of the trouble is known to be due to resonances of the walls of the enclosure; these can give rise to a coloured* sound, the commonly used term 'boxy quality' adequately describing the result. To overcome this effect extreme measures have been advocated[1] such as the use of bricks and mortar, marble, concrete and similar materials, for the enclosure. Whilst the use of such materials may indeed yield the desired sound quality, the resulting construction is obviously unsuitable for the great majority of purposes.

The traditional material for the construction of loudspeaker enclosures is wood in some form or other and it is well known that wood can give excellent results. Nevertheless, very little basic information has been published on the structural design of loudspeaker enclosures, i.e. cabinets, such little as there is being mainly qualitative.[2,3,4]

Colourations due to the characteristics of the cabinet remain a problem. In many cases these, in turn, arise because the manufacturer has departed from the construction originally called for by the designer. This situation may arise for example, because the specified damping materials may no longer be available and the relatively small quantities involved would render special manufacture prohibitively expensive.

While searching the alternative damping materials, advantage has been taken of the existence of the equipment necessarily designed for the associated measurements to examine the properties of some of the types of potentially suitable cabinet materials and, in particular, to look into the properties of wood and wood products more closely. In addition a new method of test for complete loudspeakers has been devised and a tentative working performance specification has been produced.

2. General

Resonances of the panels of a loudspeaker cabinet can affect the sound quality from the loudspeaker in two ways. In the first place the mechanical impedance of the panel is low at resonance and therefore an appreciable amount of the sound inside the cabinet can be transmitted to the outside. The sound pressure inside the cabinet is generated from the rear of the loudspeaker cone and is in antiphase with that radiated from the front of the cone; the sound transmitted by the panel therefore interferes with that from the front and can cause irregularities in both the steady-state axial response/frequency curve and in the polar diagram. In addition, the stored energy in the panel results in a poor transient response of the system, causing further colouration to an extent which depends on frequency, Q, phase and the relative levels of the direct and stored energy (called the 'dilution' in this report).

From the point of view of the manufacturer, the construction of a closed cabinet loudspeaker appears to be simple but from the acoustic aspect it is not so. With the usual rectangular cabinet design, the resonance frequencies of the front, rear, side and end panels are all different and each has in principle, an infinite series of overtones. The air-filled cavity formed inside the cabinet will resonate in many modes; in addition the loudspeaker unit can resonate on its mounting panel and the magnet on the loudspeaker frame. All these resonant elements are coupled together in various degrees. As a result, it is impossible to base a design solely on theory.

The effects of each of the abovementioned factors will now be discussed in more detail.

(a) Panels

Clearly the construction of the panels must ensure that the cabinet is strong enough to withstand reasonable handling; secondly the panels should ideally, prevent sound inside the cabinet from being radiated outside. The first requirement can be met with relatively thin panels; when these are attached firmly to a frame the resulting structure is quite strong. With regard to the second requirement, the panel is stiffness controlled below the fundamental resonance and mass controlled between overtones above this frequency. It is fairly easy to determine these two conditions, the difficulty lies in the effects of the resonances. As mentioned above, each panel has its own series of resonances, the frequencies depending on the dimensions, the way it is fixed at the edges, the density and the modulus of elasticity. Timber is not isotropic, hence the elastic modulus varies according to the direction of measurement, being greatest along the grain. The resonance frequencies for a given panel can be raised by fixing struts along the surface of the panel and this effectively increases the stiffness without significantly increasing the mass.

One force driving the panels comes from the sound inside the cabinet and of course this acts outwards on each pair of opposing panels at the same time (in a symmetrical design). Increased stiffness can be obtained by connecting the centres of opposing pairs of panels by a stiff rod, thus suppressing the fundamental mode of resonance. This scheme has been used in at least one high-quality loudspeaker.

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* Colouration:— an apparent undue emphasis of a narrow part of the spectrum thought to be caused by some form of resonance.

Appreciable mechanical damping can also be applied to the panels. This was first adopted by the author in a loudspeaker designed for portable use where the use of massive panels was impracticable. The panels were made of 9 mm birch plywood, a 9·5 mm layer of soft fibreboard being stuck to the inside as a lossy element. The maximum value of mechanical resistance easily obtainable using commercially available damping materials of reasonable cost is not very high. However such a lossy layer will have the maximum effect on a system having relatively low mechanical impedance, which implies a fairly thin panel. The use of such a design results in an easily portable loudspeaker and in a lower first cost.

(b) Air resonance

The cabinet will exhibit all the air modes of resonance of a miniature room and these will affect the sound pressures on both the panels and the loudspeaker cone. As the cone is much thinner than the walls of the cabinet these resonances must be heavily damped and therefore a considerable amount of acoustic treatment is normally applied to the inside of the cabinet. Some resonances remain however. The largest of these occurs in a vented cabinet at low frequencies where the system acts as a Helmholz resonator with a Q of the order of 10. Fortunately at such frequencies the panels are stiffness controlled and act as a stiffness in parallel with that of the air; care must therefore be taken that the panel stiffness is sufficiently high to ensure that the resonance frequency is not affected to any great extent and to prevent the panel radiating appreciably in antiphase with the sound output from the vent.

(c) Loudspeaker unit

The magnet of the loudspeaker unit is subjected to a force equal and opposite in phase to that imparted to the voice coil. However the efficiency of a loudspeaker unit is very low (a common figure being about 1%) due to the large impedance mismatch between the cone and the radiation resistance of the air, and this means that the force applied to the magnet system is many times greater than the sound pressure generated; it will immediately be appreciated that the panel of the cabinet on which the unit is mounted is subjected to a considerable degree of vibration.

Fortunately the mass of the magnet system is high but two forms of resonance can occur. The first is that due to the mass of the whole unit and the stiffness of the front panel, and one of the easiest solutions to this problem is to make the front panel only slightly wider than the diameter of the unit, thus ensuring a very high panel stiffness; this solution has the incidental advantage of improving the radiation characteristics of the loudspeaker.[5]

The second mode of resonance is not so easily dealt with and the problem it poses is more difficult if the arms of the frame of the loudspeaker are curved. In such circumstances the stiffness of the arm is relatively low and the magnet mass resonates with this stiffness at mid audio frequencies with a very high Q. The only practicable means for obtaining a mechanical resistance sufficiently high to damp such a resonance consists of a strong brace across the cabinet just behind the magnet together with a piece of dense felt compressed between the magnet and the brace; however, large forces are communicated to the panels.

3. Properties of timber

It is clear that the physical properties of the panels are principal factors in the loudspeaker design. Wood is the conventional material and the choice in practice lies between solid timber and manufactured sheet materials such as plywood, chipboard and fibreboard; fibreglass reinforced resin is also a potential material. Timber will be discussed first.

On examining the literature describing various forms of timber it is found that they are divided into two sections labelled 'hardwoods' and 'softwoods' respectively. This, superficially, appears to be very sensible but on closer examination it can be misleading. The division in fact is simply between those forms of timber derived from deciduous and non-deciduous trees and as an example of the way the division can cause problems, balsawood, the softest known wood, is classified as a hardwood. It is therefore meaningless merely to call for 'hardwood' fillets in a loudspeaker; in the past, difficulties have arisen as a result of such specifications.

A tree trunk consists of concentric circular bands or rings of early and late wood. Consequently a piece of wood will have different properties if it is cut tangentially rather than across a diameter; furthermore, similar cuts of timber from different trees show different numbers of rings per inch. The variation in elasticity thus obtained can be expressed in statistical terms, and between the 1% confidence limits the variation in Young's Modulus can be 350 to 400% for a given type of timber[6] when measured by means of static deflections along the grain. It has been stated[7,8,9,10] that for, any given sample, the difference between the static and dynamic elastic moduli is small at low frequencies, particularly in comparison with the variations quoted above, so that, the much more readily available figures based upon static tests can initially be utilised.

Figures for the elastic modulus across the grain are not very common and, for different species, range from 1/30th to 1/10th of those along the grain, still further emphasising the anisotropic nature of timber.

These is very little published data concerning the variation of the elastic modulus with frequency particularly at high audio frequencies, but such as there is[12] suggests that it is constant. There is still less data concerning Q* and its variation with frequency[19,14,15] but surprisingly it appears that the Q is also independent of frequency, at least up to the middle of the audio frequency band. The mechanism behind this is obscure but it appears that a combination of series resistance, parallel resistance and hysteresis may be involved. However, this property is advan-

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* Although a highly damped material, i.e. one with a large loss factor, is clearly desirable for the construction of loudspeaker cabinets – it is customary to use the inverse factor namely Q.

tageous for it has been shown elsewhere[16] that the audibility of a resonance is related to its decay period i.e. Q and frequency. In the case of timber the most audible resonances therefore occur towards the lower end of the band where they can give rise to a 'boxy' quality. The loss factor across the grain is said[17] to be about three times that along the grain.

It is now evident that ordinary timber cannot be regarded as a precision engineering material for loudspeaker cabinets. The variation by a factor of four of the elastic modulus along the grain corresponds to a variation of 12 dB in height of a resonance peak which could have a major effect of the audibility; timber does however appear to possess some features, such a relative constancy of Q with frequency, which are useful.

4. Properties of wood based materials

The materials to be discussed in this section are blockboard, plywood chipboard and hardboard.

All these materials are produced by bonding together a large number of small pieces of wood and the size of the individual pieces varies with the material, being relatively large in common blockboard, less in the laminboard variety and reducing to fibres in fibreboard. Such materials are likely to be less anisotropic and less variable between samples than solid timber.

Hardboard is uniform in properties in the plane of the sheet and has a lower Q than most other materials, but in some forms at least has only a low elastic modulus. It is made in various densities varying from 'standard' to 'tempered' board. Until recently however it has not been available in a suitable combination of hardness and thickness for use in loudspeakers, no details of the dynamic elastic modulus or Q are available.

Chipboard is made in three principal forms. In one manufacturing process the raw material is extruded from a die as a continuous sheet, and the wood flakes lie at right angles to the plane of the sheet; the bending modulus and ultimate strength are therefore low. It is basically unsuitable for panels on its own and is only used as the inner core of a sandwich type of construction where the orientation of the particles becomes an advantage. In a second process the board itself is effectively of sandwich construction. The inner core is of a lower density than the outer two layers which also contain a higher percentage of resin bonding. It is made in sheets with the plane of the flakes in the same plane as the sheet, and is thus suitable for panels, although care is necessary in joining the edges to form a cabinet because of the lower density of the inner core. It is extensively used in the manufacture of cabinets for the 'hi-fi' industry. The third type of chipboard is again made with the plane of the flakes in that of the sheet but is uniform in density throughout. It can be obtained in a variety of densities.

No details of the variation with frequency of the elastic modulus or Q are known for any of these three types of chipboard.

The general construction of plywood is well known but it is clear that the degree of anisotropy becomes less as the number of plies is increased. Thus, for a 4·8 mm three-ply construction the ratio of elastic modulus across the surface-grain to that along it[18] may still be 10 to 20. It is evident therefore that a large number of thin plies will give a more satisfactory engineering material than a few thicker ones. This also has the advantage that, as pointed out in the section on the properties of raw timber, the Q across the grain is only about one-third of that along it and this will mean that the Q of plywood should tend to be less than that of timber along the grain. Once again there is no known data on the variation with frequency of the modulus of elasticity and Q. Plywood does however have one useful advantage over many other materials in that it is made in a closely graded range of thicknesses.

Blockboard consists of a number of strips of wood forming a core glued on each side to a fairly thick wood skin. It is clear that the degree of anistropy will be greater than that of the other composite materials but should still be less than that of solid natural timber and also less variable in properties from sample to sample. Various combinations of core and skin are available and no difficulty should be experienced in making cabinets from it. As with the previous two materials no data is available on the elastic modulus and Q or their variation with frequency. The range of thicknesses available is much less than that for plywood.

5. Properties of glass reinforced plastic

This material is included in the survey as it has the advantage that by its use departures from the simple rectangular form of cabinet can be constructed economically. It can be made in a variety of mixtures and carbon fibres can be substituted for glass fibre if necessary; the fibres can have random orientation or may consist of a woven cloth and various ratios of fibre to resin can be obtained. At the present time the material is expensive and would not compete in cost with a simple rectangular wooden cabinet but, with the rapidly rising cost of wood it may soon be competitive, particularly for cabinets which are not of a simple shape.

