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THE DESIGN OF A MODULAR SOUND ABSORBER FOR VERY LOW FREQUENCIES

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Summary

Studios and sound control rooms usually have their walls acoustically treated to control the reverberation time. In the BBC, this treatment often takes the form of modular absorbers of which there are a number of BBC designed types for sound absorption in different frequency bands.

This Report describes an investigation of the feasibility of a modular absorber for the 50 - 100 Hz frequency range.

A method of measuring absorption coefficient over a continuous frequency range using a standing wave duct is described. This allows a single modular absorber to be tested instead of requiring a batch of prototypes to be constructed for a reverberation room test. This technique was used to test a variety of absorbers, including porous, Helmholtz and membrane types.

These tests led to a design of membrane absorber, and a small batch of prototypes was constructed and tested in a reverberation room. This test verified that the prototype module had useful absorption in the frequency range of interest.

Index terms: *Acoustics; absorbers; sound; rooms; reverberation*

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1. INTRODUCTION

Studios and sound control rooms usually have their walls acoustically treated to control the reverberation time. In the BBC, this treatment often takes the form of modular absorbers, of which there are a number of BBC designed types for sound absorption in different frequency bands.

It is desirable that the reverberation time in a studio or sound control room should be reasonably constant when measured in the ⅓ octave frequency bands of the audio frequency range. (Reverberation time is usually measured over the range 50 to 10 000 Hz.) Measurements of reverberation time in such areas often show a 'bass rise' with reverberation time increasing at low frequencies. An example of this is shown in Fig. 1.

The existing range of modular absorbers did not include one with strong absorption at these low frequencies, so an investigation was made into the feasibility of such an absorber. This Report describes this investigation and the resulting design for a very low frequency modular absorber.

2. MODULAR ABSORBERS

A modular system has been developed in the BBC for acoustic treatment. This uses standardised prefabricated modules which are easily interchanged. The system is based on a 600 mm square grid. The individual modules are 580 mm square (except for the double size D2) leaving 20 mm spacing between units for fixing to battens. There are various depths of module, the most commonly used being the 'A-series' modules which are 184 mm deep. The full range of modular absorbers is described in the BBC Engineering publication 'Guide to Acoustic Practice' [1].

The majority of small and medium sized studios use A2 and A3 units. These are respectively a low frequency absorber with a peak of absorption centred on 125 Hz, and a wide band absorber effective at frequencies above about 200 Hz. A lower frequency absorber is the D2; this is deeper (292 mm) than the A2 and is double size (1180 × 580 mm).

Fig. 2 shows typical reverberation room measurements of these absorbers. Note that the A2 module is not very effective below 125 Hz. Even the D2 module does not absorb much in the lowest frequency bands.

A new absorber to complement the existing range would absorb in the range 50 - 100 Hz. It would need to fit into the 600 mm grid system and ideally be the same depth as the A-series modules (184 mm).

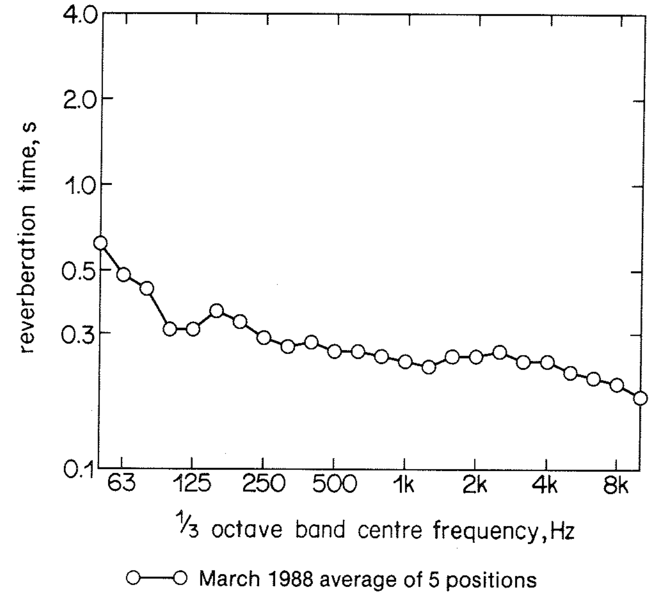

Fig. 1 - Reverberation time measured in Bush House N42 Cubicle showing typical bass rise.

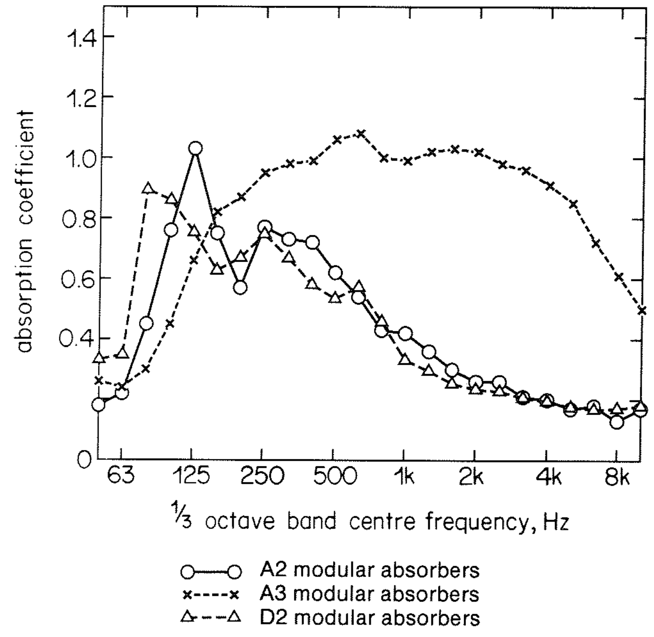

Fig. 2 - Absorption coefficients of modular sound absorbers; measured in an ISO-standard reverberation room.

3. EARLIER WORK ON SOUND ABSORBERS

A detailed investigation of the absorption mechanism in the A2 module was made[2]. This found that the low frequency absorption did not arise from a Helmholtz resonance of the air contained in front panel perforations, which was the basis on which the unit was designed, but from the front panel resonating as a limp panel. The investigation also showed that unwanted absorption around 400 Hz was associated with the side panels.

An absorber was designed with the objective of combining the low frequency absorption of an A2 with the mid and high frequency absorption of an A3[3]. The low frequency component of absorption in the experimental module was a comparatively narrow peak around 100 Hz, and it was not found possible to obtain as high an absorption coefficient as the A2 module.

Absorbers with controllable characteristics were also investigated[4]. Both a controllable high frequency absorber and a controllable low frequency absorber were designed. The low frequency unit had good absorption below 100 Hz but was of rather massive construction and had to be sealed to the room surface on which it was mounted.

