MEASUREMENTS OF THE ACOUSTIC PERFORMANCE OF MATERIALS: FIBRE REINFORCED MATERIALS AND WEDGES

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1. INTRODUCTION

The search for improved performance is leading to the use of a wide range of new materials in applications where their acoustic characteristics are important. In many cases compound or complex materials are being considered in order to tailor or control their properties. Thus the materials are not necessarily homogeneous or isotropic and may have a complex structure. The use of these materials is being facilitated by the rapid development of a range of acoustic modelling techniques such as those described elsewhere in this volume [1,2]. There remains, however, a requirement to measure the acoustic performance of new materials for comparison with these theoretical predictions and to guide future developments, as well as for quality assurance. In this paper the application of an existing free field technique to the measurement of the transmission and reflection properties of two complex materials, namely fibre reinforced composites and wedges, is illustrated.

Fibre reinforced materials are being employed more widely because they can be used to form strong lightweight structures with mechanical properties that can be controlled by the fibre material and fibre layup. However the use of such fibres leads to the possibility that the material is anisotropic and has different mechanical and acoustic properties in different planes.

The drive to investigate acoustic wedges comes from the need to develop better anechoic materials for laboratory test tanks. The use of wedges in anechoic chambers in air is of course widespread, and wooden wedges have been used for some time in acoustic water tanks. However, information on the performance of wedges, especially as a function of angle of incidence, is actually rather sparse.

2. MEASUREMENT TECHNIQUE

2.1 Review

In the area of underwater acoustics there are two principal techniques that are used to measure the transmission and reflection properties of materials. The first is to use a water filled impedance tube that attempts to produce plane wave conditions in a thick-walled steel tube. The alternative approach is to use freefield conditions in a water tank.

Impedance tubes can produce very good results at frequencies below the cut-off frequency of the tube where only the plane wave mode propagates, although care has to be taken to avoid a number of possible sources of systematic error. As the tube contains a relatively small volume it is easy to pressurise. However as the sample under test has to be cut to fit the bore exactly this type of testing is not suited to materials which have large scale inhomogeneities and is destructive rather than non-destructive. It is also not practical to make measurements as a function of angle of incidence.

Free-field measurements are conceptually simple, requiring only a source, a receiver, a large enough sample of the material under test and a suitable tank or water volume. This approach has been used by a large number of workers with a wide range of adaptations to improve the performance of the system. Any free-field measurement is, however, a compromise between the need to make measurements on a small sample and the ideal of making measurements with a plane wave. The diffraction errors associated with the limited size of the sample can be reduced by the use of a directional source and receiver (such as a large area PVDF hydrophone). This type of measurement technique is much more suitable for making measurements as a function of angle of incidence and for testing materials which are inhomogeneous or have large scale structure.

2.2 Parametric array facility

The results presented in this paper were obtained using an existing facility that employs a parametric array as the source to produce the wave-field used to test the sample. A parametric array uses the non-linear propagation of primary wavefields to generate additional lower frequency (secondary) components that are then used to make measurements. There are two characteristics of this type of source that make it ideal for this type of measurement. Firstly, it can produce beams with a narrow cross-sectional area in the nearfield region. This greatly reduces the problems associated with multiple reflections from tank walls or the water surface in small tank facilities. In addition the "region under test" can be confined, enabling measurements to be made on relatively small samples without significant edge effects. Secondly, the parametric array may be used to produce short pulses with a very wide frequency content. This greatly facilitates testing as a function of frequency by Fourier analysis.

