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PREDICTION OF TIME AND FREQUENCY DOMAIN PERFORMANCE OF PIEZOELECTRIC POLYMER TRANSDUCERS

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INTRODUCTION

Ultrasonic inspection techniques for a variety of materials and structures are conveniently carried out using a water coupling medium. This might be accomplished either with a water jet impinging on the sample to be studied or indeed by the use of a scanning device based on a water bath. Numerous materials and structures have been examined in this way and the recent trend is towards higher and higher resolution made possible by high frequency wide bandwidth transducers. The use of conventional ceramic materials in these applications leads to a problem in the construction of transducers in that: (a) the ceramic crystal has to be machined to very small thickness dimensions; (b) the acoustic impedance is very large compared with that of water, leading to a poor transmission and reception efficiency; (c) very often an extremely narrow beam of ultrasound is required necessitating a focused transducer and this is even more difficult to achieve using the hard and brittle ceramics.

An alternative approach is to employ materials such as polyvinylidene fluoride (PVDF) whose mechanical properties lend it well to the production of self-focusing transducers, as well as the ability to operate at very high frequencies. PVDF is known to be much less efficient than ceramics such as lead zirconate titanate (PZT), however, in comparison work for high frequency wide bandwidth devices it is very often found that the reduction in 'go and return' sensitivity is only some 6 to 10 dB and well within the acceptable range for the ease obtained in terms of system design and operation [1].

An even more promising development over recent years is the discovery of much higher activity from copolymers of, for example, trifluoroethylene (TrFE) and vinylidene fluoride (VDF). Again, in making comparisons for high frequency wide bandwidth operation, this material is within a dB or so of the 'go and return' sensitivity of wide band PZT-based transducers [1].

Mathematical models of transducers based on ceramic materials have been existence for a long time and these are very useful in the design stage, allowing the transducer manufacturer to examine numerous alternatives using a small computer and enabling him to arrive at an optimum design without the need for a lengthy process of experimentation [2]. However, if these existing models are used to attempt to assist the design of polymer based transducers, it is found that the marked differences in the characteristics of polymers lead to very imprecise models of transducer performance. We have therefore investigated the use of a slightly more complex model in this application and the results of this are presented in this paper. Our approach has been based on the pulse echo use of ultrasound and the outputs from the computer model provide time domain and frequency domain information on the echo produced from a plane surface in a water medium.

ABOUT THE MODEL

Of all the ultrasonic measurement systems, ultrasonic transducers are mainly used in two modes: pulse echo mode and pitch-catch mode. In the latter mode, the receive transducer and the ultrasound source are two different devices, while in the pulse echo mode, which is widely adopted in ultrasonic imaging systems, the same transducer transmits and receives ultrasound pulses, the received pulses forming the wanted image.

A simple pulse echo ultrasonic A-scan system is illustrated in Figure 1.

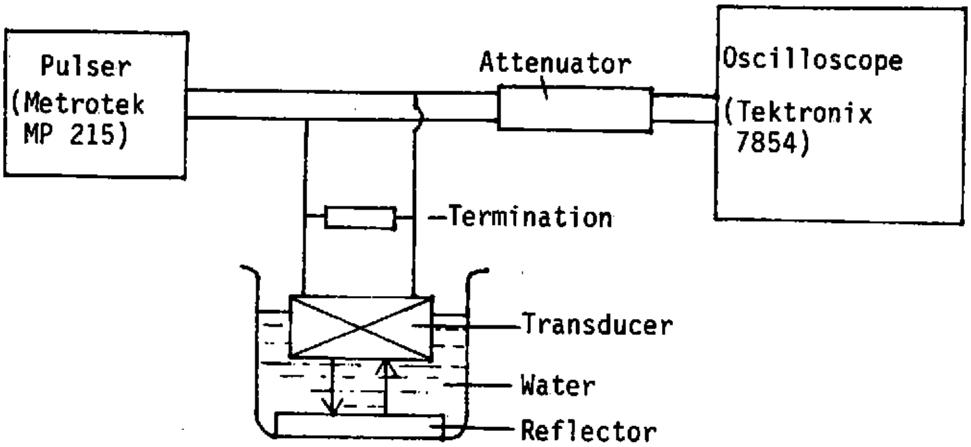

Figure 1 Experimental set-up for pulse echo testing

The system consists of a pulser, a transducer and a display unit or oscilloscope. Because of the high frequency (over 10 MHz for high resolution imaging systems), the connecting leads should be RF transmission cable and proper termination stubs must be employed at the ends of the cables to avoid ringing. To model this system we can divide it into several functional components or 'black boxes', as shown in Figure 2.