4. MECHANISMS OF SOUND ABSORPTION

There are three main mechanisms of sound energy absorption. These are: porous absorption; membrane absorption; and Helmholtz absorption.

4.1 Porous absorption

Porous absorption occurs in porous materials such as mineral wool, and arises from frictional losses as air moves within the material. High absorption begins to occur when the depth of material exceeds a certain fraction of a wavelength. The exact relation between depth of absorbent material and the limit of low frequency absorption is dependent on the arrangement of the absorbent material.

To illustrate this, Fig. 3 shows reverberation room measurements of 180 mm and 270 mm depths of mineral wool as a 10 m^2 patch contained within a wooden perimeter frame, and also of open fronted modular absorber boxes (each 580 mm square) containing approximately 180 mm depth of mineral wool and with a similar total area.

For the large area patches, the low frequency limit of absorption occurs when the depth of absorber is about 4% of the wavelength.

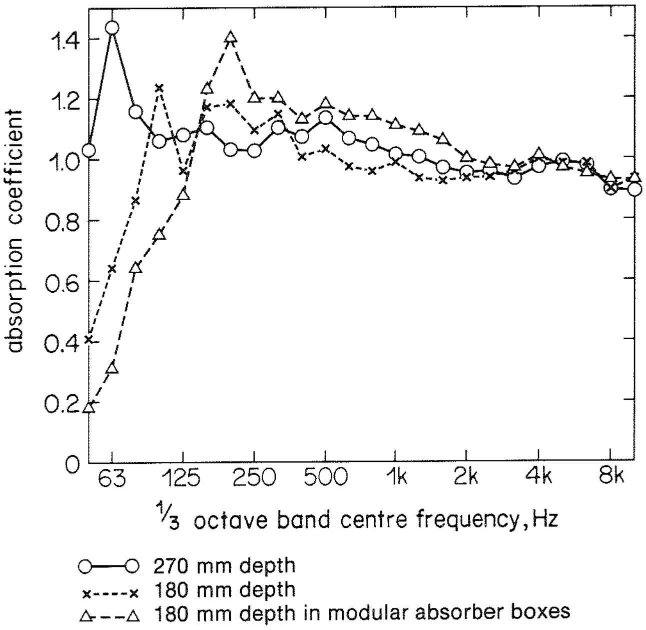

Fig. 3 - Absorption coefficients of RW2 mineral wool; measured in an ISO-standard reverberation room.

The subdivided (180 mm deep) sample is less effective, needing a depth of about 7% of the wavelength at the low frequency limit.

For a very low frequency modular absorber, porous materials are not suitable because the depth required would be too great.

However, for wideband absorption, except at very low frequency, a simple porous absorber is very effective. Such an absorber is described in a companion Research Department Report[5].

4.2 Helmholtz absorption

Helmholtz absorbers were used with some success in a BBC studio back in the 1950s[6]. Helmholtz absorption arises from losses in a Helmholtz resonator. This is an enclosed volume with a small opening or port. The mass of air in this port and the stiffness of the air in the enclosed volume form a resonant system.

The resonant frequency of a Helmholtz resonator is given by:

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{l'V}}$$

where:

A is the area of the port

l' is the effective depth of the port (greater than the true depth)

V is the volume enclosed

The effective depth of a circular port is sometimes given as

$$l' = l + 0.8 \times d,$$

where:

l is the actual port depth, and

d is the port diameter.

4.3 Membrane absorption

The use of membrane absorbers in BBC studios also dates back many years[7]. Membrane absorption arises from the losses in a vibrating panel, for example the hardboard front of an A2. The vibration may be an inherent mode of a stiff panel or it may be a resonance of a panel over an enclosed air space.

The resonant frequency of a completely limp panel over an enclosed air space is given by:

$$f = \frac{4}{\pi^3} \sqrt{\frac{\gamma P l_1 l_2}{\sigma V}}$$

where:

γ is the ratio of specific heats of air (about 1.4)

l_1, l_2 are the dimensions of the front panel

P is the air pressure

σ is the mass per unit area of the panel

V is the volume enclosed.

5. METHODS OF MEASURING ABSORPTION COEFFICIENT

5.1 Reverberation room method

The conventional method of measuring the absorption coefficient of a material uses a reverberation room[8]. This is a large chamber with acoustically reflective surfaces. The reverberation time is measured with and without the sample present and from this the absorption coefficient is calculated.

This method has been investigated in detail at Research Department[9] and has been found to give repeatable and reproducible results which are a good guide to the performance of acoustic treatment when installed in an operational area.

A large sample of absorber (10 - 12 m^2) is required, so the testing of many different designs of prototype absorbers becomes impractical.

5.2 Standing wave tube method

The normal incidence absorption coefficient of a small sample can be measured in a standing wave tube (also called an impedance tube)[10]. The sample is sealed across the end of a tube and at the other end the air in the tube is excited by means of a loudspeaker. Measurements of the standing wave pattern in the tube are used to calculate the absorption coefficient. The tube must be longer than half the longest wavelength to be used and the cross-section should be less than half the shortest wavelength to be used.

Conventionally, a pure tone excitation is used and the standing wave pattern is measured using a movable microphone to locate and measure maxima and minima. This is rather laborious if measurements at many frequencies are required.

There are alternative methods of using a standing wave tube which do not require a moving microphone and which give results over a continuous frequency range. These methods use a noise signal as the excitation with two microphones spaced along the tube. A Fast Fourier Transform (FFT) analyser is used to measure the transfer function between the microphones; from this, the acoustic impedance or normal incidence absorption coefficient can be calculated.

Fahy[11] gives the following formula for calculating acoustic impedance:

$$\frac{\tilde{z}_0}{\rho c} = \frac{H \sin kx_1 \sin\phi + j[\sin kx_2 - H \sin kx_1 \cos\phi]}{H \cos kx_1 \cos\phi - \cos kx_2 + j[H \cos kx_1 \sin\phi]}$$

$\tilde{z}_0$ is the sample complex impedance

$He^{j\phi}$ $= \tilde{H}$ the complex transfer function measured from microphone 1 to microphone 2

x_1 and x_2 are the respective distances from the sample face to microphones 1 and 2 with $x_2 > x_1$

k is the wavenumber, ρ the density of air and c the speed of sound in air

The absorption coefficient, α, can be calculated from the impedance using the expression:

$$\alpha = 1 - \left| \frac{1 - \tilde{z}_0/\rho c}{1 + \tilde{z}_0/\rho c} \right|^2 = \frac{4 \mathrm{Re}\{\tilde{z}_0/\rho c\}}{|1 + \tilde{z}_0/\rho c|^2}$$

Note that if only the absorption coefficient is required, only the microphone separation $x_2 - x_1$ is significant. The distance from the sample is not significant and any value can be used for the sake of the calculation.

