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DIFFRACTION EFFECTS IN THE PULSED AND CONTINUOUS WAVE FIELDS

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INTRODUCTION

The transient pressure field radiated by idealised piston-like transducers into a fluid has been explained using an impulse response method [1-5] which lends itself to both physical interpretation and numerical calculation. A good physical understanding is obtained by considering the pressure field as the sum of two components [3,5-8]: a direct "plane wave" of the same area as the transducer which propagates in the geometric region straight ahead of the transducer and a diffracted "edge wave" which is a spreading wave centred on the transducer periphery. At most of the field points considered in previous studies of short ultrasonic pulses [3,5], good agreement was obtained between pressure waveforms measured using a miniature hydrophone and those calculated using an impulse response method. In addition, the output of the transducer when used in the transmit-receive mode to detect a small target, proved consistent with results calculated for an idealised point-like target.

Such earlier studies have emphasised the differences between the transient and continuous wave fields. In this paper we attempt to demonstrate the progressive transition from the short pulse, to the continuous wave field. To this end, stroboscopic visualisations are presented which show the field patterns radiated by a transducer excited to produce a progressively increasing number of cycles of a sinusoid. Experimental measurements of pressure waveforms at points in the field of a circular transducer emitting various numbers of cycles have also been measured and compared with calculated results obtained using the impulse response method.

The results obtained are relevant to the measurement of pulsed and CW beam-profiles using a miniature hydrophone to probe the field. An alternative approach is to use a small reflecting target to make beam-profile measurements in a transmit-receive mode. The differences between the profiles obtained using these two methods are explained in terms of plane and edge waves. Since the complicated nature of the beams radiated by conventional transducers is due to the interaction of plane and edge waves, attempts have been made to produce a simpler field structure by using transducers designed to emit plane waves alone, or edge waves alone [9,10]. Here, we demonstrate the use of one such transducer in B-scan imaging and compare the resolution achieved with that of a conventional transducer of the same aperture.

THEORY

Calculations of the pressure waveform at any point in the field of a source undergoing arbitrary motion and radiating into a fluid medium may be made using an impulse response approach. Such a method has been described in detail elsewhere [1,2,4] and only a brief resumé is given here. The velocity potential impulse response of an idealised piston source undergoing uniform motion and radiating into a lossless fluid is given by

$$\phi_i(r,t) = c\Omega(c\,t)/2\pi \ , \qquad (1)$$

where r is the distance from the field point to an (equidistant) arc on the piston surface, $\Omega(ct)$ is the angle of equidistant arc included on the piston surface and c is the velocity of sound in the propagating medium. For a circular source, analytical expressions for $\Omega(c\,t)$ have been given by a number of authors; those tabulated by Robinson et al. [4] have been used here.

The pressure impulse response at the point is given by

$$P_i\,(r,t) = \rho \frac{\partial \phi_i}{\partial t} \ , \qquad (2)$$

where ρ is the density of the fluid.

Calculations of the output pressure waveforms P(r,t) of a piston-like disc transducer undergoing any motion can be performed by convolving the pressure impulse response with the source velocity motion v(t) that is

$$P(r,t) = P_i(r,t)*v(t) \ . \qquad (3)$$

The source motion v(t) to be used here was a simple approximation to that resulting when a wide-band transducer is excited by gated sinewaves - see below.

STROBOSCOPIC SCHLIEREN IMAGING

The Schlieren system used [11] employs a Z arrangement of two spherical mirrors (60 mm diameter, f/10). Light from a stroboscope is focussed onto a small slit and then collimated so as to illuminate a transparent material (here, water housed in a glass tank) into which ultrasound can be propagated. The light is brought to a focus on a knife-edge stop which is arranged to prevent light reaching a video-camera. In the presence of ultrasound (which propagates as a density fluctuation), refractive index changes occur allowing light to be deflected past the stop and the ultrasound to appear luminous. If the stroboscope is flashed (in the present work, 250 ns duration flashes are used), the ultrasonic pulses appear "frozen" at an instant determined by a variable delay. Since the resultant video images are two-dimensional projections of the ultrasonic field, a clearer view of the plane- and edge-wave structure can be obtained if the radiated field is also two-dimensional. Thus for the visualisation results a rectangular, slit-like transducer of width 15 mm was employed. Such a source radiates an edge wave from each of its sides, each wave having a locally cylindrical wavefront.

