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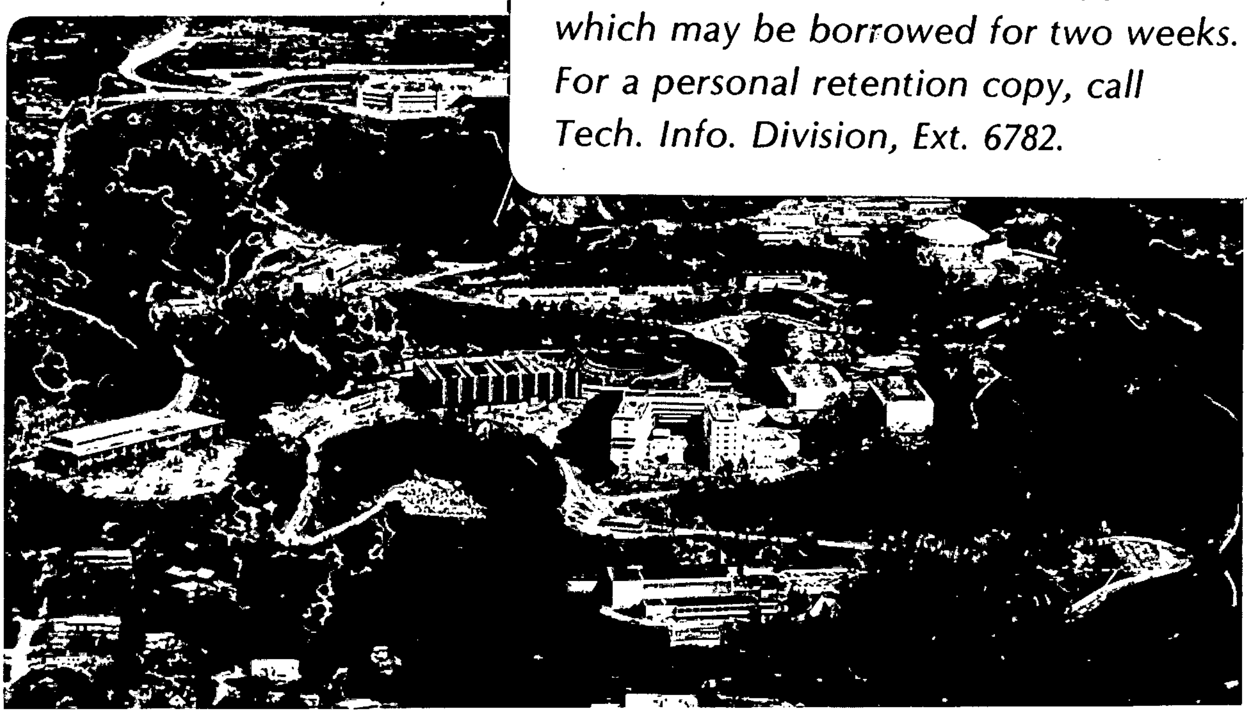

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ACOUSTIC IMAGING OF VAPOR BUBBLES THROUGH OPTICALLY NON-TRANSPARENT MEDIA

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ABSTRACT

A preliminary investigation of the feasibility of acoustic imaging of vapor bubbles through optically non-transparent media is described. Measurements are reported showing the echo signals produced by air filled glass spheres of various sizes positioned in an aqueous medium as well as signals produced by actual vapor bubbles within a water filled steel pipe. In addition, the influence of the metallic wall thickness and material on the amplitude of the echo signals is investigated. Finally several examples are given of the imaging of spherical bubbles within metallic pipes using a simulated array of acoustic transducers mounted circumferentially around the pipe. The measurement procedures and a description of the measuring system are also given.

I. INTRODUCTION

In nuclear power reactors cooled by water or liquid sodium, it is important that a continuous flow of coolant be maintained on the walls of the various heat exchangers used to extract thermal energy from the reactor. Because of the dangers of dryout in these cooling systems, it would be highly desirable to be able to observe the presence of vapor bubbles and liquid film flow within the cooling structure. Since the heat exchangers are made of metal and operate under conditions of high pressure and temperature, it is not generally possible to provide windows or other means to permit optical viewing of their interior conditions.

A number of methods[1,2] have been employed to investigate two-phase flow conditions existing in reactor safety research facility cooling systems. Direct optical viewing with TV or other cameras has frequently been applied to studies of transparent model systems. The present authors have developed[3] an electro-optical system for the imaging and computer analysis of two-phase flow parameters in such model systems. For opaque systems, the methods used include conductivity and capacitance probes, thermocouples, flow-meters of various types, and gamma ray and flash x-ray absorption techniques. Although the above mentioned methods have been an effective tool for reactor safety research, there is a need for non-intrusive measurements of local two-phase flow phenomena through optically non-transparent media.