6. Measurement of elastic modulus and Q of various materials

From the foregoing it is evident that further information on the properties of some of the materials described in the previous sections would be very valuable and equipment has been developed for the purpose of obtaining it. A simple approach consists of vibrating a strip of the material under study and finding the various frequencies of the fundemental resonance and the overtones. From the mass and dimensions of the sample the elastic modulus can then be calculated; the Q can also be obtained from the shapes of the resonance curves. Of the various ways of mounting the test strip, that most closely resembling a cabinet panel is the one with the two ends firmly clamped. A free length of 50 cm is representative of the range of panel sizes used

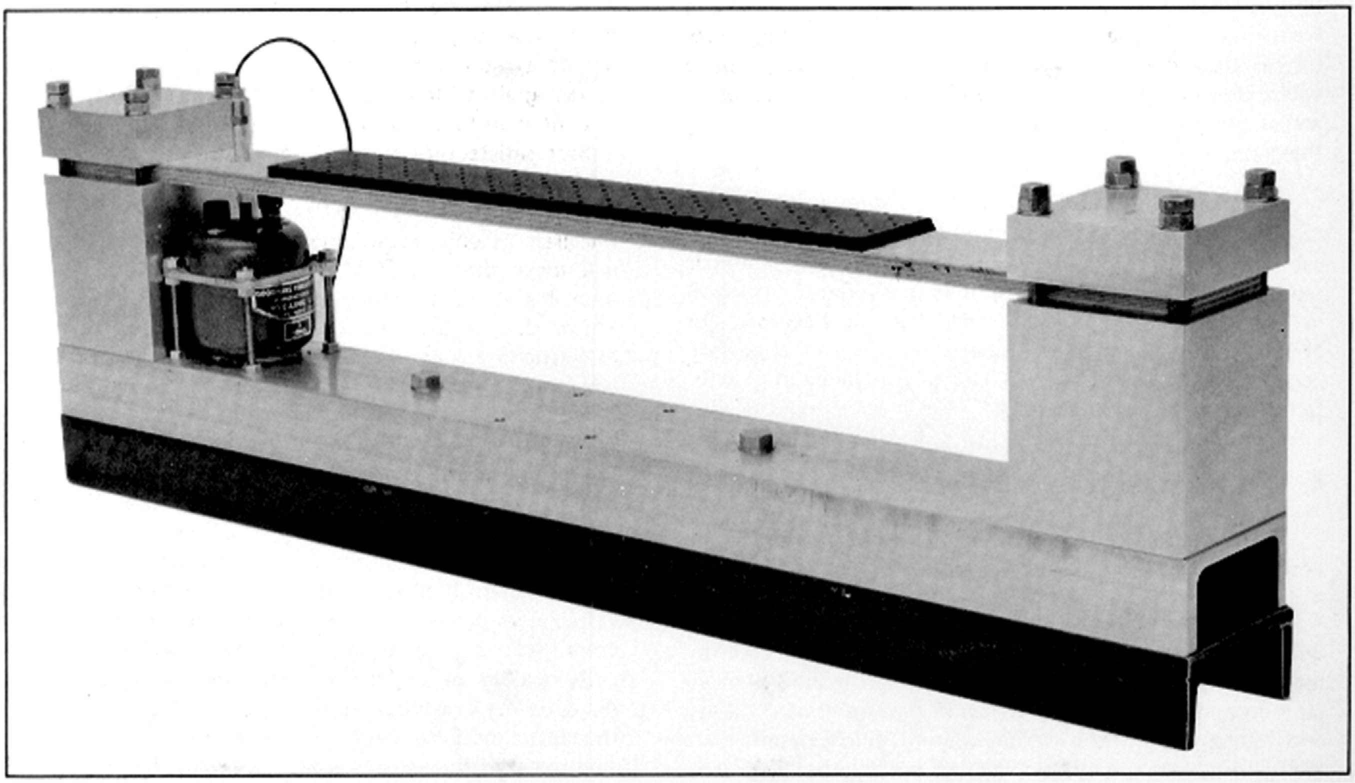

Fig. 1 - View of sample testing equipment with sample mounted for testing damping properties

for loudspeakers. The width of the test specimen is conveniently made small to keep the mechanical impedance low, to prevent high level radiation of sound and to reduce the incidence of transverse modes of resonance. A width of 5 cm was chosen as a suitable compromise. In all the wood samples measured the ambient conditions were such as to give an estimated moisture content of 15%.

The equipment is shown in Fig. 1. The base is made of two heavy channel sections, 7·5 cm x 4 cm, firmly bolted together and the 7·5 cm square pillars are solid. The sample is clamped firmly at each end and driven near one end by a lightweight vibration generator; to avoid electromagnetic damping at resonance the generator is driven from a constant-current source. The motion of the sample is detected by a lightweight accelerometer attached to the stalk of the vibration generator. The weight of the generator coil, driving stalk and accelerometer is about 18 gm and can therefore be neglected in comparison with that of the sample (particularly as it is driving at a high impedance point on the sample); it has been calculated that the effect on the results is small, particularly in comparison with the variability still possible between samples.

It will be appreciated that with this method of test the frequencies concerned are sufficiently close together to permit an adequate account of the variation of Young's Modulus E and Q with frequency to be obtained.

A value of E thus obtained may be expected to agree closely with that obtained by using only the fundamental mode and varying the length of sample to vary the resonance frequency. This does not necessarily apply however to the values for Q as the effect of material irregularities on the positions of the nodal points when vibrating in the higher modes may well be greater than for the fundamental. However these circumstances resemble more closely the modes of vibration of a loudspeaker panel, and are therefore more appropriate.

The resonance frequencies of a beam firmly clamped at both ends is given by the formula.[19]

$$f_n = \frac{\pi}{2L^2}\sqrt{\frac{Ek^2}{\rho}} \cdot \beta_n{}^2$$

where E is Young's Modulus
L is the free length of the sample
k is radius of gyration
ρ is density
$\beta_1 = 1{\cdot}5056$, $\beta_2 = 2{\cdot}4997$, $\beta_n = n + 0{\cdot}5$ $(n > 2)$

Measurement of the resonance frequencies up to the fifteenth overtone permits the elastic modulus to be calculated over the greater part of the audio frequency range.

The first few overtones expressed as a ratio of the fundamental frequency are 2·756, 5·404, 8·933, 13·345 and 18·639 and illustrates the fact that the overtones are not harmonically related; this of course affects the tonal quality if they are audible.

Apart from the case of 9 mm birch ply measured along the grain of the outer surface, tests were made on only two samples of each material, as the object was to discover the order of magnitude of the values of the physical constants rather than to carry out a detailed statistical investigation of their variations. A number of samples of 9 mm birch ply were needed to carry out tests on damping materials so in this case additional information on consistency was obtained.

In addition to the composite materials mentioned in the previous section, several samples of timber were also measured as in the past these have been used for fillets in loudspeaker cabinets and some have given rise to colouration.

In the tests the sample vibration amplitude used was small and was invisible even at resonance and a check was made for linearity by measuring at more than one value of excitation.

7. Results

The density, elastic modulus, maximum Q and cost in September 1974 per 100 m^2 for the various timbers tested are given in Table 1 (roughly 1 m^2 is required for a medium-size cabinet). Each figure for elastic modulus is the mean value obtained at one frequency for the two samples tested and it is evident that there is an appreciable variation with frequency.

The results for the Q factor vary considerably between materials. For oak both along and across the grain and for deal and parana pine (across the grain) the Q is fairly constant with frequency. On the other hand for deal, parana pine and beech (along the grain in each case) the value of Q for the fundamental mode is some 50% higher than for any other mode. It is clear therefore that in all cases the value at the fundamental will determine the longest decay time and therefore the maximum audible effect. Only the maximum value is therefore given in the table.

In the last column the value of the factor $\sqrt{E\rho}/(Q)$ is given. This is a measure of the minimum attenuation of a sound wave through the walls of the loudspeaker cabinet and as such is a figure of merit of the material for this purpose; in order to arrive at a single figure of merit for each material, the value of E at 250 Hz has been taken as representative.

Table 2 gives the corresponding figures for manufactured materials where it will be seen that for some the value of E varies substantially even at the lower frequencies. However even in these cases the value at 250 Hz has been taken both to allow comparison with the earlier table and because it is representative of low frequency loudspeaker-cabinet panel vibration frequencies.

Typical curves of elastic modulus with frequency are given in Figs. 2(*a*) to 2(*f*) plotted on logarithmic scales to facilitate comparison of the curve shapes. The small variation in E for deal along the grain at low frequencies is evident as is the much greater variation of blockboard. The relative constancy of E at high frequencies for deal across the grain and the unusual variation for a glass reinforced plastic material are also seen.

For the manufactured materials, the variation in Q with frequency again differs considerably between materials. For those made from more finely divided particles the Q is roughly constant but, for chipboard, the tendency is for it to rise with increasing frequency, the value at 2 kHz being some 20% and 50% above that for the fundamental for 15 mm and 18 mm thick samples respectively. Other materials which also show a rise in Q with frequency are the glass reinforced plastic series. In this case the rise follows a preliminary slight fall and the increase above the values at low frequencies is about 25%. As for timber the maximum decay times occur with the fundamental mode so this value for Q is given in the table. For the plywoods the value of Q for the fundamental mode is appreciably greater than for the higher modes.

8. Discussion of results

It will be seen from the Table 1 and Figs. 2(*a*) and 2(*b*) that the elastic modulus not only has very different values along the grain of timber to that across the grain but also that the variation with frequency is very different for the two cases; the difference in value for deal is about 30 at low frequencies. For plywood this variation is, as expected, seen to get less with the number of plies and is negligible for the thirteen ply samples.

It should be appreciated that in the formula previously quoted for E it was assumed that the material was isotropic at least in the direction of propagation of the wave and for some of the materials discussed this clearly does not apply. For instance blockboard measured along the surface grain, i.e. with the core as a transverse grain, the material more closely resembles a sandwich construction with the core contributing little to the elastic modulus but acting as an efficient spacer. To some extent this also applies to the chipboard samples which are of the three layer type. Furthermore for timber measured along the grain the latter can still be either in the plane of the sample or at right angles to it. In the former case it seemed plausible that the hard layers might be decoupled from each other by the softer layers at high frequencies and in this frequency region the elastic modulus might fall towards the value appropriate to a number of laminae able to slide over each other. To check this, samples of deal, which of course has an open grain, were taken and in which the two extreme cases were illustrated, but no difference was found in the variation of elastic modulus with frequency up to 6 kHz. This effect presumably occurs therefore above the frequencies in which we are interested.

The curves for the glass reinforced plastic* material,

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* For composition see Appendix

TABLE 1

Properties of Timber

Material	Density ρ	Max Q	Elastic modulus $E \times 10^{-9}$ N/cm^2								12 mm thick Cost per 100 m^2†	$\frac{\sqrt{E\rho}}{Q} \times 10^{-5}$ at 250 Hz	$\sqrt{E\rho} \times 10^{-5}$ at 250 Hz
			62·5 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	6 kHz			
Oak along the grain	0·63	96	14·8*	14·8	14·7	14·0	12·8	10·8	8·4	7·6	£ 775	0·032	3·04
Oak across the grain	0·585	50	1·0	1·0	0·97	0·88	0·76	0·77	0·82	—	775	0·015	0·75
Deal along the grain	0·57	120	14·7*	14·5*	14·2	13·9	12·7	10·0	6·5	5·2	233	0·024	2·84
Deal across the grain	0·56	41	0·475	0·43	0·40	0·38	0·37	0·36	—	—	233	0·011	0·47
Parana Pine along the grain	0·50	111	10·1*	10·1	10·0	9·8	9·3	7·9	5·9	4·6	252	0·020	2·74
Parana Pine across the grain	0·50	46	0·54	0·54	0·53	0·46	0·41	0·43	0·48	—	252	0·011	0·51
Beech along the grain	0·68	125	15·0*	15·0*	14·6	14·0	13·0	11·2	9·0	7·5	474	0·025	3·15
Beech across the grain	0·68	40	1·04	1·02	1·0	0·88	0·82	0·82	—	—	474	0·021	0·82