Elliot[12] describes an analogue method for the calculation of absorption coefficient. This was designed to be implemented by an electrical circuit but the equations can be implemented by frequency domain processing.

This leads to an expression for absorption coefficient, α:

$$\alpha = 1 - \left| \frac{1+\tilde{H}+(1-\tilde{H})\omega_0/j\omega}{1+\tilde{H}-(1-\tilde{H})\omega_0/j\omega} \right|^2$$

$\tilde{H}$ is the complex transfer function measured from microphone 1 to microphone 2

ω is angular frequency

$\omega_0 = 2c/\Delta x$ where Δx is the microphone separation.

Given the same data, the two methods give almost identical results (within 0.01 units of absorption coefficient with few exceptions).

6. EXPERIMENTAL VERIFICATION OF THE CONTINUOUS FREQUENCY STANDING WAVE TUBE METHOD

6.1 Experimental set-up

There is a standing wave duct with a rectangular cross-section 620 × 800 mm at BBC Engineering Research Department, and this seemed well suited to measurements of modular absorbers 580 mm square. The theoretical upper frequency limit of this duct is just over 200 Hz.

Two B & K 4145 microphones were positioned centrally in the duct with a separation of about 400 mm. The separation should not exceed ¼ of a wavelength but the larger the separation, the less sensitive the measurement is to phase and amplitude mismatch between the microphones. Various distances from the test sample to the first microphone were used, ranging from 700 mm to 1300 mm.

As a reference condition, a paving slab was positioned in the duct at the sample position. It was placed behind wood battens such that the aperture was completely filled. For the absorber tests, the absorber was placed in front of the battens with the slab behind. This was intended to be similar to the mounting of a modular absorber on a studio wall.

6.2 Reference measurements with no absorber present

Fig. 4 shows results for the paving slab alone. The two measurements were made with different microphone positions and are in reasonable agreement. Although the absorption below 100 Hz is rather higher than might be hoped for, the results are quite believable.

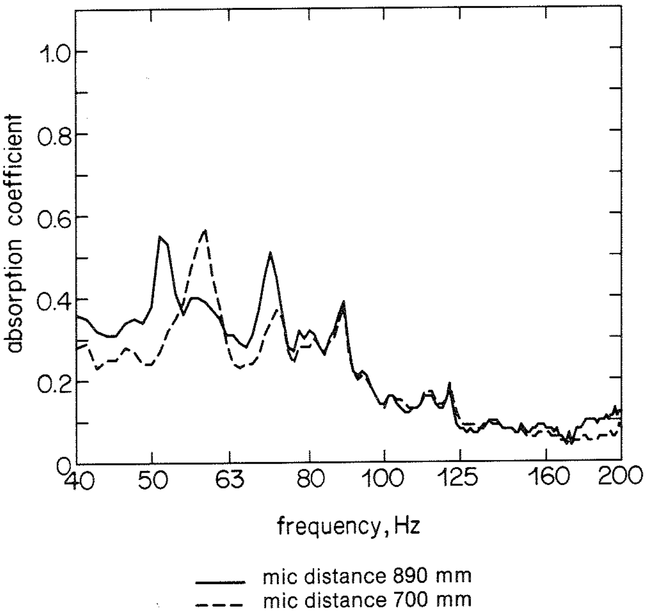

Fig. 4 - Duct measurements with no absorber present.

6.3 Measurements of an A2 modular absorber

Fig. 5 shows results for an A2 modular absorber placed in front of the paving slab. Again, there is reasonable agreement between results at different microphone positions; particularly in the region of peak absorption between 125 and 160 Hz.

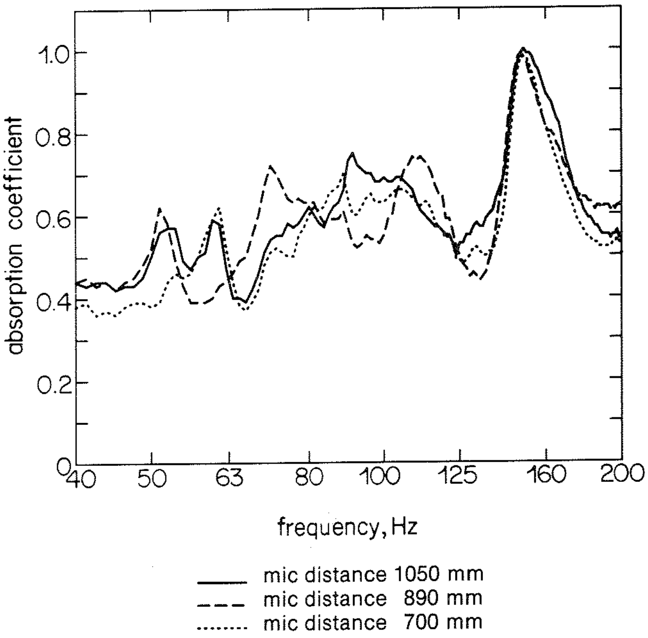

Fig. 5 - Duct measurements of an A2 modular absorber.

6.4 Comparison with a conventional standing wave tube measurement

An A2 modular absorber was measured in the conventional way by recording maxima and minima in the standing wave pattern. Measurements were made at ⅙ octave intervals. Fig. 6 shows these results compared with the continuous frequency two-microphone measurement. There is good agreement between the two sets of results.

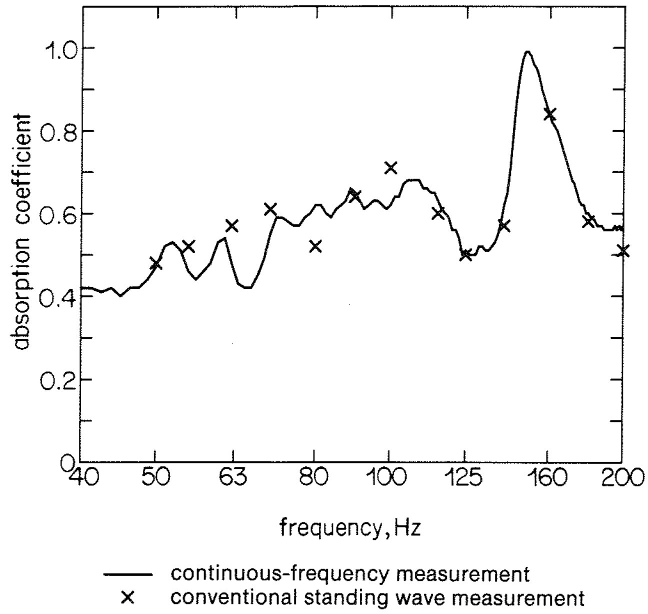

Fig. 6 - A2 modular absorber: comparison of standing wave tube measurements.