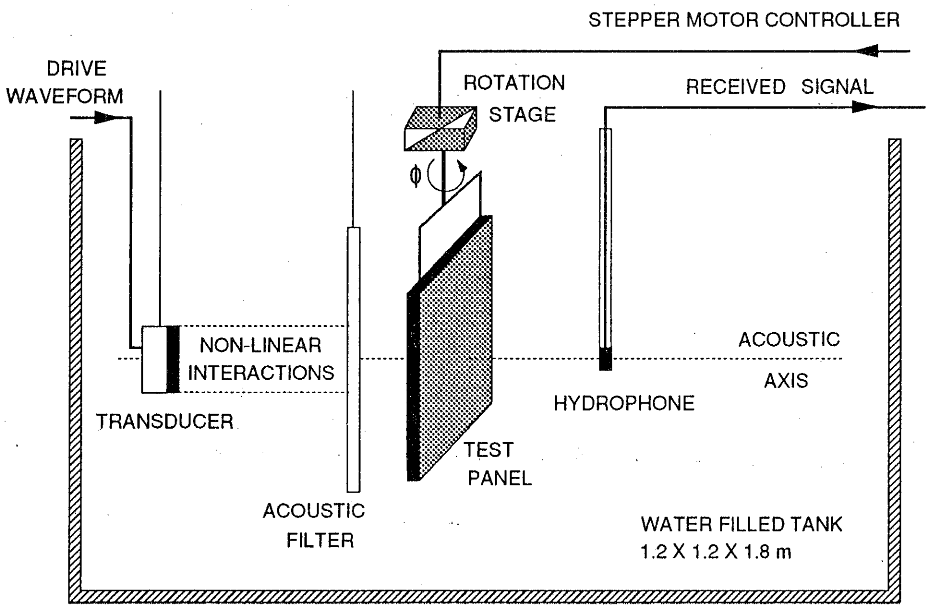

Figure 1. Experimental arrangement.

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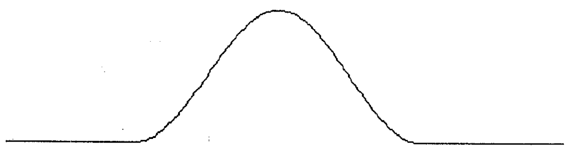
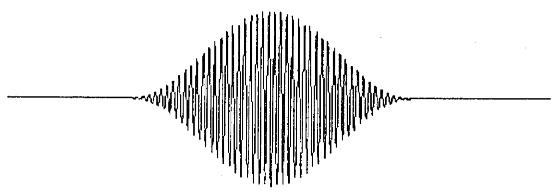
The experimental system used for these laboratory measurements is shown in Figure 1 and has been described in detail elsewhere [3,4]. The parametric array utilizes the non-linear propagation of high amplitude, high frequency, primary waves to produce lower frequency secondary waves. These secondary waves appear to come from "pseudo sources" distributed throughout the interaction region of the primary waves transmitted by a conventional transducer. The wideband nature of the source depends on the fact that the secondary sources can be altered by changing the primary frequencies transmitted within the bandwidth of the transducer. The transducer must, therefore, be reasonably efficient in order to generate adequate primary levels but must also have sufficient bandwidth.

Although it is possible to drive the transmitting transducer with two frequencies to generate a single secondary frequency (useful in low signal to noise applications) these measurements were performed by transmitting a short pulse of carrier frequency (Figure 2(b)), with a raised cosine bell (Figure 2(a)) or other appropriate envelope. In this case the low-frequency secondary waveform generated on axis (Figure 2(c)) can be shown to be proportional to the second derivative, with respect to time, of the square of the transmitted pulse envelope [5]. Hence for a raised cosine bell envelope based on a 20kHz sine wave the resulting secondary signal has a -6dB bandwidth extending from 15kHz to 45kHz (Figure 2(d)). In addition the generated waveform shape and spectrum can easily be adjusted by altering the length and shape of the envelope function.

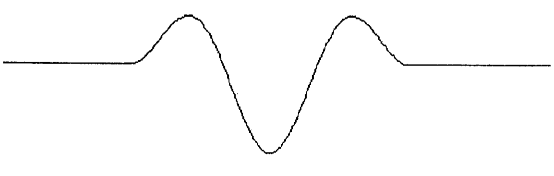
The resulting wavefields were detected with a small wideband hydrophone, low pass filtered and processed appropriately. In this case an ANALOGIC DATA 6000 was used to average and process the signals using FFT routines before they were transferred to a PC for subsequent analysis and storage. The rotation of the panel and all of the signal processing were controlled by the PC via an IEEE interface.



