INTRODUCTION AND BACKGROUND

Silicon backplate capacitance air-coupled transducers have particular advantages over other types of air coupled ultrasonic transducer. Such advantages include the ease of manufacture and the ability to reproduce field characteristics. This is achieved by using a polished silicon backplate and introducing controlled surface roughness by etching holes into the backplate to create a series of air springs. The performance of such devices has been investigated [1], and it was found that the combination of bandwidth and sensitivity leads to a range of NDE applications. The aim of the present paper is to compare the pressure field of these transducers to that predicted by theory for a plane piston transducer in air.

The construction of a typical capacitance air-coupled transducer is shown in Figure 1. A series of uniformly-spaced holes is etched into the top surface of a flat rigid silicon plate. Gold is then evaporated onto the top surface of the plate to produce a conducting backplate. A 6\(\mu\)m and 2.5\(\mu\)m Kapton polymer membrane, with a conducting top surface, is placed on top of the etched silicon backplate for the
source and receiver respectively, trapping pockets of air to form the air springs mentioned above. Applying a transient voltage between the backplate and the front metallized surface of the membrane forces the membrane into motion, hence generating ultrasound into air. The backplate dimensions are given by Figure 2, the holes having a diameter of 40μm with the centres spaced at 80μm apart, and covered by the Kapton film. Detection occurs by an identical device, but a d.c. polarization voltage is required to cause induced charges to be generated by membrane motion. The construction outlined above leads to a device with a good response into the MHz region, well-damped and with excellent sensitivity.

EXPERIMENTAL PRESSURE FIELD MEASUREMENTS

The pressure at any position throughout the field of these transducers was determined using an apertured second device as a miniature hydrophone. The source transducer under test had a 10mm diameter active area, whereas the scanned receiver was fitted with a 1mm diameter aperture. In the experiment illustrated in Figure 3, the receiver was attached to an X-Z stage while the source is in a fixed position. A Matec gated power amplifier was used to drive the source with tonebursts at various frequencies (e.g. 500kHz and 700kHz in the present experiments). Alternatively, a Panametrics pulser/receiver unit could be used to give a transient pulsed excitation with a fast rise-time. The signal produced by the receiver was sent to a Cooknell CA6/C charge sensitive amplifier, which also supplied a 200V bias between the backplate and the membrane. The signal waveform was digitized at any particular point in the field using a Biomation model 8100 oscilloscope and stored on a PC for analysis. Pressure amplitude variations were plotted by taking the maximum peak to peak amplitude of the stored signal at each point. The detector was scanned in a 2D X-Z plane, to give a pressure field with a 0.5mm spatial resolution in the X (radial) direction and a 1mm resolution in the Z (axial) direction. The total X-Z scan area was 30mm in X and 70mm in Z, the field starting at 6mm from the front face of the transducer membrane. Typical results from these scans are shown in Figure 4 for pulsed excitation by the Panametrics pulser, and in Figures 6 and 8 for tone-burst operation.

THEORETICAL PRESSURE FIELD MEASUREMENTS

Using established theory for the radiated field of a plane piston transducer [2], we can predict the pressure variations for any size of aperture in air. The mathematical model assumes that the pressure at any point across and away from the transducer face can be computed from the interference of the plane and edge components, and also assumes that the front face is vibrating with a uniform amplitude and phase (although variations in these parameters can be included if required). The theory can predict either waveforms at a particular field point, or, as here, the spatial variations in peak-to-peak pressure amplitude. The relevant set of expressions for calculating the field are those for the plane and edge wave components, that interfere with the appropriate time delays at any point, and are given by

\[ S = aH(T-T_0) + \beta H(T-T_1) \]  

(1)
where, for the plane wave,

$$\alpha = \rho C$$

and for the edge wave

$$\beta = (\rho C/\pi) A \cos(\lambda)$$

The variable $\lambda$ is given by

$$\lambda = (CT)^2 - Z^2 + X^2 - A^2) / ((CT)^2 - Z^2)^{0.5} 2X$$

$C =$ Velocity of sound in a medium
$T =$ Time
$Z =$ Axial distance from the face
$X =$ Radial distance from the face. In these expressions,
$A =$ Radius of the transducer face
$T_0 = $ Time taken for a plane wave to reach a position
$T_1 = $ Time taken for the first edge wave to reach a position
$T_2 =$ Time taken for the second edge wave to reach a position
$H =$ Heaviside step function
$S =$ Scalar velocity potential impulse response