6.5 Comparison with a reverberation room measurement

Fig. 7 shows the continuous frequency two-microphone measurement of the A2 absorber compared with the results from a reverberation room test. At 50 and 63 Hz the lower limit of absorption coefficient measured with only the slab present is reached. At higher frequencies, the reverberation room result shows a peak centred on 125 Hz, whereas the narrow band measurement shows the peak to be nearer 160 Hz. Nevertheless, the general form of both sets of results is similar.

The differences between normal incidence and random incidence absorption coefficients may account for differences of the order of 15%[13]. In addition, the reverberation room measurement is a summation in each ⅓ octave band; and if the modal density is low, then the results may depend on how modal frequencies of the reverberation room correspond to peaks and troughs in the continuous frequency absorption coefficient of the absorber.

Therefore, close agreement between impedance tube and reverberation room measurements of absorption coefficient is not expected. However, the results of the continuous frequency two-microphone method are a useful guide to the absorption coefficient of a sample, and allow rapid experimentation using a single prototype absorber.

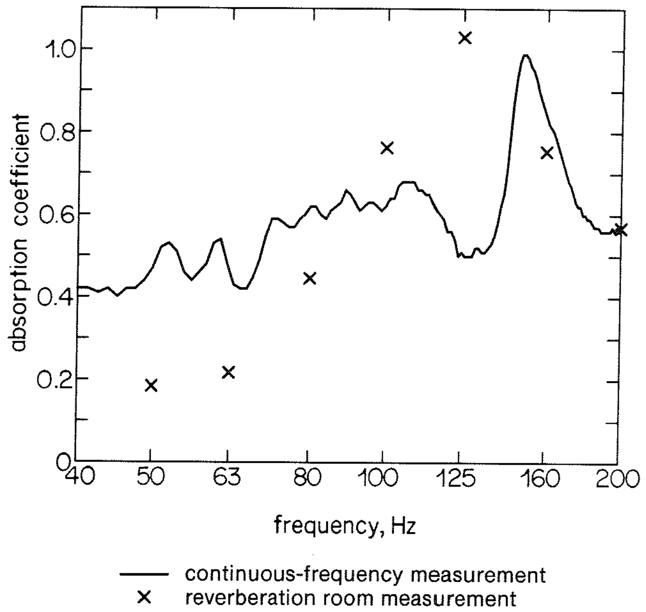

Fig. 7 - A2 modular absorber: comparison of standing wave tube and reverberation room measurements.

7. EXPERIMENTS

7.1 Porous absorber

Fig. 8 shows a duct measurement of an open-fronted box containing approximately 180 mm depth of mineral wool (Rockwool RW2 grade). It is

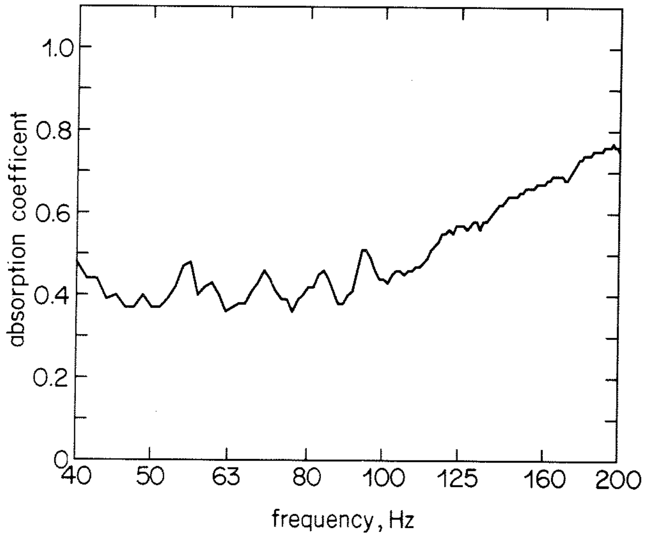

Fig. 8 - Open-fronted wooden box filled with RW2 mineral wool; measured in standing wave duct.

interesting to compare this with the corresponding reverberation room measurement (shown in Fig. 3). Both show significant absorption once the frequency exceeds 125 - 160 Hz. It is an observed characteristic of the duct measurements that measured absorption coefficients are lower than in reverberation room measurements. This is because the duct measurement is a normal incidence measurement and there are no diffraction effects.

7.2 Helmholtz absorbers

7.2.1 Plywood/hardboard box

A module was constructed with plywood sides and back, and a 6 mm hardboard front fitted with a port of 76 mm diameter tube, 73 mm long. The theoretical resonant frequency was just over 40 Hz. As shown in Fig. 9, this Helmholtz resonance was not apparent in the measured absorption coefficient curve but several other resonances, presumably mechanical, were.

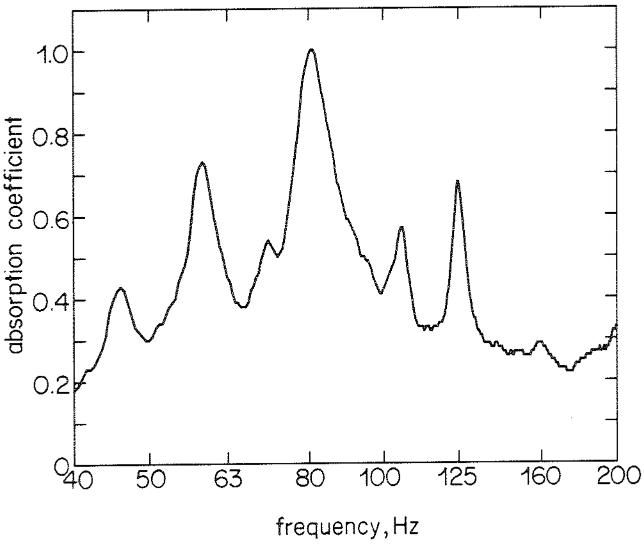

Fig. 9 - Plywood box with 6 mm hardboard front, ported with 76 mm diameter tube, 73 mm long; measured in standing wave duct.

7.2.2 Chipboard box

It was suspected that the plywood/hardboard box was too flimsy and so a box was constructed from 18 mm chipboard, this time with a 51 mm diameter hole in the front panel. This box had a theoretical resonant frequency of 49 Hz and the measured absorption coefficient curve in Fig. 10 shows a clear peak at 45 Hz.