Acoustic imaging techniques have been developed in recent years for use in medical diagnosis, nondestructive testing, microscopy, underwater imaging and seismic exploration[4,5,6]. In the nuclear power field, acoustic methods have not to our knowledge been used for the imaging of fluids within piping structures. Lynnworth et al[7] have reviewed other uses of ultrasonic techniques in nuclear reactor applications. In addition, acoustic flowmeters[8] have been developed for measuring the flow rates of fluids passing through metallic pipes.

In this paper we report a preliminary investigation of the use of acoustical imaging as a technique for studying the conditions within a metallic pipe.

II. EXPERIMENTAL APPARATUS

The experimental apparatus used to generate and detect the acoustic echo signals is shown in Fig. 1 and described in greater detail in Ref. 9. A commercially available ultrasonic transducer (Parametrics model V112) was mounted on a flattened portion of the outside wall of a steel pipe, using a coupling fluid (mineral oil) to maintain acoustic contact. The pipe was filled with water and a reflecting object suspended in the acoustic beam. Micrometer driven positioners were provided to enable the suspended object to be moved in the x, y and z directions.

Electrical pulses to drive the transducer were generated by an HP model 8012B pulse generator and driver amplifier. Symmetrical pulses of amplitude approximately 10 V and width 150 ns were used. A receiver consisting of two wide bandwidth operational amplifiers with a total gain of 80 dB was used to detect the echo signals produced by the transducer. An active gating circuit decoupled the transmitter during the receive phase.

A multiple stop time digitizer[10] was used to convert the acoustic echo arrival times into digital form for analysis and imaging by a PDP 11/34 computer. This CAMAC based unit has a time resolution of 0.125 ns and provisions for loading both the time range during which echo timing pulses are accepted and the dead time (140 ns min.) between accepted pulses. The digitizer timing was initiated by the transducer excitation pulse and multiple stop pulses were generated by one of two discriminators connected to the receiver output. Depending on the nature of the echo pulses received, a level discriminator could be used to detect any signals of amplitude greater than a preset threshold, and a differential discriminator could be used to detect rapidly changing pulses on a more slowly changing baseline.

A first in-first out (FIFO) derandomizing register with a capacity of 128 stop times was employed to buffer the digitizer output. The timing data was then stored in a multi-channel analyzer and transmitted to the computer via a serial data link. For some measurements in which the anticipated number of stop times was less than the capacity of the FIFO, the data was read out to the computer directly via a CAMAC interface.

III. ECHO SIGNALS FROM SPHERICAL REFLECTORS

Due to surface tension effects, vapor bubbles produced in a cooling system have a tendency to be spherical in shape. In addition, their smooth boundary surfaces will produce specular reflections of acoustic pulses. For this reason it is worthwhile to examine the echo signals produced by spherical reflectors.

The acoustic field produced by the ultrasonic transducer is confined to a narrow beam directed along the normal to the transducer face. At short distances (less than the Fresnel length), the diameter of the beam is nearly constant and approximately equal to the diameter of the transducer, while, at greater distances, the beam diameter increases linearly with distance. If a flat reflector is placed in the field with its normal vector parallel to the beam, the acoustic energy will be specularly reflected back to the transducer and detected as an echo. The amplitude of this echo signal will be approximately proportional to the ratio of the transducer diameter to the beam diameter at a distance equal to the total path length.

If a spherical object is placed in the acoustic field with its center on the beam axis, the reflected wave will not only be returned to the transducer plane, but off-axis rays will diverge into a cone, thereby resulting in an echo signal whose intensity is significantly reduced over that from a planar reflector. Combining the divergence produced by the sphere with that of the acoustic beam in the far field, one would expect the echo amplitude for a given sphere to decrease approximately as $(1/z)^2$. In addition, for a fixed transducer-reflector distance, the amplitude should be approximately proportional to the diameter of the sphere.

In Fig. 2 we have plotted a family of curves showing the echo amplitudes produced by spheres of three different diameters. The figure shows the signal as a function both of distance and lateral displacement of the sphere center from the acoustic axis. At the bottom of the figure is shown the geometrical arrangement employed. The transducer was mounted on one wall of a rectangular plastic tank containing the sphere.

From the figure, one can see that the echo amplitudes are approximately proportional to the diameter of the sphere and decrease rapidly with distance as expected. The effect of a lateral displacement of the sphere from the beam axis is to decrease the amplitude of the reflected signal. The rapid decrease of signal amplitude with lateral displacement is of particular significance to the imaging problem. It implies that vapor bubbles will be "seen" by a given transducer only when their local centers of curvature lie close to the transducer axis. For the transducers used in these experiments, the effective range of acceptable displacement is about 2 mm.