† At September 1974

* Extrapolated

TABLE 2

Properties of Manufactured Materials

Material	Density	Max Q	Elastic modulus $E \times 10^{-9}$ N/m^2								Cost[†] £/m²	$\frac{\sqrt{E\rho}}{Q} \times 10^{-5}$ at 250 Hz	$\sqrt{E\rho} \times 10^{-5}$ at 250 Hz
			62·5 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	6 kHz			
Sundeala A	0·475	54	*1·75	1·70	1·60	1·40	1·08	0·92	0·69	0·53	177·5	0·016	0·87
12 mm Karlit Panel Extra	0·77	42	*3·1	3·1	3·0	2·75	2·3	1·87	1·38	1·09	104·0	0·036	1·52
10 mm Duopanel	0·99	51	*5·1	5·05	4·8	4·4	3·75	3·08	2·45	2·1	162	0·043	2·18
16 mm Three layer chipboard 0·600 density	0·60	50	*2·08	2·02	1·95	1·8	1·52	1·15	0·83	0·67	117·5	0·021	1·08
18 mm Three layer chipboard 0·600 density	0·61	45	*2·42	2·37	2·2	1·95	1·6	1·17	0·74	0·53	134	0·026	1·16
9 mm Resin bonded Birch 7 ply along outer grain	0·72	67	*12·2	12·2	12·0	11·1	9·8	7·8	5·4	4·1	207	0·044	2·94
9 mm Resin bonded Birch 7 ply across outer grain	0·72	63	*5·7	5·5	5·3	4·8	4·2	3·55	2·8	2·4	207	0·031	1·95
9 mm Casein bonded Birch 7 ply along outer grain	0·67	77	*11·1	11·1	11·0	10·2	8·8	7·0	4·9	3·9	207	0·035	2·71
17 mm Resin bonded Birch 13 ply along outer grain	0·74	54	*7·5	*7·5	7·3	6·6	5·6	4·1	2·55	1·8	393·5	0·043	2·32
17 mm Resin bonded Birch 13 ply across outer grain	0·73	54	*7·0	*7·0	6·9	6·3	5·3	3·95	2·55	1·8	393·5	0·042	2·24
10 mm Mahogany 5 ply along outer grain	0·61	97	*8·5	8·3	7·9	7·2	6·1	4·7	3·2	2·2	214	0·023	2·20
10 mm Mahogany 5 ply across outer grain	0·61	82	*3·8	3·8	3·6	3·2	2·65	2·1	1·63	1·38	214	0·018	1·48
12 mm Birch faced Red Pine core blockboard along surface grain	0·535	68	*9·0	*8·4	7·4	6·0	4·3	2·55	1·5	1·25	269	0·029	1·99
12 mm Birch faced Red Pine core blockboard across surface grain	0·535	75	*4·9	4·9	4·9	4·75	4·3	3·65	2·95	2·4	269	0·021	1·62
G.R.P. 20% random fibres	1·315	31	5·8	5·8	5·7	5·2	4·8	4·9	5·5	–	C1500**	0·086	2·74
G.R.P. 50% random fibres	1·55	47	10·7	10·7	10·3	9·2	8·5	8·7	10·0	–	1220**	0·085	4·00
G.R.P. 70% random fibres	1·51	54	9·4	9·3	8·9	8·1	7·7	7·8	8·3	–	1052**	0·068	3·67
G.R.P. 50% woven rovings	1·59	46	12·8	12·8	12·5	11·8	11·1	10·8	10·5	–	1415**	0·097	4·46
Carbon Fibre/Honeycomb Sandwich	0·255	170	–	–	–	7·2	5·2	3·0	–	–		0·009	1·48

* Extrapolated

† September 1974

** For 12 mm thick material

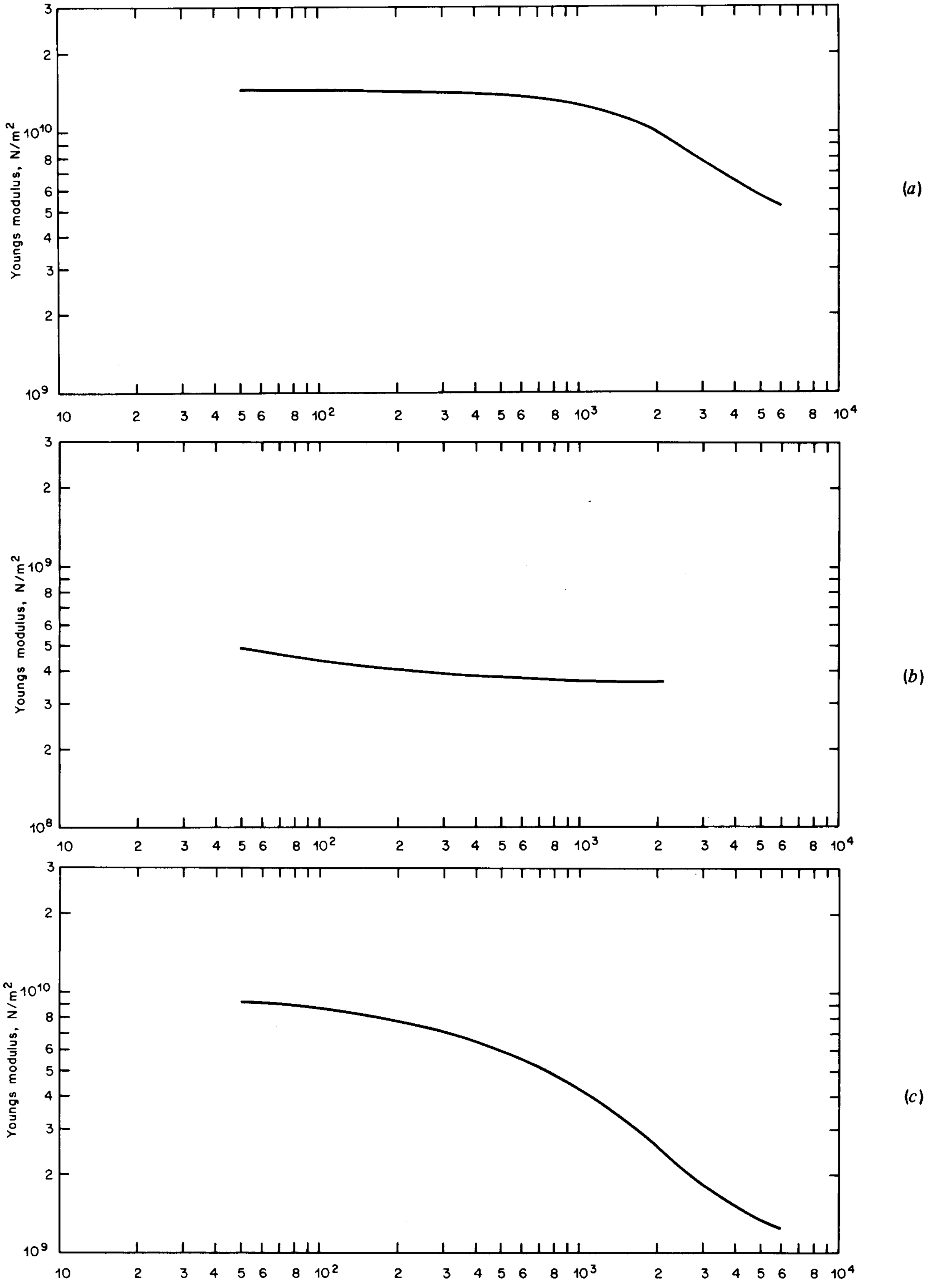

Fig. 2 - Variation of Young's Modulus E with frequency

(*a*) Deal along the grain (*b*) Deal across the grain (*c*) 12 mm blockboard along the outer grain

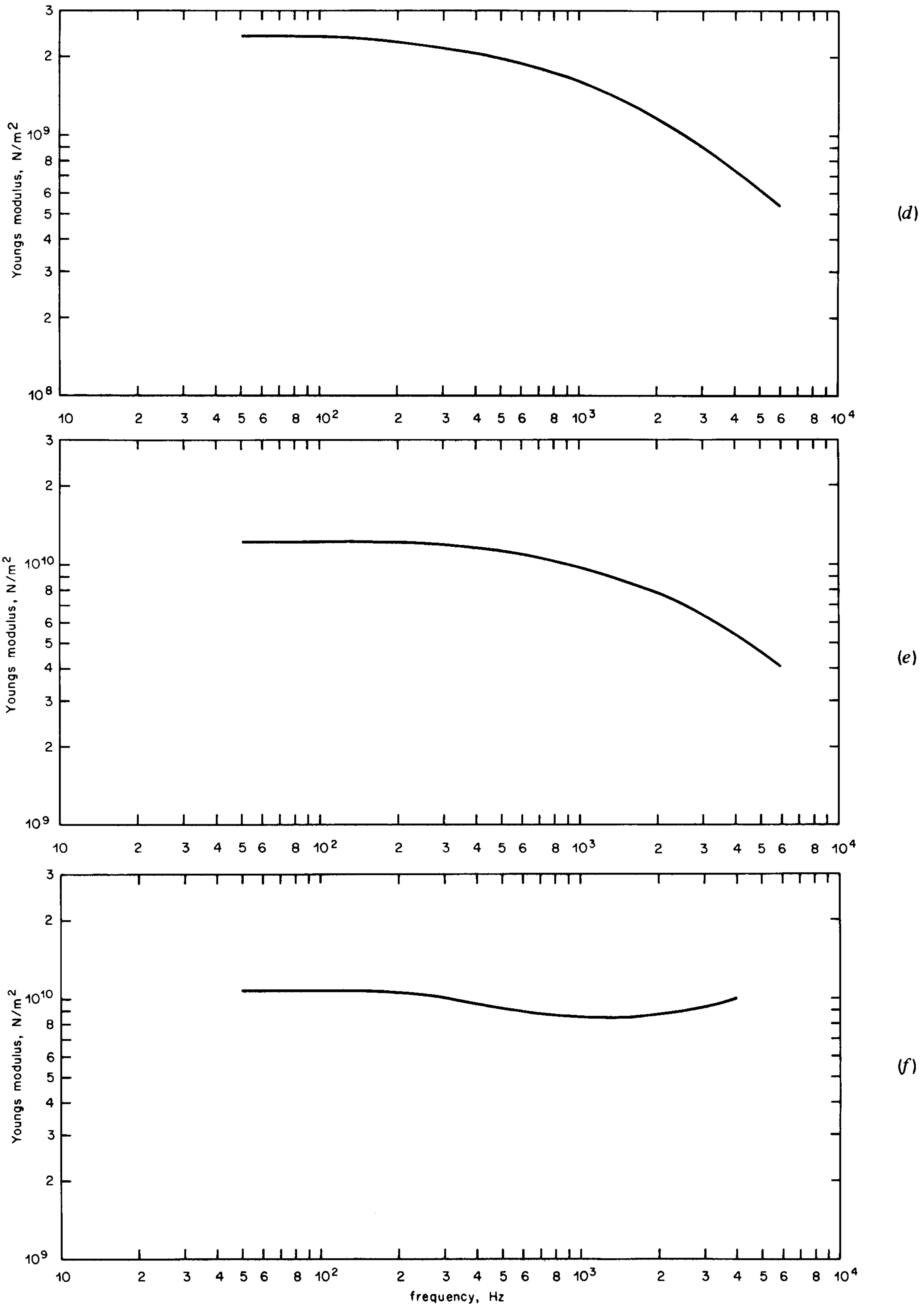

Fig. 2 (continued)

(*d*) 18 mm chipboard (*e*) 9 mm Birch 7 ply along outer grain (*f*) 50% glass reinforced plastic (random fibres) for example Fig. 2(*f*), are much more uniform with frequency than are those of the wood based materials and show an interesting recovery in modulus at high frequencies. There appears to be an increase in modulus with glass fibre content up to a certain point but not beyond about 50%.

The attenuation of a panel at resonance will be a function of the characteristic impedance of the material divided by the Q. This has been calculated for the different materials taking the value of E at 250 Hz as a representative value. It will be seen that on this basis, of the wood based materials, birch ply gives the highest value together with 10 mm Duopanel. The former is the standard material used for loudspeaker cabinets by Research Department but the latter, which has only recently become available, is of interest. The corresponding cost per 100 m^2 is shown in the last column in the Table. However the figures of merit obtained for the glass reinforced plastic materials clearly exceeds that for the woodbased types and although the cost is high at present they have the virtue that their cost is not rising as quickly as that of the woodbased products which have risen by 100% in the last eighteen months. When therefore an irregularly shaped cabinet is being designed the advantages of this type of material should be remembered.

However it should be noted that all of the materials tested are seen to have an excessive Q, the lowest values being about 30. It is therefore evident that additional mechanical damping is required for the panels and under these conditions the natural Q of the material is of much less importance, and the values of the characteristic impedance alone are therefore also given in the Table. For this parameter Duopanel becomes rather less attractive than birch ply but it should be noted that the glass reinforced plastic materials retain their first place. Chipboard, a material widely used in the 'Hi-fi' industry in the construction of loudspeaker cabinets is clearly less attractive, apart from its low cost, particularly as the value of E varies with frequency more rapidly than for plywood.

