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LABORATORY STUDIES OF ACOUSTIC SCATTERING

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1. ABSTRACT

Two complementary techniques of investigating acoustic scattering from discrete objects in the laboratory are described and their performance illustrated. The first technique uses a Schlieren system that has been designed to visualise low-frequency pulsed and continuous ultrasonic waves in water over the frequency range 100-500kHz. Although this approach is mainly limited to structures with translational symmetry the system allows the development of the acoustic field to be studied in detail. The use of the Schlieren system to study the fluid column, shell and Stoneley wave resonances of a fluid filled cylindrical shell is considered and illustrated. The second technique uses a parametric array as an acoustic source to enable accurate broad-band scattering measurements to be made over the frequency range 10-270kHz. Sample measurements of the scattered field for cylinders are shown as a function of scattering angle and frequency, and compared with theoretical predictions. The potential application of these techniques to scattering from irregular particles is indicated.

2. INTRODUCTION

As new theoretical developments are made in the area of acoustic scattering from discrete objects there is a need for careful experimental measurements to confirm the theoretical predictions. There is also a requirement for accurate techniques that can be applied to the measurement of scattering from irregular shapes, such as sediment particles, for which theoretical predictions are not available. This paper describes two complementary experimental facilities that have been developed for making accurate observations of scattering over a wide range of frequencies in the laboratory. These facilities are now being used to improve the understanding of scattering processes.

The first facility uses the Schlieren technique to visualise the waves scattered from objects in water. This method of visualising phase objects is over a hundred years old and has been widely used for investigating ultrasonic scattering [1,2] although most of the work has been confined to frequencies in the megahertz region. The facility described here has been especially designed to work at much lower frequencies, and is capable of visualising both pulsed and continuous waves in the frequency range 100-500kHz [3].

The second facility is based on a parametric array as an acoustic source and is used to make accurate scattering measurements over the frequency range 10-270kHz in a relatively small test tank. The use of a parametric array allows short duration broad-band pulses to be obtained and enables individual contributions to the scattered signal to be identified. In addition the narrow beam cross-section of this source minimises reflections from the walls of the tank.

3. LOW-FREQUENCY SCHLIEREN SYSTEM

3.1 Experimental System

The Schlieren technique relies on the fact that light is diffracted as it passes through an acoustic field in water. A diagram of the Schlieren system is shown in Figure 1. Light from the high power light emitting diode (Toshiba TLRA150/C), radiating at 660nm, is collected and focused onto a pinhole aperture by a pair of condensing lenses. The light transmitted by the pinhole is collimated by the first parabolic mirror, of 15cm diameter and 1.2m focal length, and allowed to pass through a water tank in which an ultrasonic transducer produces the wavefield to be observed. The emerging light is then brought to a focus by the second parabolic mirror, which is identical to the first, to form a diffraction pattern corresponding to the phase grating produced by the acoustic field in the tank. A spatial filter is introduced at this point to remove one or more of the diffraction orders and the remaining light then combines to form an image of the acoustic field. The type of image obtained depends on which orders are filtered out but it is usual for the centre, or zero, order to be removed so that the image has a dark background. Considerable care must be taken in interpreting the images as they are very dependant on the acoustic pressure and spatial filter used [4].

If the ultrasonic transducer is pulsed, an image of the wavefield at any point in its development can be obtained by pulsing the optical source at the same repetition frequency. As the time delay between the acoustic and optical pulses is slowly increased, this stroboscopic technique allows the propagation of the ultrasonic pulse to be visualised and studied in slow motion. Individual wavefronts are resolved if the light pulse is short enough.

In the spatial filter plane, the separation of the diffraction orders is inversely proportional to the acoustic wavelength so that for the present system the separation is only 100µm for a frequency of 200kHz. In order to ensure that the diffraction orders do not overlap significantly it is necessary to use a small pinhole and minimise the optical aberration of the system. The use of a small pinhole, however, causes a reduction in the light passing through the acoustic field to the final image. This has been overcome by using a random array of pinholes to multiply the amount of light present. This is possible since the light source used is incoherent and so unwanted diffraction effects do not occur. One pinhole array used for frequencies above 200kHz consists of a set of eight holes in a semi-random pattern, each hole 100µm in diameter and 300-400µm apart. Two main sources of aberration exist in the system - the mirrors being used off-axis and the presence of the glass water-filled tank. The mirrors used in the present system produce some astigmatism since they are not specifically designed for use off-axis. This astigmatism has been reduced by the use of a compensating cylindrical lens. The aberration introduced by the tank walls has been minimised by careful selection and testing of the glass used before construction of the tank. In addition thick plate glass is used to prevent bowing under the pressure of water in the tank.

