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ACOUSTIC IMAGING IN A WATER FILLED METALLIC PIPE

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April 1984

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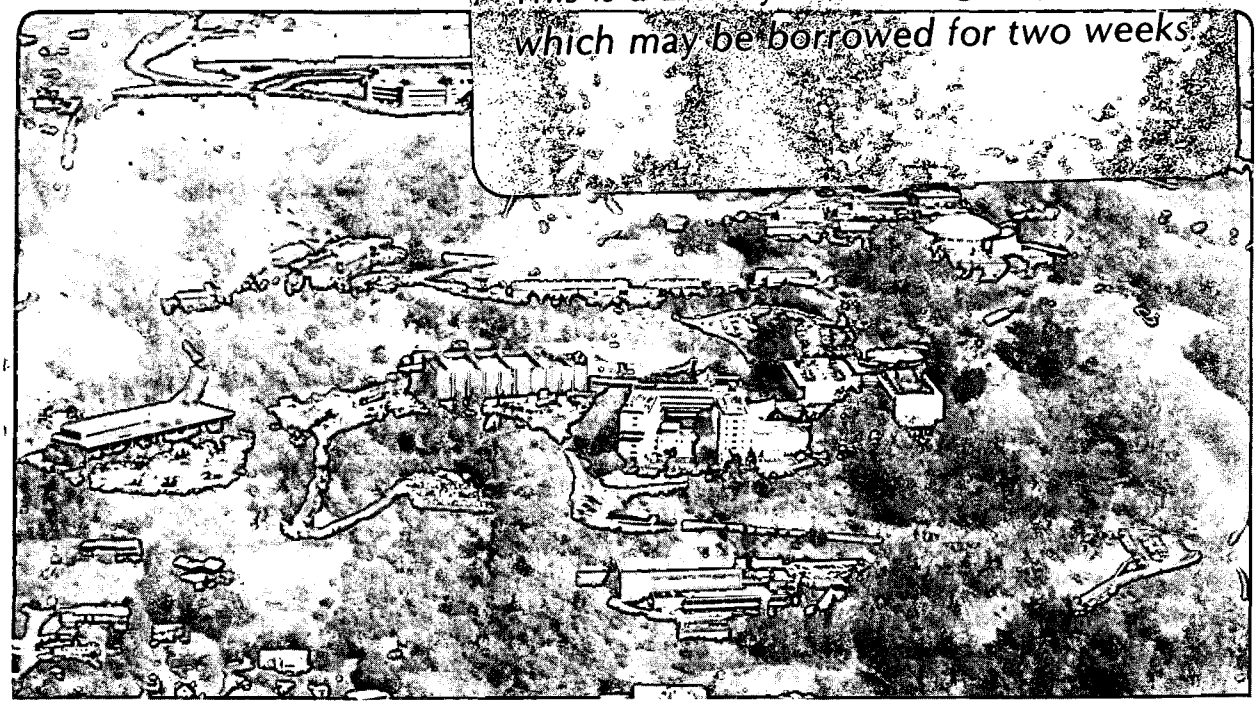

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ACOUSTIC IMAGING IN A WATER FILLED METALLIC PIPE

LBL-17697

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ABSTRACT

A method is described for the imaging of the interior of a water filled metallic pipe using acoustical techniques. The apparatus consists of an array of 20 acoustic transducers mounted circumferentially around the pipe. Each transducer is pulsed in sequence, and the echos resulting from bubbles in the interior are digitized and processed by a computer to generate an image. The electronic control and digitizing system and the software processing of the echo signals are described. The performance of the apparatus is illustrated by the imaging of simulated bubbles consisting of thin walled glass spheres suspended in the pipe.