Differentiating $S$ with respect to $T$ gives the impulse response for the pressure field of the transducer. Convolving the impulse response at any position with the simulated motion of the membrane then produces the theoretical waveform at any one position. As the model simulates a transducer working in air, attenuation needed to be included in the model. Using an experimentally-derived expression [3] for attenuation in air, this could be included in the theoretical model. The attenuation is now a function of frequency and distance away from the transducer face. The expression for attenuation is given by

$$\sigma = 15.895 \times 10^{-11} \times ((T / T_0)^{0.5} \times F^2 / (P / P_0)) \times m$$

$T_0 =$ Reference Temperature ($20^\circ$C)
$T =$ Measured Temperature
$P_0 =$ Reference Pressure (atm, 101.325kpa)
$p =$ Measured Pressure
$F =$ Frequency to be attenuated
$m =$ Distance away from the face of the transducer
$\sigma =$ Attenuation (expressed in dB)

Note: $(T / T_0)$ and $(P / P_0)$ were both assumed to be unity.

At each field position, the Fourier transform of the predicted waveform was taken, to give a frequency spectrum of the signal. This was then modified according to the expression for the calculated attenuation $\sigma$, so that the higher frequencies were suppressed more than the lower frequencies. An inverse Fourier transform then gave the resultant attenuated waveform. The maximum pressure was found as before by
RESULTS AND DISCUSSION

Consider first the experimental result for a pulsed input, the spectrum for the driving signal having a central frequency of approximately 500kHz. This was shown in Figure 4, with the corresponding theoretical result for the same conditions being taken the peak to peak amplitude of the signal. Predictions of theory, including the attenuation term, are given in Figure 5 for pulsed excitation, and Figures 7 and 9 for tone-burst signals.
Figure 4 Experimental pulse with frequency centralised at 500kHz.

Figure 5 Theoretical pulse with frequency centralised at 500kHz with attenuation.

Figure 6 Experimental 500kHz toneburst input.

Figure 7 Theoretical 500kHz toneburst with attenuation.

Figure 8 Experimental 700kHz toneburst input.

Figure 9 Theoretical 700kHz toneburst with attenuation.
given by Figure 5. The two look very similar in appearance, with the edge and plane waves interacting to produce the expected maximum at the nearfield/farfield boundary. Some departures of theory from experiment are thought to be due to the receiver used in the experiment having an aperture diameter of 1mm, which tended to average the signal across the area, with a resultant loss of detail. Both theory and experiment show that a pulsed input produces a well-defined pressure field with little evidence of side lobes, this being of interest for location and imaging purposes.

For the toneburst driving signals at 500 and 700kHz, experimental results (Figures 6 and 8 respectively) resemble the corresponding theoretical pressure field plots (Figures 7 and 9). In both cases the theoretical and experimental results show the edge and plane waves interfering as before. Also note the nearfield/farfield boundary occurs at the same position away from the transducer face (Z=0) in each pair of 3D plots. For the 500kHz experimental and theoretical results (Figures 6 and 7), it is shown in both cases that there is more interference between the edge and plane waves in the nearfield region than in the pulsed case. This would be expected, due to the increased capacity for interference, with more cycles in the time waveform and a reduced bandwidth. Again, this nearfield interference is not as clearly shown in the experimental result as in the theory. This is also due to averaging of the signal due to the 1mm diameter aperture of the receiver, and the aperture of the source did not fit tightly against the membrane at all locations. Interference effects occurred which did not allow a symmetric edge wave to be produced. If the same comparison is done for the 700kHz results (Figures 8 and 9), more maxima and minima are present in the near field region due to the higher frequency of drive signal (again, as would be expected). Averaging of the signal by the receiver is again present and non symmetric edge waves being produced. At both tone-burst frequencies, the theoretical and experimental results show side lobes being produced from the edge waves in the near field region. These side lobes are stronger at the higher frequency of operation.

CONCLUSIONS

At frequencies of up to 1MHz, the scanned pressure field of an air-coupled capacitance transducer shows many of the characteristics of a plane piston radiator. Thus, it is reasonable in future work to use the theoretical model to design different transducer configurations, predicting their pressure fields for different situations (e.g. such as focusing). This would be especially useful in determining the optimum transducer configuration for the accurate detection of defects in air-coupled non-contact imaging of materials.

REFERENCES