CHARACTERISATION OF A MINIATURE WIDE-BAND ULTRASONIC PROBE TO MEASURE COMPRESSION AND SHEAR WAVES IN SOLID MEDIA

X. Jian[*], J. P. Weight[+], K. T. V. Grattan[+]
+City University, Department of Electrical, Electronic and Information Engineering,
London EC1 0HB, UK
[*] Now at: University of Warwick, Department of Physics, Coventry CV4 7AL, UK
x.jian@warwick.ac.uk

Abstract

The characterisation of a typical miniature piezoelectric transducer is described for use as a receiver directly coupled to a solid surface to measure field-point waveforms for both longitudinal (compression) and transverse (shear) ultrasonic waves. The devices used are fabricated as needle-like probes using a 0.3mm diameter lead metaniobate (PMN) disc as the active element. Typically, their size and bandwidth allow point-like measurements to be made over a frequency range of 0.2-8MHz .

To initially characterise the action of a miniature probe, measurements are made of compression and shear plane-wave amplitudes for various angles of incidence. The results show that such probes approximately respond to the normal component of the incident particle velocity. Results obtained using a probe to measure field-point waveforms compare well with results obtained using recently developed theoretical models to predict the pulsed field in solids.

I Introduction

Measurement of the ultrasonic field is of great interest in ultrasonics, both in the design of non-destructive testing (NDT) procedures using pulse-echo techniques and the interpretation of the echo waveforms encountered. Miniature piezoelectric probes have long been used to make field-point measurements in fluids, see for instance[1-3]. Field-point measurements can be made at the surface of a solid using optical interferometry [4,5] and electromagnetic acoustical transducers (EMATs) [6]. Here we describe a relatively simple method to make such measurements using a miniature piezoelectric ultrasonic transducer directly coupled to a solid surface.

The action of such a probe is investigated by making a series of measurements of locally plane waves as launched into a solid from a typical compression wave transducer water-coupled at arbitrary angle to a suitable surface of a solid test piece. The relative amplitudes of infinite plane waves as a function of incident angle can be predicted using well-known transmission coefficients. Comparison of the measured and theoretical results leads to a reasonably accurate assumption that can greatly simplify the use of directly coupled miniature transducers.

A miniature probe so characterised is then used to make pulsed field-point measurements in the near field of a typical NDT transducer, water coupled at short range to a solid. Such measurements show the complicated multipulse structure of the near field in solids and are compared to theoretically predicted results using a newly developed model [7].

In the present work only relative measurements are given. However if absolute amplitudes are required, the miniature-receiving probe could be calibrated using standard techniques, together with the information given here

II Measurement Set-up

The miniature receiver used here was constructed as a needle-like structure using a piezoelectric element of 0.3mm diameter. A Lead Metaniobate (PMN) element was chosen for its good sensitivity and relative freedom from unwanted radial modes of vibration. Typically, the measured bandwidth of the miniature probe extended from 0.2 to 8MHz. The transmitting transducer was a Panametrics PMN wideband ultrasonic transducer (19mm diameter), excited with a shaped electrical pulse to give an ultrasonic pulse approximating to one cycle at 2MHz, with a 3dB spectrum extending to about 6MHz. At 6MHz, the wavelengths of longitudinal and transverse waves in steel are about 1mm and 0.6mm, respectively and so the miniature probe was small enough to act as a point-like receiver. To overcome the problem of signal loss in connecting cables, the miniature probe was plugged directly into a head amplifier (gain 10dB; 3dB bandwidth 0.01 – 50MHz).

Figure 1 shows the measurement setup. The test pieces were constructed from mild steel with density 7800kgm^{-3}, and phase velocity 5960ms^{-1} and 3210ms^{-1} respectively, for compression and shear waves. Two types of test piece were used: a series of discs having different thickness, the receiving probe being normal to the (far) incident surface and a wedge shaped piece cut from a disc so that the receiving probe was at angle of 60^{o} to the incident surface. The test piece rests on a support immersed in water. The position of the support could be adjusted in two planes to achieve a maximum echo from the incident surface of the test piece, thereby ensuring (initial) normal incidence. Both the position and angle of the transmitting transducer could be adjusted. The miniature probe was coupled to the far surface of the test piece at the bottom of a round-bottomed hole to minimise the problem of unwanted reverberation.