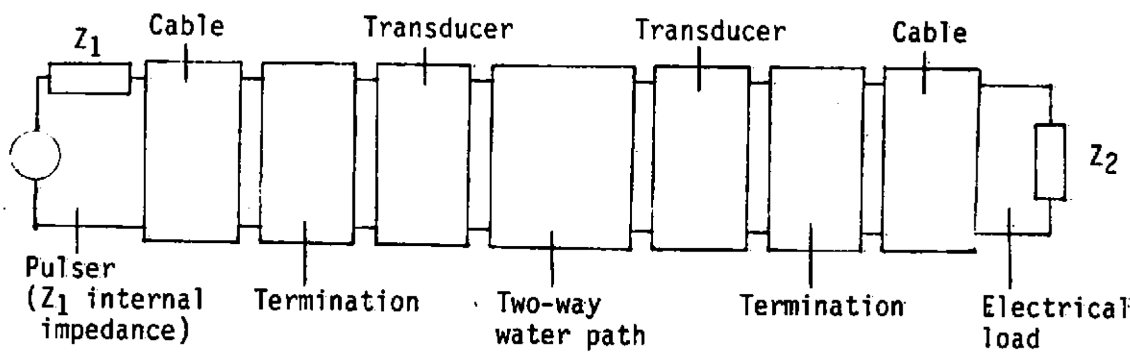

Figure 2 Equivalent circuit for the pulse echo testing system shown in Figure 1

Two-dimensional matrices may be derived for each of these 'black boxes'. The matrices for the cables and termination stubs can be derived directly from electrical network theory, the one for the transducer must be derived from the standard linear piezoelectric equations and the appropriate boundary conditions.

There is a considerable body of literature devoted to modelling the piezoelectricity in quartz and piezoelectric ceramic materials [3]. If we turn to materials such as PVDF, for example, then because of the higher internal mechanical and electrical losses, results for ceramic materials cannot be directly applied. Considerable amendment is needed in order to predict the performance of transducers based on these new materials [4].

Drive pulse

From experiments, we find that the drive pulse has a strong effect on the resulting echo pulses and the conventional method of assuming a Dirac delta function drive pulse for predicting time domain waveforms cannot give satisfactory results when the centre frequency of the transducer is over 10 MHz. At these high frequncies, the drive pulses of most commercial pulsers cannot be regarded as infinitely short. In fact, the duration of the drive pulse is usually of the same order as that of the echo pulse itself. The following mathematical functions have been used in our model to simulate the drive pulse of commonly used drive sources based on discharging a capacitor through an avalanche transistor switch:

$$V(t) = 0 \qquad \text{for } t < 0$$
$$V(t) = A\sin(\pi t/2T_1) \qquad \text{for } 0 \le t < T_1 \qquad (1)$$
$$V(t) = A\exp[-b(T - T_1)] \qquad \text{for } T_1 \le t < \infty$$

where A is the pulse height, T and T_1 are the pulse width and pulse rise time respectively, as defined in Figure 3; b is equal to $\ell_n[10/T - T_1]$. The simulation is based on the physical principles of the electrical circuit of the drive sources, as shown in Figure 4.