IV. ECHO SIGNAL TRANSMISSION THROUGH METALLIC WALLS

The transmission of an acoustic wave through a metallic wall into the water medium is accompanied by a large reflected wave caused by the impedance discontinuity[11] at the boundary. As a result, the fraction of the incident acoustic energy which passes into the water medium and is available for echo formation is significantly reduced. In addition, the reflected wave bounces repeatedly between the two metallic walls and produces a reverberation signal which can obscure the desired echo signal.

The reflection coefficients for an acoustic wave incident normally on an interface between materials of impedances Z_1 and Z_2 is given by (11)

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad .$$

Calculations show that, for normal incidence, only 11.7 percent of the initial amplitude is returned to the transducer plane after a two-way transmission through a steel wall. For an aluminum wall, the impedance discontinuity is less and 29.5 percent of the amplitude is returned to the transducer plane. For angles of incidence other than 90 degrees, the longitudinal transmission and reflection is accompanied by the generation of shear waves in the metallic medium and refraction of the acoustic beam at the interface. Within the liquid medium only longitudinal waves are propagated.

In addition to the transmission loss which occurs at the metallic boundary, there are other effects which contribute to the amplitude of the echo signals observed through the metallic wall. Measurements were made of the echo signals produced by reflectors of differing geometrical shapes detected through alumimum and steel plates of various thicknesses. In Fig. 3 is shown a graph summarizing these results for the case of aluminum. For spherical reflectors, the echo amplitude is found to be proportional to 1/t, where t is the wall thickness, while for cylindrical reflectors, the signal is proportional to the square root of 1/t. On the other hand, for planar reflectors, the echo signal is almost independent of the wall thickness. For a steel wall, similar results are obtained after accounting for the increased losses due to the less favorable impedance discontinuity.

These results can be explained qualitatively by examining Fig. 4 in which an acoustic ray path for a reflection from a spherical or cylindrical object is shown. Two cases are illustrated in the figure: a thin metal wall and (dotted) a thick wall. The incident ray has been chosen to intercept the sphere slightly below its center. As a result, the reflected ray crosses the metallic boundary at a small angle and is refracted away from the normal. In the case of a thin wall, this ray is intercepted by the transducer, while for a thick wall it is not. For a sphere, this refraction spreading of the beam occurs along both axes in the transducer plane while, for a cylinder, the beam is spread in one direction. Since the detected energy is inversely proportional to the area of the beam crossing the transducer plane, the results observed in Fig. 3 are explained.

The significance of the above observations to the acoustical imaging problem can be summarized as follows: (1) an appreciable fraction of the incident acoustic energy will be lost at the metal-water interface due to the impedance mismatch, (2) reverberation effects within the metal wall can obscure the desired echo signals and (3) imaging through a thick wall will reduce the amplitude of the echos from spherical reflectors.

V. ACOUSTICAL IMAGING

In the above discussion we examined the generation and detection of acoustical echo signals from spherical and other reflectors located in an enclosed water medium. With a single transducer it is possible to locate only one spot on the surface of the reflector. In order to obtain a two dimensional image of the object, it is necessary to employ an array of transducers appropriately positioned to provide a complete view of the region being imaged. A number of possible options exist for choosing the locations of the transducers making up the array. In this preliminary investigation, we have chosen to position the transducers around the outer circumference of the pipe at equal angles within a single plane. With this arrangement, the object being imaged will be detected by a number of transducers as it passes through the plane of observation. The distance ranging information generated by these transducers can then be processed by the computer to produce a polar display of the imaged region.

In order to reduce the experimental complexity, instead of an array, a single transducer was used together with the apparatus shown in Fig. 1. The object, a thin wall glass sphere, was suspended in the water filled pipe at a fixed position. Measurements were then made with the transducer mounted at one position around the circumference of the pipe and the results were stored in the computer. These measurements were repeated at all of the chosen angular locations. The computer then converted the echo timing and angular data into an appropriate form for graphical display.

To perform real time imaging of a moving object it would, of course, not be possible to use a single transducer. In this case an actual array of transducers would be mounted on the pipe. These would then be pulsed in rapid succession and the data collected using a multiplexer to scan the array. Such an arrangement is under consideration for the next phase of this work.

In the following sections we consider two examples illustrating the generation of acoustical images of spherical objects within water filled pipes. In the first case, a plastic pipe was used and in the second, a stainless steel pipe was employed.

A. Imaging in a Plastic Pipe

Because the acoustic impedance of plastic (lucite) is more nearly equal to that of water, a better impedance match is achieved at the solid-liquid interface than can be obtained with metallic walls. As a result, the reverberation echos within the wall are dramatically reduced, making it easier to obtain echo signals without interference. In addition, it is convenient to be able to view the inside of the pipe.