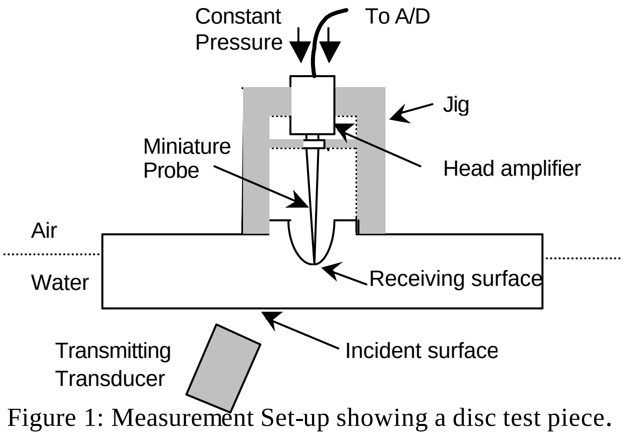

Figure 1: Measurement Set-up showing a disc test piece.

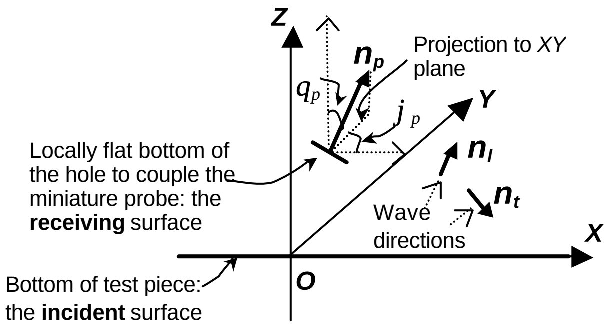

Figure 2: General coordinate system for the test pieces. Here the miniature probe is shown angled to the incident surface as in the wedge test piece.

III Measurement of particle velocity

A Normal components of waves in the test pieces.

The coordinate system adopted is shown in Figure 2. In general, with oblique incidence of the circular transmitting transducer, an elliptic beam is radiated into the solid, the major and minor axes lying on the X and Y axes, respectively, the beam being symmetric to *XZ* plane. For the special case of normal incidence, the beam is circular and symmetric to the *Z axis*. q_p is the angle with the *Z* axis of the miniature probe normal vector $\boldsymbol{n_p}$ .The projection of $\boldsymbol{n_p}$ on the *XZ* plane makes an angle j_p with the *X* axis. The corresponding angles q_l and j_l for the compression wave and q_t and j_t for the shear wave are defined in the same way. NB: For clarity $\boldsymbol{n_p}$, $\boldsymbol{n_l}$ and $\boldsymbol{n_t}$ are not shown to the same scale

The unit normal vector of the receiving miniature probe is given by,

$$\boldsymbol{n}_p = \begin{bmatrix} \sin q_p \cos j_p \\ \sin q_p \sin j_p \\ \cos q_p \end{bmatrix} . \quad (1)$$

Similarly, the unit normal vectors of particle velocity for the longitudinal and transverse waves are, respectively,

$$\boldsymbol{n}_l = \begin{bmatrix} \sin q_l \cos j_l \\ \sin q_l \sin j_l \\ \cos q_l \end{bmatrix} \text{ (2) and } \boldsymbol{n}_t = \begin{bmatrix} \cos q_t \cos j_t \\ \cos q_t \sin j_t \\ -\sin q_t \end{bmatrix} . \text{ (3)}$$

The normal components of the compression and shear wave particle velocities are then, respectively,

$$v_{\ln} = v_l \boldsymbol{n}_l \cdot \boldsymbol{n}_p \quad , \qquad (4)$$

$$v_{tn} = v_t \boldsymbol{n}_t \cdot \boldsymbol{n}_p \, . \qquad (5)$$

B Miniature probe normal to incident surface

Figure 3 shows normalised measured amplitudes of compression plane-wave pulses with respect to the wave direction using a disc test piece (metal path at normal incidence 15mm) and the set-up shown in Figure 1. As the angle of the water-coupled transmitting transducer was changed, its position was carefully adjusted so that the miniature probe was on the axis of the compression beam. As is known [8,9], the field point waveforms themselves have both "plane" and "edge-wave" components and for the experimental conditions encountered here these components partially overlap to interfere (see for instance Figure 7). However with the present set of results, such "diffraction errors" can be avoided by taking the amplitude of just the first half-cycle of the composite pulse as measured by the miniature probe.