INTRODUCTION

In nuclear power reactor systems it is essential that a continuous flow of water or liquid sodium coolant be maintained on the walls of the heat exchangers used to extract thermal energy from the reactor. Because of the danger of dryout in these systems, it would be very desirable to be able to observe the presence of vapor bubbles and liquid film flow within the cooling structures. Since the heat exchangers are made of metal and operate under hostile environmental conditions, it is not normally feasible to provide windows or other means which will permit optical viewing of the interior conditions.

A number of methods[1,2] have been developed for use in reactor safety research facilities to investigate the two-phase flow conditions which are frequently present. The authors have developed[3,4,5] electro optical systems 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. In transparent model systems, direct optical viewing with TV or other cameras has been employed. Although the above methods have been an effective tool for reactor safety research, there is need for better nonintrusive measurements of two-phase flow phenomena through optically nontransparent media.

Our preliminary investigation[6] showed that acoustic techniques offer promise for imaging through optically non-transparent media. Acoustic imaging uses sound waves to probe a sample volume and to produce reflection signals that can be converted into visual images of its internal structure. Acoustic imaging techniques have been developed in recent years[7,8] for use in medical diagnosis, nondestructive testing, microscopy, underwater imaging and seismic exploration. To our knowledge, acoustic methods have not been used for the imaging of fluids in piping structures, although Lynnworth et al[9] have reviewed other uses of ultrasonic techniques in nuclear reactor applications.

In a recent paper[6], we reported the results of a study of the feasibility of applying acoustic techniques to the problem of imaging the interior of a metallic pipe. Measurements were 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. The influence of the pipe wall thickness and material on the amplitude of the echo signals was also investigated.

In the above work, the electronic system used for generating the acoustic probe pulse and for digitizing and recording the echo signals was capable of controlling only a single transducer at a time. Simulated images of the pipe interior were produced by moving the transducer in steps around the pipe circumference and recording the echo information at each step. After all the data was recorded, the image was generated by computer analysis of the echo signals. In this paper we extend our previous work by reporting the development of a system capable of pulsing and decoding the echo signals from an array of 20 transducers in rapid sequence thus capable of producing a real image.

EXPERIMENTAL APPARATUS

A. Transducer Mounting Arrangement

The experimental apparatus used is shown in Fig. 1. An array of 20 acoustical transducers was mounted around the perimeter of a stainless steel pipe of inner diameter 57.5 mm and wall thickness 3 mm. The pipe was sealed at the bottom and filled with water to a depth sufficient to cover the transducer plane. For imaging purposes, thin walled glass spheres were suspended in the water and positioned by means of x, y and z axis micrometer drives.

In order to couple the acoustic energy into the pipe, flat mounting surfaces are machined on the pipe surface at 18 degree intervals. An acoustic coupling fluid (mineral oil) was used between the transducer and the pipe to provide an intimate contact. Because the acoustical impedance of steel is much larger than that of water, most of the acoustic energy is reflected back to the transducer at the steel-water interface. The result is a persistent reverberation signal between the two walls of the pipe which obscures the desired echos from the interior of the pipe. We have found[6] that this problem can be solved by machining the flat surfaces on the pipe at a small angle with respect to the normal to the surface. When this is done, the reverberation echos traverse a zig-zag path along the length of the pipe and are not returned to the transducer. As a result, the effects of reverberation are significantly reduced. Further damping of the reverberation echos was achieved by wrapping the lower portion of the pipe with a damping (duxseal) material. For the tilt angle of 10 degrees used, the acoustic beam in the water is inclined by only 2.5 degrees because of refraction at the metal-water interface.

The transducers used (Panametrics, Inc. model V112), were constructed from a lead niobate disk 6 mm in diameter, resonant at 10 MHz, and heavily damped to permit the generation of acoustic pulses of a few hundred nanoseconds in width. The acoustic energy is radiated from the face of the transducer in a narrow beam of diameter approximately equal to the diameter of the transducer element.