The transducer, which was fabricated using a heavily damped plate of lead metaniobate, was excited with gated 0.5 MHz sinusoidal waves passed via a synchronised gated amplifier and radio-frequency power amplifier.

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PRESSURE WAVEFORM MEASUREMENTS

Pressure waveform measurements were taken using a circular, commercially available transducer (Panametrics V315) of diameter 19 mm as the transmitter and a miniature (0.2 mm diameter) hydrophone as the receiver. The transmitter was excited as described above using gated 2 MHz sinewaves of 1/2 ,4 and 12 cycles, respectively. As a result of the finite bandwidth of the transducer, its velocity motion consisted of an extra cycle of velocity with an approximately exponential rise and fall of amplitude at the onset and termination of excitation, respectively. Thus, in order to provide a better comparison between measured and calculated results, the source velocity function v(t) to be inserted into Eq. (3) consisted of, respectively, 1.5, 5 and 13 cycles, with a similar rise and fall to that observed experimentally. For both the visualisation and the pressure waveform results, the peak-to-peak amplitude of the voltage appearing across the transducers was 50 volts and their sensitivities were such that the amplitudes of the ultrasonic pulses radiated were below that at which non-linear propagation effects become important.

The pressure measurements were taken using the miniature hydrophone positioned at two ranges which corresponded with, a) an axial maximum and b) an axial minimum in the continuous wave (near) field at 2 MHz (wavelength λ= 0.75 mm). The actual ranges used were such that the axial path-difference (PD) between waves arising from the centre and the periphery of the source are $5\lambda/2$ for the maximum on axis (23.1 mm) and 2λ for the minimum on axis (29.3 mm). At the shorter range considered, the edge waves are incident (on-axis) at an angle of about 23°. At such an angle, the sensitivity of the hydrophone over the frequency range of interest here is within 3 dB of its straight-ahead response. Thus there is only a small error in the amplitude and shape of the edge-wave pulses recorded.

RESULTS

A Schlieren image of the waves radiated by the 15 mm width rectangular transducer when excited by a 1/2 cycle 0.5 MHz sinusoidal pulse is shown in Figure 1(a). As such images are 2D projections, the plane wave is seen as a straight line in front of the transducer and the cylindrical (for a rectangular source) edge wave as 2 circular arcs centred on the transducer edge and hence, extending beyond the geometric region straight ahead of the transducer. Figure 1(b) shows the field pattern of the transducer excited with a 0.5 MHz gated sinusoid of 4 cycles duration. A side-lobe structure due to the interference between edge waves from each side of the source is beginning to emerge. As the excitation pulse length is increased still further to approach the CW situation, a definite side-lobe structure exists as shown in Figure 1(c). Close to the transducer in Figure 1(c), the plane and edge waves interfere to give rise to a complicated near-field structure. Further away, the path difference between the plane and edge becomes less and the distance between axial maxima and minima becomes greater, until in the far field where the path difference is less than $\lambda/2$ no further (axial) fluctuations can occur.

