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A DETAILED COMPARISON OF ULTRASONIC FIELD MEASUREMENT TECHNIQUES

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1. INTRODUCTION

The developments in reliable, affordable, digital electronic devices capable of operating at high frequencies ($\geq$1MHz) in the last two decades have emphasised transducers as the limiting factors in ultrasonic measurement systems. While there has been considerable interest in the exploitation of 'new' piezoelectric transducer materials (e.g. ceramics in the late 1950's, plastics in the early 1970's), comparatively little effort has been expended in the development of methods for detailed characterization of the behaviour of the transducers used. The efforts reported have been directed at characterizing sources, with almost no consideration, until recently [1] of the behaviour of transducer receiving characteristics.

The essential problem is that unless the behaviour of the transducers is known, it is difficult if not impossible to know the extent to which the assumptions made about the radiated ultrasonic field are being achieved in a given practical situation. At megahertz frequencies and above, the wavelengths are in the millimetre or submillimetre range. The transducers used are finite in size (rather than being small) because there is generally a need for them to be directional, and to have adequate signal-to-noise ratio. This means that they are highly diffractive. It is recognised that the plane wave assumption invoked in measurements to determine the acoustic properties, such as velocity and attenuation, of specimens is not valid. Diffraction corrections have long been employed to overcome this problem (e.g. [2]). However, these assume that the source behaves in some ideal way (usually as a piston radiator). There is considerable evidence in the literature that this is often not true. To be certain of the actual radiation conditions being used in a given situation it is necessary to obtain detailed measurements of the source behaviour.

It appears that no confirmed techniques exist for direct measurement of the vibration distribution on the surface of an ultrasonic transducer radiating into a fluid. Lypacewicz & Filipczynski [3] have used a capacitive sensor scanned over the surface of the transducer. The sensor was in contact with the surface, thus producing an unknown mechanical loading, and the measurements were performed in air. Optical interferometric techniques are attractive. They work well in air [4], and have been used in water [5]. However in the latter case the radiated field may be distorting the path travelled by the laser beam of the interferometer due to the optical refractive index changes induced in the water by the (unknown) ultrasonic field. The first steps in the analysis of this as a direct problem have been taken [6], but it is not yet clear whether the inverse problem is tractable. Even if a procedure for solving the inverse problem was available, it would be necessary to validate its practical use by comparison of the results it gives with those obtained by an independent method.

In the absence of a method for direct measurement, it is necessary to use the approach suggested by Reibold [7], of measuring the (complex) pressure over a plane in the near field, and calculating the source distribution by back-projection. The technique used for measuring the pressure distributions was optical diffraction tomography [8]. While this has a good theoretical basis, the measurements can be accurately made, and the potential sources of error can be carefully assessed, it is nevertheless an indirect technique. It requires a computational inversion of the measured data to obtain the pressure distribution. There is thus still some room for doubt (albeit very small) as to whether the source distribution obtained in such a manner is realistic. The present work was aimed at a detailed comparison of measurements made using the optical diffraction tomography technique (at the PTB in Germany), with those made on the same transducers using a scanned miniature hydrophone at the University of Surrey.

2. COMPUTATION

Prior to the comparison of measurements, the computational procedures to be used to forward and back-project the measured data was checked. The most elegant approach to this is the plane wave spectrum (Fourier optic) method. Starting with a given source distribution the program for forward propagation using the plane wave spectrum approach was tested by comparing the results obtained using a different computational approach (the Huygens' construction, in the case of Surrey, and the impulse response technique, in the case of the PTB). This was done separately by each laboratory using their own code. Then the results obtained using the same source distribution but the forward (plane wave spectrum) routines from the two laboratories were compared. These comparisons were all successful (as was a similar exercise in back projection). Thus confidence was established in the field projection routines.

