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THE USE OF IMPULSIVE EXCITATION TEST METHODS TO EVALUATE THE PERFORMANCE OF UNDERWATER VISCOELASTIC ACOUSTIC COATINGS

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1. INTRODUCTION

1.1 Underwater acoustic coatings have many uses in both military and civilian applications. Frequencies of interest span many decades stretching from a few tens of Hertz to greater than 1 MHz. The majority of these coatings are based on a polymeric matrix, and as a result, the acoustic properties are frequency and temperature dependent. Mathematical models have been developed to predict the acoustic performance of complex multilayer systems but the coating designer also needs accurate measurements, made under controlled laboratory conditions, to validate his computer predictions.

1.2 In principle, measurements at high frequencies are straightforward, wavelengths are short, diffraction effects are minimal and adequate time domain resolution can be achieved in small test tanks. However at low frequencies measurements become more difficult. Diffraction effects cannot be ignored and in restricted volumes of water multipath reflections make it difficult to isolate the signals of interest. Whilst measurements can be carried out under free field conditions, sea trials are expensive and they require expensive test panels of large lateral dimensions to minimise diffraction effects. Sea state conditions and temperature are beyond the control of the operator and such trials are only used to validate the performance of fully optimised coatings.

1.3 At ARE (HH) a number of methods for evaluating coating performance have been developed, both for free field and laboratory measurement. This paper will confine itself to two laboratory techniques. The first of these is the pulse tube and the second is a high frequency parametric array.

2. PULSE TUBE MEASUREMENT

2.1 During the second world war the Germans realised that submarines could be camouflaged against an active sonar threat by coating the outside of the submarine with an "anechoic" coating. These early, resonant cavity, coatings were code named "Alberich" after a mythological dwarf whose magic hat rendered him invisible. In order to evaluate the performance of these coatings the Germans developed the first pulse (or impedance) tubes. These were simply long steel tubes with a projector (used in the send/receive mode) at one end, with the sample introduced at the other end. By measuring the signal reflected from the sample and comparing this with the signal reflected from a perfect reflector (the air interface at the top of the tube) it was possible to calculate the reflection coefficient or echo reduction (ER) for the sample.

2.2 The major advantage of the pulse tube is that it behaves as an acoustic wave guide. Below the cut-off frequency (determined by the diameter of the tube) only a plane compressional wave will propagate[1]. Provided the steel walls are massive the effects of tub wall compliance are negligible[2]. The temperature of the water in the tube can be controlled by the addition of a cooling/heating jacket and the tube can be pressurised to simulate deep immersion.

2.3 Figure 1 shows a schematic diagram of a typical pulse tube configuration. As well as measuring the ER of samples it is also useful to be able to measure the transmission (or insertion) loss (TL). At low frequencies all materials that are thin compared to a wavelength will have low reflection coefficients (high ER) because most of the incident energy penetrates the sample (ie TL is low). This will happen irrespective of whether the sample is designed as an absorber or not. By summing the transmission and reflection coefficients a measure of the energy dissipated by the sample can be deduced. With a lossless sample the sum of these two coefficients will of course be unity. The terminating cone at the top of the tube is present to absorb any energy transmitted through the sample to prevent it being reflected from the top of the tube and being re-transmitted back through the sample to interfere with the signal of interest reflected from the front face of the sample. This effect poses the first limitation on the low frequency performance of the tube. It is not possible to manufacture a termination that has adequate absorption at very low frequencies and interference between the signal reflected from the front face of the sample and the signal reflected from the top of the tube results in a measured ER that is a composite answer for the sample and cone combined. This effect can become a major problem at frequencies lower than 1 kHz.