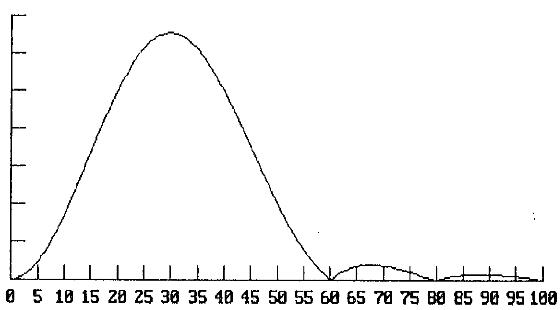
a) Modulation envelope.



b) Modulated carrier waveform



c) Secondary frequency waveform.



d) Spectrum of secondary frequency wave.

Figure 2. Signals involved in the generation of the secondary frequency wave (theoretical).

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One of the principal difficulties of using a source based on a non-linear effect is that care must be taken so that other non-linear effects do not complicate or invalidate the measurement process [3,4]. In these measurements complications were avoided by truncating the interaction region with an acoustic low pass filter; that is, a material which transmitted the secondary waves but attenuated the primary waves. This produced a secondary source free region beyond the filter in which measurements were easily performed without complications.

Experimental measurements of transmission loss were made by recording the reference signal at the hydrophone $\psi(t)$ and then inserting the test panel between the acoustic filter and receiving hydrophone at an angle θ. The new transmitted waveform $\psi_t(t, \theta)$ was recorded and the respective spectra $\Psi(\omega)$ and $\Psi_t(\omega, \theta)$ calculated using a FFT. The transmission coefficient T was then calculated using

$$T(\omega, \theta) = \frac{\Psi_t(\omega, \theta)}{\Psi(\omega)}$$

and the transmission or insertion loss TL using $TL = 20\,\mathrm{Log}(T(\omega, \theta))$. With the test panel rotated under computer control it is possible to perform a complete angular run in less than an hour obtaining detailed information over a wide range of frequencies and angles of incidence.

3. FIBRE REINFORCED MATERIAL

3.1 Anisotropic test panel

To illustrate the type of results that can be obtained on anisotropic materials measurements were made on a glass-reinforced-plastic panel 450mm x 450mm x 11.4mm in size. This panel was constructed with glass fibres principally aligned in one direction to produce a material with hexagonal symmetry. For such a material the transmission depends on both the plane of incidence (ϕ), (that is, the angle between the projection of the wavefront normal onto the panel and the fibre direction), and the angle of incidence (θ) as shown in Figure 3.

The experimental results are compared with the predictions of a theory for the acoustics of anisotropic planar layered media given by Skelton and James [6] and described elsewhere in this volume [1]. Assuming plane wave solutions to the elastic equations of motion for an anisotropic layer, a matrix equation is obtained whose general solution - when specialized to the layer surfaces - yields a relationship between surface spectral stresses and displacements. This 'layer dynamic stiffness relation' can be used to study all forms of wave propagation involving planar anisotropic layers; continuity of stress and displacement at the layer surfaces enable the layer, as a 'finite element', to be incorporated into a scattering system. Excitations of the system are acoustic or mechanical disturbances at the layer interfaces.

For the current case the scattering system comprises a single anisotropic layer which is assumed to have hexagonal symmetry, to be infinite in extent and to be bounded by acoustic half-spaces. The excitation is a plane wave incident on the upper interface (Figure 3) and the transmitted field is the wave radiated into the lower half-space by motion of the lower interface.