A glass sphere of diameter 29.5 mm was suspended in a lucite pipe of outer diameter 152 mm and wall thickness 6.3 mm. The transducer was clamped directly to the curved surface of the pipe using a coupling fluid. The acoustic echo signals were digitized and stored in the computer for 18 angular positions around the circumference of the pipe after which the data was analyzed and plotted. Figure 5(a) shows a typical bubble echo signal obtained with this arrangement. In the figure a few echos from the front wall can be observed and two echos from the bubble can be seen.

In Fig. 5(b) is shown the computed image of the bubble positioned at the center of the pipe. In the figure, dotted circles have been plotted corresponding to the inner diameter of the pipe and the centered bubble; the echo positions are indicated by crosses. The computer was instructed to plot only single front wall and bubble echos for each angle. Note the presence of bubble echos at all angular positions.

In Fig. 5(c) results are shown for a bubble located off-axis at coordinates (11.4 mm, -19.7 mm). In the figure, all of the echo signals detected by the discriminator are plotted. Since the bubble echo signals are produced only when the center of the sphere is near the acoustic beam line as described in section III, only two opposing faces of the sphere are imaged.

B. Imaging in a Steel Pipe

The imaging of vapor bubbles within a steel pipe is complicated by the presence of reverberation echos within the pipe wall which obscure the reflections from the bubbles. Figure 6(a) shows the echo signals produced by a 29.5 mm dia. sphere positioned in a stainless steel pipe of dia. 63 mm and wall thickness of 3.2 mm with the transducer mounted on a flat surface perpendicular to the pipe axis. The multiple echos make it very difficult to detect the position of the face of the bubble.

If the outside wall of the pipe is furnished with a transducer mounting surface consisting of a flat area inclined at a small angle with respect to the surface normal, the multiple echo pulses will no longer be returned to the transducer. Instead they will traverse a ziz-zag path down the length of the pipe and not be detected. Figure 6(b) shows, for the same pipe and spherical reflector, the echo signals detected by a transducer inclined at an angle of 10 degrees to the normal. It is evident from the figure that a dramatic reduction in the number of spurious echos can be obtained by tilting the transducer. Although a tilt angle of 10 degrees is used, the actual tilt angle of the refracted acoustic beam in the water medium is only 2.5 degrees.

An identical steel pipe to that described above was fitted with an array of 20 mounting surfaces at 18 degree intervals. Each surface was inclined at an angle of 10 degrees to the normal. Two examples of the imaging of spherical bubbles using the above pipe are illustrated in Fig. 7. In 7(a) a 29.5 mm diameter bubble was located at the pipe center. With a 14.8 mm diameter bubble located at (5.6 mm, - 4.2 mm), the image in 7(b) consists of two echos diametrically opposed.

VI. DETECTION OF ECHOS FROM REAL VAPOR BUBBLES

We have investigated the echo signals produced by phantom vapor bubbles constructed from thin wall glass spheres filled with air, and demonstrated the formation of images produced by these bubbles. It is important to compare these results with echo signals generated by real air bubbles in the liquid in order to evaluate the potential for imaging them. Air bubbles were produced by pulsing an electrically operated valve which was mounted on the bottom of a steel pipe and connected to a compressed air supply. The transducer was attached to the wall of the pipe using a 10 degree tilted mounting surface as described above. In order to photograph the echo signals produced by the bubbles, a coincidence circuit (9) was combined with the apparatus shown in Fig. 1 to trigger the oscilloscope only when an actual bubble passed the transducer.

Figure 8 shows a typical echo signal produced with this arangement. In the upper trace, a double exposure was taken to show both the bubble echo at delay 26 μs and the rear wall echo from the pipe at 75 μs. The lower trace shows the acceptance gate used to provide the oscilloscope trigger signal.

The above measurements show that reliable echo signals can indeed be detected from real bubbles within the pipe. Since the apparatus used in this experiment included only one transducer, it was not possible to generate an image of these moving bubbles. Actual imaging of the bubbles will be investigated in future experiments using an array of transducers.

VII. SUMMARY

We have seen that it is possible to produce two dimensional images of spherical reflectors by acoustical ranging through the walls of a steel pipe in spite of the large impedance discontinuity which exists at the metallic boundary. In addition, while no actual images were generated, it was demonstrated that suitable echo signals are produced by real vapor bubbles as well.

Measurements of the echo signals produced by spherical reflectors of various sizes and at various positions within the water medium were made. These measurements show the dependence of the echo amplitude on bubble size and distance from the transducer. More importantly, they illustrate the fact that for an echo to be observed at all, the bubble center must lie close to the center of the acoustical beam line. For non-spherical bubbles, the same argument applies to the local center of curvature of the bubble. As a result, for an array of transducers, only a limited number of elements of the array will yield echo signals. For a single spherical bubble, as we have seen, the echo signals can be used to determine uniquely the diameter and center of the bubble. For situations in which the bubble is non-spherical or a number of bubbles are present, the imaging problem is more complex. In such cases, more sophisticated transducer arrays and associated data processing algorithms may have to be employed.