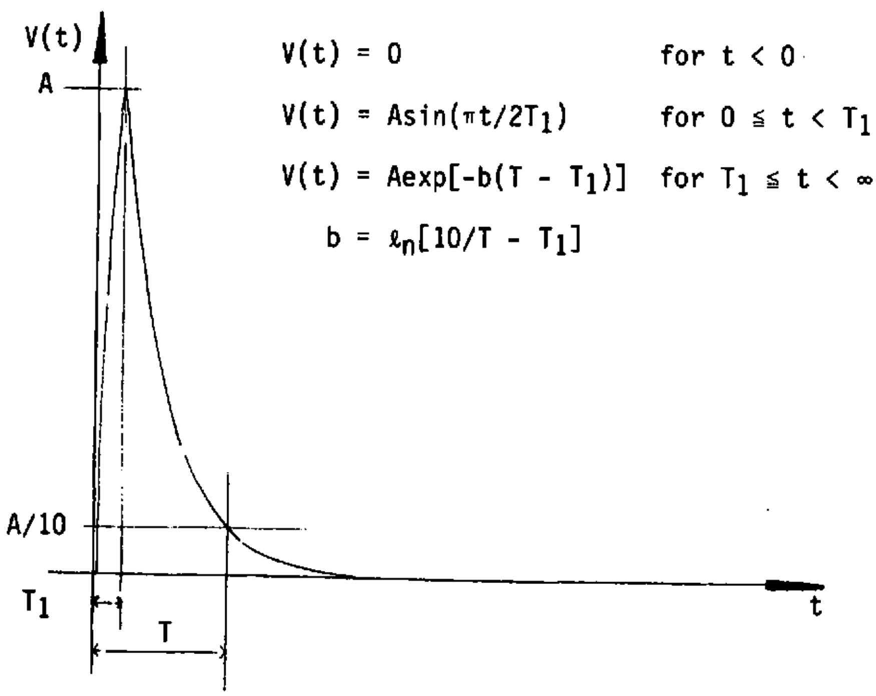

Figure 3 Drive pulse simulation

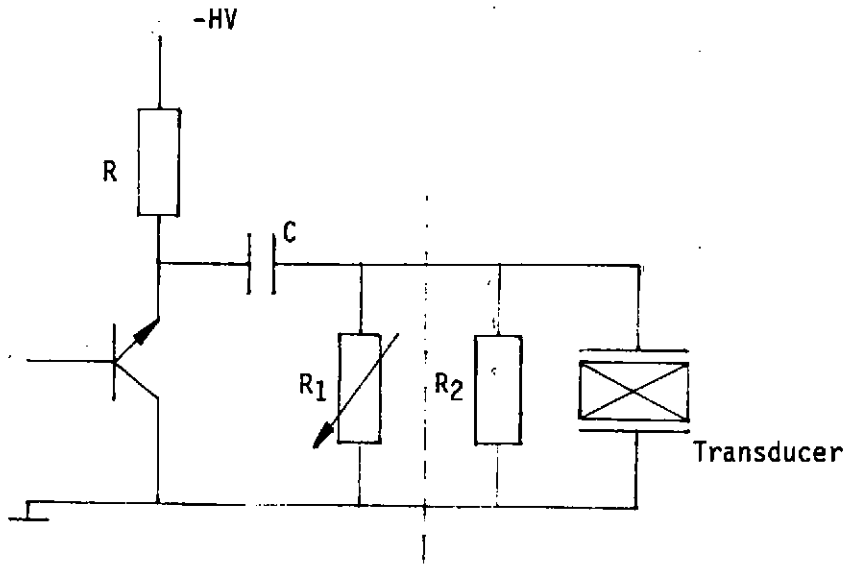

Figure 4 Circuit diagram of the output stage of a pulser connected to a transducer. R_1 is the resistor for damping control and R_2 is the transducer termination resistor

The rise time of the drive pulse is determined by the avalanche breakdown process of the transistors employed. This is a complicated process, but we have found it satisfactory to use a ¼ period of a sinusoidal waveform in the simulation. The fall time of the drive pulse is determined by a discharge process and we can use an exponential function to accurately simulate this. The actual parameters for the simulated functions are determined by the shape of the practical drive pulse employed during testing and are very easily changed in the model.

From the model we can establish a transfer function between the input drive pulse and output echo pulse. It is not difficult to derive the Fourier transform of Equation (1) and by multiplying this by the transfer function, we obtain the frequency spectrum of the predicted echo pulse. By using an inverse FFT calculation using this frequency spectrum data, the theoretical echo pulse can be obtained.

After pre-manipulating and re-arrangement of the complex theoretical expressions, we can use a microcomputer (BBC B+ with a 6502 second processor) to perform the calculation. It takes about five minutes for the computer to digitise the frequency spectrum expression and three minutes to perform the inverse FFT calcualtion.

Several other theoretical drive pulses have been included in the program in order to observe their effects on the resulting echo pulse, for example, a square pulse, a delta function, a half-period sinusoidal pulse, etc.

RESULTS AND DISCUSSION

The experimental set-up shown in Figure 1 was used to verify the model. The pulser used was a commercial device (Metrotek MP 215) which has variable amplitude and pulse shape controls. A polished stainless steel plate was used as a reflecting target. The attenuator was employed to reduce the peak voltage of the drive pulse to the oscilloscope input terminals. The oscilloscope employed was a Tektronix 7854 digital oscilloscope. During testing the transducers are placed very close to the target (approximately 5 mm distant) in order to reduce the effect of diffusion through the water medium.