B. Electronic Digitizing and Control System

A single CAMAC module is used to house the electronic circuits, controlling the transducer array. Each transducer is connected to one of 20 identical analog channels containing a transmitter and a linear gate as shown in the general block diagram (Fig. 1). The transmitter provides a short electrical pulse which is converted by the transducer into an acoustic wave. After the completion of the transmitting pulse, the transducer is used as an acoustic sensor, sending the detected echo signals back to the receiver amplifier through the linear gate. The linear gates and transmitters are controlled by a programmable digital sequencer, with the start of each sequence initiated by an externally provided pulse.

Each transducer is served by an identical pulser - linear gate circuit. The pulser output is a fast square pulse, capable of driving a 50 ohm cable and the relatively large transducer capacitance. The width of the pulse and its timing are controlled by the logic circuits and its amplitude is adjustable from 0 to 40 volts. The output impedance of the pulser is only a few ohms during the pulse and very high at other times. The wide band characteristic of the transducer (10 MHz) requires good matching at the receiving end. Accordingly, the input impedance of the linear gate is mainained at 50 ohms whether the gate is open or closed except during the operation of the pulser, when its impedance is made high in order to minimize the load.

Since the echo signals vary in amplitude and shape, a differential discriminator was designed, sensitive both to the rate of change and the amplitude of the waveform at the output of the amplifier. Each echo that fires the discriminator is digitized and stored. A 20-channel time digitizer clocks the arrival of the echos. A counter in the digitizer counts 512 clock pulses during each "listen" period, advancing the address of a 20 x 512 word random access memory. Each successive echo pulse from the discriminator is accordingly assigned to a memory address, corresponding to the time of arrival and stored there. At the end of the sequence, a request for data transfer is generated and passed by the control logic to the CAMAC crate controller after which the echo data is read out by the computer. The overall timing of the module is controlled by a master clock provided by an external variable frequency oscillator.

An external clear input to the sequencer enables the data readout phase to be bypassed, thereby permitting the echo waveforms to be rapidly displayed on an oscilloscope.

C. Data Acquisition and Processing

The data processing system consists of a Hewlett Packard model 86 computer with dual floppy disk drives, printer and an HP-7470A plotter. Communication with the imaging module is via a GPIB (IEEE-488) bus to the CAMAC system containing the module. A Lecroy model 8901 crate controller is used to interface the GPIB and CAMAC busses.

As described above, when the control module is triggered, it generates a sequence in which the echo data is loaded serially into its internal memory, one bit at a time. At the end of the sequence the module generates a look-at-me (LAM) signal on the CAMAC bus. The computer responds to this interrupt by transferring the memory contents to a buffer array in its own memory. When the transfer is completed, the echo data is decoded. In the decoding process, each non zero bit is used to generate an element in an array ECHO(J) with each element of the array having the form ECHO(J)=N+1000*NTRANS where N is the memory address number and NTRANS is the transducer number (N=1...512 and NTRANS=1...20). When the data is decoded, it is further processed as described in section V below and then plotted on the computer screen or external plotter. Two plotting formats are provided, retangular and polar. In the former, which is useful for an inspection of the echo pattern, the echo channel number is simply plotted as a function of the transducer number. In the polar plot, the echo channel number is transformed to a representation of the position of the echo source in the pipe. The computer program is written in BASIC and includes routines for changing and listing the parameters, decoding and manipulating the data, plotting the results and storing or retrieving the data from the disk.

ECHO SIGNALS

In order to observe the echo signals produced, the electronics system was operated in the oscilloscope mode as described above. The pipe was filled with water only, thereby making possible the detection of echos from the opposing wall of the pipe. Figure 2 shows the rear wall echo signals from a single transducer. In the upper trace of 2(a), a series of echos at intervals of 75 μs can be seen. The repeated echos result from reflections of the sound wave back and forth across the pipe. They are rapidly attenuated because of the 2.5 degree tilt of the sound beam and the defocusing of the beam caused by the circular shape of the pipe. In the lower oscilloscope trace is shown the discriminator output signal produced. Figure 2(b) shows an expanded view of the first rear wall echo signal and the residual reverberation echos from the front wall. All echos resulting from bubbles in the pipe interior will be detected between these two signals.