For comparison, the dashed line shows the calculated refraction coefficients for compression plane-waves. Clearly, the miniature probe only responds to the actual amplitude of the wave (dashed line) at angles close to normal incidence. However, there is good agreement between measured and calculated results if the normal component of the coefficient is plotted (the solid line).

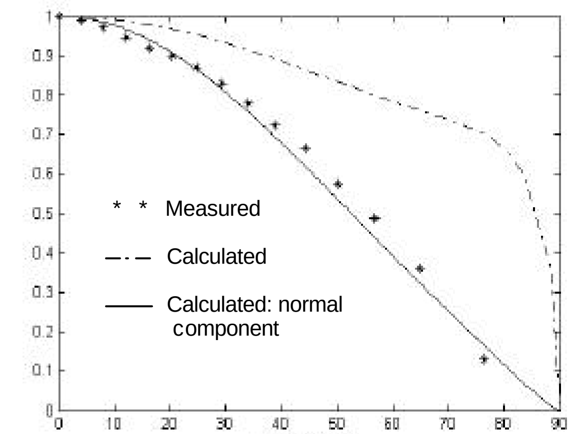

Figure 3: Normalised amplitude of C waves in a disc test piece.

Similarly, Figure 4 shows the corresponding results obtained by positioning the transmitting transducer so that the miniature probe was at the centre of the shear-wave beam. Again for most angles there is reasonable agreement between the measured amplitude and the normal component of the calculated coefficients.

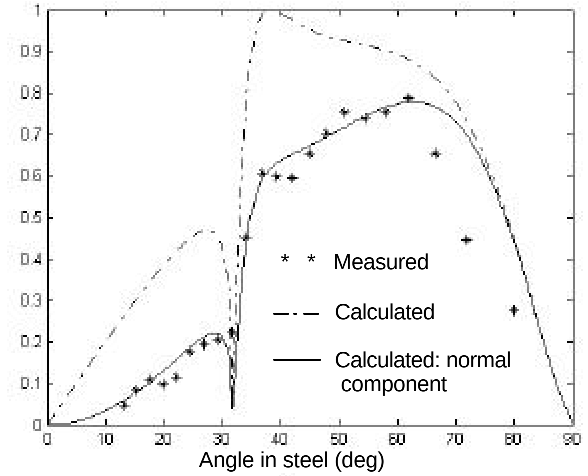

Figure 4: Normalised amplitude of shear waves with angle in a disc test piece.

However the predicted zero at the first critical angle is not seen in the measured results. Such behaviour is not unexpected, since it should be borne in mind that the theoretical results assume infinite plane waves and do not take account of the existence of, for instance, surface waves generated at the refracting surface.

C Miniature probe oblique to incident surface

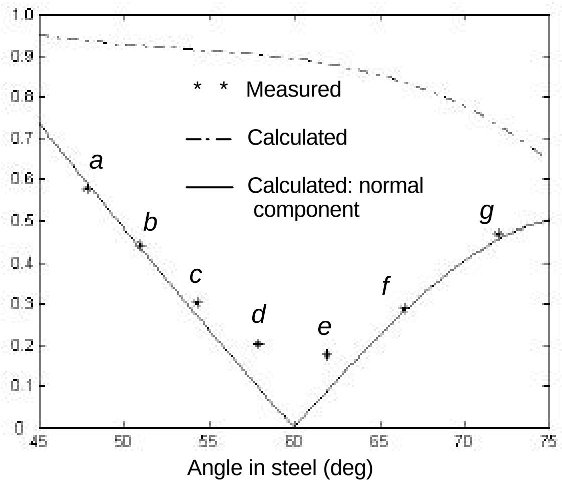

Figure 5: Normalised amplitude of shear waves with angle in the wedge test piece.