Experimental echo waveforms are sampled and stored in the oscilloscope's memory. These data can then be transferred to the computer, where the frequency analysis can be performed.

Frequency domain comparison
Figure 5(a) gives frequency spectra for echoes obtained as described using a 25 μm thick PVDF film transducer with an active area 6 mm diameter, backed by air (acoustic impedance ≈ 0 rayls). It can be clearly seen that the agreement between experimental and theoretical data, represented by these two spectra is very good.

Time domain comparison
Figure 5(b) shows the drive pulse and echo waveforms for the same transducer described above (25 μm thick, air-backed). Excellent agreement is also apparent here.

Figures 6 and 7 provide further comparable results, but for a PVDF transducer 46 μm and 50 μm thick with air or PVDF backing. Again, we have very good agreement between experimental and predicted results.

From these comparisons, we can conclude that polymer transducers can work, as the model assumes, in a very pure thickness vibration mode, and the one-dimensional matrix model employed in our work can be used for performance prediction.

Effect of drive pulse
The rise time of the drive pulse used in the case of Figures 5(a) and (b) is 15 ns; if we change it to 30 ns, the result shown in Figure 8 is obtained. It is apparent that the rise time of the drive pulse has strong effect upon the resulting echo waveform.

Similarly, if we double the fall time of the drive pulse, we obtain the result shown in Figure 9. This time, the echo pulse shape is largely unchanged. In fact, the frequency spectrum of the resulting echo pulse is the product of two parts: the impulse response of the pulse echo system and the frequency spectrum of the drive pulse itself, as mentioned before.

Effect of backing impedance
Using this model, we obtain a family of curves depicting the relationship between the centre frequency of the echo pulse spectrum and the backing impedance. Figure 10 shows these curves. It is interesting to note that when the acoustic impedance of the backing material takes a value between 2 and 6 rayls, the centre frequency is strongly dependent upon the backing impedance. It is widely accepted that when the backing impedance is less than that of the piezoelectric element itself, the centre frequency can be predicted by considering a half-wavelength resonance inside the piezoelectric elements [3], i.e. we can use the following equation:

$$\lambda/2 = v/(2f) = \ell \text{ or } f = v/(2\ell) \quad (2)$$

where λ is the wavelength of the ultrasound wave inside the piezoelectric

(a)

(b)