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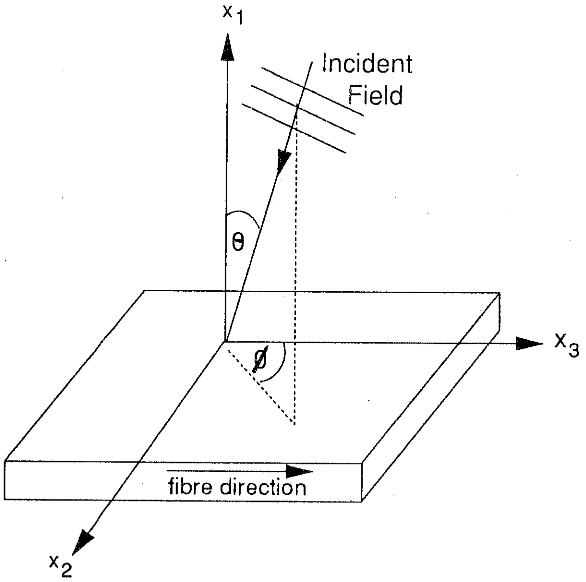
In order to make theoretical calculations it is necessary to know the five elastic constants (see Figure 3) of the test panel. Obtaining such data is, in itself, not an easy task. The values used here were based on velocity measurements made at 500 kHz by D Ryall and G Sutton (private communication) using the immersion technique. As no attenuation data for this material was available, damping was simulated by using complex stiffness constants $C_{ij}(1 - i\eta)$ with η=0.01.



PANEL PROPERTIES

Stiffness Constants (GPa)

C11 = 13.2
C12 = 6.2
C23 = 6.4
C44 = 3.6
C33 = 29.0

Density = 1660 kg/m^3
Thickness = 11.4 mm

FLUID PROPERTIES

Speed of Sound = 1480 m/s
Density = 1000 kg/m^3

Figure 3. Geometry and panel properties for anisotropic GRP panel.

3.2 Transmission Measurements

Measurements were made with the panel fixed such that the plane of incidence cut the panel at various angles to the fibres; $\phi = 90°, 45°$ and $0°$. In each case the incident angle (θ) was varied from 0° to 60° in 1° steps. The results for 150.4 kHz are shown in Figure 4 (points). These results show that the transmission loss does vary significantly with the plane of incidence with high loss present at incident angles greater than 30° when the plane of incidence is at 45° to the fibres. There are significant differences in the angular variation of transmission loss in the three cases. When the plane of incidence is the plane of transverse isotropy (Figure 4(a)) the velocities in the layer do not change with direction and therefore incident angle; pure compressional/shear waves propagate in this plane. In cases (b) and (c) wave velocities in the layer *do* change as the incident angle is varied and the transmission loss is correspondingly more complicated. In case (c) all waves within the layer are quasi-compressional/shear waves.