3. MEASUREMENT METHODS

3.1 Optical tomography (PTB)

The principles and practice of this approach have been described in detail by Reibold and Molkenstruck [8]. It has the requirement of high mechanical precision and thermal stability. The spatial reslution achieved in the measured pressure data is determined by the total number of individual measurements made. In order to obtain a resolution of 0.25mm ($\lambda/2$ at 3MHz) over a typical area of 40mm $\times$ 40mm, 16100 measurements would be required. The time to take these would be typically 16 hours.

3.2 Scanned hydrophone (Surrey)

The principles of the measurement in this case are relatively straightforward as the acoustic pressure is measured directly. The key element is a piezoelectric hydrophone of dimensions small compared to the wavelength. These tend to be of the needle type design and a new-generation commercial device of this type was available for the work [9]. The stringent requirements of mechanical precision and thermal stability are comparable to those required for optical diffraction tomography, being of particular importance in the measurement of the phase [10].

Usually, quasi-continuous excitation of the transducers is employed. While previous workers have used analogue techniques to determine the amplitude and the phase of the received toneburst, a digital approach was used here. A portion of the signal output from the hydrophone was digitized and, having averaged the data over typically 16 pulses to reduce the noise level, a sinusoid of the known excitation frequency was fitted to the data to obtain values of the amplitude and phase [1]. The spatial resolution was typically 0.25mm over an area of 26mm × 26mm which required 11025 measurements. Such a typical scan lasted of the order of 12 hours, which is comparable to the optical diffraction tomography measurement times. A regular check was made (by returning to a central point) to ascertain whether any temperature change had affected the measurements, thus permitting appropriate corrections to be made if needed.

The main difference between the two techniques used was that whereas the optical diffraction tomography can be used to take measurements within a millimetre of the front face of the transducer under investigation, the minimum distance with a hydrophone is much greater. It is determined by the electrical breakthrough from the excitation pulse, and depends on the pulse length. A technique has been developed [1], which takes into account the size of the source to enable reliable measurements to be made closer to the source than the conventionally accepted limit of half the pulse length.

4. TEST TRANSDUCERS AND MEASUREMENTS

Four transducers were used in the comparison (two being provided by each laboratory). Two had PZT as the active element, while the other two used PVdF. Further details are given in Table 1. Several measurement planes in the field of each transducer were chosen for the comparison. The closest of these distances was selected based on practical considerations and on the requirement that for accurate source reconstruction, the measurement plane should to be as close as possible to the source. Another plane close to this (usually within 10–15mm) was also chosen so that source reconstructions from two planes within the near field could be obtained and compared. Two other planes were chosen to coincide with the theoretically expected last axial maximum and minimum.

For transducers B, C and D, the hydrophones used had element diamters of 0.5mm. For transducer C, a 0.25mm element diameter hydrophone was employed. For the comparison of absolute pressure values, a calibration was obtained for one of the hydrophones used in the exercise. The typical uncertainty on the quoted values of the end-of-cable sensitivity was 12.5%. The rest of

Table 1: Details of the transmitting transducers investigated.

Source	Serial number	Nominal frequency (MHz)	Operating freq. (MHz)	Geom. radius (mm)	Element material
B	188928	1.0–5.0	2.5	10.0	PVdF
C	147150	1.0–5.0	2.5	10.0	PVdF
D	2.12/3	2.12	2.25	9.5	PZT-5
E	TSWB 0.8-3	0.8–3.0	3.0	12.0	PZT

the hydrophones used were cross-calibrated with the primary hydrophone. Optical diffraction tomography is a self-calibrating technique and therefore no external calibration was required.

When hydrophone measurements were being performed, it was sometimes necessary, because of the low sensitivity of certain hydrophones, to amplify the excitation signal to the transducers beyond the level used for the optical diffraction tomography measurements. For these cases, the pressure values have been normalized to the excitation levels used in the optical diffraction tomography measurements, assuming linearity. For the comparison of relative phase values, the hydrophone data has also been normalized, at the central point, to the optical diffraction tomography measurements (which are quoted relative to the transducer excitation signal).