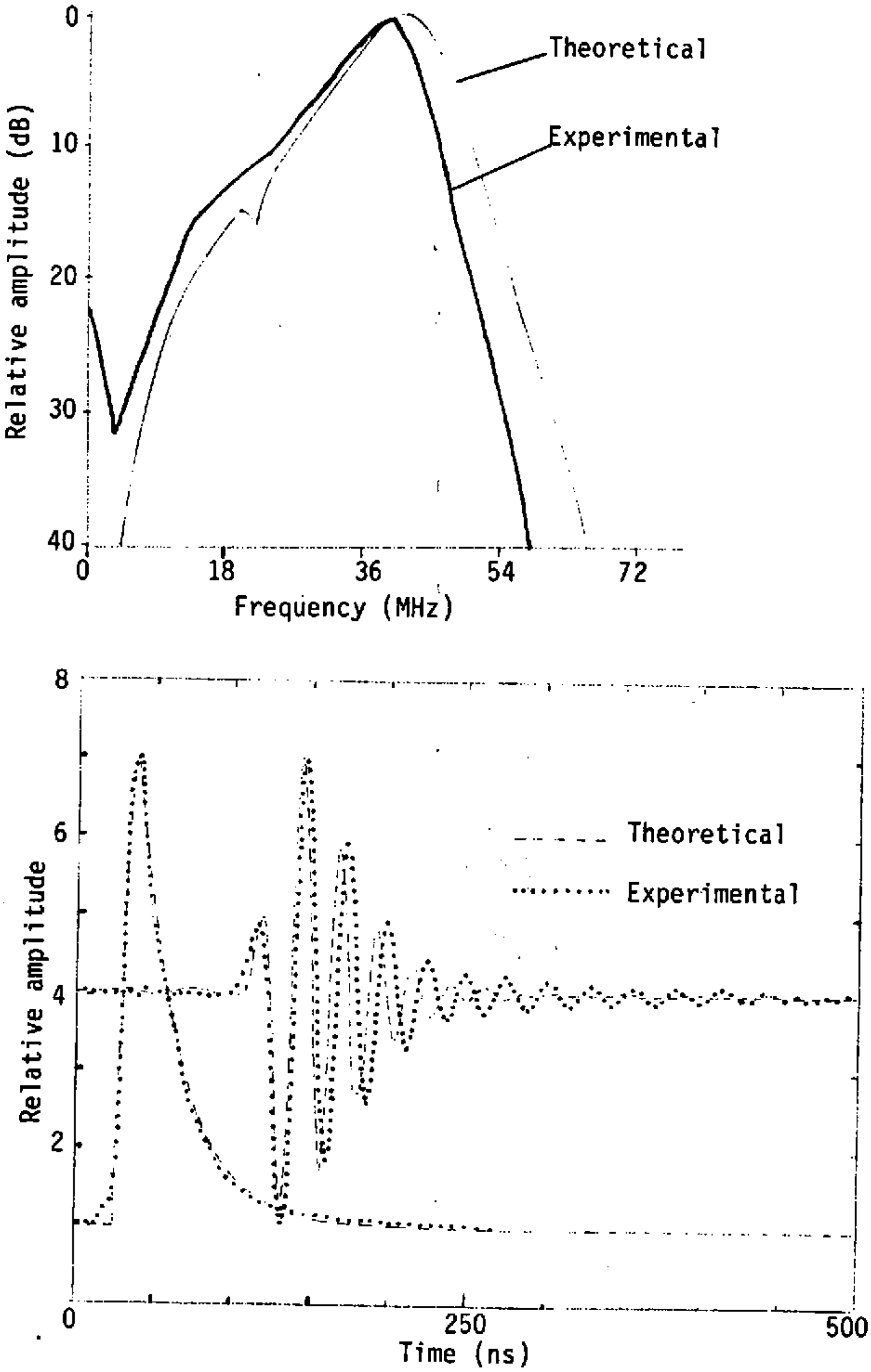

Figure 5 Comparison of (a) Theoretical and experimental spectral data; and
(b) Theoretical and experimental time domain data.