3.2 Performance

An example of the type of image obtainable at low ultrasonic frequencies is seen in Figure 2 which shows the scattering of a 230kHz toneburst from a flooded stainless-steel cylinder. The cylinder used here has an inner radius of 13.7mm and an outer radius of 15.8mm. The transducer, of 30mm diameter, may be seen at the right of the picture with a bright streak across its face due to a small temperature gradient set up in the water near the radiating element. Figure 2 shows the wavefield partially reflected from the front surface of the cylinder and partially transmitted into the interior fluid. The waves within the fluid have been reflected and focused by the curved inner surface of the cylinder.

Although the system was designed to operate in the pulsed mode it has been found to be particularly useful when the source is driven continuously. In this case it may be used to study the resonance behaviour of fluid filled cylindrical shells. Under resonance conditions the incident acoustic field generates a standing wave pattern in the fluid column that can be observed using the Schlieren system. This is illustrated in Figure 3a which shows the (7,4) fluid column resonance of the same stainless-steel shell at 315kHz. It is also possible to detect the standing wave patterns created by Stoneley wave resonances and shell resonances. The observed images are in very good agreement with theoretical predictions [5] as shown in Figure 3b.

4. PARAMETRIC ARRAY FACILITY

4.1 Experimental system

The experimental configuration used is shown in Figure 4 and has been described in detail elsewhere [6,7]. The drive waveform (Figure 5a) consists of a carrier frequency, in this case 920kHz, amplitude modulated with a raised cosine bell envelope (Figure 5b). This waveform is then applied to the transducer via a power amplifier. The resulting low-frequency waveform generated by the parametric array on axis is proportional to the second derivative with respect to time of the square of the envelope (Figure 5c). Thus the length and frequency content of the generated waveform can be adjusted by altering the frequency of the raised cosine bell envelope, f_c.

The acoustic measurements were made in a laboratory tank of 1.2 x 1.2 x 1.8m. The parametric array is truncated about 0.6m beyond the transducer by an 'acoustic low-pass filter' which attenuates the carrier frequency by more than 30dB and means that the receiving hydrophone is in a region free from high amplitude primary waves. This ensures that errors due to hydrophone nonlinearity are not a problem. The output from the hydrophone (Brüel & Kjær 8103) is passed through a passive low pass filter, amplified and recorded prior to processing within an ANALOGIC DATA 6000E.

The measurement technique uses the stability of the acoustic output to enable the coherent background signal in the tank to be subtracted leaving only the scattered signal. For measurements at normal incidence the scattered signal (Figure 6a) is recorded with the hydrophone at a known observation range (r) and angle (ϕ). The cylinder is then removed and the coherent background is recorded (Figure 6b). This can be subtracted to leave only the scattered signal (Figure 6c). The hydrophone is then moved to the position of the centre of the cylinder and the incident signal recorded (Figure 6d). It should be noted that the start of the time window for Figure 6d is not the same as that for Figures 6a-c. The signals shown in Figure 6 are for an incident pulse with f_c = 100kHz, scattered from an aluminium cylinder with a radius (a) of 0.0135m at an observation distance of 0.3m and an angle of 90°. The experimental form function is obtained from the ratio of the spectrum of the scattered signal to that of the incident signal, multiplied by $\sqrt{2r/a}$.

4.2 Examples of performance

The performance of the system is illustrated with measurements of the scattering from an aluminium cylinder of radius 13.5mm. Figures 7 and 8 show the experimentally measured form function for a normally incident wavefield observed at 180° (backscatter) and 90° respectively. In this case the experimental results were repeatable to within 3% and hence any differences between theory and experiment are unlikely to be due to random error. The results have been compared with a theoretical prediction which assumes an infinite cylinder and an incident plane wave of infinite extent [8]. In general the agreement between theory and experiment is reasonable, although there are several differences. In the backscattered case (Figure 7) the shadowing effect of the hydrophone and its support becomes significant and this results in a lowering of the experimental values which becomes more pronounced at higher frequencies.

The results presented in Figures 7 and 8 show a narrow resonance feature at a ka value of 8.1, which is not present in the theoretical predictions. The observation of this resonance at normal incidence is attributed to the fact that the incident wavefield is not a single plane wave. The incident field can be considered to be a spectrum of plane waves with some components incident on the cylinder at oblique incidence. This means that the observed form function will include the response of the cylinder over a range of angles, not just normal incidence. There are other features visible in the theoretical plots (Figure 7) which are not seen experimentally. These differences may be partially attributed to the frequency resolution of the experimental results not being adequate for very narrow band features. The main differences, however, occur because the experimental measurements integrate the form function over the plane wave spectrum of the incident wavefield. A similar effect has been observed by Maze, Izbicki & Ripoche who found it necessary to account for the oblique components of the incident wavefield when using a short tone burst at normal incidence on a solid cylinder [9]. The plane wave spectrum has been found to affect measurements of transmission through panels in a similar way [10]. This effect is currently being investigated further with the initial results showing very good agreement with experimental observations.