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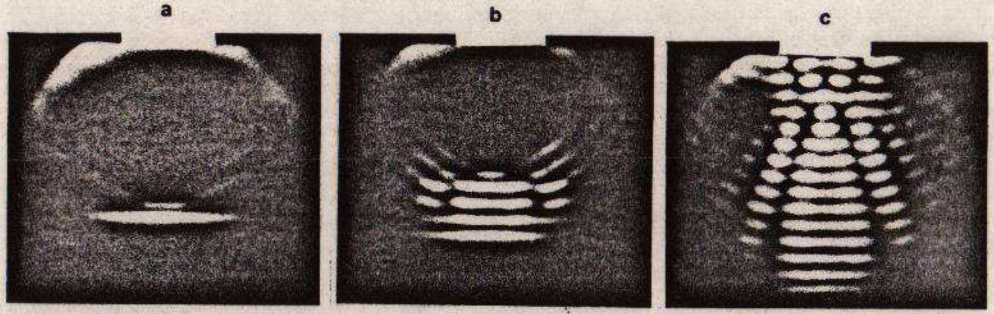

Figure 1. Schlieren visualisation of pulses propagating (in water) from a rectangular source (white bar at top) excited by gated sinusoidal waves at 0.5 MHz. a) 1 cycle pulse, b) 4 cycles, c) 15 cycles.

Figures 2 to 5 show some pressure waveform measurements in the field of a circular transducer of diameter 19 mm. The 2 MHz gated sinusoidal electrical pulses of 1/2, 4, and 12 cycles used to excite the transducer are shown in the upper traces of Figure 2(a) ,(b) and (c) and the corresponding ultrasonic pressure pulses measured on axis at a range of 29.3 mm are shown below. In Figure 2, the pressure waveforms are shown in their true time relationship to the excitation pulse, but to provide a clearer view of the pressure waveforms, views of the lower traces expanded 5 times are shown in Figure 3.

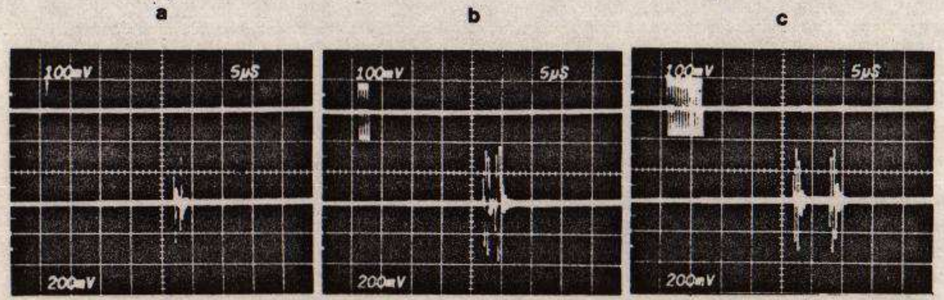

Figure 2. Excitation waveforms (top) and resulting ultrasonic pressure waveforms in water (bottom) at an axial point at range 29.3 mm from a circular transducer of diameter 19 mm. The excitation waveforms are gated 2 MHz sinusoidal waves. a) 1/2 cycle excitation, b) 4 cycles, c) 12 cycles.

The plane- and edge-wave components of the shortest pulse radiated (Figs. 2(a) and 3(a)) are clearly seen. The edge wave is shown to be equal in amplitude and opposite in polarity to the earlier arriving plane wave. Increasing the excitation pulse duration to 4 cycles causes the plane- and edge-wave components of the transmitted pulse to partially overlap and, at this range (PD = 2λ), destructive interference occurs in the region of overlap (Figs. 2(b), 3(b)) to produce a central null region. As the excitation pulse length is increased still further to 12 cycles (quasi-continuous wave), the overlap region of the plane- and edge-wave pulses becomes greater and hence the null region (Figs. 2(c), 3(c)) longer. The corresponding calculated waveforms are shown at the bottom in Figure 3 and are seen to be in close agreement with those measured.