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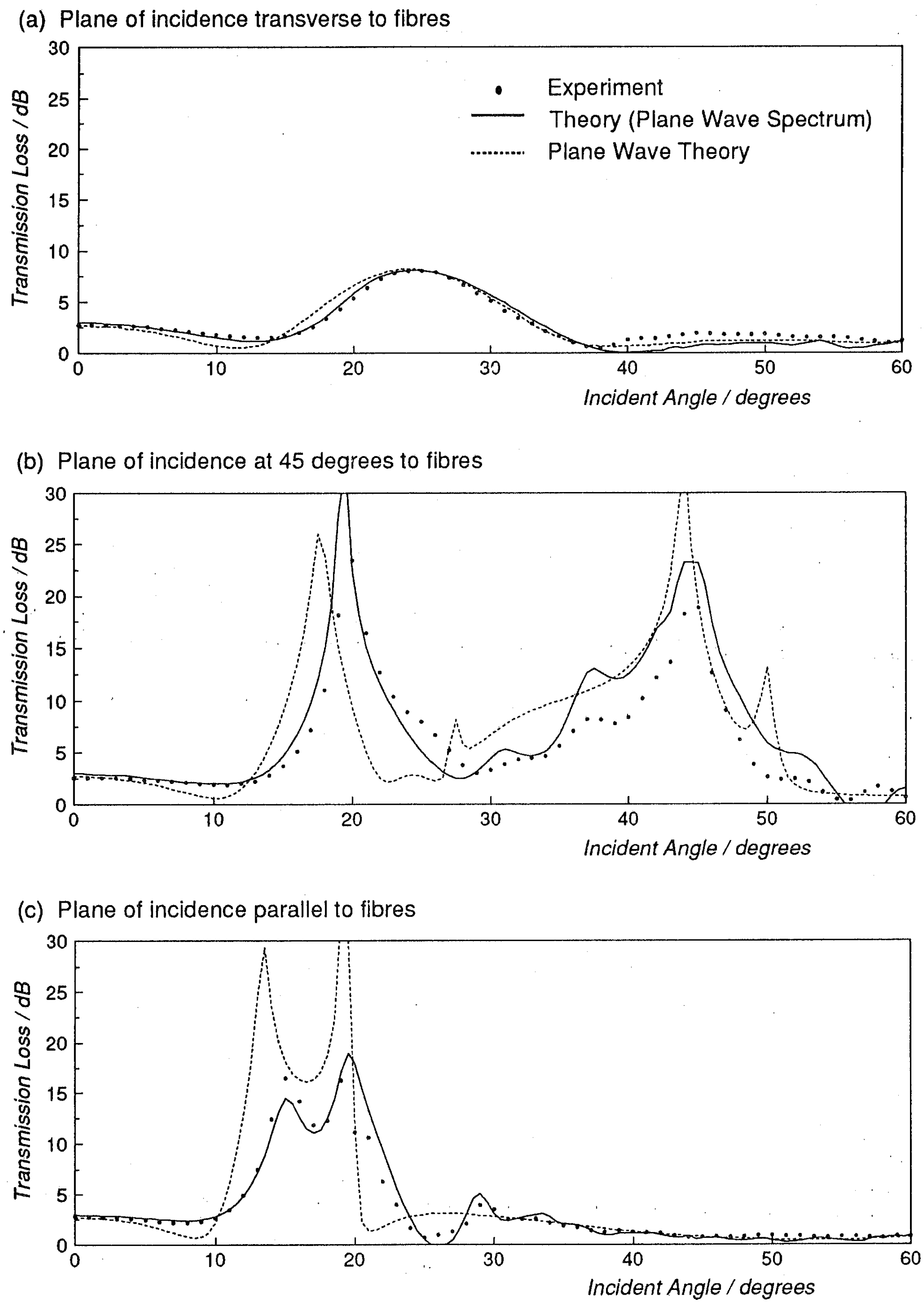

Figure 4. Transmission loss as a function of angle of incidence for a GRP uniaxial panel at 150.4kHz; (a) 90°, (b) 45° and (c) 0° to the fibre direction.

Figure 4 also shows theoretical predictions (dashed line) based on the theory of Skelton and James [6] for the transmission loss at the same angle of incidence. The results appear to be in reasonable agreement with the theoretical predications showing the same general forms for the three different planes of incidence. However, there are number of ways in which the theory and experiment do not agree in detail or quantitatively. For example the positions of the loss peaks are shifted in angle in Figures 4(b) and 4(c). In addition the high predicted losses are not observed for case (c).

Previous measurements on acoustically thin isotropic panels have shown excellent agreement with plane wave predictions [3]. However, measurements on acoustically thicker panels have been shown to differ significantly from plane wave theory [7]. These differences can be attributed to the fact that the measurements are not made with a plane wave but with a finite source and receiver at close range in the test facility. The effect of this on the measurements can be predicted by representing the incident field in terms of its plane wave spectrum and considering the effect of the panel on each component of the angular spectrum. The resulting field beyond the panel can then be evaluated by integrating over all of the plane wave components [7].