In the references previously cited[12] it was stated that the elastic modulus of timber was independent of frequency. In this reference transverse modes were used up to 1370 Hz and a longitudinal mode from 1·6 kHz to 8·9 kHz. It is evident from Tables 1 and 2 that the modulus varies little for timber up to 1000 Hz and the greatest variation takes place above this frequency; this wrong conclusion cited can therefore be understood. What is not at all clear is the reason why the longitudinal method of measurement fails to show up the variation found here at higher frequencies and raises the question whether the anisotropic nature of the materials is the cause, or whether it is due to the different mode of transmission. It will be noted from the Tables that a number of materials do not show this falling off at high frequencies, but as a check a steel bar was measured in the same way. The elastic modulus was found to be substantially constant over the whole frequency range thus checking the techniques employed here. It is obvious however that as far as loudspeaker cabinets are concerned the transverse method used here represents most closely the mode of vibration of a panel.

If the values of E for timber measured along the grain or those for the wood based manufactured samples are plotted on a linear frequency basis it is evident that they all form a series of exponential curves essentially of the form $E = A + e^{(Bf + C)}$. Curves have been computed on this basis and the resulting constants are given in Table 3 together with the least squares error. It will be seen that in most cases the fit is extremely good and it has been possible to extrapolate the value of E for most materials down to 62·5 Hz.

The factor B taken for all materials varies only over a limited extent but if a selection is made of only the manufactured materials omitting the extremes of Sundeala A which has a rather irregular curve, and of blockboard, which is too close to raw timber, the remainder cover only a very narrow range. The values of B are plotted in Fig. 3 on an arithmetic probability scale and it will be seen that the series forms a very close Gaussian distribution with a mean value of 0·395 and a standard deviation of only 0·028. This therefore appears to suggest a fundamental property of quite a wide range of manufactured materials even when made from different kinds of wood. On reflection it is not, in itself, surprising that chipboard and hardboard fall into the same category as plywood for the wood particles in the former are orientated in random fashion. It has been shown that the modulus E along the grain is many times that across the grain and will therefore predominate as it does for the layers of ply in this direction. The effect of particles can therefore be resolved into two directions at right angles as for plywood and the materials are therefore physically similar up to very high frequencies, resulting in the narrow range of values of B.

9. Measurement of damping properties of materials

(a) It is evident from Tables 1 and 2 that the Q of most materials is very high with the result that a cabinet with panels made of such materials will colour the sound reproduced by the loudspeaker both because of its transient response at resonance and because at such a frequency the panel is relatively transparent. The obvious cure is to apply mechanical damping to the panel and for practical reasons this can only be applied to the surface of the panel on the inside of the cabinet. The availability of particular commercial materials designed for damping panels is variable and it is essential to have alternatives available. Tests have therefore been carried out on a number of them to check their relative efficiencies in this regard. To imitate actual use they were applied to one surface of the test piece only.

The same equipment and test procedure as that described in the previous section was used. The materials employed for damping were necessarily those available from commercial sources. Advantage was taken of this investigation to see if materials designed for more general use would be suitable, for as already stated the requirements of the BBC are not great enough to warrant special manufacture without prohibitive cost.

It should be appreciated that unlike the previous set of results, the value of Q in these tests using damping

TABLE 3

Material	$A \times 10^{-9}$	$-B \times 10^{2}$	C	Mean square error x 10^{-18} in E^2
Oak along the grain	6·58	0·036	22·87	0·27
Deal along the grain	3·05	0·029	23·22	0·73
Parana Pine along the grain	2·56	0·021	22·80	0·17
Beech along the grain	4·10	0·020	23·11	0·16
Sundeala A	1·96	0·030	21·09	6·27
12 mm Karlit Panel Extra	0·840	0·040	21·56	0·02
10 mm Duopanel	1·65	0·041	21·95	0·11
15 mm three layer chipboard 0·600 density	0·371	0·034	21·24	1·57
18 mm three layer chipboard 0·600 density	0·300	0·042	21·46	2·61
9 mm Resin bonded birch 7 ply along outer grain	3·45	0·038	22·94	0·08
9 mm Resin bonded birch 7 ply across outer grain	1·89	0·038	22·01	0·07
17 mm Resin bonded birch 13 ply along outer grain	1·14	0·039	22·60	0·05
17 mm Resin bonded birch 13 ply across outer grain	1·09	0·037	22·55	0·08
10 mm Mahogany 5 ply along outer grain	1·72	0·041	22·64	0·11
10 mm Mahogany 5 ply across outer grain	0·086	0·038	21·81	0·15
9 mm Casein bonded birch 7 ply along outer grain	3·58	0·045	22·81	0·21
12 mm Birch faced blockboard red pine core along outer grain	1·18	0·091	22·76	0·24
12 mm Birch faced blockboard red pine core across outer grain	1·73	0·028	21·93	0·01
Carbon fibre/honeycomb sandwich	1·55	0·089	22·90	0·03

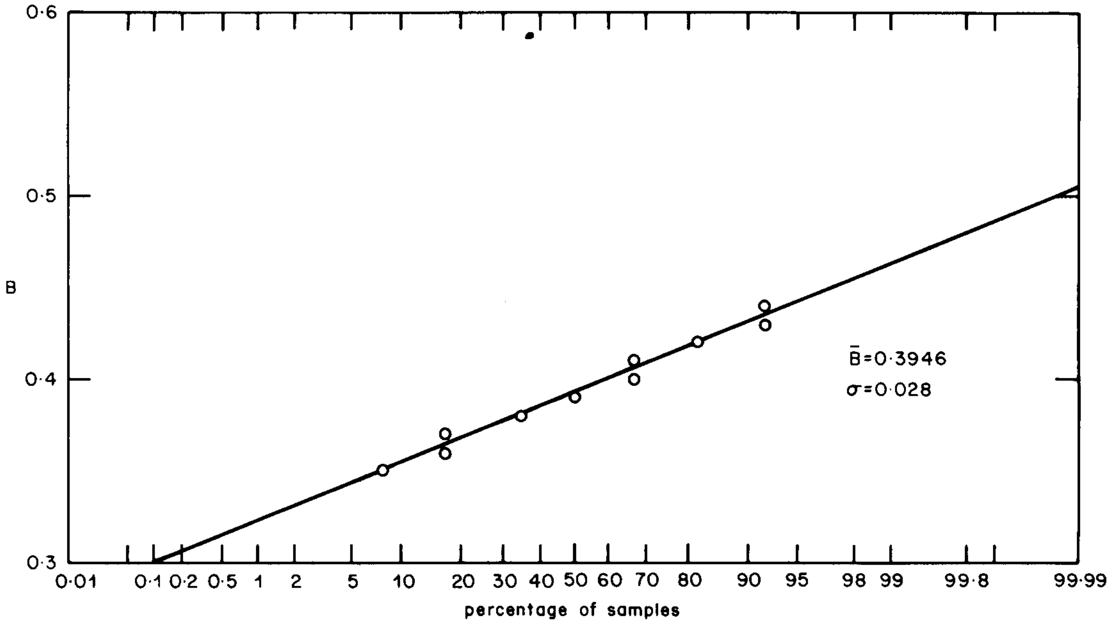

Fig. 3 - Distribution of factor B amongst samples

material is not an absolute quantity, but will vary with the mechanical impedance of the test substrate, i.e. with the length, thickness and material; the absolute mechanical impedance could be calculated but this is of doubtful value for, as already mentioned, the complex coupling of all the resonant elements renders the final response incalculable. However, the rank order of efficiency of damping will always hold and as the specimen length is typical of that of a medium size cabinet the Q figures should be approximately correct in this case. The test substrate was of 9 mm resin bonded birch seven ply along the surface grain.

The results of the tests are given in Table 4 below. As the frequency of resonance varied with the mass and elastic constants of the damping material the Q is given for the resonance mode number rather than the absolute frequency.

Discussion of the results

(a) General

It has been shown[20] that the damping introduced by viscous material used in an extension mode, as in item 1 to

TABLE 4

Effects of Damping Treatment on 9 mm Birch 7 Ply Along Surface Grain

Treatment	Mode Funda-mental	Q										η fund	η for damping material	Thickness of damping mtl. mm	η/d	Damping cost /m²	η ÷ cost/m²
		2	3	4	5	6	7	8	9	10	11						
1. Nothing	70	56	55	47	50	50	39	30	50	24	21	0·0142					
2. 1 layer Mutacell with Thixofix	59	54	21	37	41	46	36	27	25	—	17	0·0170	0·0028	1·65	0·0023	£ 0·18	0·0155
3. 2 layers —do—	35	37	31	33	35	—	26	22	20	—	—	0·0286	0·0144	3·3	0·0044	£ 0·35	0·0411
4. 4 layers —do—	27	23	21	18	20	26	13	—	—	—	—	0·0370	0·0228	6·6	0·0035	£ 0·71	0·0321
5. 2 layers Mutacell with Aquaseal	37	37	30	26	33	—	24	22	21	—	—	0·0270	0·0128	3·3	0·0039	£ 0·35	0·0366
6. 1 layer Pluvex with Thixofix	34	19	26	24	25	21	21	17	—	—	—	0·0294	0·0152	3·65	0·0042	£ 0·72	0·0211
7. 1 layer Sundeala K with Thixofix	48	39	25	31	31	28	32	23	23	—	—	0·0208	0·0066	10·25	0·0006	£ 0·92	0·0072
8. 1 layer 3 ply roofing felt with Thixofix	47	38	27	31	35	30	26	23	23	16	—	0·0213	0·0071	2·35	0·0030	£ 0·35	0·0203
9. 2 players 3 ply roofing felt with Thixofix	30·5	28	21	—	12	—	—	—	—	—	—	0·0328	0·0186	4·7	0·0040	£ 0·71	0·0262
10. 1 layer Bostik self adhesive	24	21	19	20	22	23	17	—	18	13	14	0·0417	0·0275	1·82	0·0151	£ 0·91	0·0302
11. 2 layers Bostik	12	11	10	—	10	13	9	—	—	—	—	0·0833	0·0691	3·64	0·0190	£ 1·82	0·0380
12. 3 layers Bostik	8·5	7·5	7	—	—	—	—	—	—	—	—	0·1176	0·1034	5·45	0·0190	£ 2·73	0·0379
13. 1 layer Permanite with Thixofix	31·5	22	14	—	—	—	—	—	—	—	—	0·0317	0·0175	10·45	0·0017	£ 1·20	0·0146
14. 1 layer Permanite with Aquaseal	24	6·5	—	—	—	—	—	—	—	—	—	0·0417	0·0275	10·45	0·0026	£ 1·20	0·0230
15. 1 layer 3 ply roofing felt with Aquaseal	42	36	31	29	28	—	20	—	14	—	—	0·0238	0·0096	2·35	0·0041	£ 0·35	0·0271
16. 1 layer Aquaplas* with Thixofix	10	11	11·5	14	15	—	14	—	—	—	—	0·1000	0·0858	2·9	0·0296	£ 2·20,	0·0390
17. 1 layer Mutacell + steel + Thixofix	20	13·5	10	13	16·5	17·5	14	12	—	—	—	0·0500	0·0358	2·2	0·0162	£ 1·78	0·0201
18. 2 layers —do—	13	10	8·5	11	13	18·5	11·5	—	—	—	—	0·0769	0·0627	3·85	0·0163	£ 1·95	0·0322
19. 4 layers —do—	7	6·5	6·5	9·5	—	—	—	—	—	—	—	0·1428	0·1286	7·15	0·0180	£ 2·30	0·0559
20. 1 layer 3 ply roofing felt + steel + Thixofix	11	8	5	—	11	—	10·5	—	—	—	—	0·0909	0·0767	2·9	0·0264	£ 1·95	0·0393
21. 1 layer Celotex Insulation Board + Thixofix	39	42	36	31	28	38	29	—	—	—	—	0·0256	0·0114	12·0	0·0095	£ 0·65	0·0175

* This material is supplied also with a self adhesive backing.

16 in Table 4 should vary as the thickness for thin layers but that as the thickness becomes comparable with that of the beam the damping becomes more nearly proportional to the thickness squared and is thus relatively more effective.

The damping factor η for the differing materials can be calculated from the Q factors and the ratio η/d where d is the thickness of the damping layer, is given in the Table for the fundamental mode; this enables the differing materials to be compared on the same basis. Furthermore the cost per unit area and the ratio η/cost are also given in the Table thus providing an estimate of the cost of achieving a given degree of damping. This ratio is for raw materials only and takes no account of the fact that the cost of adhesive, labour and drying time is appreciable for some materials such as multilayer Mutacell, whereas the Bostik material is self-adhesive.

It will be noted that the results for roofing felt in tests number 8 and 15 differ. This is due to the fact that when the Aquaseal adhesive is used the adhesive impedance is much lower than that of Thixofix and the adhesive acts as a damping layer with the roofing felt performing the function of a constraining layer.

It will also be noted that the more efficient materials vary in their effectiveness with frequency. Thus both the 10·5 mm thick Permanite and three layers of Bostik damp out the resonances completely in a few modes but on the other hand the latter material provides an appreciably greater damping at the all important fundamental.