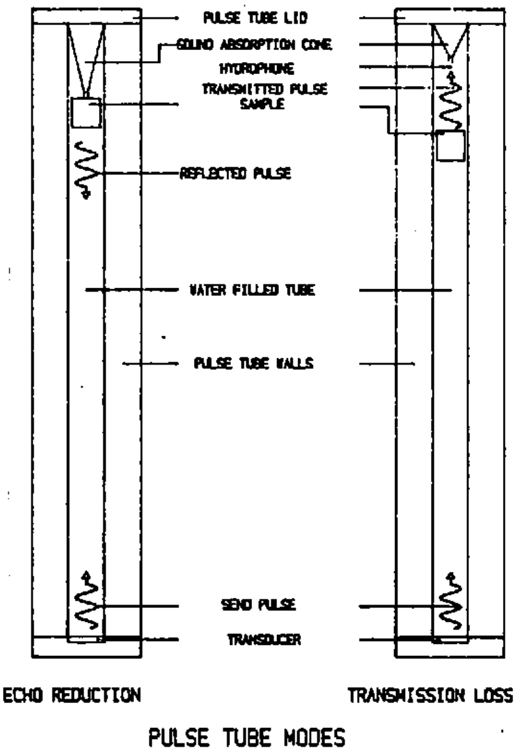

Figure 1. Pulse tube schematic diagram.

2.4 In order to overcome this limitation the measurement technique has been modified. Hydrophones have been embedded in the wall of the tube at points 1/3, 1/2 and 2/3 along its length. The sample is suspended on a nylon monofilament thread just below the top hydrophone ie some distance down the tube. The absorbing cone is dispensed with so that the reflection from the top of the tube is clearly defined. The transducer at the bottom is now only used as a projector. The top hydrophone is used to monitor the signal transmitted through the sample whilst the bottom hydrophone monitors the incident and reflected signals. The signals from these two hydrophones are sampled with 16 bit precision and time domain averaging is used to improve the signal to noise ratio. By using a 1/10th cosine taper window arbitrarily positioned on the traces the incident, reflected and transmitted components can be isolated from the bottom and top hydrophone signals. After transformation to the frequency domain the transmission loss and echo reduction can then be computed, the need for blank measurements from a perfect reflector is eliminated and since the ER and TL values are derived from the same incident signal, accuracy and consistency are greatly improved.

3. EXCITATION SIGNALS

3.1 When acoustic measurements are made in pulse tubes or small water tanks high time domain resolution ie signals that are short in duration is required to enable incident reflected and transmitted signals of interest to be isolated from unwanted multipath reflected and diffracted signals. With traditional techniques using tone bursts the reflection coefficient was calculated by dividing the peak amplitude in the reflected tone burst and comparing it with the peak level of the signal reflected from a perfect reflector eg an air interface. Figure 2 illustrates the limitations imposed by this method.

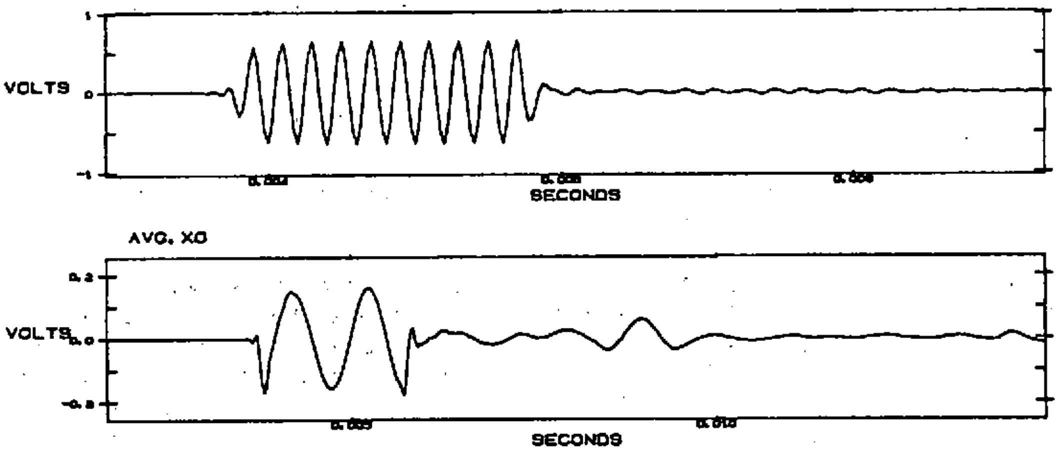

Figure 2. High and low frequency tone bursts.