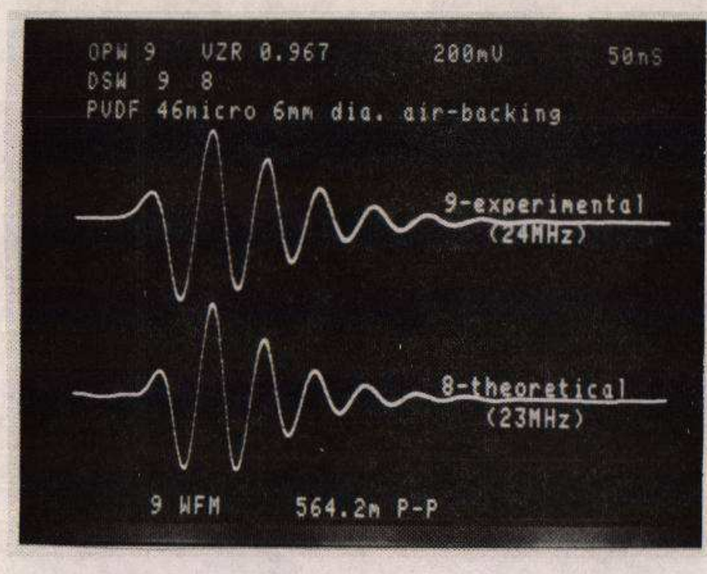

Figure 6 Time domain comparison of 46 µm, 6 mm diameter air-backed transducer

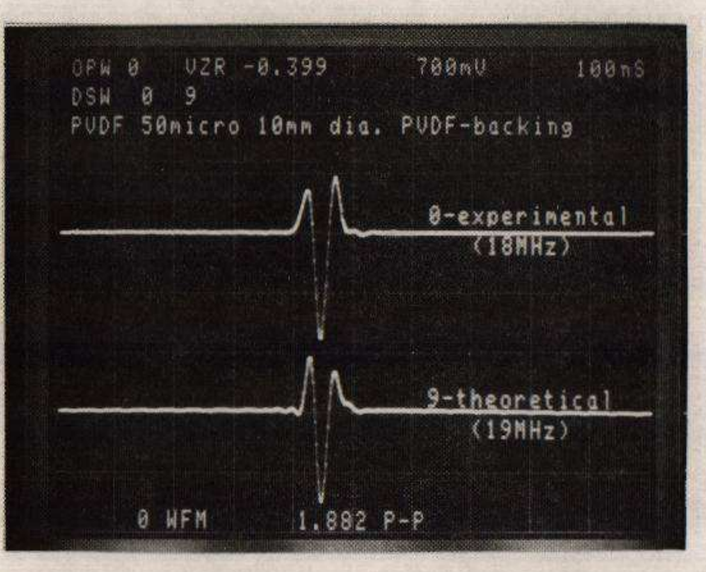

Figure 7 Time domain comparison of 50 µm, 10 mm diameter PVDF-backed transducer

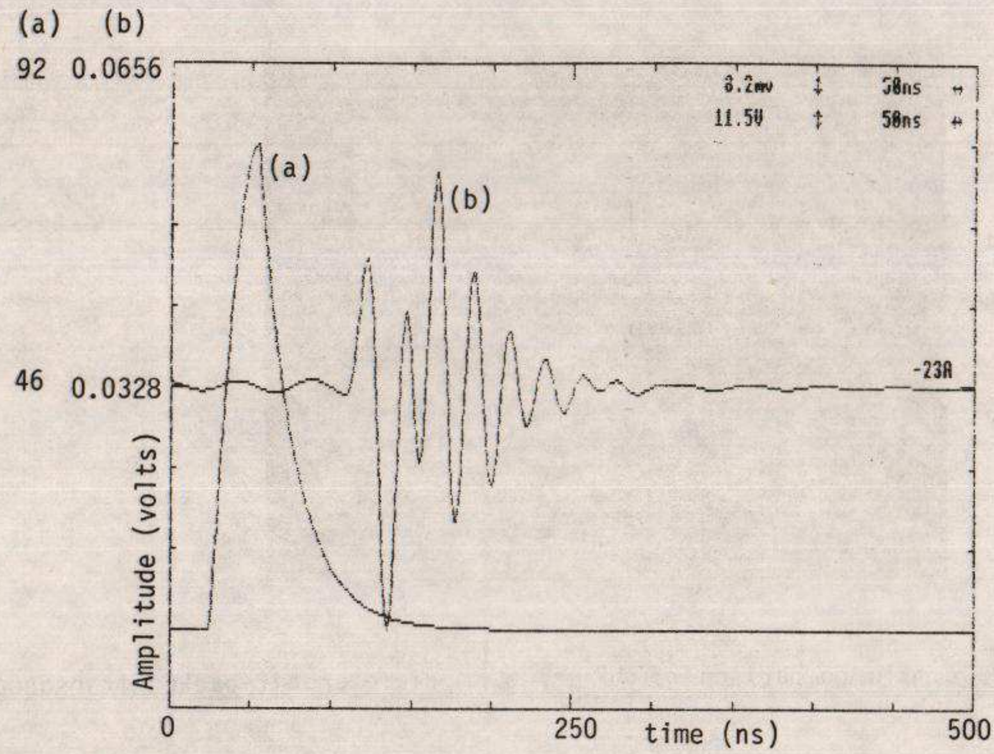

Figure 8 Effect of longer drive pulse rise time

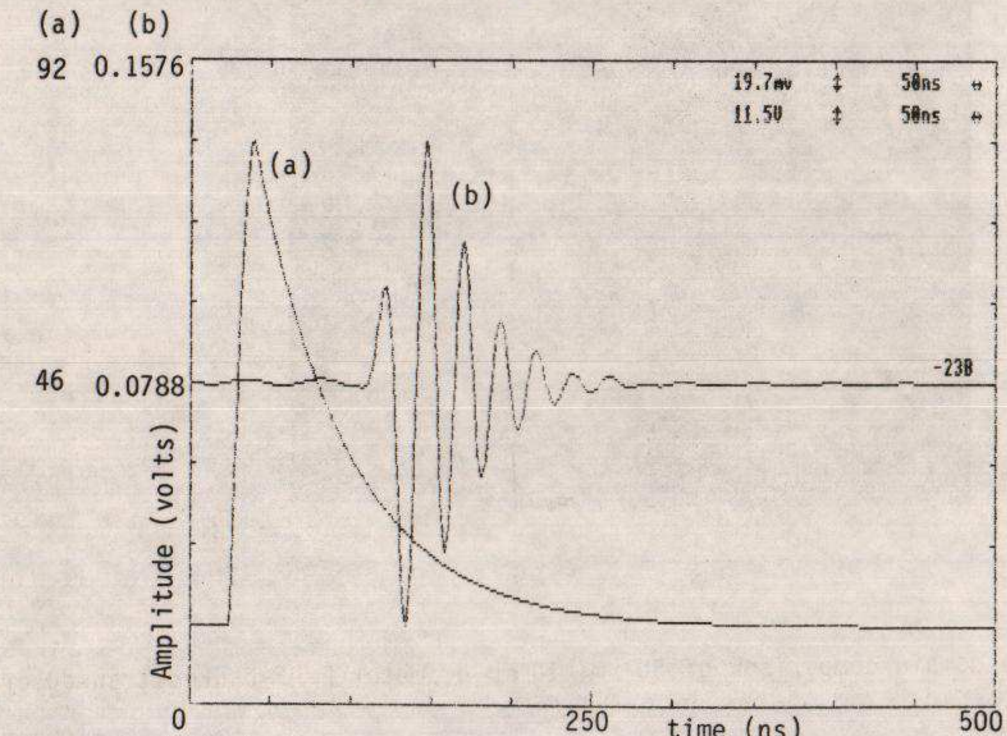

Figure 9 Effect of longer drive pulse fall time

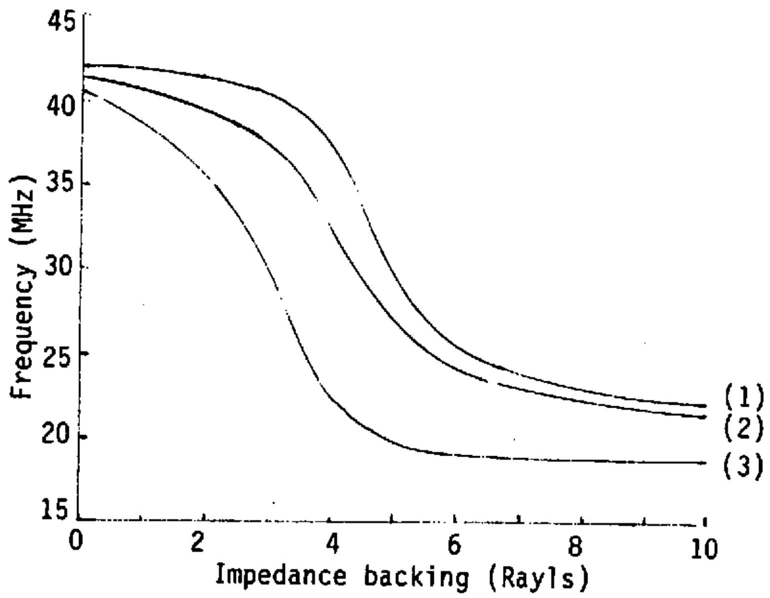

Figure 10 Calculated results of centre frequency versus backing impedance for a 25 μm thick PVDF transducer with 6 mm diameter active area driven by (1) a delta function pulse; (2) a half sinusoidal pulse with bottom width 15 ns, height 100 v; (3) a combination of sinusoidal and exponential waveform pulse with pulse width 80 ns, height 300 v, rise time 15 ns

element, f is the centre frequency, v is the acoustic velocity for the piezoelectric element, and ℓ is the element thickness.

Similarly, when the backing impedance is much larger than that of the piezoelectric element, the centre frequency can be predicted by considering a quarter wavelength resonance, the following equation holds:

$$\lambda/4 = v/(4f) = \ell \text{ or } f = v/(4\ell) \qquad (3)$$

These two simple relationships can be obtained by standing wave analysis [4]. However, they hold only when the backing impedance is very small or very large and the drive pulse is very short compared with echo waveforms. When the backing impedance takes intermediate values and/or the drive pulse length is comparable with that of the echo pulse, Equations (2) and (3) cannot give correct results. Our model's predictions clearly support this. From Figure 10 we can see that at 0 and 10 rayl backing impedance values, the model predicts 42 MHz and 22 MHz as centre frequencies for a PVDF transducer with 25 μm thick PVDF film driven by a delta function drive pulse, while from Equations (2) and (3), we have 42 MHz ($f = 2100/(2 \times 25 \times 10^{-6}) = 42$ MHz) and 21 MHz ($f = 2100/(4 \times 25 \times 10^{-6}) = 21$ MHz) respectively.