Figures 2(c) and (d) show the rear wall echo signal produced at two different pulse excitation voltages, 42V and 4.0V, together with the discriminator output produced. The same discriminator threshold setting was used in both cases. At 42V excitation, three discriminator pulses are detected. The first of these is due to the main echo signal and the others result from wrinkles in the signal produced by reverberation and other distortions. At the lower pulse amplitude only one discriminator pulse is produced. A comparison of (c) and (d) shows that echo signals can be discriminated successfully over a dynamic range of more than ten to one. Over this dynamic range, the time walk of the leading edge of the discriminator signal is no more than 100 ns, which corresponds to a change in the detected position of the reflector of 0.075 mm.

In order to successfully image a moving bubble in the pipe interior, it is desirable to scan through the 20 transducers in the array in as short a time as possible. Because of the multiple echos which can occur from the rear wall of the pipe and the bubbles themselves, it is important to determine the interference between channels occurring at high scan rates.

Figure 3 shows the analog signal output for the first (approximately) 6 channels of the 20 channel sequence. As described above, the time interval between successive channels in the sequence is controlled by the master clock frequency. In the figure, the individual channels can be identified by the large pulses that occur when each receiver is gated on.

In the upper trace of the figure the clock frequency has been chosen to include the first rear wall echo in each channel. As can be seen, the first channel is free from spurious echos but successive channels contain increasing numbers of unwanted signals. By judiciously selecting the clock frequency, it is possible to cause all the multiple wall echo signals to overlap each other since they occur at equal

multiples of time. The effect of this change is shown in the lower trace of the figure. All the spurious echos are now eliminated.

For completeness, Fig. 4 shows the analog and discriminator signals for the entire 20 channel scan. The clock frequency (13.4 MHz) has been chosen to eliminate the spurious rear wall echo signals as described above. The total time of 1.5 ms is the minimum time in which the entire interior region of the pipe can be imaged, for the pipe diameter used and the velocity of sound in the aqueous medium. Thus, aside from digital processing time, a maximum rate of 670 frames per second is possible.

IMAGING OF PIPE INTERIOR

In order to illustrate the generation of an image of the pipe interior, a thin walled glass sphere of diameter 29.5 mm was positioned in the water filled pipe with its center in the transducer plane and its horizontal position at (0, -2) mm relative to the center of the pipe. A single scan of the 20 transducer array was triggered to capture the echo data which was then transferred to the computer and decoded as described above.

Figure 5 shows the results obtained for a low pulse excitation voltage of 4.1V. The application of a small excitation voltage is equivalent to the use of a high discriminator threshold in which weaker echo signals are excluded from the data. In 5(a) the echo data is plotted in rectangular form in which the echo channel numbers (1 through 512) are listed for each transducer. In the plot, the data points at low channel numbers are due to discriminated front wall reverberation echos and the points in the vicinity of channel 125 are produced by the spherical reflector. The latter points lie along an s-curve because of the off-axis position of the reflector. The intensity of the echo signal at each angular position can be estimated from the number of discriminated points detected. Because of the bubble offset, the echo amplitude is a minimum near channels 1, 10, and 20. At these angles the specularly reflected sound wave is directed away from the receiving transducer. In Fig. 5(b) the same data has been plotted in polar form to display directly the bubble image. The exact position of the bubble is plotted in the figure as a dotted circle. As in the previous plot, one echo point is missing from the bubble image.

In order to capture as many echos as possible from bubbles located at off-axis positions, it is desirable to use a larger pulse excitation voltage. Figure 6 shows, in rectangular and polar form, the data obtained for the same reflector positioned at coordinates (0,-4) mm and excited with a pulse voltage of 20V. In addition to the increased number of front wall and bubble echos detected, two new sets of echo patterns are generated. These are located at channel numbers which are multiples of the primary bubble echo positions. They are caused by the acoustic wave bouncing repeatedly between the face of the bubble and the front wall of the pipe. In the polar plot of Fig. 6(b), the multiple echo patterns can be seen as artifacts mapped into the interior of the actual bubble.