Attempts were made to increase the damping of the Mutacell material by providing a constraining layer. This converts the extensional mode of operation to a shear mode and is capable under optimum conditions of providing a much higher resistance. However in our case the problem was also one of economics, that is the resulting treatment had to be comparable in cost with that provided by conventional damping; the constraining layer was therefore confined to mild steel 25 BG. The results obtained with this and various layers of Mutacell are shown in items 14 to 20 in the Table. It will be seen that the damping is increased in all cases but that the results with four layers of Mutacell give the greatest improvement showing that the constraining layer is not of high enough impedance for the other conditions. (Unlike the extensional mode of operation, with a constraining layer and optimum conditions the thinner the damping layer the greater the damping.)

It therefore appears that operationally the most economic item to use is Bostik material particularly in view of the fact that it is a self-adhesive material and will thus involve lower labour costs.

(b) Effects of reducing area of damping material

It is evident that with an encastré beam the portions near the ends are of much higher impedance than that near the centre and it therefore follows that the damping material is relatively inefficient at the ends. It is therefore of interest from the economic aspect to see to what extent the area of damping material can be reduced without appreciably degrading the total damping. This has been investigated for the sample with three layers of Bostik material. Five per cent of the damping material was removed at a time from each end and the Q factors re-measured; the results being given in Table 5 below.

TABLE 5

Condition	Q		
Mode	Fundamental	2	3
Material covering beam	9	7·5	7·1
5 cm removed each end	11	7·7	7·5
7·5 cm removed each end	11·7	8·0	8·5

The length of beam between supports is 50 cm so if we take the last condition it will be seen that 30% of the damping material can be removed before an appreciable effect on the Q is produced. This means that on a panel the area, and therefore cost, can be reduced by a factor of 50% with little effect on the damping and it follows that the exact positioning of the damping material is not critical.

(c) Effects of breaks in damping material

The final test was to discover the effect of a break in the damping material in the centre of a panel. This may occur in practice, for example, if the panel is considerably larger than the sheets of damping material and a join is necessary. To check the maximum effect this could have, the same test speciman with three layers of Bostik material was taken and a cut made across the centre line of the speciman one layer at a time. The Q factors under these conditions are shown in the Table 6 below.

It will be seen that the effect of the cut is negligible for the top layer alone but is substantial if all layers are cut.

TABLE 6

Material	Q		
Mode	Fundamental	2	3
Damping material whole	11·7	8·0	8·5
Cut across centre of top layer	12	8·2	8·8
Cut across centre of top 2 layers	–	8·5	9·8
Cut across centre of all 3 layers	20	8·5	11·2
Top layer only replaced whole	12·5	7·8	8·4

If the lower two are cut but the top layer bridges the gap the damping is restored to almost its original value.

10. Tests of complete loudspeakers

As explained in the previous section, the tests of damping material do not give an absolute measure of the resulting *Q*; furthermore as mentioned in Section 2, it is not possible to calculate the output resulting from the complex coupling of all the panels and loudspeaker unit together, so some form of overall test is required which will yield this result. In addition in the past few years there have been several cases where colourations of loudspeaker quality caused by cabinet panel resonances have occurred and so once again it is clearly desirable to be able to measure such loudspeakers in a complete form. Finally, it should then be possible as the result of experience or experiment to build up a subjective scale relating the degree of colouration to the objective parameters such as frequency and dilution, hopefully also including the limits of audibility.

In the past[21] the present author has used a completely closed cabinet for this purpose. This was energised by a horn pressure driver mounted inside the cabinet and the attenuation determined by measuring the sound pressure on the inside and on the outside of each of the panels by means of a pressure operated microphone. By also measuring the sound pressure developed by the appropriate loudspeaker unit when mounted in the wall of the cabinet, it is possible to arrive at a figure showing how far the sound pressure from the cabinet walls is below the direct sound. Such a method, however, is clumsy and is inappropriate when a complete commercial-type loudspeaker has to be assessed.

Ideally it should be possible to place an airtight acoustically terminated duct having thick walls over the loudspeaker unit and measure the remaining radiation from the cabinet at various angles. Such a duct would have to be large enough to absorb all the sound from the cone without disturbing its motion and a different duct would be needed for each size of loudspeaker unit; (in addition it would be difficult to use without affecting the resonances of the panels) — it is therefore rather impractical.

Efforts were therefore made to measure the relative sound pressures of a complete loudspeaker directly by means of a pressure operated microphone, by placing it in turn about one inch away from the side or rear panels. This method failed at low frequencies because in this region the loudspeaker is almost omnidirectional. It follows that the sound pressure radiated from the cone and spreading to the sides and rear of the cabinet is very little below that developed in the front, thus concealing the measurement of radiation from the panels.

The solution finally adopted was to use a pressure gradient microphone close to the source to be measured. This, by virtue of its mode of operation, has a figure-of-eight polar characteristic, the attenuation at 90° relative to the axial response normally being in excess of 20 dB. When this is used to measure the sound radiated from the sides or rear of the cabinet the microphone capsule is so placed that sound radiated from the cone is received by the null of the microphone, thus ensuring that much lower sound pressures from the cabinet walls can be detected. In addition, again by virtue of its mode of operation, such a microphone will give a very large bass rise when close to the source, the output relative to that for the same sound pressure in a plane wave being given by the expression

$$V_S/V_p = [1 + (\lambda/2\pi d)^2]^{1/2}$$

where λ is the wavelength of the sound and *d* is the distance

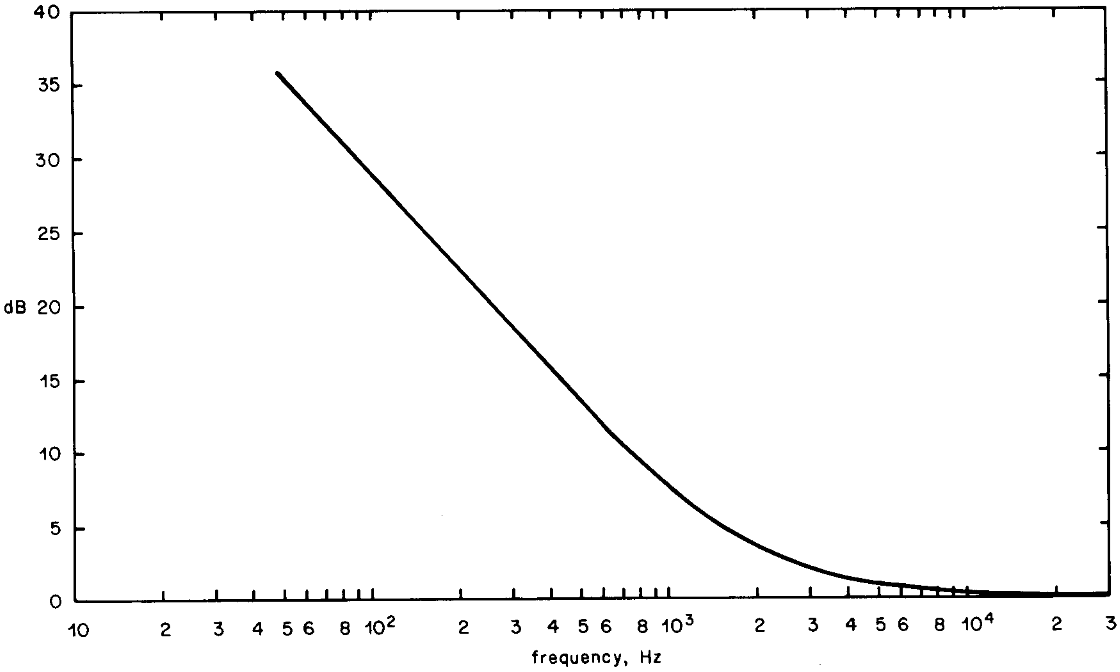

Fig. 4 - Bass rise in pressure gradient microphone for point source distant 2·5 cm

from the point source. V_S is the pressure gradient in a spherical wave and V_p in a plane wave. This means that when placed close to a panel the microphone will discriminate in favour of the close source compared with the same sound pressure from a distant source as described by this expression and as illustrated in Fig. 4. This augments the discrimination at the bass which is where it is most needed. The bass rise can be compensated exactly for a point source by a series C.R. circuit and although it may be argued that, for example, an eight inch diameter loudspeaker unit is hardly a point, for these long wavelengths it behaves as if it were so. Of course, the absolute frequency response close to the source is not exactly the same as that in the more distant Fraunhofer sound field at the higher frequencies or at the vent resonance, but it is the ratio of sound pressures radiated by the cone and by the cabinet that is important here, rather than the absolute curves of response/frequency characteristic. A further limitation of this type of test which in theory could be more serious arises for overtones of the panels. For example when a tall cabinet is being tested wave motion between the top and base will occur inside the cabinet and the phase of the sound pressure on the top of, say, the rear panel, may be 180° out of phase with that at the base. Under these conditions a first overtone of the panel will be stimulated and a pressure gradient microphone placed at the centre of the panel will pick up very little sound. Now it could be that this may represent close approximation to the truth as the radiation from the two halves of the panel will then to cancel, being in antiphase; however it is clear that the output of the microphone will vary rapidly with position. For the second overtone the microphone in this position will pick up a large signal and this will exaggerate the apparent total for sound field. The test is therefore most rigorous for the frequencies where the phase variation across the panels is fairly small. Fortunately this is the region of most importance and the test is extremely useful in practice.

Fig. 5 shows the curves obtained using this method of test on an LS 3/6 type loudspeaker when only one layer of damping material was erroneously applied to the panels. It demonstrates the effect of the close coupling between the panels, which are not of the same size, but it will be seen that, in spite of this face, their separate resonance frequencies are not easily discernable. The total sound reproduction on programme was coloured in the region of 200 Hz to a quite noticeable degree. Fig. 6 shows the corresponding curves when two layers of damping were applied as prescribed. In this case the resonance peaks are reduced and are no longer audible. This also illustrates the small range over which it is possible to allow such peaks to exceed the permissible limit before the effect is objectionable and also why the use of plain timber with its very variable properties is not advocated for the construction of cabinet panels.

For reasons connected with speed of production, one of the BBC licensees who manufactures the type LS 3/6 loudspeaker for sale to the public wished to change the type of damping material applied to the panels to one pre-