This technique has been adapted to investigate the effect of the incident plane wave spectrum on measurements of anisotropic materials, taking into account the components incident upon the layer at different angles (θ, ϕ); the total transmitted field is found by integrating over all the components, each with its own plane wave transmission coefficient.

The resulting predictions of transmission loss allowing for the plane wave spectrum of the source are also shown in Figure 4 (solid line). It can be seen that the inclusion of the plane wave spectrum in the calculations significantly improves the agreement with the measured transmission loss. In particular the loss peaks are seen to shift in angle to tie up much more closely and the loss peaks in case (c) are reduced to similar levels to that observed experimentally.

Overall the agreement obtained indicates the potential of the experimental system for making experimental measurements and also confirms the validity of the theoretical model.

5. WEDGES

The use of wedges as a lining for anechoic chambers is widespread in airborne acoustics and common in underwater acoustics for tank facilities. In the latter case wood, polymer or polymer/filler composites are often used. Despite this common use there is little in the way of measurements of the performance of wedges, especially at oblique incidence. Here we describe some initial results of an experimental programme to investigate one material with surface wedges.

The wedges tested were manufactured at DRA (Holton Heath) and were constructed from a polyurethane with added fillers. The wedges were 33.5mm long with a pitch of 22.5mm as shown in Figure 5. In order to construct a large enough sample for testing, four wedged tiles each approximately 0.45m square were held together in a metal frame and suspended from the rotation stage. There was some evidence of variability in the results resulting from the join between the tiles and variation in individual tiles. This was evident, for example, when the wedges were rotated through 90° from vertical to horizontal, as the part of the panel on the acoustic axis did not remain the same.

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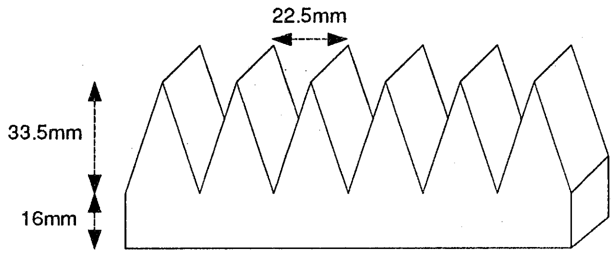

Figure 5. Geometry of panel with wedges.

Echo reduction measurements were made by recording both the reflected signal from the panel and also a reference signal without the panel present. For oblique incidence a bistatic configuration was used with the hydrophone rotated away from the acoustic axis so as to lie in the direction of the specular reflection.

Figure 6 shows a set of results obtained for angles of incidence up to 65° for a range of frequencies up to 60kHz. In this case the panel had water backing. The results clearly show peaks in the echo reduction at about 10kHz and 20kHz for low angles of incidence, as well as a higher loss of about 30dB around 40kHz. The loss does not vary significantly at low frequencies for angles below 20°. It is only for angles of incidence of 45° and above that the loss is significantly reduced. The experimental results for normal incidence correspond to the theoretical predictions of Figure 6 in the paper by Willis and Bedding in this volume [2]. Overall the results appear to be in good agreement with the prediction of the model.