Measurements of the effect of wall thickness on the echo signals from spherical reflectors show that the amplitude of these signals is significantly reduced when the pipe wall is thick. In addition, the presence of reverberation echos within the front wall can obscure the desired echo pattern, making imaging more difficult. We have found that a solution to the problem is afforded by machining an inclined transducer mounting surface on the pipe. With this arrangement, reliable echo signals can be discriminated from reflectors which are positioned as close as one millimeter from the pipe wall.

For practical monitoring applications in nuclear reactor systems, the imaging apparatus must be operable under conditions of high pressure, temperature and radiation fields. The transducers employed in the present experiments were constructed of lead niobate and have a rated operating temperature of no more than 60°C. As a result they would not be suitable for high temperature applications. On the other hand, ceramic transducers of the PZT type can be used(12) at temperatures up to about 250°C. For even higher temperatures, electromagnetic transducers employing nickel or other magnetic materials may be applicable(7). In addition, it is possible to employ a buffer rod to maintain a safe operating temperature for the transducer. However, as we have seen, one must use caution in introducing an excessively thick wall between the transducer and the liquid medium.

ACKNOWLEDGMENTS

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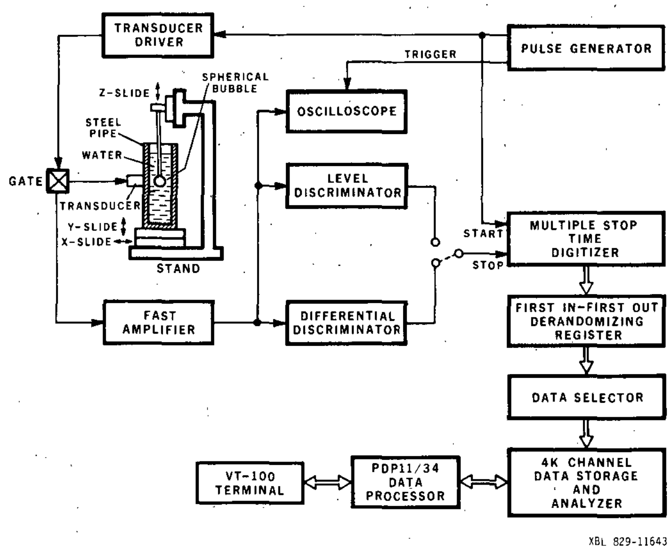


Fig. 1 Block diagram showing the apparatus used for observing acoustic echo signals and for obtaining digital information for the computation of images.