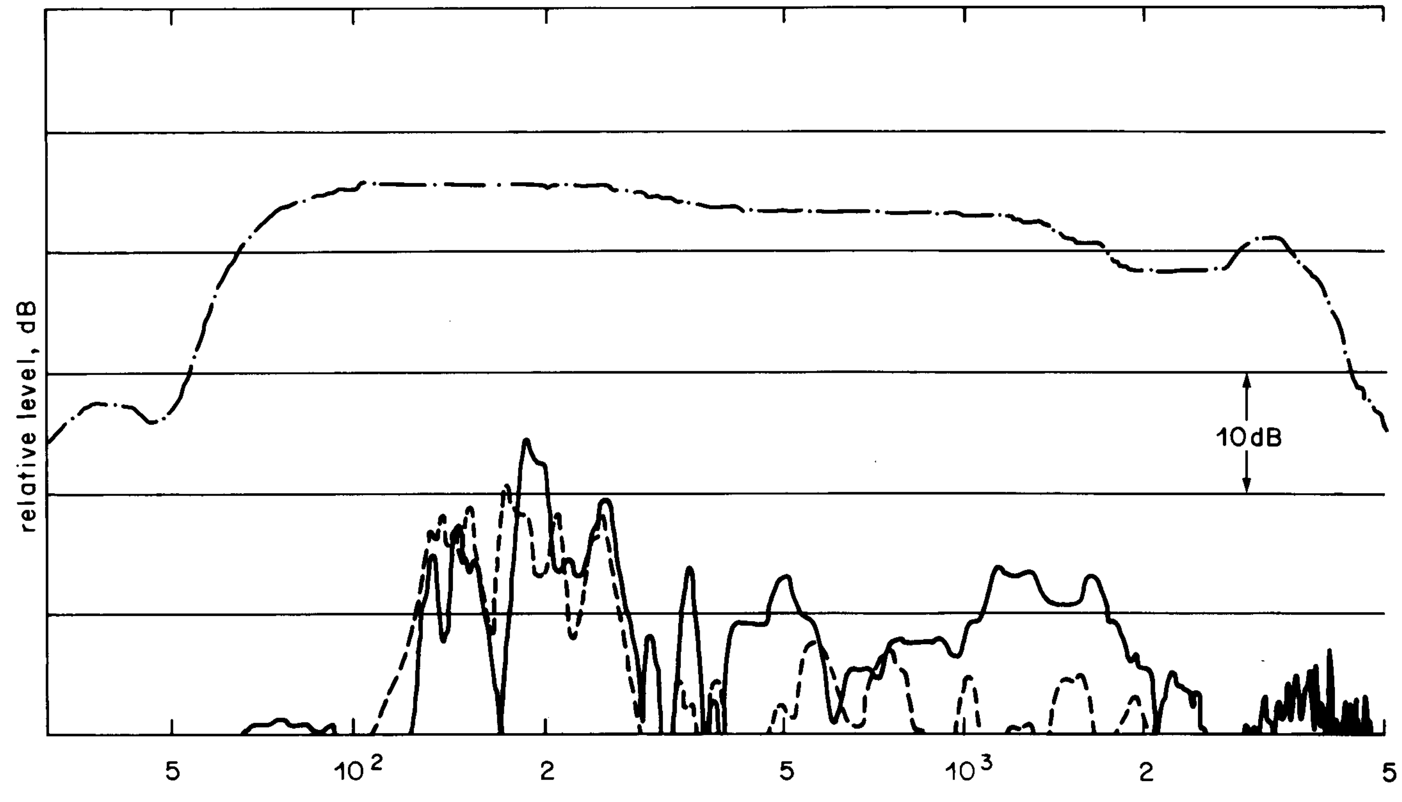

Fig. 5 - Relative response of LS 3/6 loudspeaker with inadequate panel damping

—·— Axial —— Side – – – Back

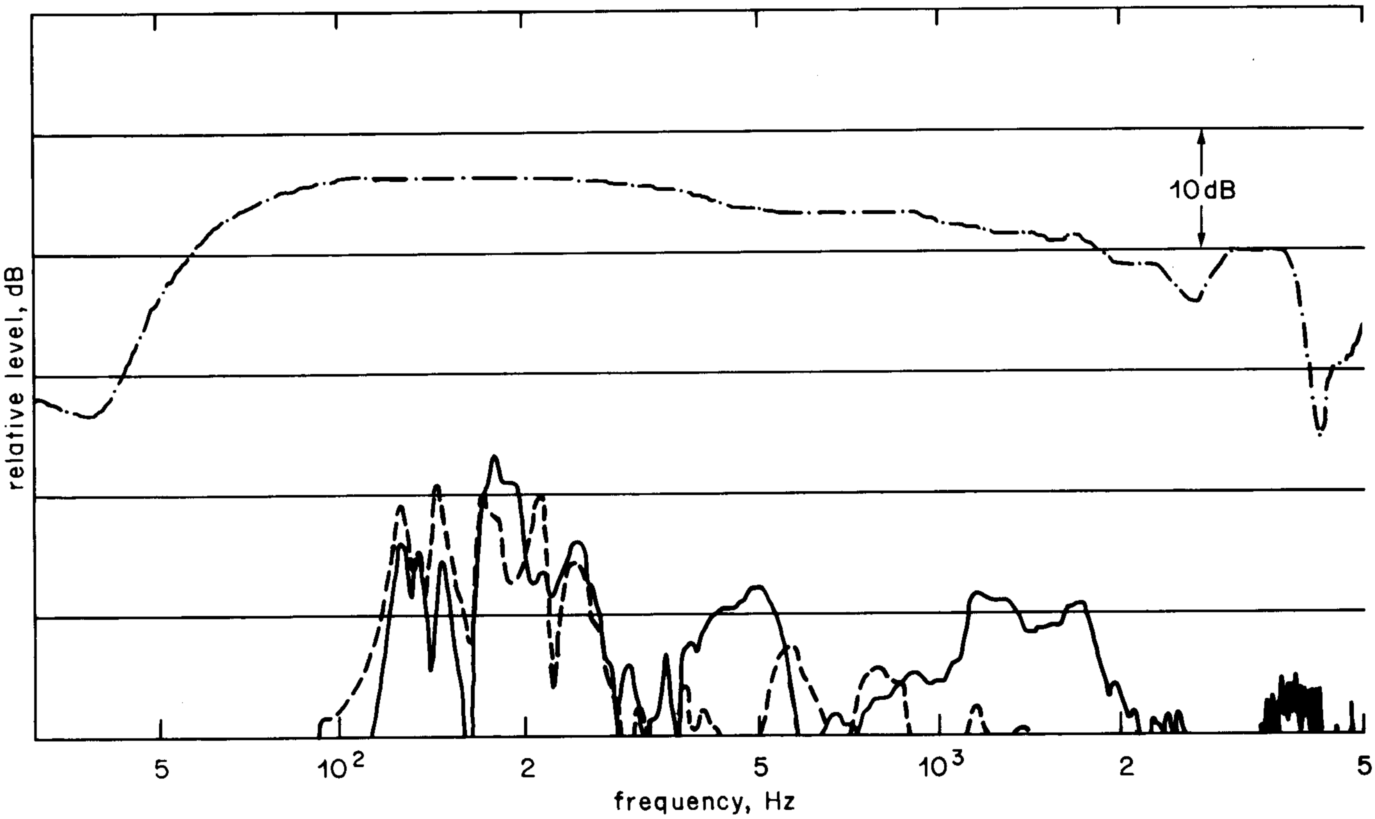

Fig. 6 - Relative response of LS 3/6 loudspeaker with adequate panel damping

—·— Axial ——— Side – – – – Back

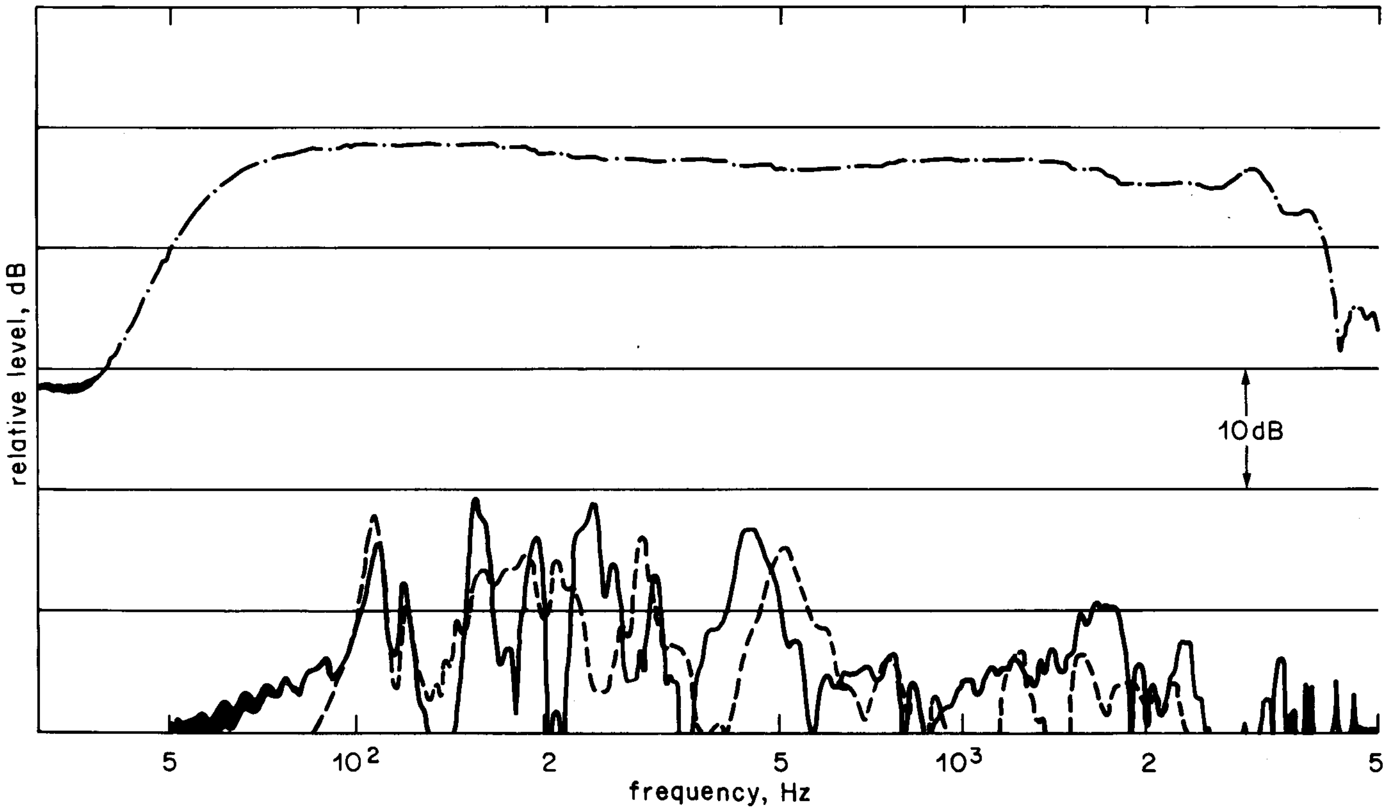

Fig. 7 - Relative response of LS 3/6 loudspeaker with loose fillets

—·— Axial ——— Side – – – – Back

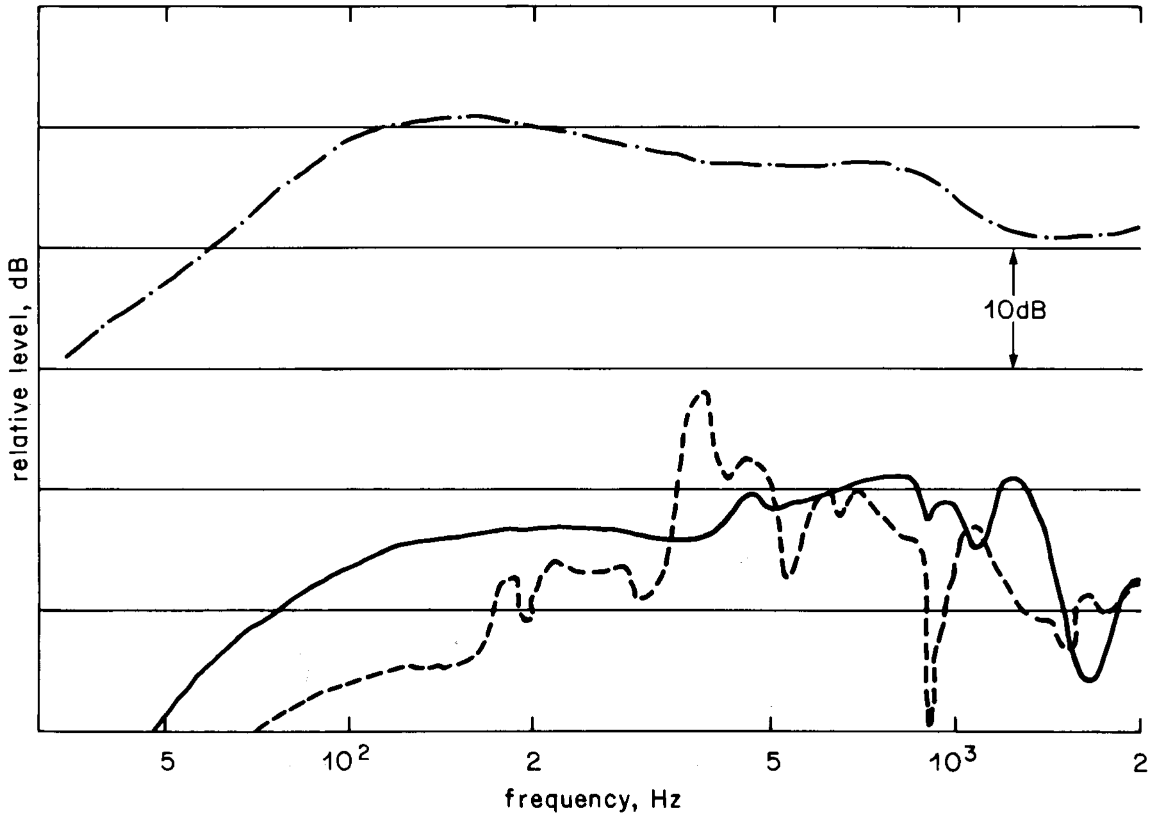

Fig. 8 - Relative response of LS 3/5 loudspeaker with Parana fillets

—·— Axial   ——— Side   - - - - Back

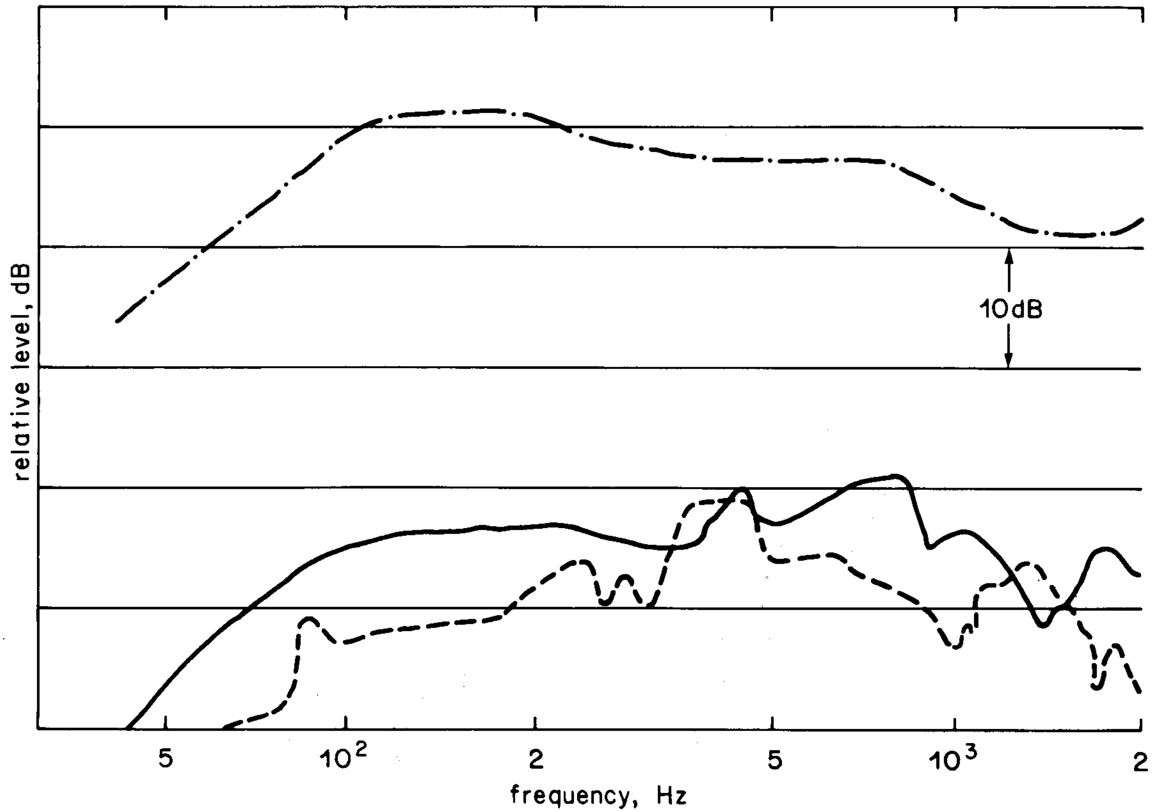

Fig. 9 - Relative response of LS 3/5 loudspeaker with Beech fillets

—·— Axial   ——— Side   - - - - Back

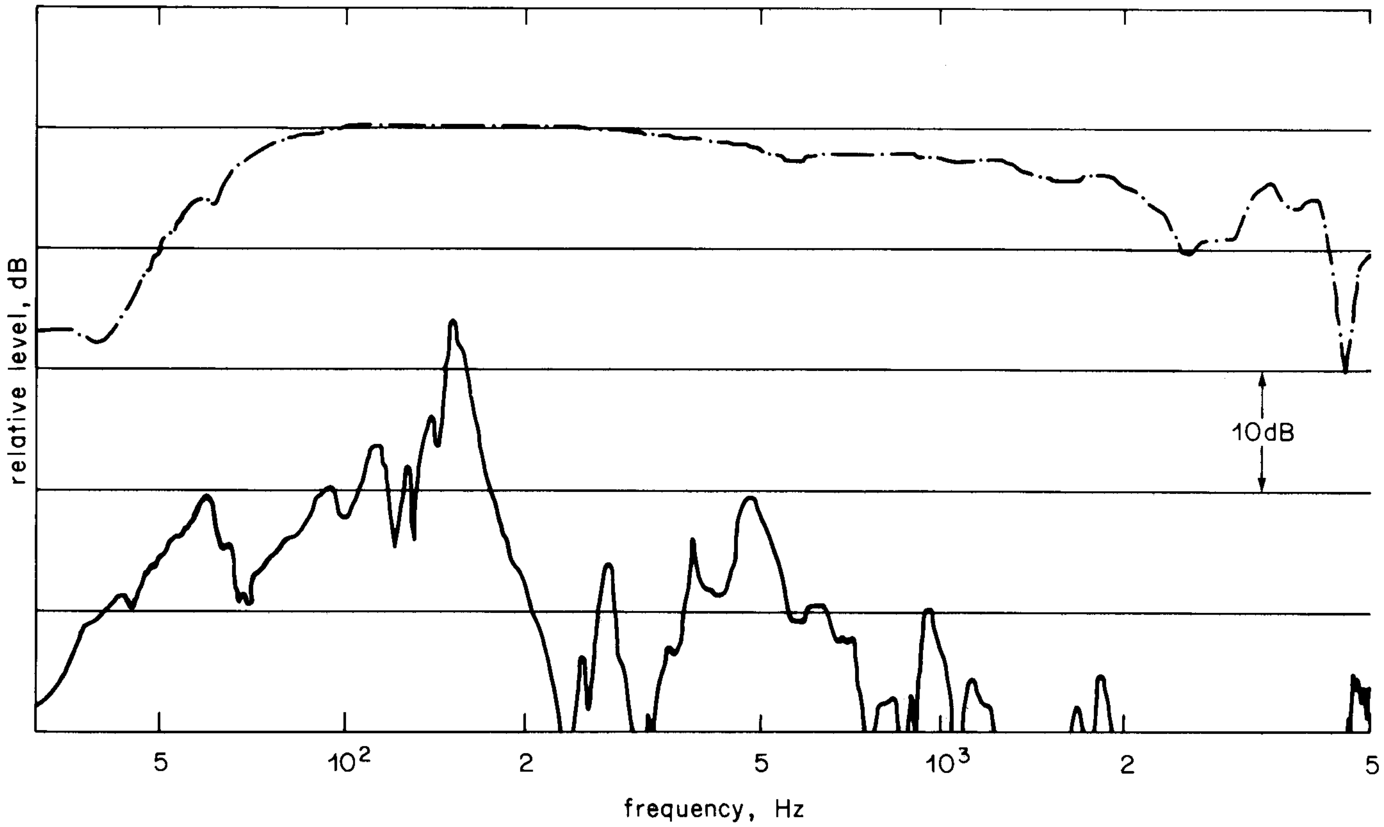

Fig. 10 - Relative response of LS 3/4 loudspeaker with inadequate panel damping

—·— Axial —— Back

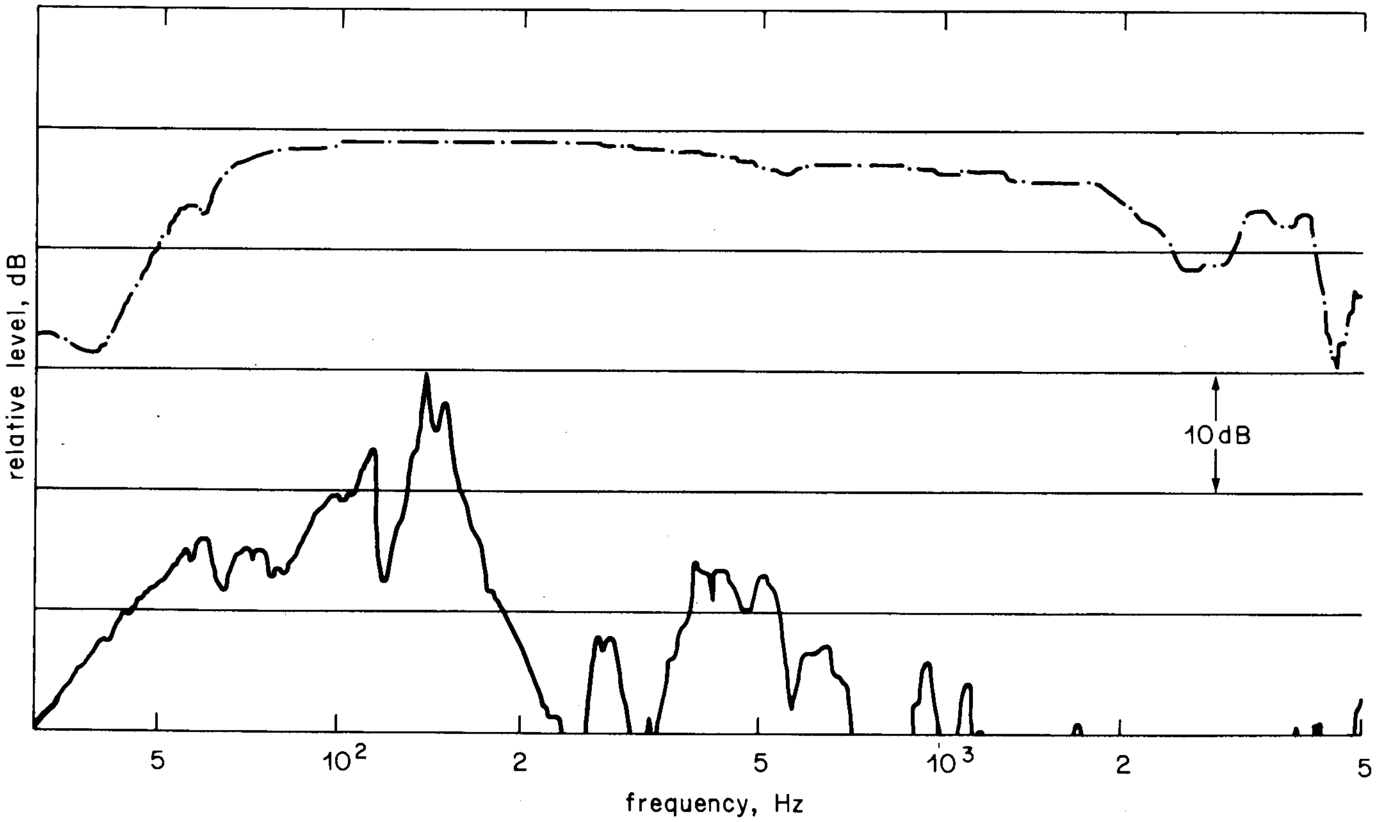

Fig. 11 - Relative response of LS 3/4 loudspeaker with adequate panel damping

—·— Axial —— Back

treated with adhesive. A sample was sent for examination and the corresponding curves are shown in Fig. 7. It will be noted that not only are the peaks of much lower level even than those in Fig. 6, but also quite unexpectedly the general shape of the curve of the sound output from the panels is very different, the peaking nature indicating much lower coupling between the panels. When the back of the cabinet was removed it was discovered that of the battens holding it in position, one was loose, one was attached to the cabinet at the two ends only and the other two were not much better. This is obviously an effective if unconventional method of achieving the same end as damping, but is somewhat difficult to specify! On enquiry the licensee stated that he had subsequently changed his cabinet maker.