To investigate further the action of the miniature probe, a wedge shaped, steel test piece was prepared. The wedge angle was chosen so that shear waves could impinge at normal incidence to the miniature probe. The shear waves were generated using the same transducer and procedures as for the earlier results of Figures 3-4. At a wave direction of 60^o, the shear wave is received at normal incidence and hence the component of particle velocity normal to the surface is zero. Further more there is a change in sign of the normal component as the wave direction goes through 60^o. From Figures 5 and 6 we can see that although the measured amplitude does not drop to zero at 60^o, there is a sharp drop in amplitude, reinforcing the hypothesis that the probe responds to the normal component. Also, we do observe a polarity change in the measured pulses through 60^o (results *a-d* have opposite polarity to *e-g*). One reason for the amplitude of results *d* and *e* being larger than predicted, is the likelihood that other modes of vibration occur in the miniature probe, an effect that is likely to be more noticeable as the shear wave approaches normal incidence to the receiving surface.

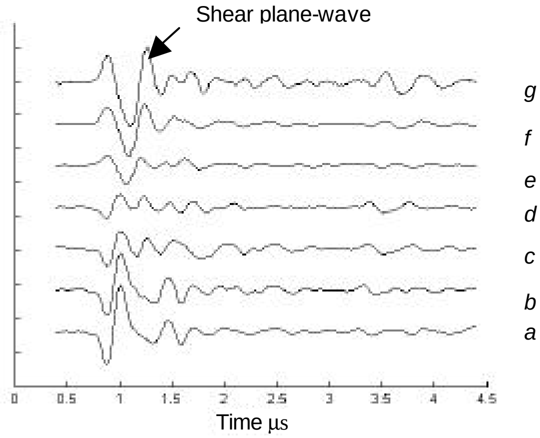

Figure 6: Measured field-point waveforms for Figure 5.

IV Measurement of field-point waveforms

To demonstrate the use of the miniature probe to characterise the ultrasonic field in a solid, measured and calculated [7] field-point waveforms are given in Figures 7 & 8. In all cases, the calculated results have been made for the normal component of particle velocity. Figure 7 shows axial results with the transmitting transducer water-coupled (water path 6mm) at normal incidence to the disc test pieces. The compression plane- and edge-wave pulses and the shear edge-wave pulse are labelled as PC, EC and ES, respectively. At normal incidence, there is no refraction of the incident compression plane wave and hence no shear plane wave is generated. As shown, there is good agreement between the two sets of results, bearing in mind that a typical NDT transducer only approximates to the ideal piston source assumed in the modelling. The reasonable agreement of the compression and shear edge-wave pulse amplitudes justifies the assumption that the miniature probe responds to the normal component of the received particle velocity.

Figure 8 shows field-point waveforms (labelled similarly to Figure7) with the transmitting transducer water coupled at various angles to a disc test piece. A 6mm water path was used and at normal incidence the metal path was 10mm. At each angle of the transmitting transducer, it was repositioned so that the miniature probe received the compression edge wave at maximum amplitude. Again, the measured results compare well with the corresponding calculated [7] pulse shapes for the normal components.

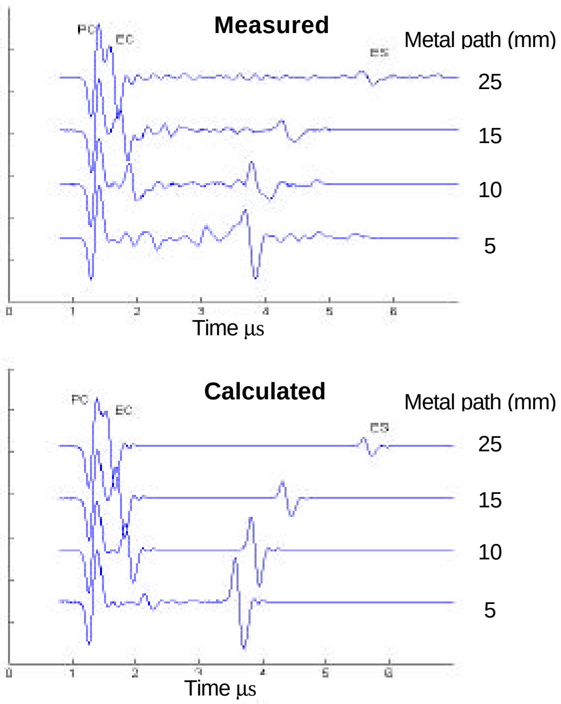

Figure 7: Field-point waveforms with the transmitting transducer water-coupled (6mm water path) at normal incidence to the disc test pieces.