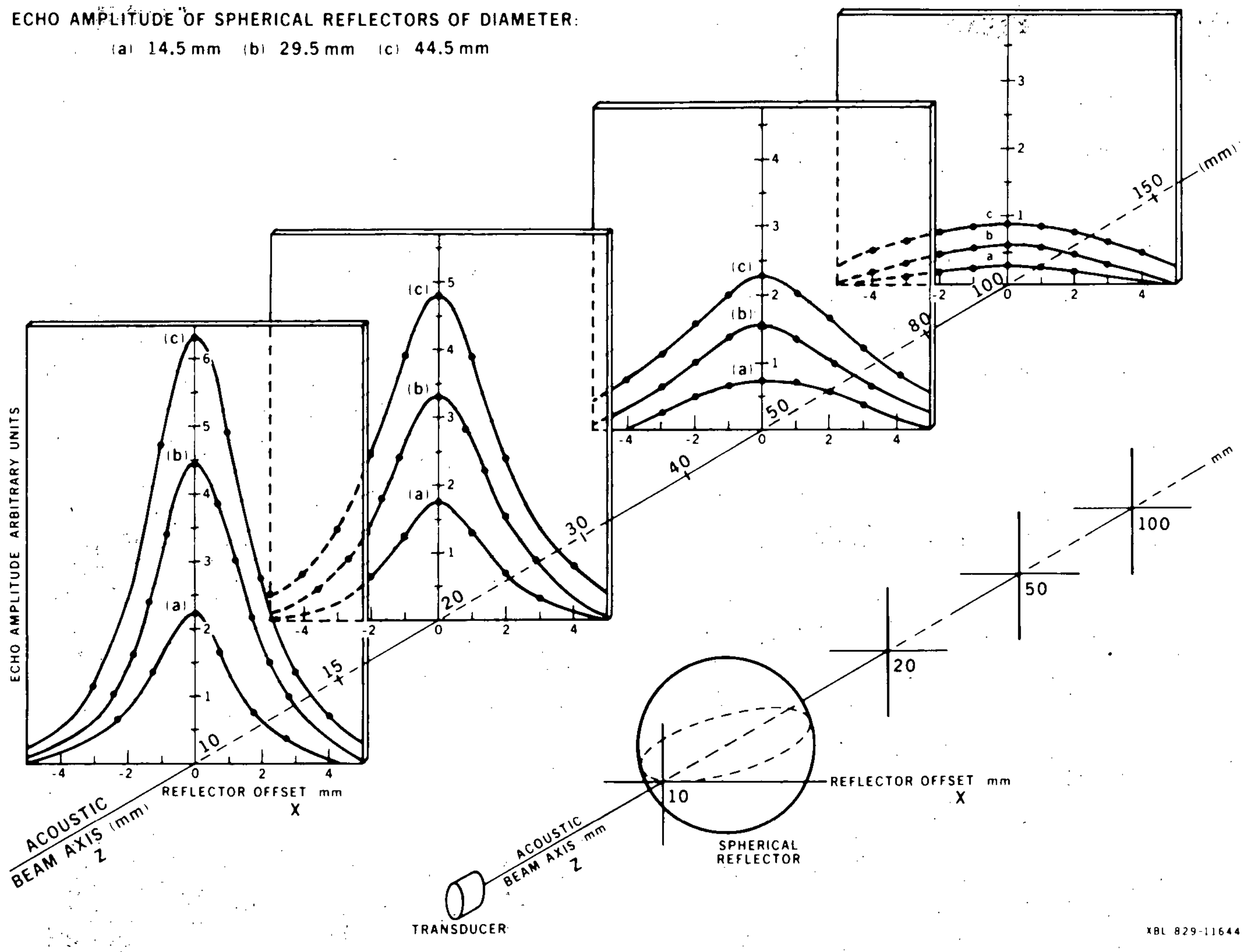


Fig. 2 Graphical presentation of echo signals from spherical bubble immersed in water as a function of bubble size, distance from transducer and lateral position.

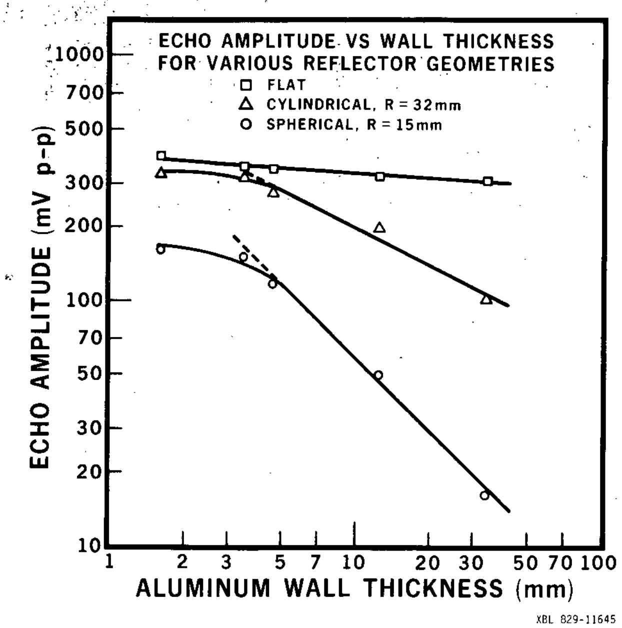


Fig. 3 Graph showing the echo amplitude for various reflector geometries as a function of the wall thickness, t.

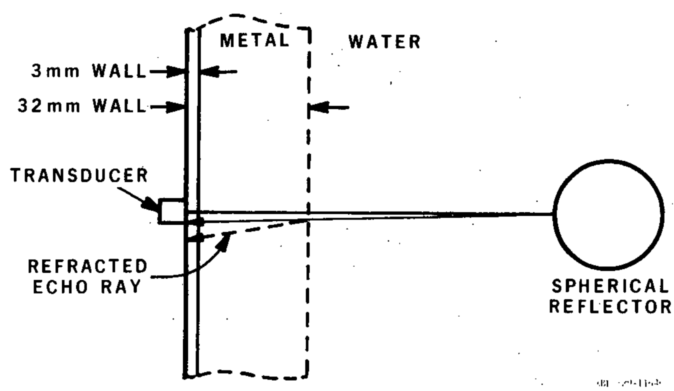
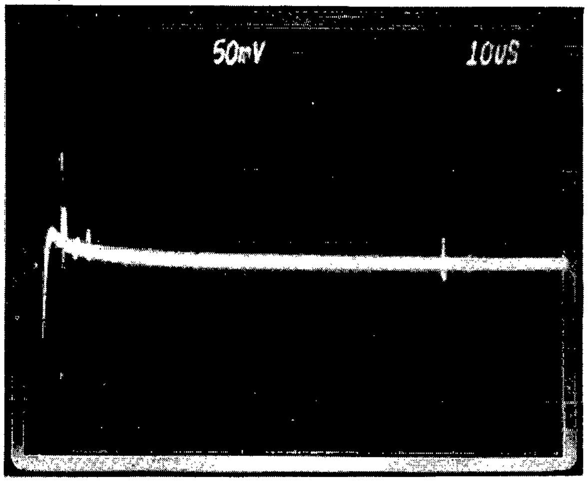