The measurements are detailed elsewhere [1]. Some typical results, in the form of pseudo-3D plots and radial cross-sections, are presented here. Fig. 1 illustrates the pressure measurement at a source-to-receiver distance of 5 mm, in the field of transducer C. There is good agreement in the pressure amplitude towards the edges of the distribution, but poor agreement of absolute values at the centre, where a 40% difference, with respect to the optical tomography values, is seen. This is the worst case seen in all the measurements performed and should be seen in the light of the observed instability of transducer C (the response of this transducer was found to change significantly over time, due probably to a combination of water absorption and temperature drift [1]). It should also be noted that the calibration available at the driving frequency (2.5MHz) was an interpolated value, since the original calibration was only available at integer multiples of 1MHz. The phase distributions show good agreement, with discrepancies of less than 10°.

Fig. 2 illustrates the pressure measurement at a source-to-receiver separation of 145.5 mm, in the field of transducer E. The measurements obtained for this transducer showed the best agreement. For the plane displayed, both techniques have identified the on-axis minimum, which is nearly zero. Over the four peaks, seen in the x and y cross-sections through the measurements (Figs. 2c and 2d), the average difference in amplitudes is approximately 12%. This is within the uncertainty of 12.5% claimed for the primary calibration. The very good agreement seen for this transducer is perhaps not so surprising if it is observed that the operating frequency was 3MHz, at which a cross-calibration without interpolation was available. The agreement in phase is also very good. The reason for the offset is simply the unreliability of the phase measurement at the centre (where the amplitude was nearly zero) and the manner in which the distribution was normalized (see above).

5. SOURCE RECONSTRUCTION

The typical reproducibility of the source reconstructions obtained from measurements over the two nearest planes to the source, using the same technique (in this case the scanned hydrophone), can be seen in Figs. 3 and 4. The figures depict the source normal velocity distributions of transducers C and D respectively. It should be observed that the reconstructed pressure distributions were very similar. In the case of transducer C (Fig. 3), a flat amplitude and phase distribution, consistent with a piston radiator, is seen. However, the pressure distribution (not seen here) does not exhibit the characteristic large pressure fluctuations expected at a piston surface. In the case of transducer D (Fig. 4), an unusual source vibration pattern is observed, with a ring-like structure and a peak at the centre. This may reflect the unusual coaxial electrode construction of this transducer. The electrode is wrapped around the rim of the transducer element to reduce the edge effect, and this could well have resulted in some radial mode activity.

6. CONCLUSION

This comparison study has produced some interesting results. Very good qualitative agreement is seen between the pressure amplitudes measured using the two techniques. The hydrophone measurements consistently exhibit more fine structure both in amplitude and phase. This may be due to some mechanical imprecision in positioning as well as the fact that the optical tomography results have been subjected to polynomial smoothing. The relative phase distributions show very good agreement for all cases considered.

The source reconstructions presented here indicate the excellent reproducibility of intra-laboratory measurements and source reconstructions. The latter were calculated from two planes, using the plane wave spectrum propagation method. This tends to support the contention that the reconstructed vibration distributions are genuine and represent the true vibration patterns of the transducers investigated.