A similar chipboard box with a 76 mm diameter hole was also tested. Its absorption coefficient curve, shown in Fig. 11, shows a peak at 56 Hz, compared with a theoretical resonant frequency of 63 Hz.

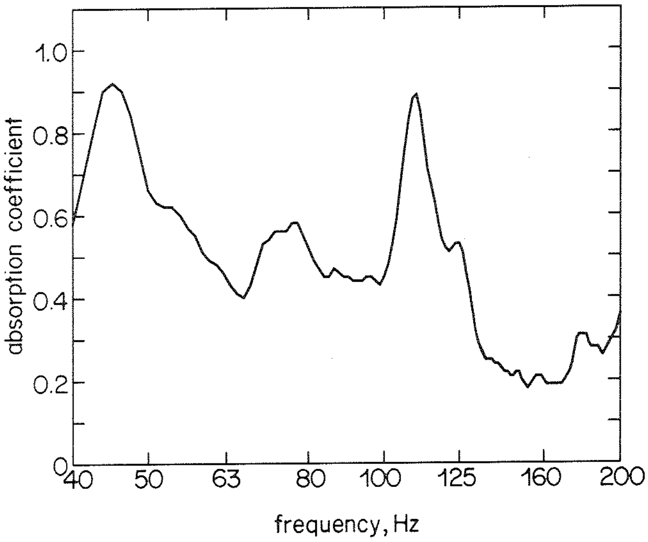

Fig. 10 - Chipboard box ported with 51 mm diameter hole; measured in standing wave duct.

Sealing of the joints of the box is important for an absorber of this type. Fig. 12 shows a measurement of the box (76 mm diameter hole) when the front panel was not well sealed. Note the extra peak of absorption.

The peak which occurs in the region of 110 Hz was identified as a resonance of the back panel. This was found using an accelerometer on the back panel; a peak in the vibration spectrum at this frequency was observed when the panel was tapped, with or without the front panel in position.

The results for the chipboard boxes were quite encouraging; showing that a high absorption coefficient could be achieved at low frequencies with a standard size modular absorber. The peak of absorption

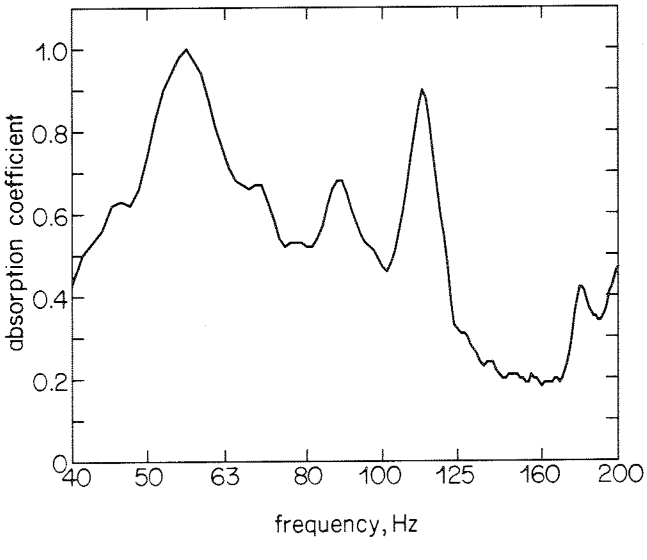

Fig. 11 - Chipboard box ported with 76 mm diameter hole; measured in standing wave duct.

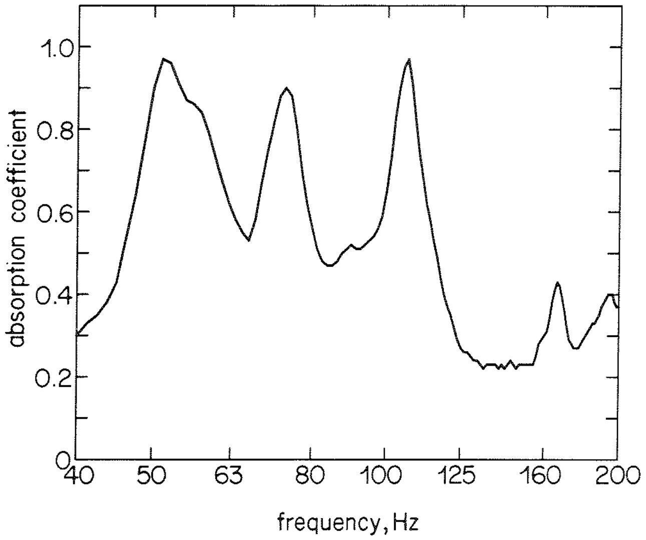

Fig. 12 - Chipboard box ported with 76 mm diameter hole, without careful sealing; measured in standing wave duct.

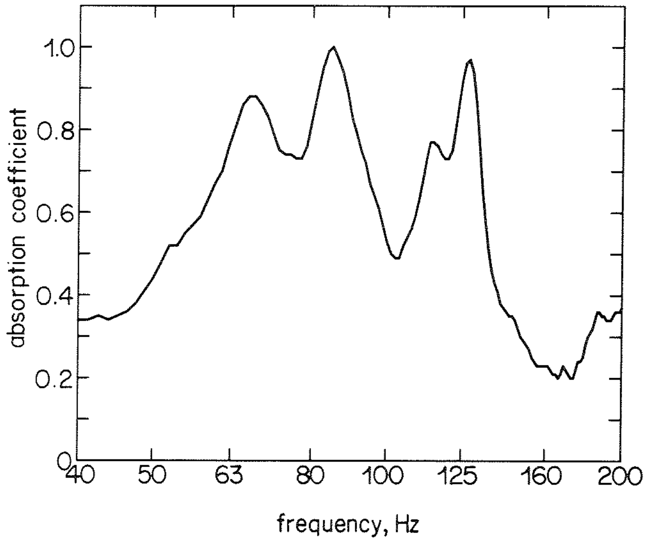

Fig. 13 - Chipboard box with two ports 64 and 76 mm diameter; measured in standing wave duct.

corresponding to the Helmholtz resonance was, unfortunately, rather narrow compared with the frequency range over which a low frequency modular absorber would be required to operate. The possibility of incorporating more than one Helmholtz resonance in one box was, therefore, investigated.