3.2 Figure 2 shows high (≈5 kHz) and low (≈1 kHz) frequency incident and reflected tone bursts measured in the ARE pulse tube. It can be seen that for the high frequency signal, steady state conditions have been achieved for both incident and reflected components and a value for the reflection coefficient can be computed. However for the low frequency signal, steady state conditions have not been achieved for the reflected component. Incident and reflected signals are starting to overlap and it is becoming difficult to separate the two components. The reflected signal cannot be used to give a meaningful answer for the reflection coefficient of the sample and the low frequency limit of resolution for the tube has been reached. Apart from limited low frequency resolution, a tone burst only yields an answer at one frequency therefore it is necessary to repeat the experiment at many other frequencies to obtain a wide frequency range plot of acoustic performance.

3.3 Acoustic coatings of whatever type may be regarded as low pass, high pass or hand pass acoustic filters and the properties of interest eg ER or TL are fully defined by their impulse response in the time domain or by their transfer function in the frequency domain. Modern signal processing techniques allow data to be sampled with high precision (16 bit) at high sampling rates. FFT techniques applied to the resultant time series allow easy transformation from time to frequency and vice versa whilst polynomial waveform synthesizers allow complex wave forms used to excite the sample to be generated easily.

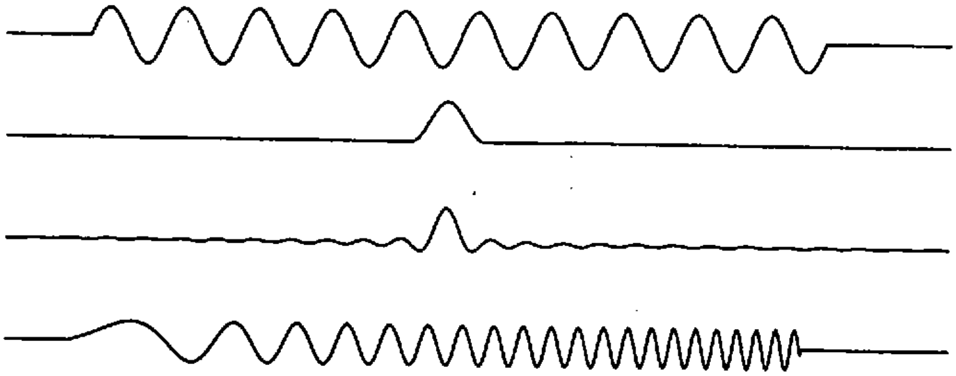

Figure 3. Various time domain excitation signals top to bottom tone burst haversine, sinx/x. chirp.

3.4 Figure 3 shows a number of time domain signals that have been used for performing measurements at ARE (HH) and Figure 4 shows their corresponding spectra. The limitations of the tone burst have already been discussed and this method is no longer used. The haversine (0.5(1-cosϕ) has very high time domain resolution allowing diffracted or multi-path reflections to be isolated from the signal of interest and this excitation source is preferred for pulse tube and small tank measurements. Its spectrum has the characteristics of a low pass filter. The sinx/x function has the advantage that more energy can be projected into the water, whilst the time domain resolution is relatively poor its spectrum is an ideal bandlimited boxcar. the chirp (swept sine wave) allows even more energy to be coupled into the water but again time domain resolution is poor. However these two latter signal types have proved useful in sea trials where multipath reflections are not a problem.

4. PRACTICAL CONSIDERATIONS

4.1 Figure 5 shows the incident signal and the signal reflected from an absorbing cone in a 7.5 m long pulse tube, the incident signal being a 5 kHz haversine impulse. It can be seen that the reflected signal has been considerably stretched in time, distinct components from the front and rear surfaces of the cone are apparent indicating strong resonant behaviour in the frequency domain. Between the incident and reflected signals a number of small perturbations are apparent, these are caused by reflections from discontinuities in the tube walls resulting from the insertion of the side mounted hydrophones and other defects unfortunately built into the tube at manufacture.