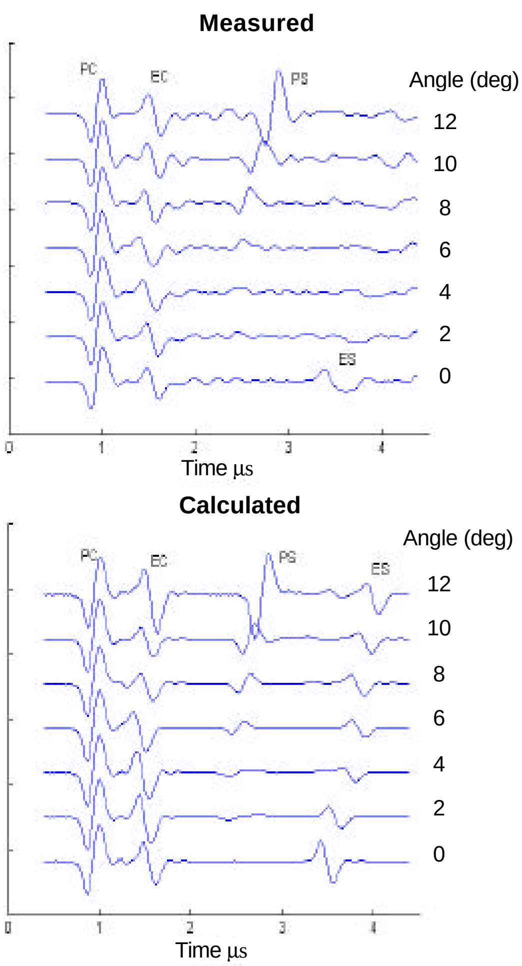

Figure 8: Field-point waveforms with the transmitting transducer water-coupled (6mm water path) at various angles to a disc test piece.

V Conclusion

Measurements of the amplitude of pulsed, refracted compression and shear waves made using a miniature piezoelectric transducer directly coupled to the surface of a solid have been compared with predicted amplitudes given by well-known expressions for the reflection coefficients of infinite plane waves. Such comparisons have shown that to a reasonable approximation, the miniature probe responds to the normal component of the particle velocity of both the incoming compression and shear waves. Furthermore, the measured particle velocity at the surface is proportional to that within the solid. The miniature probes used here have a bandwidth of around 0.2 – 8MHz and are small enough to make point-like measurements over this frequency range when used coupled to solids typically encountered in NDT.

Field-point measurements have been made of the pulsed compression and shear waves radiated into steel from a water-coupled transmitting transducer typical of those used in NDT. The measurements compare well with calculations of normal components of particle velocity made using a recently-developed theoretical model [7].

Acknowledgement

The authors are grateful to Professor Fradkin L. J., South Bank University for her helpful review and advice. The work is supported under a grant from EPSRC.

References

[1] A.J. Hayman and J.P. Weight, "Transmission and reception of short ultrasonic pulses by circular and square transducers", *JASA. vol. 66*, pp.945-951, 1979.

[2] P.R. Stepanishen and G. Fisher, "Experimental verification of the impulse response method to evaluate transient acoustic fields", *JASA, vol. 69*, pp. 1610-1617, 1981.

[3] J.P.Weight, "Ultrasonic beam structures in fluid media", *JASA, vol. 76*, pp. 1184-1193, 1984.

[4] C. Barriere, and D. Royer, "Optical measurement of large transient mechanical displacements," *Applied Physics Letter, vol. 79*, pp. 878-880, 2001.

[5] J.P. Monchalin , "Optical detection of ultrasound," *IEEE Trans. UFFC vol. 33*, pp. 485-499, 1985.

[6] M. C. Bakker, and M.D. Verweij, "Experiment validation of two elastodynamic models for the wave field generated by ultrasonic transducer," *JASA vol 113*, pp. 1850-1862, 2003

[7] X. Jian , J.P. Weight and K.T.V. Grattan, "A model for the propagation of ultrasound in a solid immersed in a fluid". In proceedings of the *5th WCU, Paris*, 2003.

[8] J.P.Weight, "A model for the propagation of ultrasonic pulses in a solid medium", *JASA, vol. 81*, pp. 815-827, 1987.

[9] A. Ilan and J.P.Weight, "The propagation of short pulses of ultrasound from a circular source coupled to an isotropic solid", *JASA, vol. 88*, pp.1142-1151, 1990.