Fig. 8 shows the curves obtained on an LS 3/5A loudspeaker from cone, side and rear panels when the fillets were incorrectly made of Parana pine instead of the 'hard wood' specified. The peak in response from the panels at 350 Hz was clearly audible and gave a 'honky' quality, particularly objectionable on speech. Fig. 9 shows the corresponding curves when beech fillets were used, thus changing the coupling between panels. The peak output at 350 Hz has been reduced in level by 9 dB and is no longer audible.

Fig. 10 shows the curves obtained with a type LS 3/4 loudspeaker submitted for test. There is a large peak at 150 Hz and a smaller one at 490 Hz, but a careful listening test gave the surprising result that only the smaller peak at 490 Hz was in fact audible. Examination of the cabinet revealed that the prescribed damping had not been applied and rectification of this matter yielded the curves shown in Fig. 11. Under these conditions no colouration from the cabinet was audible.

Some useful data is therefore available on the audibility of resonances of this type and it is possible from these and a number of other tests, to draw up a tentative curve relating frequency and dilution for minimum audibility. This has been done in Fig. 12 and forms a basis for testing complete loudspeakers in future. It should be noted that there is a small overlap between the audible and inaudible regions. In view of the effect of Q or bandwidth on the audibility of an irregularity in the response/frequency characteristic of a transmission chain,[11] this variation is not unexpected. In practice the variation is not greater than ±1 dB of the mean curve shown and therefore an appropriate safety factor can be allowed in the design of a cabinet. With increased experience it should be possible to add to this data but in the meantime a simple but effective test for complete loudspeakers has been devised.