7. ACKNOWLEDGEMENTS

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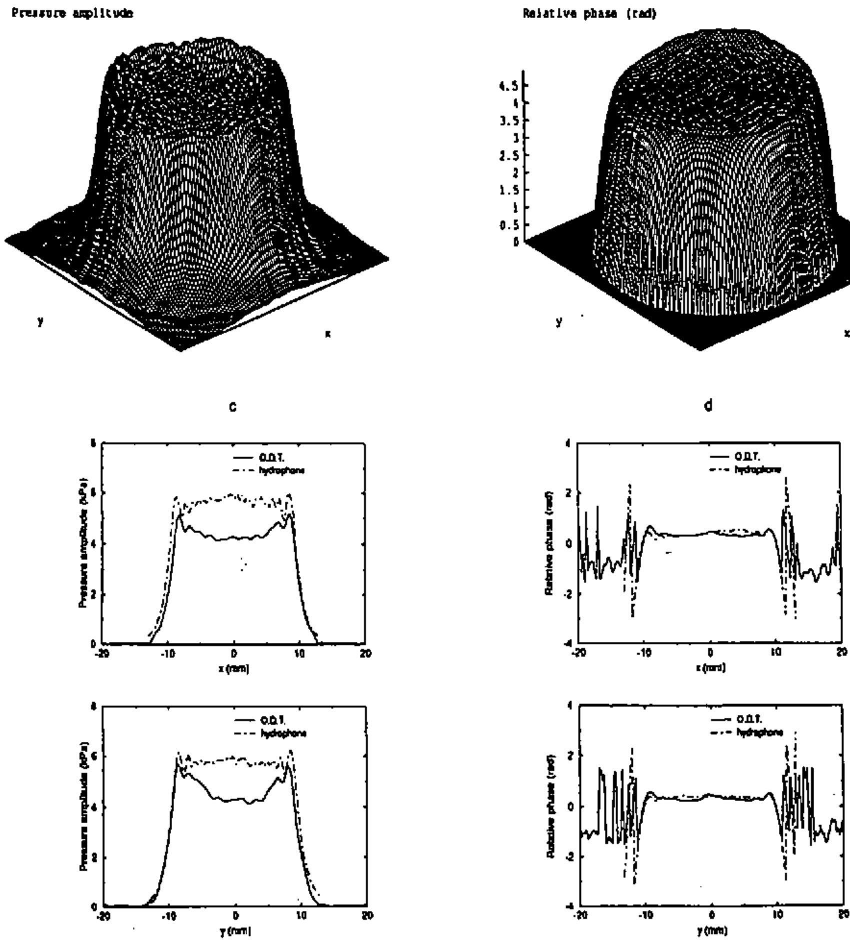

Figure 1: The measured pressure amplitude (lhs) and phase (rhs) at z=5mm in the field of transducer C: a and b are pseudo-3D plots (hydrophone only), whereas c and d are plots of the central cross-sections through measurements, using a 0.5mm element diameter hydrophone and optical diffraction tomography (O.D.T.).