The presence of multiple bubble echos and an excessive number of front wall reverberation echos can make the identification of objects in the pipe interior difficult. It would be desirable, therefore, to eliminate as many of these artifacts as possible. In the next section several computer algorithms designed to improve the quality of the image data are described.

IMAGE DATA REDUCTION

In order to reduce the number of spurious echo signals present in the data, a number of data processing algorithms were incorporated into the imaging control program. These include clipping of the data, truncation to limit the number of echos retained, background removal, harmonic echo removal and the retention of pairs of closely spaced echo groupings.

A. Clipping

In this technique the data for each transducer is simply scanned and all echos with channel numbers less than or greater than prescribed values over the range 1...512 are removed. This process has the advantage of being computationally fast and could be used, for example, to exclude the undesired front wall or rear wall echos from further processing. It has the disadvantage that valid bubble echo signals lying in the excluded regions will also be deleted.

B. Truncation

Once the numerous front wall echos are eliminated by clipping or background removal as described below, one can truncate the number of echo points in each channel to leave only a prescribed number. The logic of this process is based on the assumption that the bubble is opaque and any echos lying beyond it are spurious. Like the clipping technique this process is computationally simple to achieve.

C. Background Removal

As shown in the imaging examples above, there exists a regular pattern of front wall reverberation signals which is always present. While these can be removed by clipping techniques as described above, the desirability of imaging bubbles as close as possible to the pipe wall makes a more sophisticated removal technique advisable. Repeated measurements of this region under constant environmental conditions have shown that the pattern produced is highly repeatable. If a reference pattern generated when no bubbles are present is stored in the computer, it can be used as a template to subtract out the unwanted points. The computational process is as follows: the sample array containing the desired image is scanned through each of its points and the reference array is searched for matching points within a given tolerance. Whenever a match is found, the corresponding point in the sample array is eliminated.

In a test of this algorithm, a reference pattern was generated with a pulse excitation voltage of 20V and stored in the computer. 90 minutes later a second pattern was obtained under the same conditions with no bubbles present. After an application of the algorithm with a tolerance of +/-1 channel, of the approximately 115 echos present in each of the original patterns, only 5 were found to remain.

D. Harmonic Echo Removal

As shown in the example images above, strongly reflecting objects in the imaging field can lead to the production of multiple echo patterns which can obscure the image, making identification difficult. Since these patterns occur at predictable positions, they can be eliminated by appropriate filtering.

The following algorithm was employed to accomplish the necessary filtering: first, upper and lower limits are selected to define the range of channel numbers (1...512) over which the filtering is to be applied. Then the number of harmonics to be removed and the acceptable tolerance for a match is entered. The

computer then scans all the points in the image and computes the predicted harmonic positions. If echo signals exist at the computed positions or lie within the given tolerance, they are removed.

While the algorithm can effectively remove the spurious multiple echo signals as shown in the example images below, it will also remove valid echos if they happen to lie by accident within the rejection range. This problem can be minimized by a careful selection of the input parameters.

E. Save Pairs

This algorithm is based on the assumption that the desired echo signals originate from a strongly reflecting object in the pipe. Such reflections frequently occur in closely spaced groupings of two or more echos. On the other hand, spurious echos such as background residuals, are usually located in isolated positions. The latter can thus be removed if all unpaired groupings are deleted. The disadvantage is that some desired reflection echos which are weak will also be deleted.

The algorithm is implemented by scanning all the echo points and, for each, searching upwards over a preselected tolerance range for a second echo. If none is found, the given echo point is deleted.