7.2.3 Multiple hole boxes

A Helmholtz resonator with two ports is theoretically similar to one with a port of the combined area. However, an experiment with a two hole box suggested that the ports might behave independently and share the enclosed volume in some way. This result is shown in Fig. 13. The chipboard box with 64 mm and 76 mm diameter holes in the front panel showed two peaks at 67 and 85 Hz which are close to the theoretical frequencies of 79 and 89 Hz for boxes of half the volume with one hole in each. That is, the behaviour seemed to be as if the box were divided internally into two halves with one hole in each.

However, further experiments with two and more ports in one box showed that although more than one peak (in addition to the known back panel resonance) was usually evident, there was little relation between the number of holes and their sizes, and the frequencies of peaks of absorption.

7.2.4 Effect of coverings

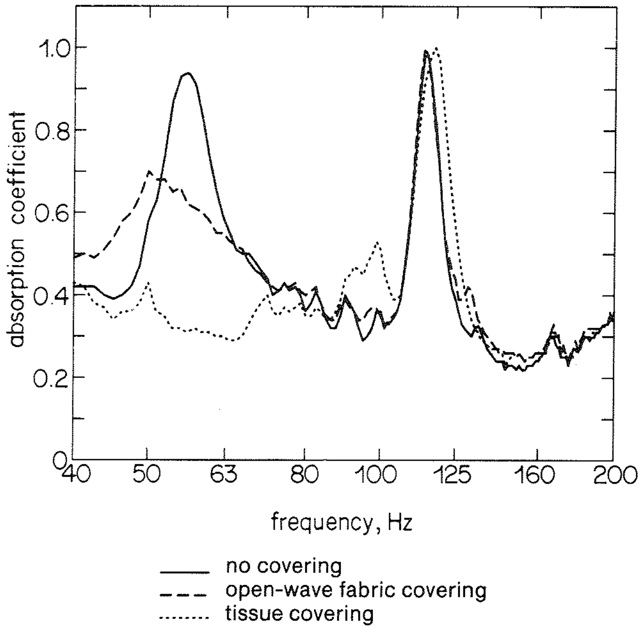

Fig. 14 - The effect of port coverings on a Helmholtz absorber; measured in standing wave duct.

A further problem with Helmholtz absorbers is that they are very sensitive to damping of the air flow through the port. This is illustrated in Fig. 14, which shows absorption measurements of a box constructed from 15 mm MDF with a 3″ diameter hole in the front panel. This has a Helmholtz resonance at 56 Hz. (The peak at 114 Hz is a mechanical resonance of the box.) The first measurement is for the box with no covering of the port, the second shows the effect of an open-weave fabric loosely draped over the port, and the third shows the effect of a piece of tissue affixed over the port. The fabric damps the resonance considerably and the tissue destroys it completely. It is usual practice for modular absorbers to be covered with fabric spaced 6 mm off the fronts so an effect similar to that shown in the second measurement would be expected.

7.2.5 Summary of Helmholtz absorbers

Helmholtz resonance gives relatively narrow peaks of absorption which cannot be multiplied by the use of multiple port boxes. The absorbers are strongly affected by covering of the port. A sturdy, and therefore heavy, box is required. Resonance of the stiff box gives rise to an unwanted narrow peak of absorption above 100 Hz.

Overall, it appears that Helmholtz absorbers have several disadvantages and that at least two modules, tuned to different frequencies, would be required to cover the frequency range 50 - 100 Hz.

7.3 Membrane absorbers

7.3.1 Initial experiments

Initially, a rather poorly sealed box with plywood sides and back was used for experiments with membrane absorption. Both hardboard and a flexible barrier mat material were tried as the front panel but the absorption obtained was not at sufficiently low frequency. At this point, the experiments with Helmholtz absorbers were started. Subsequently, the importance of sealing the box for membrane absorbers was realised and the investigation of membrane absorbers was continued.

7.3.2 Flexible barrier mat as front panel

A commercially available flexible acoustic barrier mat was chosen as a good material for the membrane of a membrane absorber. The material was impregnated PVC with a thickness of 2.5 mm and a mass per unit area of 5 kg/m^2. The barrier mat was used as the front panel of a standard A-series size box constructed with plywood sides and back. The mat was pinned to the box and the joint sealed with mastic. The theoretical frequency of the limp panel resonance over the enclosed air space of this box would be 22 Hz, but in practice a rather higher frequency would be expected because of the finite stiffness of the membrane. Fig. 15 shows the measurement from the standing wave duct. This shows a sharp peak between 80 and 100 Hz and a broader peak around 56 Hz. It is probable that the lower peak is the membrane resonance; the peak at higher frequency is probably a resonance of the back panel. Although the frequency of operation is sufficiently low, the absorption coefficient at 56 Hz is not sufficiently high. This is probably because the barrier mat material has too much inherent damping.

7.3.3 Hardboard as front panel

Fig. 16 shows the results from a similar box, this time with a 3 mm hardboard front. The box was empty and the front and back were sealed in place with mastic. There are three narrow peaks of absorption at 59 Hz, 88 Hz and 128 Hz. These are probably associated with different modes of resonance of the front and back panels.

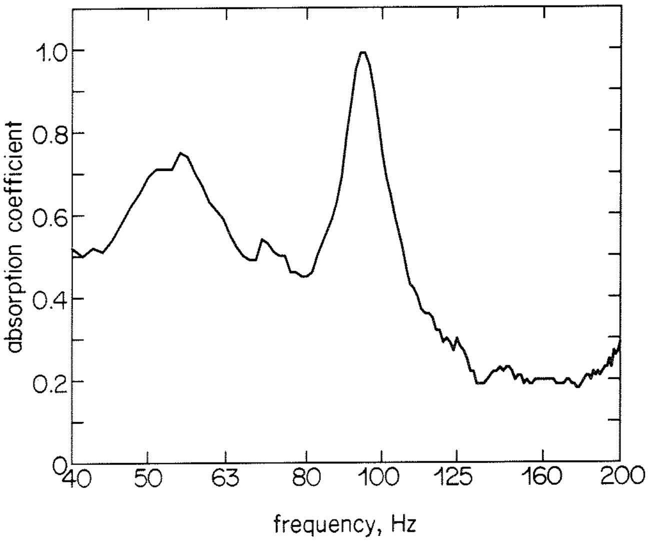

Fig. 15 - Plywood box with barrier mat front; measured in standing wave duct.

In an attempt to broaden these peaks to give a better coverage of the frequency range of absorption, the box was filled with Supawrap loft insulation (two layers of 100 mm uncompressed depth). As shown in Fig. 17, the resonant peaks have been damped to give a more even coverage of the 50 - 100 Hz octave.