Fig. 4 Illustration of the effect of wall thickness on the echo signal from a spherical reflector. For a thick wall (shown dotted), the echo signal is spread over a larger area due to refraction effects at the water-metal interface.



(a)

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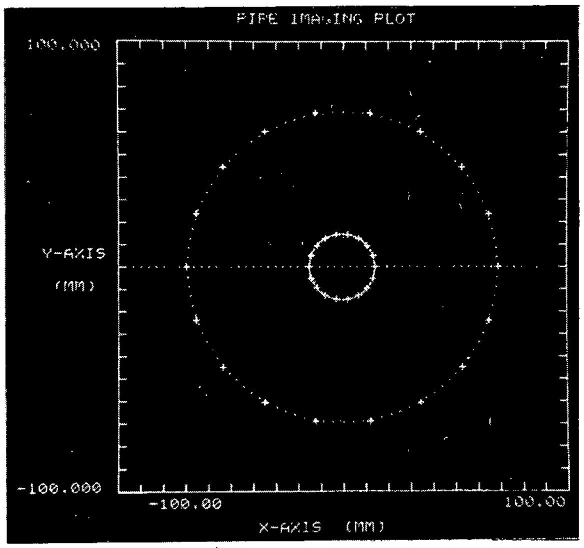

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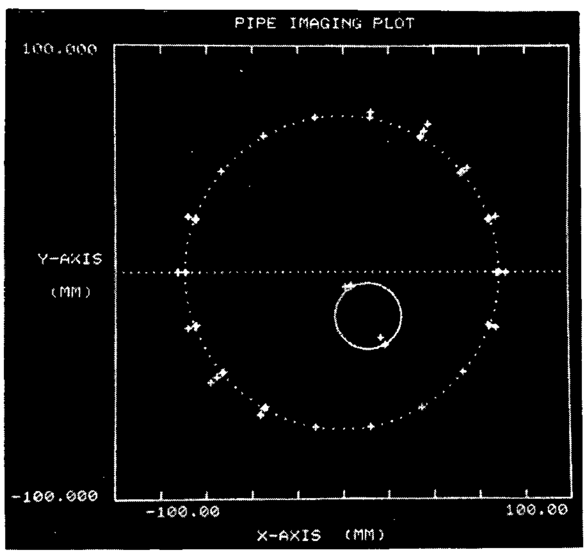

(c)

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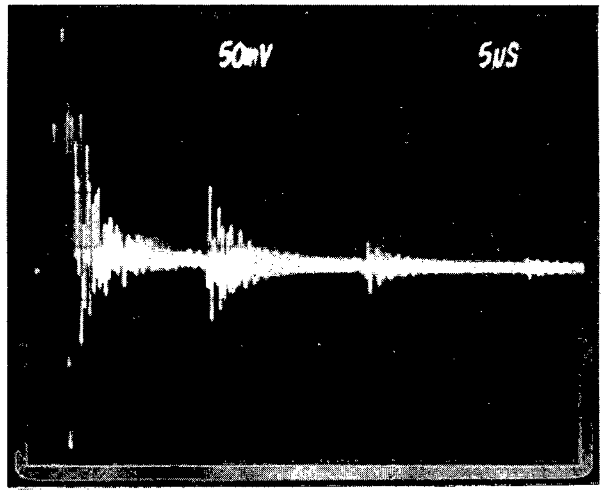
Fig. 5 Acoustic imaging of a bubble of diameter 29.5 mm mounted in a lucite pipe of outer diameter 152 mm and wall thickness 6.3 mm. (a) Oscilloscope display of bubble echo signal. (b) Computed image of bubble positioned at the pipe center. (c) Image of bubble located at coordinates (11.4, -19.7).