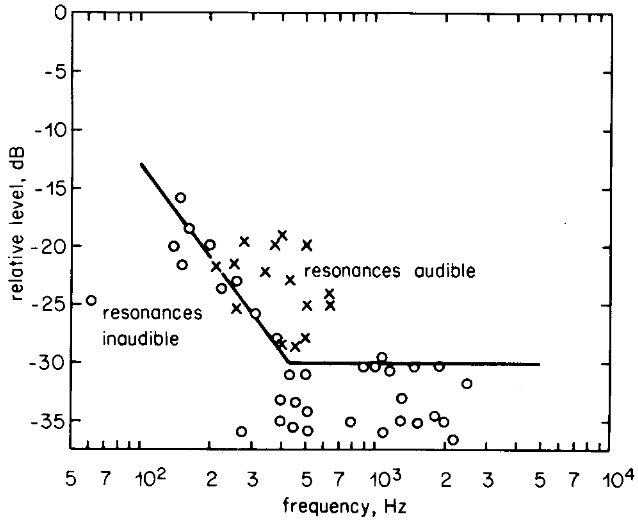

Fig. 12 - Criterion for perceptibility of panel resonance

However it should be stressed that this criterion has at present no theoretical backing whatever. There is no obvious reason why the slope of the curve should be downwards, one rising with frequency could be more easily understood on the grounds of directivity. The curve is based solely on experimental data and therefore there is always a danger that exceptions may arise in the future.

As a final test of the philosophy of loudspeaker cabinet design put forward in this report, and followed for some time in the BBC Research Department, two cabinets were made of the same external dimensions as that of the type LS 3/6, i.e. 63 cm x 30 cm x 30 cm (25 in x 12 in x 12 in); the first was of the usual thickness birch plywood the second was of the same material but of twice the thickness, i.e. 18 mm.

The cabinets were first tested as described above without any panel damping at all but with the usual air mode absorption treatment. Curves showing the relative outputs from an experimental wide range cone, from the cabinet side and from the cabinet rear are shown in Figs. 13(*a*) and (*b*) for the two cabinets, together with the criterion taken from Fig. 12 but adjusted to take account of the fact that the axial response curve from this cone is not flat. It will be seen that in both cases the output from the cabinet strays locally into the audible region and this was confirmed by listening tests. What is perhaps surprising is that the output from the thick walled cabinet is actually greater than from that with the thinner walls. However it is evident that the Q is greater in the former case and this may well account for the difference in output. This difference has been confirmed in other similar experiments.

The standard panel damping for the type LS 3/6 cabinet, i.e. two layers of Mutacell attached with Aquaseal adhesive, was then applied in each case. Curves showing the relative outputs from cone, cabinet side and cabinet rear were again taken and are shown in Figs. 14(*a*) and (*b*) together with the criterion. It will be observed that in the case of the thinner walled cabinet, Fig. 14(*a*), the criterion is met whereas it is not met in the case of the thicker walled cabinet, Fig. 14(*b*). Listening tests confirmed these results. Presumably the thicker walled cabinet could be brought within the criterion by the extensive use of much thicker, and therefore more expensive, damping material. Thus, the thicker walled cabinet is more expensive in plywood and in damping material, and is of course unnecessarily heavy, an important point from the outside broadcast aspect. It has no advantages and is clearly an inferior design to that normally used.

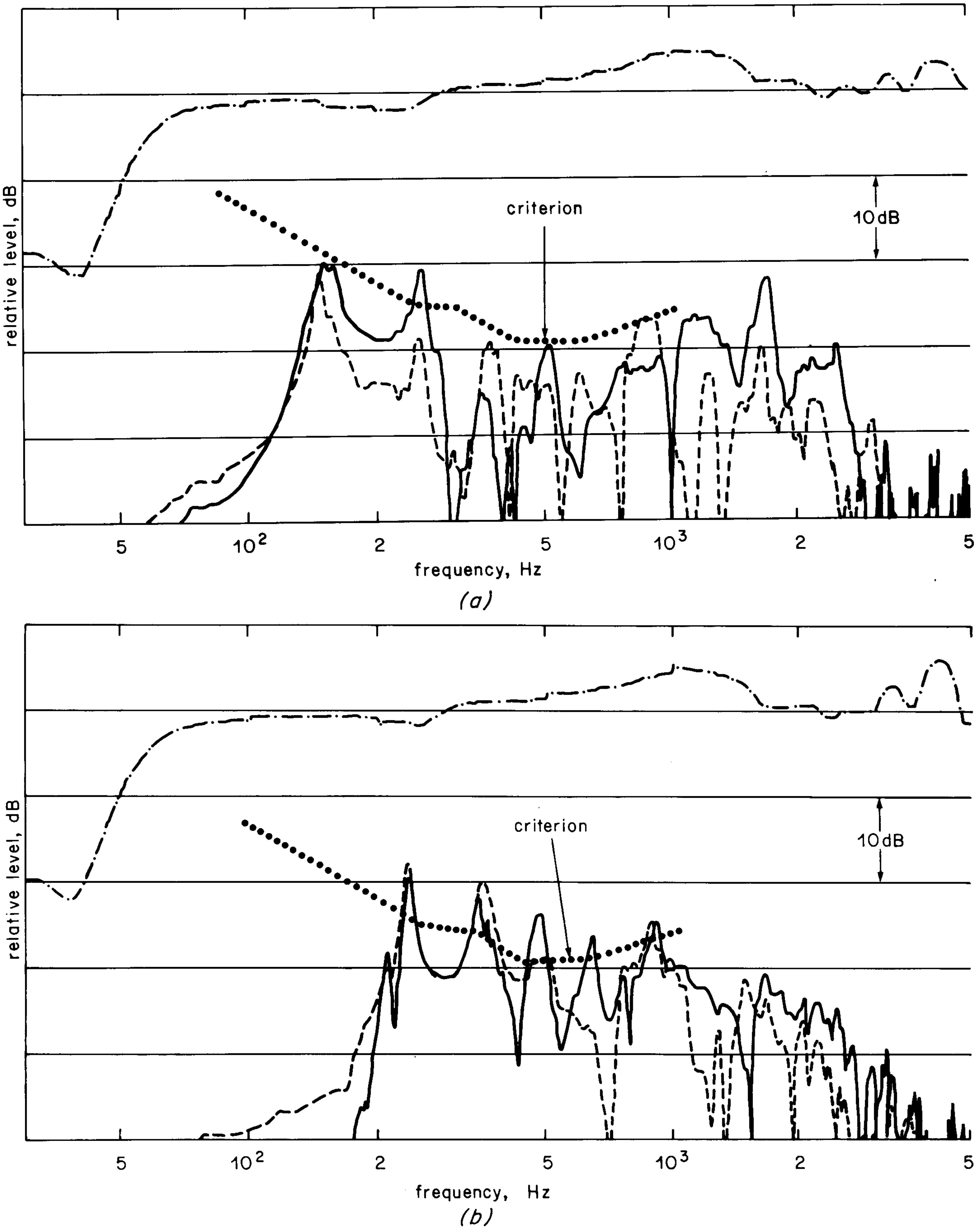

Fig. 13

(*a*) Relative response of standard thickness LS 3/6 cabinet with air damping only (non-standard L.S. unit)
(*b*) Relative response of double thickness LS 3/6 cabinet with air damping only (non-standard L.S. unit)
—·— Axial   ——— Side   – – – – Back   ●●●●●●●●● Criterion

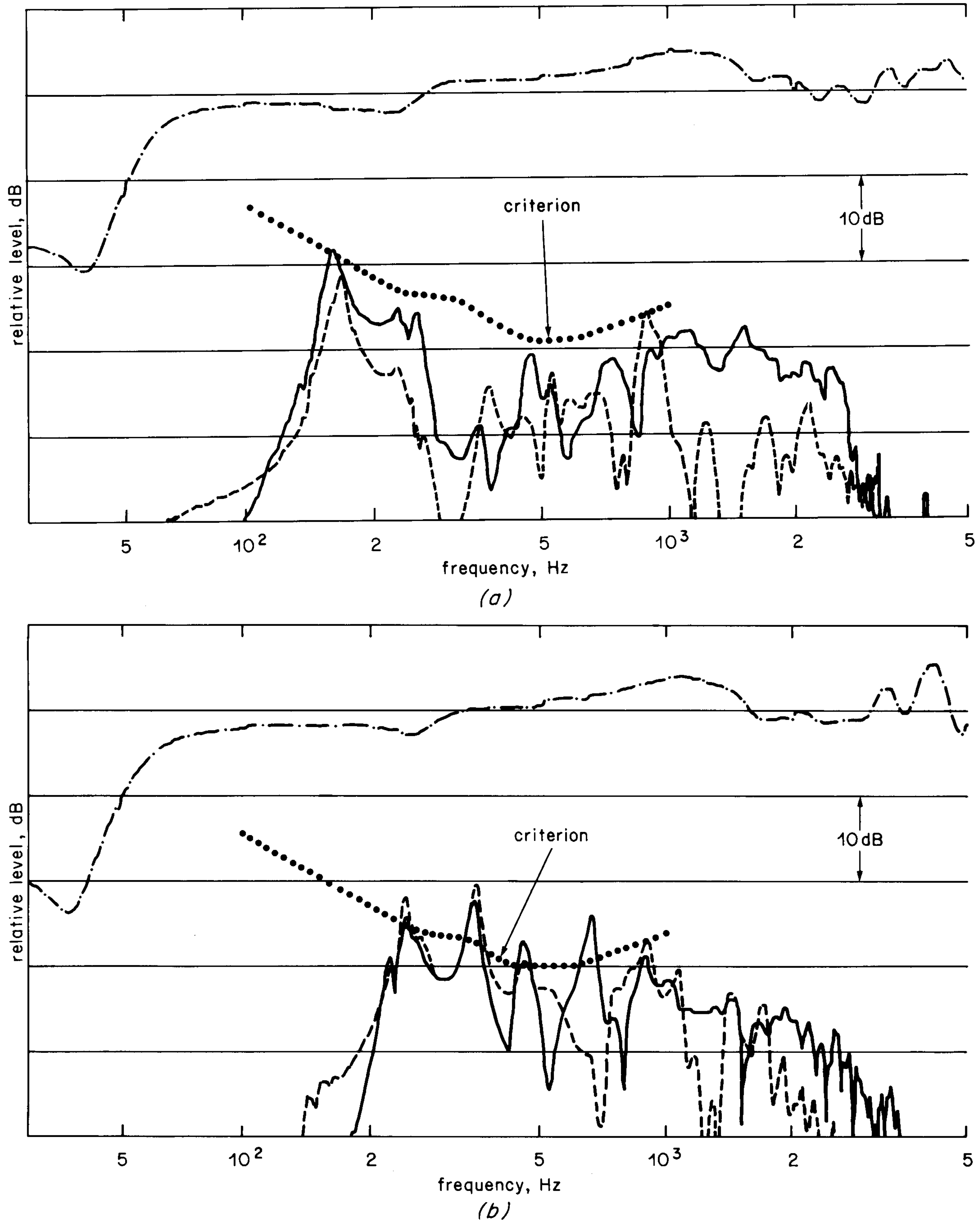

Fig. 14

(*a*) Relative response of standard LS 3/6 cabinet full standard damping (non-standard L.S. unit)

(*b*) Relative response of double thickness LS 3/6 cabinet with full standard damping (non-standard L.S. unit)

—·— Axial ——— Side – – – Back ●●●●●●●●●● Criterion

11. Conclusions

Extensive measurements have been made on the elastic modulus of wood and wood products over the whole of the audio band and show a previously unreported dependance on frequency. This information considerably extends that which was previously available and shows that plain timber is an unreliable material because of its variability and its inherent anisotropy. Manufactured products such as plywood and chipboard are more consistent and nearly isotropic and are therefore potentially suitable for use in loudspeaker cabinets. Of the two, plywood is preferred because it is manufactured in a greater range of thicknesses and has less resonant modes for a given configuration than chipboard. Although plywood appears to be the most suitable material at present, glass reinforced plastics should not be ignored as they may become competitive on a cost basis, their elastic properties are suitable and they can be moulded into any desired shape.

Damping needs to be applied to the inner surfaces of the panels of a loudspeaker cabinet; this report gives quantitative information about many damping materials. Common roofing felt which is easily available and is manufactured to satisfy a British Standard Specification seems to rank highly in the list of suitable materials. A self adhesive material such as Bostik is also suitable and cuts down the manufacturing costs. Mutacell with a mild steel backing is good but probably too expensive when labour costs are included.

A provisional specification has been proposed for a simple test method which enables the radiation from panels to be compared with that from the loudspeaker unit. Provisional figures are quoted (Fig. 12) which show the permissible relative levels over the audio frequency band.

12. Acknowledgements

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Appendix

(a) Basic resin system used in all experiments

Polyester resin – Scott Bader Crystic 199	100 pbw
Flexibiliser type 19353 Bakelite	20/25 pbw
Catalyst Butanox LA Novadel	2 pbw
Accelerator NL 49ST	2 pbw

SMW/AMM