Rockwool RW2 grade mineral wool was also tried as a filling. This is denser and less compressible than the Supawrap. Fig. 18 shows the result. The damping is much heavier. Individual peaks are no longer apparent and the absorption is much reduced.

To see if the mass of the box could be

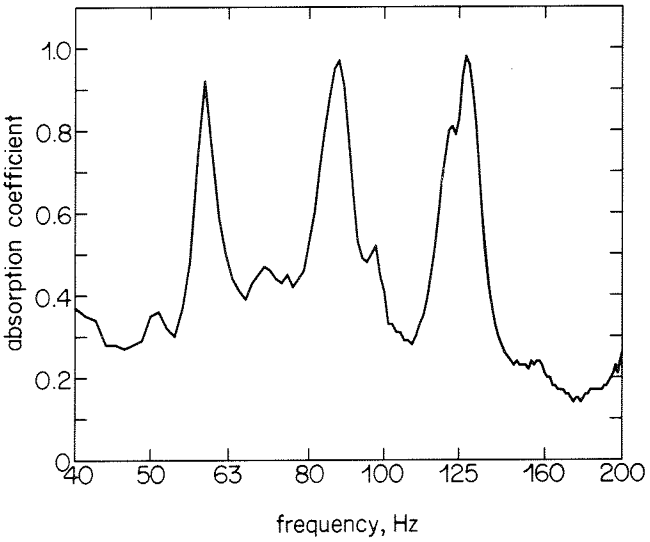

Fig. 16 - Plywood box with 3 mm hardboard front; measured in standing wave duct.

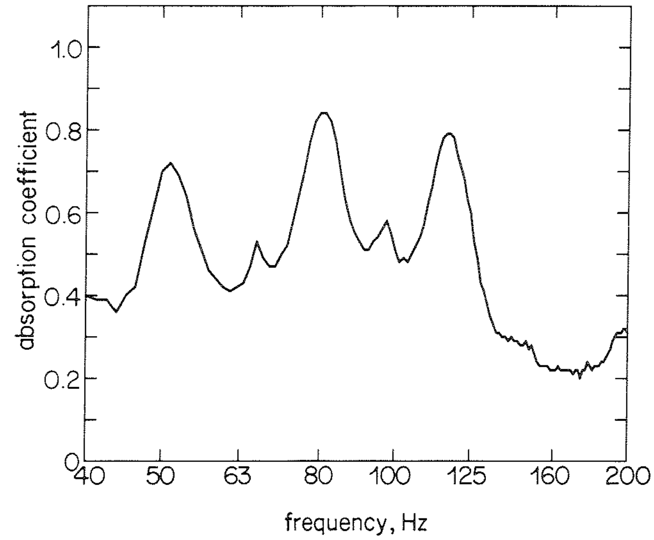

Fig. 17 - Plywood box with 3 mm hardboard front and Supawrap filling; measured in standing wave duct.

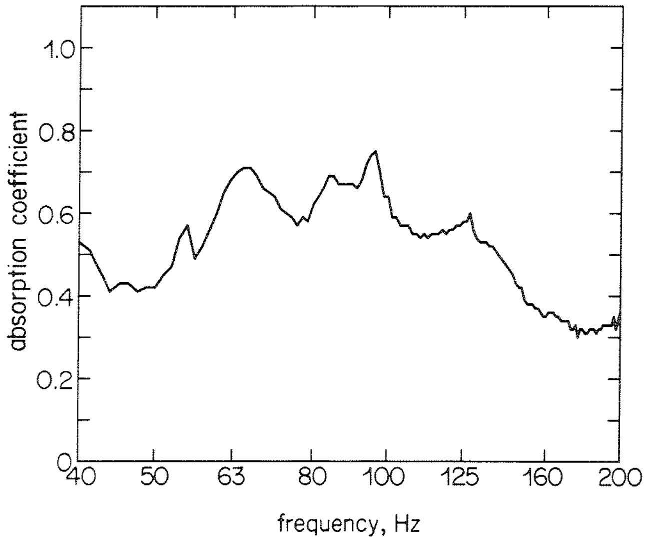

Fig. 18 - Plywood box with 3 mm hardboard front and RW2 filling; measured in standing wave duct.

reduced, the plywood back panel was replaced with 6 mm hardboard, as in the standard A-series modules. Fig. 19 shows the measured result for this box (no Supawrap filling). It fails to give a similar spectrum of absorption. This shows that the stiffness of the plywood back is necessary for the operation of the absorber.

The measured absorption of the module with plywood back, hardboard front and Supawrap filling may not look particularly impressive when compared with some of the results from Helmholtz absorbers, but this membrane absorber has several advantages. In particular, it is likely that the frequencies of absorption peaks would be less precisely fixed than with a Helmholtz resonator and so, when controlling reverberation in a room, the panel absorber should give a more uniform reverberation characteristic.

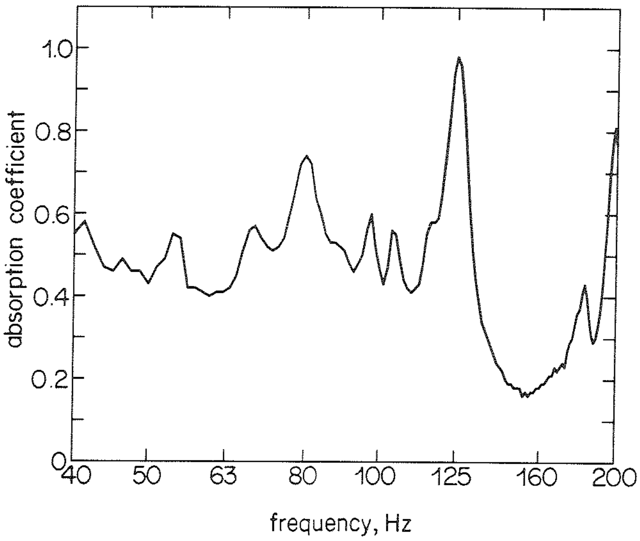

Fig. 19 - Plywood sided box with 6 mm hardboard back and 3 mm hardboard front; measured in standing wave duct.

8. REVERBERATION ROOM TEST OF PROTOTYPE MODULAR ABSORBERS

The absorber with hardboard front and Supawrap filling was sufficiently promising to warrant a reverberation room test; so a batch of 28 modules was constructed. The fronts and backs were pinned and glued in place, so additional sealing with mastic was not required. A drawing of this prototype is shown in Fig. 20.

The batch of 28 modules gave a total area (when spaced at 600 mm centres) of 10.1 m^2. They were laid out on the floor of the ISO Reverberation Room at BBC Research Department as one patch and supported on battens (approximately 20 mm off the floor).