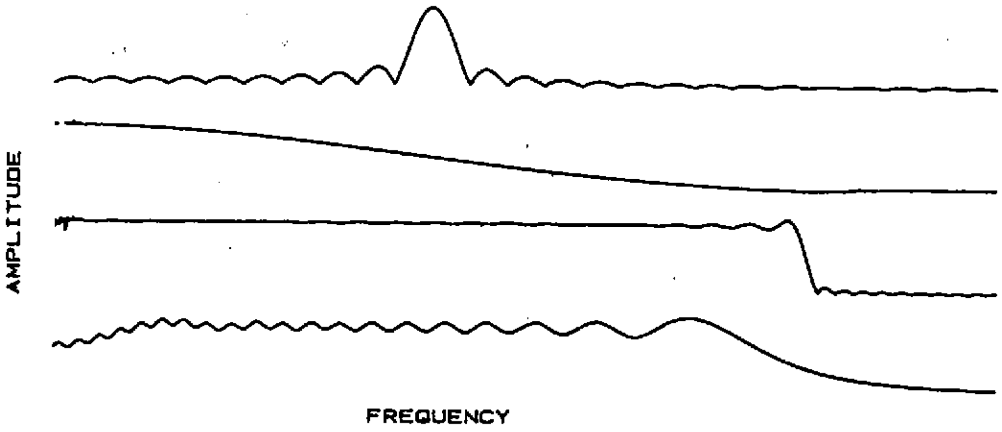

Figure 4. Spectra of various excitation signals top to bottom tone burst, haversine, sinx/x, chirp.

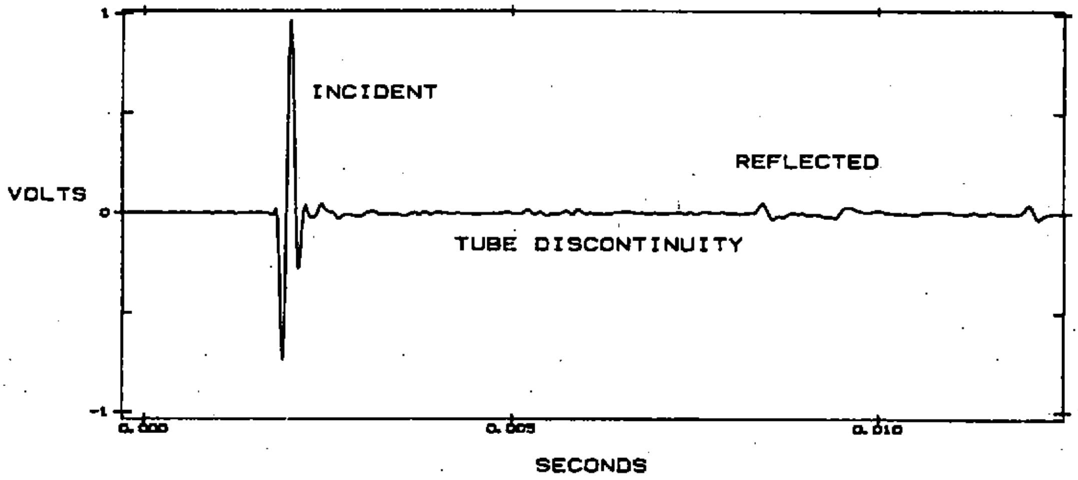

Figure 5. Incident and reflected signal from terminating cone in 7.5 m tube, 5 kHz haversine excitation signal.

4.2 Not immediately apparent in Figure 5 is a very low level signal travelling in the steel wall of the tube (it is just visible as a slight ripple prior to the arrival of the incident signal). Energy from the water born wave is continuously coupled into the steel wall where it travels, virtually undamped, up and down the tube at ≈5000 m/s. All these various artefacts have been analyzed and found to be high pass filtered attenuated facsimiles of the incident signal. Some of them cannot be eliminated using current signal processing techniques and they set the limit on the dynamic range of the tube. At 5 kHz the present dynamic range is >70 dB whilst at 10 kHz this falls to ≈25 dB. Work is currently underway to improve this high frequency limit to an acceptable level (≈40 dB). However in spite of these limitations the use of an impulsive excitation source has improved accuracy, dynamic range and frequency bandwidth dramatically. The high time domain resolution resulting from the short (≈250 μs) impulsive signal has allowed the various artefacts described above to be isolated and analyzed, something which is virtually impossible to envisage using tone burst excitation.