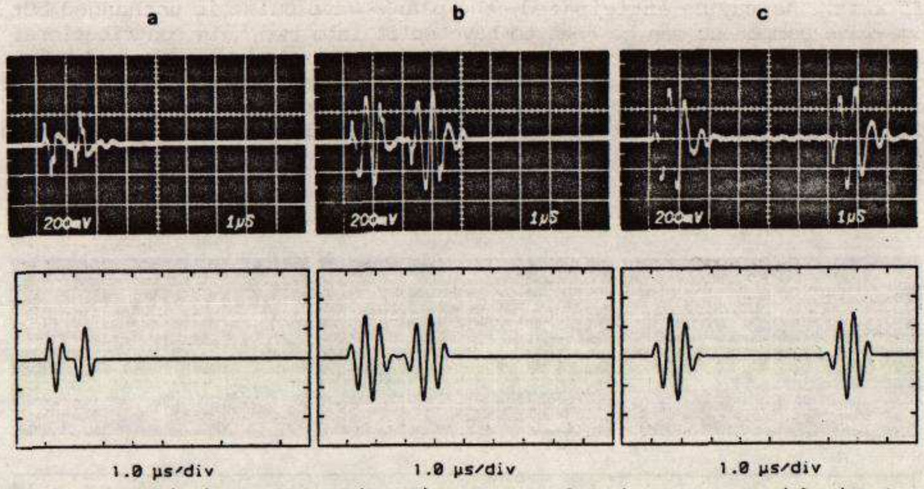

Figure 3. Measured (top) and calculated (bottom) pressure waveforms in water at an axial point at range 29.3 mm from a circular transducer of diameter 19 mm. The transducer was excited by gated sinusoidal waves at 2 MHz. a) 1/2 cycle excitation showing time-separated plane and edge waves, b) and c) 4 and 12 cycles, respectively, showing overlapping plane and edge waves.

Figure 4 shows a similar set of results to those of Figure 3 but at a range of 23.1 mm. On axis at this range, the path difference ($5\lambda/2$) between the plane and edge wave is such that where the waves overlap they superimpose to give a double-amplitude pressure pulse.

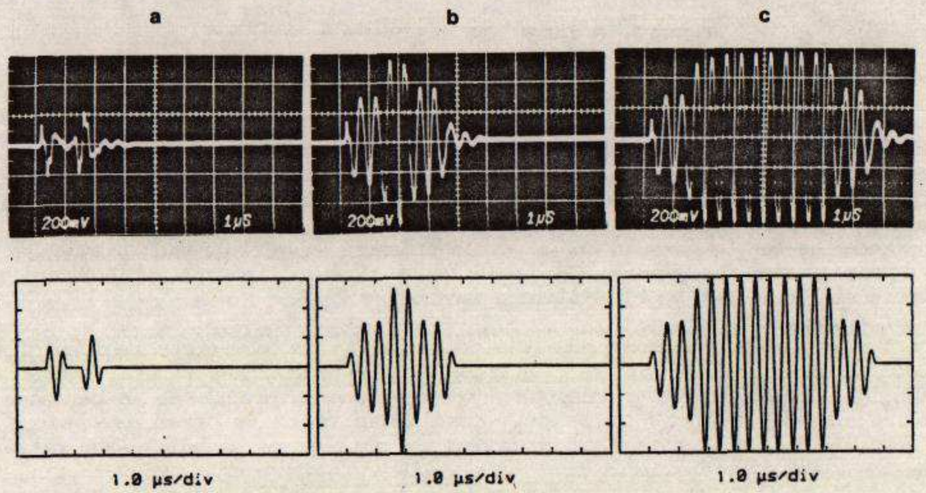

Figure 4. As Figure 3 but at a range of 23.1 mm.

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Figure 5 shows results at the same range as in Figure 3 but at a position 1 mm off axis. As may be anticipated, the plane-wave pulse is unchanged but the edge-wave component can be seen to have split into two main contributions: one from the nearer portions of the transducer rim, the other from the further portions of the rim. Since the edge-wave component is no longer an inverted replica of the plane wave, there is no longer a minimum in the region where the plane and edge waves overlap (Fig. 5 (b,c)). Again, there is good agreement with the corresponding calculated results.