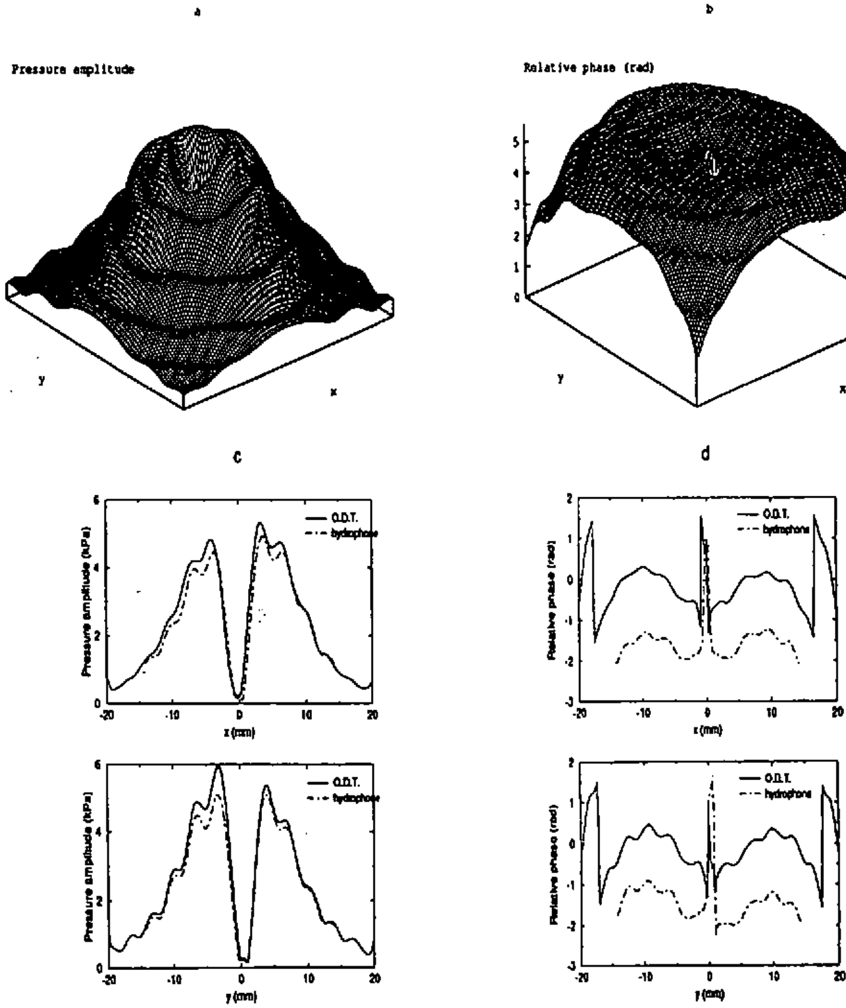

Figure 2: The measured pressure amplitude (lhs) and phase (rhs) at z=145.5mm in the field of transducer E: a and b are pseudo-3D plots (hydrophone only), whereas c and d show central cross-sections through the measurements, using a 0.25mm element diameter hydrophone and optical diffraction tomography (O.D.T.).