The test result is shown in Fig. 21. The absorption rises below 125 Hz to a peak at 63 Hz then falls off slightly at 50 Hz. The module has achieved the desired absorption at low frequency but this does not extend to such a high frequency as was suggested by the duct measurements. As illustrated by the A2 module, it seems that in controlling reverberation, the frequency of operation of an absorber is less than would be suggested by standing wave measurements in the duct. Although the module does not adequately cover the range of operation of the A2 module, it does cover the range of frequencies below which the A2 is effective and should therefore be a useful addition to the range of modular absorbers.

The prototype module also shows a much lower and broader peak in the 200 - 500 Hz range. This is characteristic of modular absorbers of this size and construction. However, the peak for this absorber

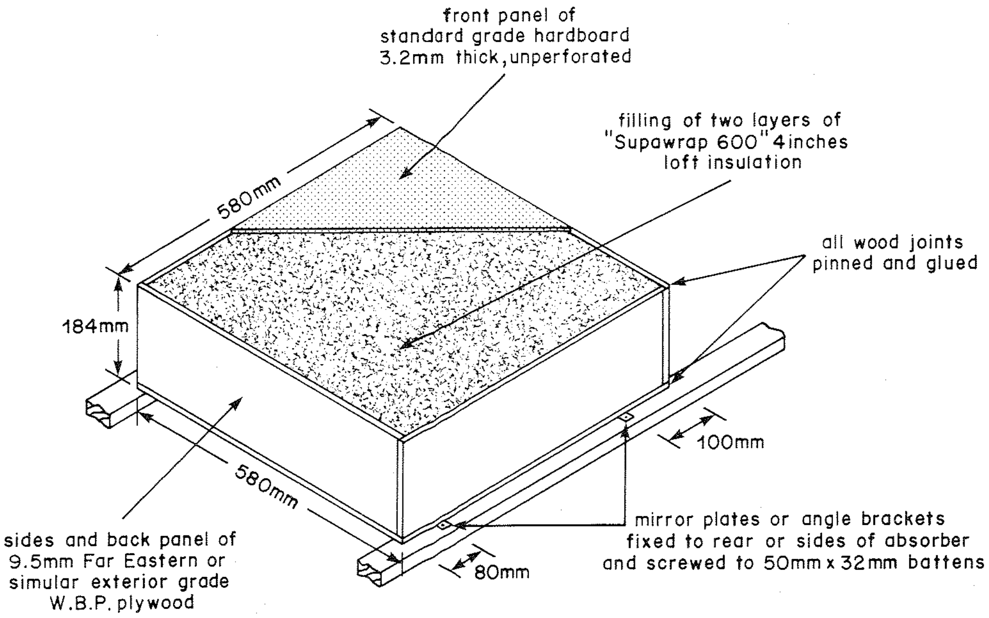

Fig. 20
Prototype low frequency modular absorber.

is much lower than that of the A2 for example. Although duct measurements are not really valid at these frequencies, they have indicated that alternative materials for the side panels (such as 9 mm MDF) would probably give a similar unwanted peak of absorption.

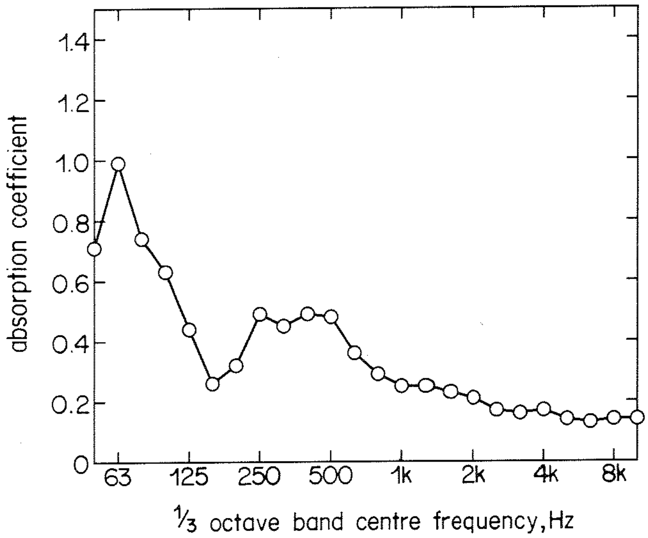

Fig. 21 - Absorption coefficients of prototype low frequency absorber; measured in ISO-standard reverberation room.

9. CONCLUSIONS

Helmholtz absorbers were found to be not very suitable as modular absorbers to cover the 50 - 100 Hz range. They give narrow peaks of absorption, and multiple resonances at closely spaced frequencies cannot be achieved in the same module. A heavy box is required and the absorption is strongly affected by fabric covering of the front.

Membrane absorbers were found to be more promising. A modular absorber of similar construction to the present A-series modules was developed which is light in weight and inexpensive to make. When measured in an ISO-standard reverberation room, it showed useful absorption in the 50 - 100 Hz range, although a rather broader peak of absorption would have been desirable.

The new module (shown in cutaway form in Fig. 22) has been designated the A10. It is a useful supplement to the A2/A3 combination currently in use, since it absorbs at frequencies below those at which the A2 is effective. Alternatively, the A10 can be used in conjunction with a new wideband absorber based on a module filled with mineral wool. This absorber, the A11, is described in a companion Research Department Report[5].

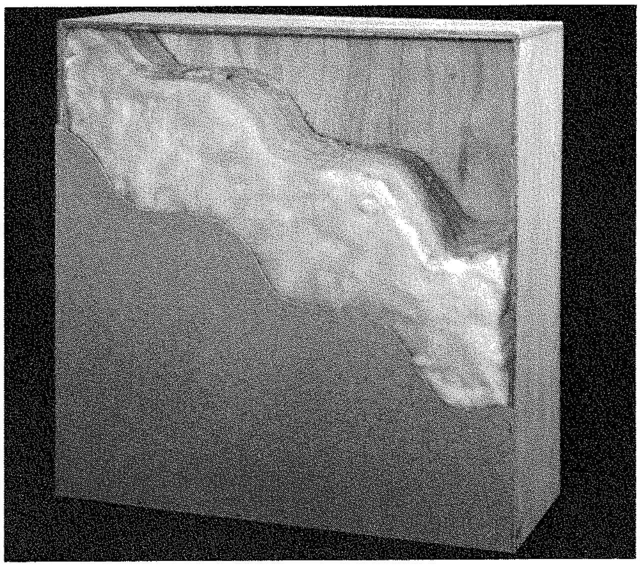

Fig. 22 - Photograph of cutaway prototype low frequency absorber.

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