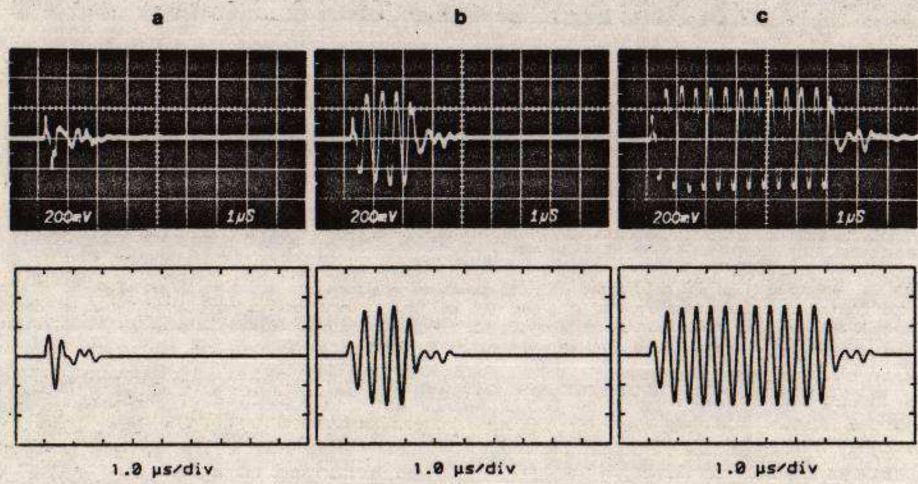

Figure 5. As Figure 3 but at a position 1 mm off axis.

DISCUSSION

The form of the results recorded here is of interest in the measurement of ultrasonic beam profiles. Detailed descriptions of pulsed and CW beam profiles have been given elsewhere [5] but briefly, in all cases their form may be explained in terms of the interactions between plane and edge waves. For instance, as can be seen in the 12 cycle pressure waveform results, axial nulls and maxima in the pseudo CW field of a circular source are due to the superposition of two equal amplitude waves.

The results clearly demonstrate the transient and steady-state regions of the field radiated by a transducer emitting a pulse containing several cycles and highlight a measurement problem if a steady-state CW profile is to be measured using pulsed pseudo CW emission. Such an approach is often used since it offers the major advantage of obviating the problem of standing-wave patterns due to unwanted reflections from tank walls etc. However, when detecting the amplitude of the waveforms care must be taken to avoid the transient pulses at the onset and termination of the pressure waveform: either time-gating can be used to exclude the transient response prior to detection , or a narrow-band filter can be employed to give the amplitude of a particular frequency in the overall pulse spectrum [5].

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Often it is convenient to produce beam profiles using a small target to probe the field in a transmit-receive mode. As is well known, the TR beam profile for the case of continuous waves is simply the square of the corresponding pressure profile. However, for the case of a transducer emitting a short pulse, the TR beam profile is much more complicated than its pressure profile. Again such an effect has been explained in earlier work [5] but briefly: for a transducer undergoing a given velocity motion in transmission, the pressure at a field point is identical in waveform to the output voltage generated by the transducer in reception if an infinitessimal source at the field point undergoes the same velocity motion. As a result of this reciprocity, extra pulses appear in the transmit-receive mode response. On the axis of a transducer emitting a very short pulse, these extra pulses superimpose to give a sharp peak in the (near-field) beam profile which is not present in the corresponding pressure profile [5].