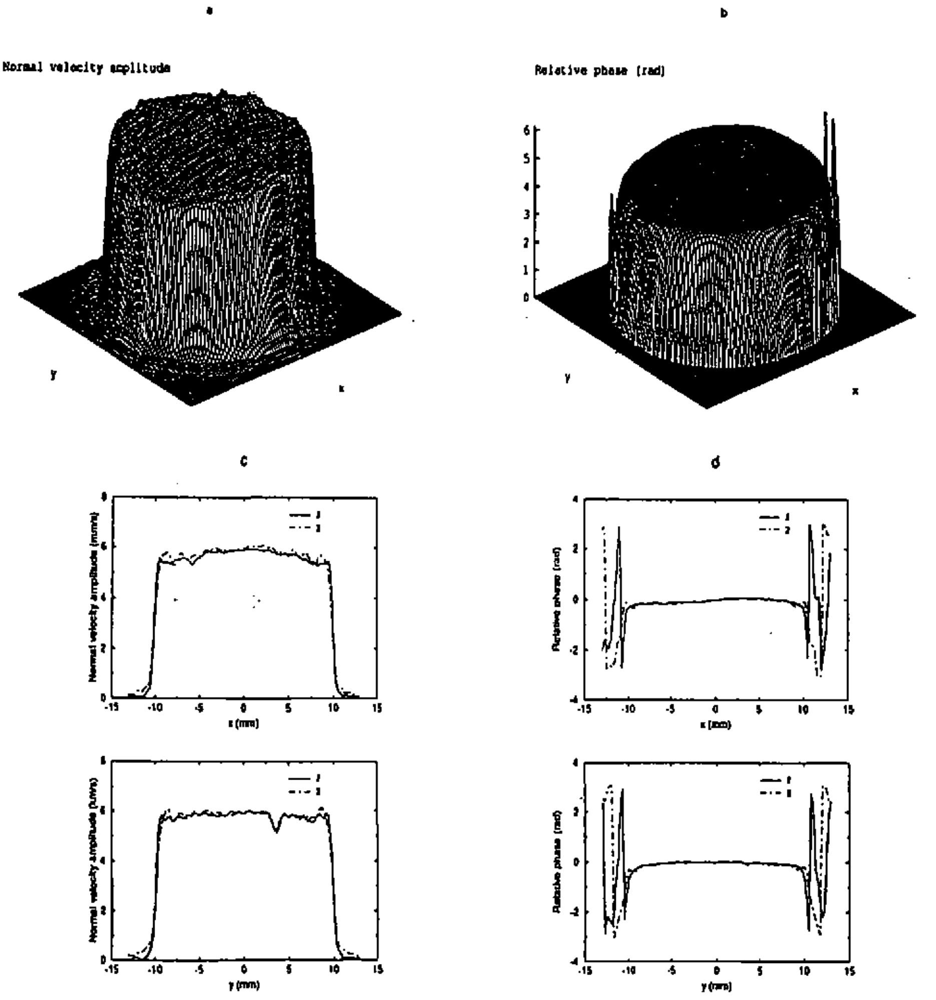

Figure 3: The reconstructed normal velocity distribution of transducer C (**a** and **b**), calculated from pressure measurements at z=5mm. Cross-sectional plots (bottom) through the centre of the distribution also show the reconstruction from pressure measurements at z=15mm (*1* and *2* respectively).

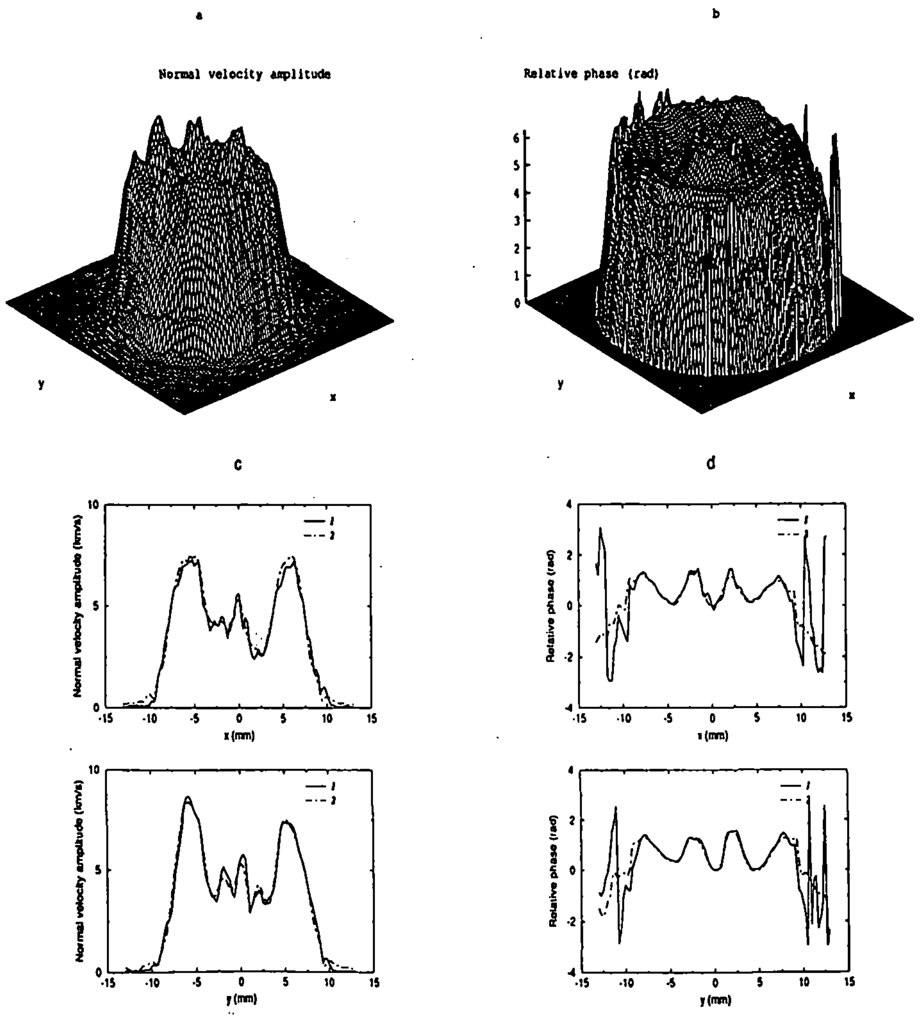

Figure 4: The reconstructed normal velocity distribution of transducer D (a and b), calculated from pressure measurements at z=5.4mm. Cross-sectional plots (bottom) through the centre of the distribution also show the reconstruction from pressure measurements at z=34.1mm (*1* and *2* respectively).