For wideband PVDF transducers the backing impedance usually has intermediate values, often close to that of PVDF itself. From Figure 10 we notice that the centre frequency decreases with an increase in the backing impedance value, the transducer vibrates in neither quarter wavelength resonance mode nor half wavelength mode. The centre frequency is strongly dependent on the drive pulse used and also on the value of the backing materials's acoustic impedance.

This explains why it is usually very difficult to predict the centre frequency of a wide band transducer. The potentially highest centre frequency value can only be obtained by using a fast drive pulse.

Figure 11 provides a further experimental verification of the concepts introduced above. We chose air (≈0 rayls), water (1.5 rayls), PVDF block (3.88 rayls) and mercury (19.7 rayls) as backing materials. The results show good agreement with those provided in Figure 10.

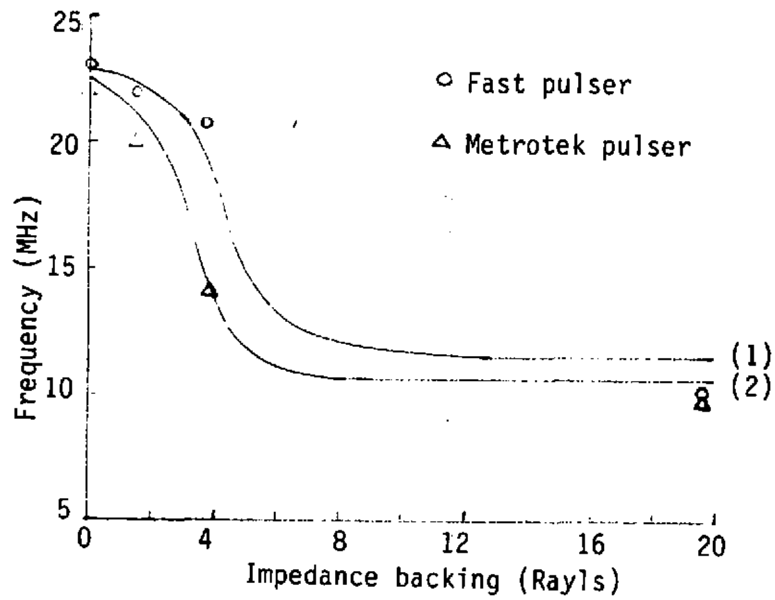

Figure 11 A comparison of experimental centre frequency versus backing impedance results with predicted ones for 46 μm thick PVDF film transducers. (1) fast drive pulse with rise time 5 ns, pulse height 400 v and pulse width 20 ns; (2) Metrotek MP 215 pulser drive pulse with rise time 20 ns, pulse height 43 v and pulse width 80 ns

CONCLUSIONS

The results obtained by using the model described are adequate justification for the approach taken. The model enables us to arrive at optimum choices of piezoelectric polymer thickness and backing material acoustic impedance for a given requirement in terms of either centre frequency and bandwidth or for a time domain specification for the echo returned from a hard plane reflector.

A basic assumption made in this model is that the polymer element operates as a simple thickness mode vibrator and the close agreement obtained in all cases seems to suggest that this is a reasonable assumption. Experimental work to visualise the vibrational behaviour of polymer elements is also underway in the Department and it is hoped that results of this will be available soon.

REFERENCES

[1] P.A. Payne, 'Medical and industrial applications of high resolution ultrasound', J. Phys. E: Sci. Instrum., Vol. 18, pp 465-473, (1985)

[2] M.G. Silk, 'Ultrasonic Transducers for Nondestructive Testing', Adam Hilger Ltd., Bristol, UK, (1984)

[3] J.W. Hunt, M. Arditi and F.S. Foster, 'Ultrasound transducers for pulse-echo medical imaging', IEEE Trans. Biomedical Engineering, Vol. BME-30, no. 8, 453-481, (1983)

[4] W.H. Chen, 'Analysis of high-field losses of polyvinylidene fluoride transducers', IEEE Trans. Sonics & Ultrasonics, Vol. SU-30, no. 4, 238-249, (1983)

[5] R.G. Swartz and J.D. Plummer, 'Integrated silicon-$PVDF_2$ acoustic transducer arrays', IEEE Trans. Electron Devices, Vol. ED-26, no. 12, 1921-1931, (1979)

[6] A.L. Stanford, 'Foundations of Biophysics', Academic Press, New York, USA, (1975)