Since all of these diffraction effects are due to the interaction of plane and edge waves, it would seem reasonable to anticipate that the field structure of a hypothetical transducer which radiates solely plane waves or solely edge waves would be much simpler. Although such idealised devices cannot be realised, they can nevertheless be approximated by certain forms of non-uniformly excited source. For instance, an edge-wave-only (EWO) source can be approximated by a transducer which is fully excited at its rim with a smooth fall-off to zero excitation at its centre [9,10]. Such a transducer has much simpler axial pulse shapes than a conventional transducer of the same aperture and in addition a response concentrated along its axis. To demonstrate the resulting improvement in lateral resolution that such a transducer offers, Figure 6 shows some images of a test target obtained with the new transducer and with a conventional transducer of the same aperture. The target consisted of arrays of 0.2 mm diameter nylon threads arranged to spell out "TCU" and below "PHYSICS", the spacing between the threads in each word being around 5 mm and 3 mm, respectively. As shown, the axial resolution of the conventional transducer is good enough to resolve the threads at each depth, but its lateral resolution is such that PHYSICS is virtually impossible to discern. However, the EWO transducer (Fig. 6(b)) clearly resolves each thread as a dot and the lower word is easily read.

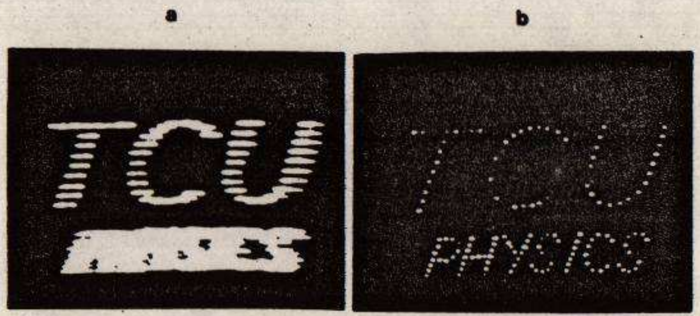

Figure 6. B-scan images of an array of nylon threads of diameter 0.2 mm suspended in water. The spacing between the threads in the words TCU and PHYSICS was approximately 5 mm and 3 mm, respectively. a) conventional 19 mm diameter transducer, b) high-resolution (EWO) transducer of the same diameter.

CONCLUSION

Schlieren visualisation of the pulse radiated into water by a rectangular slit-like transducer undergoing gated sinusoidal motion of various cycle lengths has confirmed that the structure of the field is due to the interaction of plane and edge waves. The complicated structure of the pseudo CW near field is a consequence of the interference of plane and edge waves in the geometric region straight ahead of the source, whereas the formation of side lobes outside the geometric region is due to interference between edge waves from each side of the source.

Measurements of pressure waveforms in the field of a circular transducer emitting gated sinusoidal waves also show a plane- and edge-wave structure and are in close agreement with calculated results obtained using an impulse response method. At all points on axis, the edge wave gives rise to an inverted replica of the earlier arriving plane wave, in spite of the spreading nature of the edge wave. In the quasi continuous-wave situation, measurements and calculations show that axial nulls occur at ranges where the path difference between the plane and edge waves radiated is an even number of half-wavelengths, whereas axial maxima occur at ranges where the path difference is an odd number of half-wavelengths. Such observations remind us that the edge wave is not just a simple wave from the rim, but results - as does the plane wave - from the superpositon of Huygens' wavelets from the whole surface of the source. Off axis, the plane-wave component remains constant but the edge wave splits into two smaller pulses, one contribution from the nearer portion of the transducer edge and the other from the further.

Some of the limitations in resolution which arise due to the plane- and edge-wave structure of the ultrasonic field radiated by conventional sources can be avoided by the use of non-uniformly excited transducers which radiate solely edge waves.

ADDENDUM

A video recording was presented showing:- a) Schlieren visualisations demonstrating the transition from quasi continuous wave to short ultrasonic pulse emission, reflection of a short pulse by a small target and scatter of a short ultrasonic pulse at surface irregularities; b) the variation of pressure waveform as a small hydrophone is scanned along various planes in the field of a transducer radiating gated sinusoidal waves; c) B-scan images of a test array which compare the performance of a newly-developed high-resolution transducer with that of a conventional transducer of the same aperture.

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