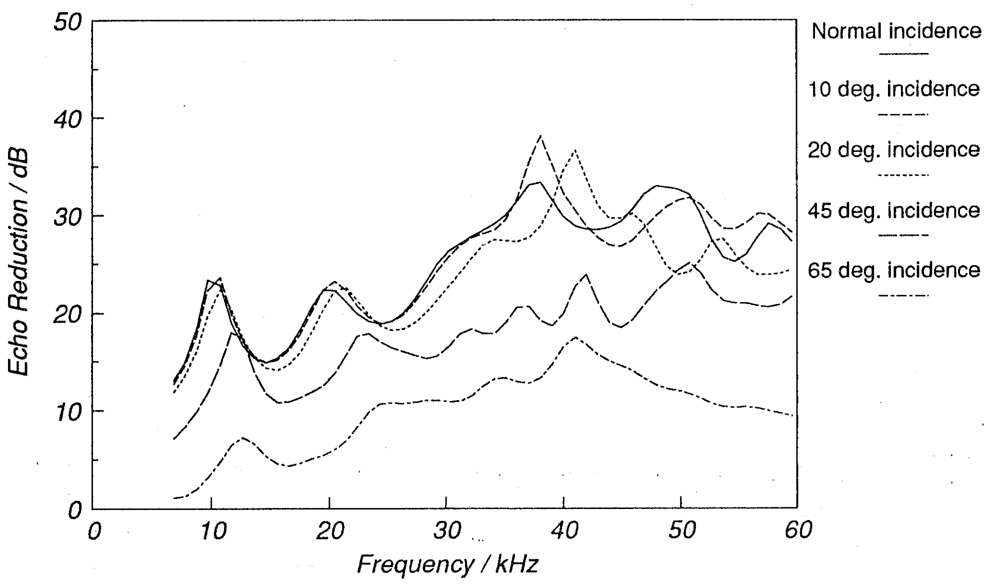

Figure 6. Echo reduction of test panel with wedges as a function of frequency for various angles of incidence; wedges vertical with water backing.

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Figure 7 compares similar results for cases when the wedges were vertical and horizontal for an angle of incidence of 45°. Since the panel is rotated about a vertical axis parts of the wedges would lie in the geometric "shadow" of another wedge in the former case. The results show, however, that the echo reduction is relatively insensitive to the wedge orientation in this case.

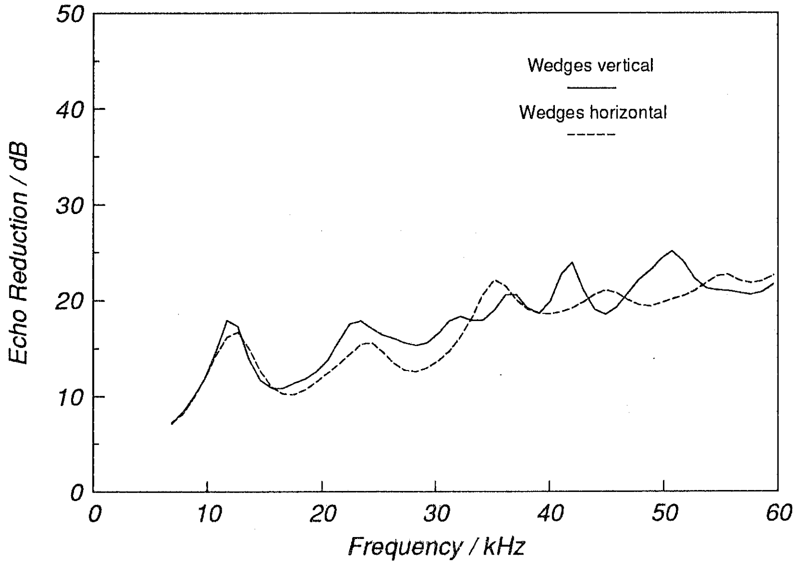

Figure 7. Echo reduction of test panel with wedges at 45° angle of incidence; comparison of results with wedges vertical (—) and horizontal (- - -).