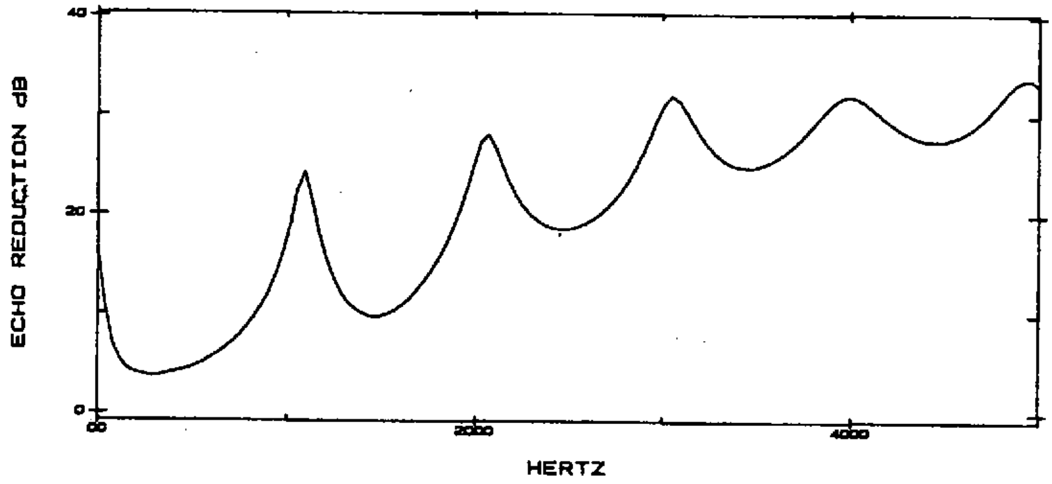

Figure 6. Echo reduction of viscoelastic terminating cone.

4.3 Acoustic coatings have varying levels of performance. Although the designer may strive for the highest levels of performance, increased sophistication may be overridden by other important parameters such as cost, weight, ease of application, and hydrodynamic considerations. Hence the coating designer must be able to measure both high and low levels of performance accurately. Figure 6 shows the excellent ER performance of a terminating cone used in the pulse tube computed from the time domain record in Figure 5. The time domain window used has set a lower frequency limit of ≈250 Hz. The strong resonant behaviour associated with cones and wedges is clearly visible and the increased viscoelastic damping associated with polymers operating in their main chain transition region manifests itself in the gradually reducing Q of the higher frequency resonant peaks. Figure 7 shows the ER and TL of a 6 mm thick steel plate (hatched line) compared with the predicted values (solid line). Agreement is good between ≈500 Hz and 6 kHz. The lower limit was set by the time window used and the higher limit was influenced by the tube discontinuities mentioned previously. Between 500 Hz and 6 kHz summation of the transmission and reflection coefficients yielded a value of 1.08. Clearly some systematic errors still exist but this result is considerably better than anything that was achieved using tone burst excitation.

5. HIGH FREQUENCY PARAMETRIC ARRAY

5.1 As mentioned previously a pulse tube will only support a plane compressional wave below cut-off. However above cut-off radial modes can propagate and since these effectively bounce off the side of the tube as they propagate up the tube they arrive at a fixed hydrophone site delayed in time relative to the normal mode.

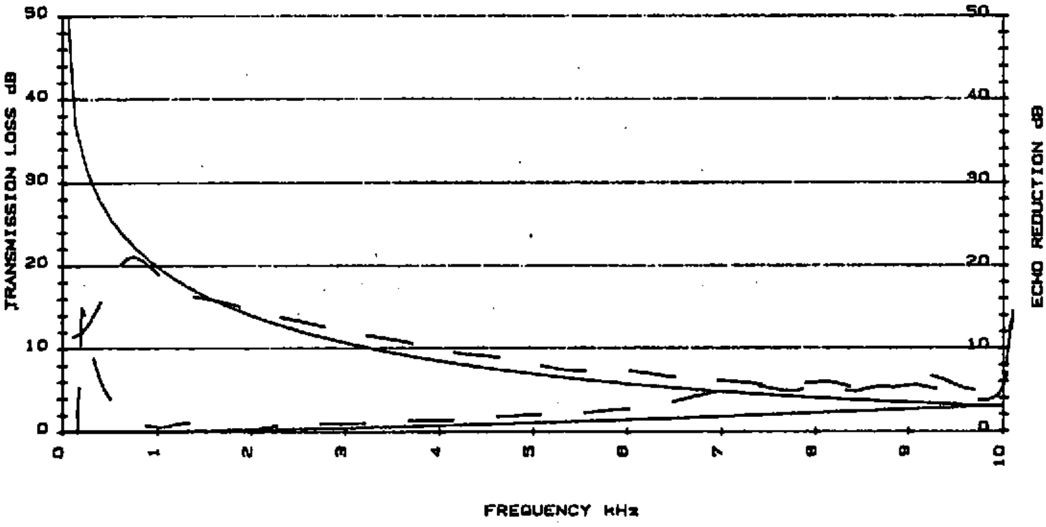

Figure 7. Theoretical and experimental ER and TL performance of 6 mm thick steel plate.