This technique has also been applied to the measurement of scattering from spheres [6], flooded and air-filled cylindrical shells with similar precision shown in the results. The technique is not limited to normal incidence but may also be used to make measurements for oblique incidence. In the longer term it is hoped to apply similar techniques to the measurement of scattering from irregular bodies and distributions of particles in order to study the scattering properties of sediments in suspension.

5. CONCLUSIONS

The two experimental systems described are powerful laboratory tools for the investigation of scattering phenomena. The Schlieren system, although confined to bodies with translational symmetry, enables the scattering process to be viewed overall, while the parametric array facility enables accurate scattering data to be obtained for a range of scattering geometries over a wide range of frequencies.

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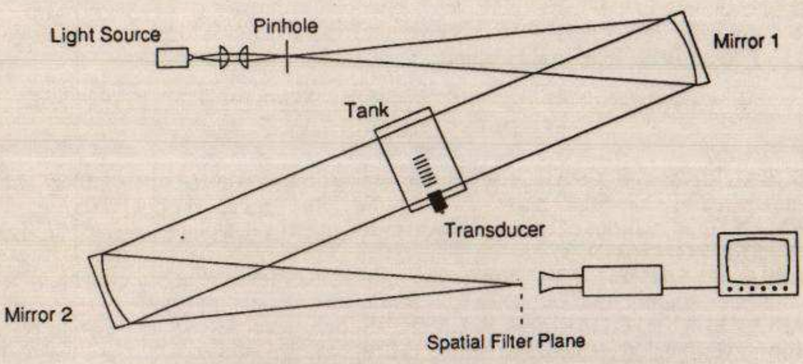


Figure 1. The Schlieren system.

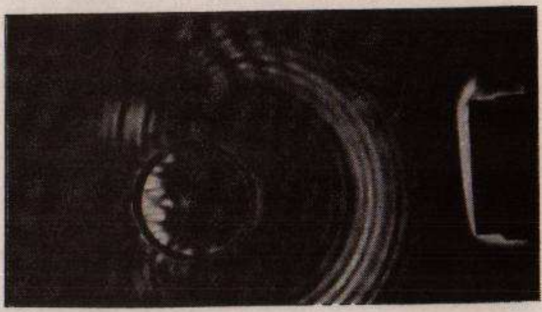
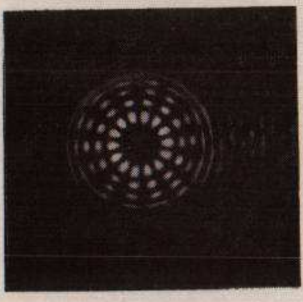
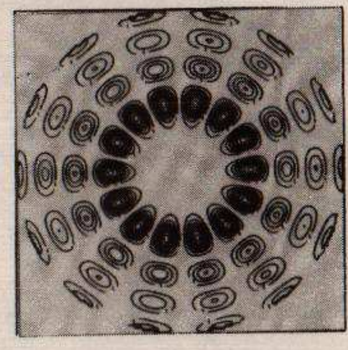


Figure 2. Scattering of a 230kHz toneburst from a hollow, flooded stainless steel cylinder.

a) b)
Figure 3. Fluid column resonance at 315kHz; a) experiment and b) theoretical prediction.

Figure 4. Experimental configuration.

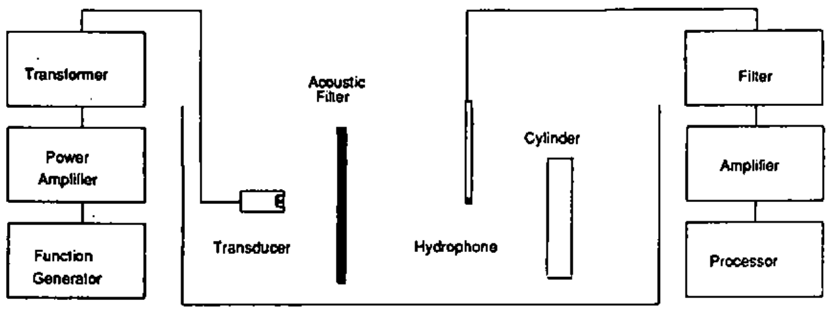


Figure 5. Experimental waveforms.