(a)

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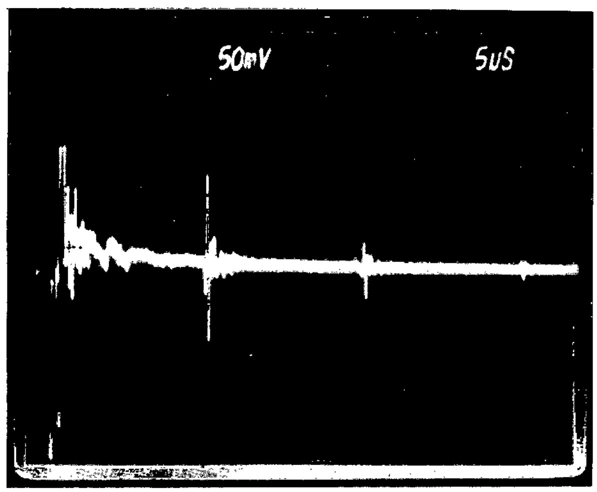

(b)

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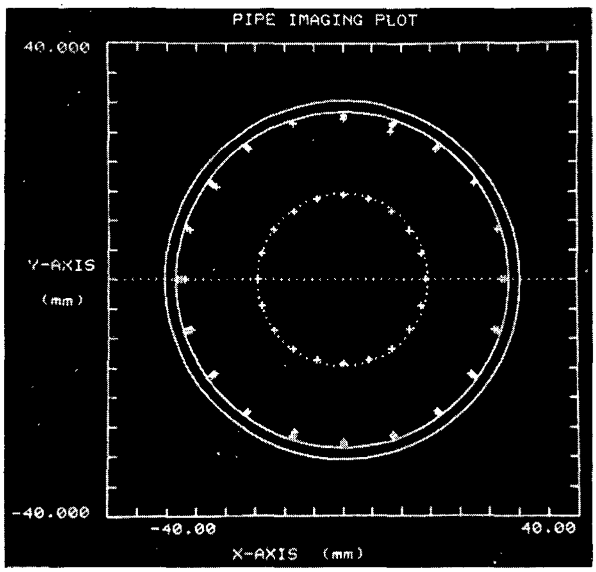
Fig. 6 Oscilloscope display showing the influence of transducer tilt angle on echo signals from a spherical reflector positioned in a stainless steel pipe. (a) Transducer mounted on a flat surface perpendicular to pipe axis. Note the reverberation echos. (b) Same as (a) except transducer tilted 10 degrees.



(a)

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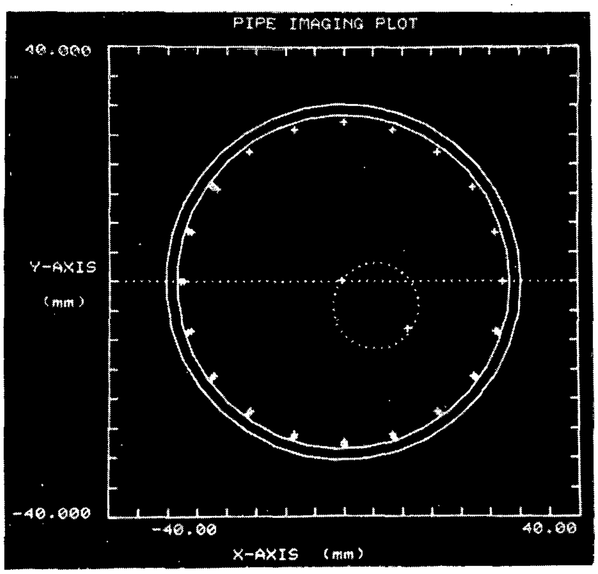

(b)

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Fig. 7 Acoustic imaging of bubbles positioned in a stainless steel pipe of diameter 63 mm and wall thickness 3.2 mm. (a) Image of 29.5 mm diameter bubble positioned at the pipe center. (b) Image of 14.8 mm diameter bubble at coordinates (5.6, -4.2).

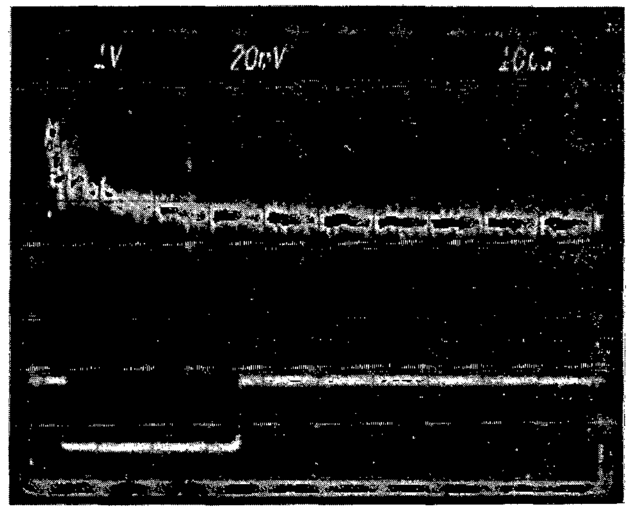

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Fig. 8 Echo signals from actual air bubbles in a 63 mm diameter pipe using 10 degree tilted transducer.

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