Since these radial modes have delays which are too short to allow windowing out, high frequency pulse tube results tend to be difficult to interpret.

5.2 A much more satisfactory technique at higher frequencies >10 kHz is to use a parametric array. Again the excitation signal used to modulate the primary is impulsive. In this case a 40 kHz triangular wave form, (a single cycle of a triangular wave with its start phase shifted by 90°) is used rather than a haversine, in order to enhance the high frequency content of the secondary signal.

5.3 Figure 8 shows a tone burst (≈100 kz) incident on two 6 mm thick Perspex plates separated by a 25 mm water gap. Multiple resonances between the two plates results in a complex reflected signal. Quite clearly steady state conditions have not been reached and it is not possible to detect whether the reflected signal contains low level diffracted and reflected components.

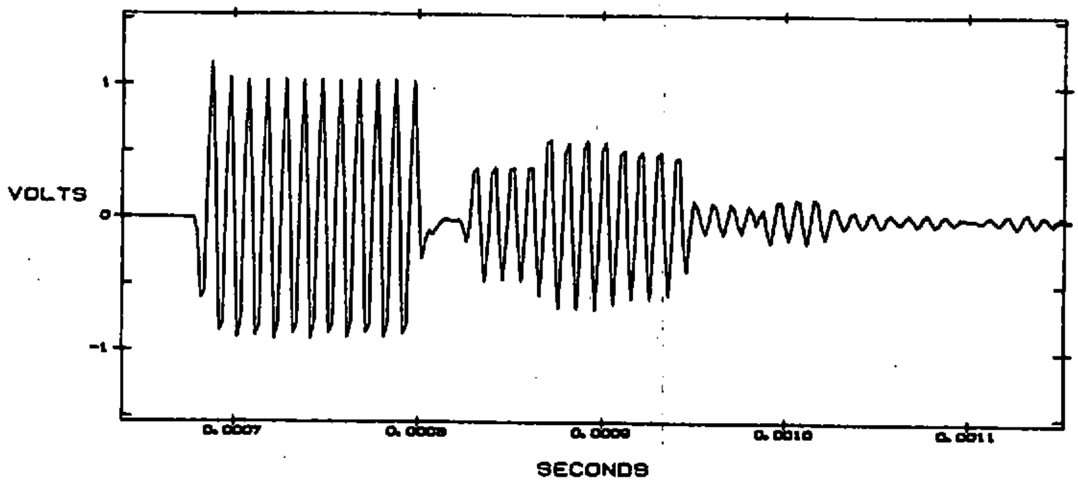

Figure 8. Tone burst reflected from two separated Perspex sheets.

5.4 Figure 9 shows the incident and reflected signals from the two Perspex sheets when the 1 MHz primary is modulated with a triangular wave form. the structure of the reflected signal is clearly seen as a series of decaying multiple reflections.