a) Drive waveform

b) Raised cosine bell

c) Low frequency signal

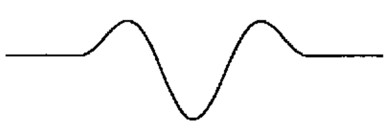
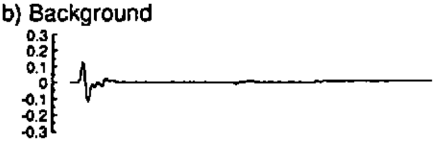


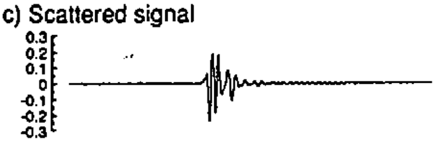
Figure 6. Scattered waveforms.

a) Scattered signal and background

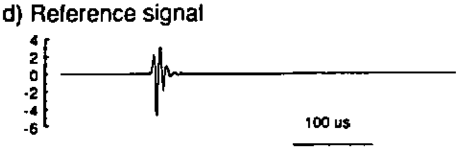
b) Background



c) Scattered signal



d) Reference signal



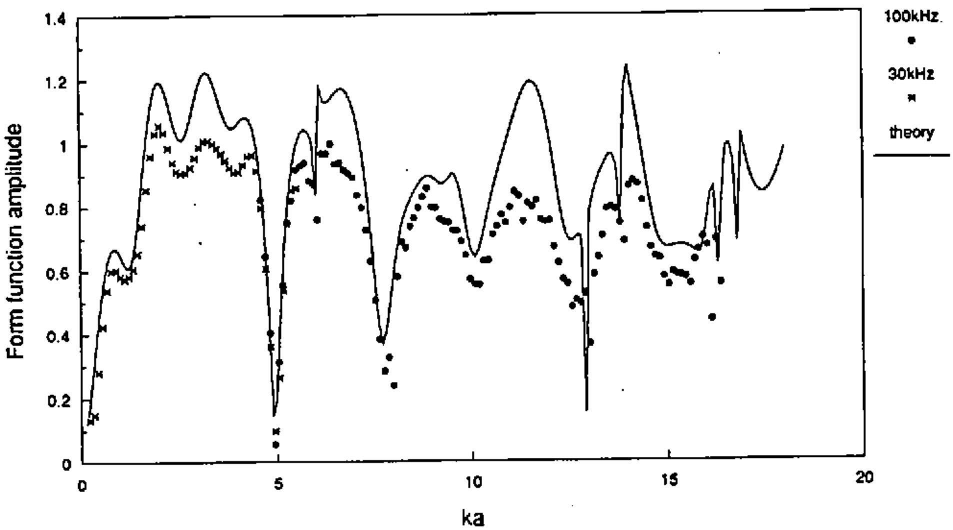


Figure 7. Form function for aluminium cylinder at normal incidence, observed at 180°.

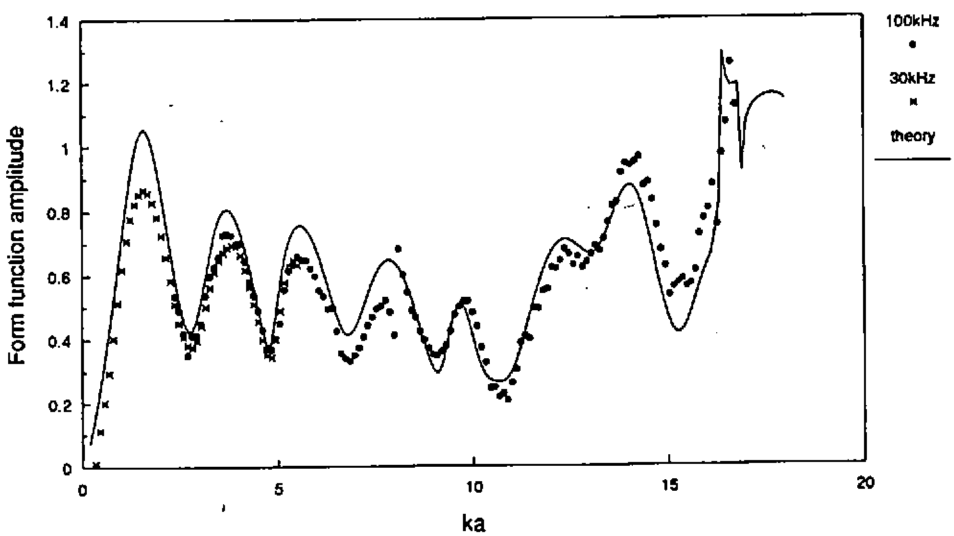


Figure 8. Form function for aluminium cylinder at normal incidence, observed at 90°.