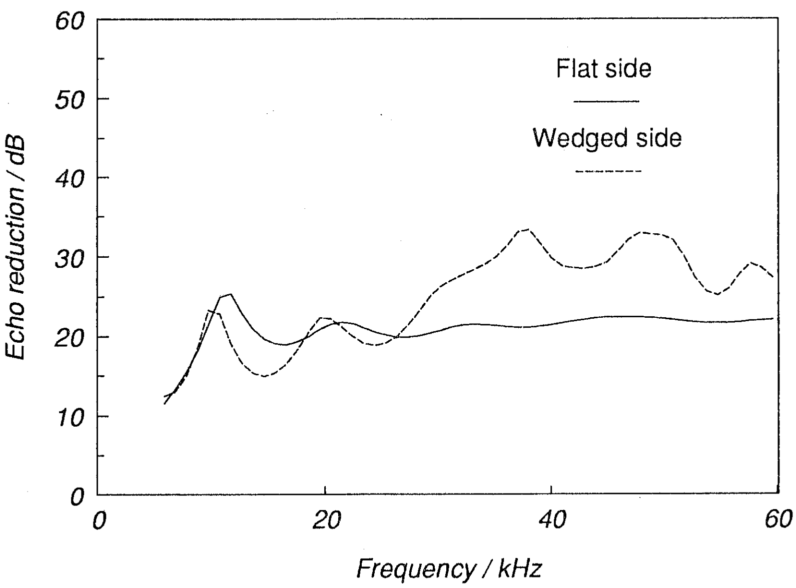

Figure 8. Echo reduction of test panel with wedges at normal incidence; comparison of reflection from wedges (- - -) and from flat surface of panel (—).

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For this particular set of measurements a reference sample of material without wedges was not available for comparison with the wedges. In order to gain a better understanding of the effectiveness of the wedges the echo reduction observed with the wedges facing the acoustic source was compared with that observed when the flat "back surface" faced the source. The results of this comparison are shown in Figure 8. This shows that the base material from which the wedges are made is an effective anechoic itself, as it is well matched to water and highly attenuating. Thus below 30kHz, rather surprisingly, the wedges do not appear to impart much extra benefit. It is only at higher frequencies that they improve the performance by producing a gradual impedance change from water to material and thus reduce the front surface reflection.

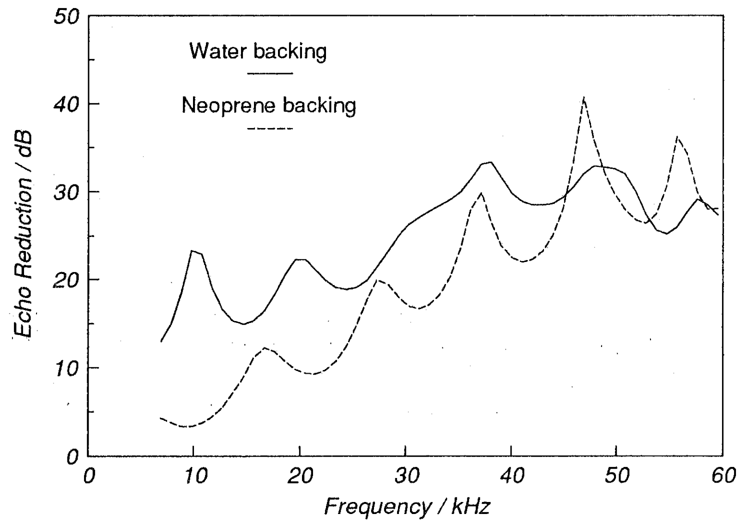

Figure 9. Echo reduction of test panel with wedges at normal incidence; comparison of reflection from wedges with water termination (backing) (—) and pressure release termination (- - -).

Figure 9 illustrates the effect of terminating the wedged panel with a pressure release backing made from closed cell neoprene rather than the normal water backing. The reduced echo reduction resulting from the significant reflection from the pressure release backing is evident at most frequencies. In addition the phase inversion at the pressure release back surface results in the loss maxima being shifted in frequency when compared with the water backed case.

6. CONCLUSIONS

The results presented show that laboratory based facilities can be used to make effective and informative transmission loss and echo reduction measurements on complex materials. The results obtained confirm, in general, the predictions of theoretical models. For low loss materials the non plane wave nature of the source can significantly affect the results; it is, however, possible to theoretically estimate the influence of the plane wave spectrum of the source in these cases. The results show that the transmission behaviour of anisotropic materials can vary significantly with the plane of incidence. The measurements on wedges indicate that their performance can be complex with a significant variation with frequency, angle of incidence and termination.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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