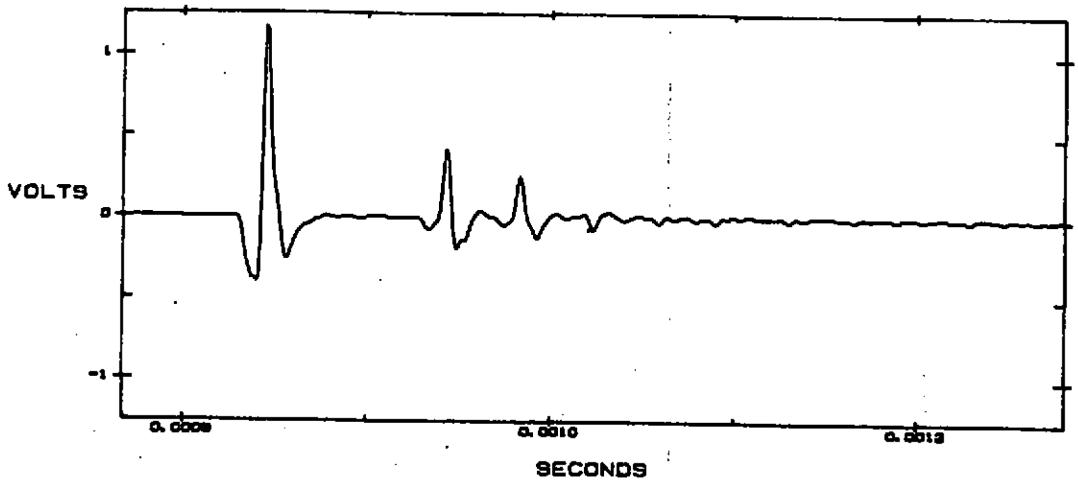

Figure 9. Haversine impulse reflected from Perspex sheets.

5.5 Using a 1/10th cosine window to separate the incident and reflected components and correcting for spherical radiation effects yields the result for echo reduction (hatched line) shown in Figure 10. The theoretical result is shown as a solid line. Agreement in the range 10 kHz to 100 kHz is good. The discrepancy between experiment and theory in this case is almost certainly due to a lack of accurate information on the loss factor of Perspex in this frequency range.

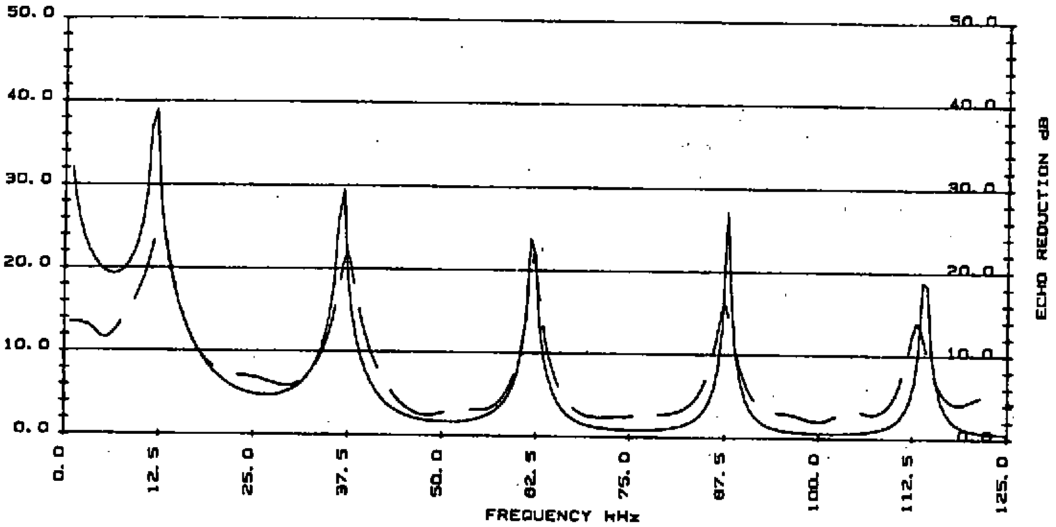

Figure 10. Theoretical and experimental echo reduction for two 6 mm Perspex sheets 25 mm apart.

6. CONCLUSIONS

The use of impulsive excitation is applicable to both low frequency pulse tube measurements and high frequency parametric array measurements. A single 5 kHz Haversine yields a bandwidth of 10 kHz in the pulse tube and a 40 kHz triangular waveform yields a bandwidth from 10 kHz to 250 kHz in the parametric array. Although the impulsive method yields low sound pressure levels time domain averaging can greatly enhance the signal to noise ratio. The high time domain resolution can greatly improve the ability to discriminate against and identify the source of unwanted signal components resulting in a much improved dynamic range.

7. REFERENCES

[1] L E KINSLER, A R FREY, A E COPPENS, J V SANDERS "Fundamentals of Acoustics", J Wiley & Sons, ISBN 0-471009410-2 1982.

[2] M C JUNGER "Wave Motions in some Composite, Porous and Layered Media", J Acoust Soc Am 88(1), July p 368-373 1990.