IMAGING EXAMPLES

In order to illustrate the generation of images and the application of the data reduction schemes described above, several examples are given of the imaging of thin walled glass spheres in the pipe. In the first example, a sphere of diameter 29.5 mm was positioned in the transducer plane at coordinates (0, -4) mm. Figure 6 shows, in rectangular and polar form, the raw data for (a) the background pattern with the bubble removed and (b) the sample pattern with the bubble in place. As can be seen in (b), the echo pattern is masked with both front wall echos and multiple echos from the sphere.

In Fig. 7 several steps of data reduction are shown. In (a), the background reference pattern has been removed using algorithm C with a tolerance of +/- 1 channel. Of the more than 100 background echos initially present, only three remain. The multiple echo pattern from the sphere is still present and is displayed in the center of the sphere. The harmonic echo suppression algorithm, D, is then applied with results shown in (b). The computer was instructed to remove the first two harmonics with a tolerance of +/- 5 channels. With these instructions, all of the harmonic echo signals are removed. Finally, in (c), the remaining data points were subjected to the pair saving routine, E, with a tolerance of 10 channels. The remaining points were then truncated to 1 per transducer with the use of algorithm B. The final image is free from all spurious data points and contains only points lying on the circle. A comparison with (b) shows that some of the weaker image points have also been deleted.

The advantages of the background suppression and harmonic echo removal algorithms in clarifying the images are evident from the figure. Although the last step of data reduction shown may actually reduce the visibility of the sphere in a graphic presentation, it has the advantage that all spurious points are removed. In this form it would be most useful as input data for further data reduction and image analysis.

In Fig. 8 we present three final examples illustrating the imaging of spherical bubbles in the pipe. In each case the data was subjected to the same sequence of data reduction routines. These were (1) background removal with a tolerance of 1 channel and (2) deletion of harmonic echos up to order three with a tolerance of 5 channels. In (a) a bubble of diameter 29.5 mm was positioned at coordinates (0, -10) mm. In (b) a bubble of diameter 14.7 mm was located at the pipe center and in (c) the same bubble was moved to (5, -5) mm.

DISCUSSION

We have demonstrated that it is possible to generate images of the interior contents of a water filled steel pipe using acoustical imaging techniques. In addition, we have shown that the quality of the images produced can be significantly improved with the use of comparatively simple data processing algorithms. While no actual vapor bubbles were imaged in the present experiments, our earlier work[6] has shown that suitable echos for imaging are readily produced by real vapor bubbles.

The present system, using an array of 20 transducers, can fulfill the goal of imaging bubbles in real time provided that faster data processing is used. As shown, when the transducers are fired sequentially, the total pulsing and echo recording time for a 58 mm diameter pipe is only 1.5 ms. Therefore, exclusive of processing time, a rate of more than 650 scans per second can be achieved. For example, an air bubble passing the transducers at a velocity of 1 m/s would move only 1.5 mm during one full scanning sequence. Furthermore, we have demonstrated that the interaction between the individual transducer channels is minimal provided that the digitizing clock frequency is carefully chosen. Thus it should be possible to pulse two or more transducers simultaneously, thereby permitting even greater scan rates or arrays with larger numbers of elements.

The data processing bottleneck which presently exists can be reduced by several techniques. The most obvious approach, and one which is currently under development, is to use a faster data processing system with the routines written in computer assembly language. In addition, the data processing algorithms currently implemented in the software can readily be added to the hardware system. If this is done, it should be possible to do most of the data processing "on the fly" as the echo signals are recorded. With these and similar improvements, a real time display of the pipe interior should be possible at frame rates of several hundreds of frames per second. Finally, if a detailed computer analysis of the echo data is desired, a large number of scans can be stored in a high speed auxiliary memory for subsequent processing. Such processing could include image analysis and the calculation of bubble volume statistics, flow rates and other parameters of interest.

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[10] at temperatures up to about 250°C. For even higher temperatures, electromagnetic transducers employing nickel or other magnetic materials may be applicable.[9] In addition, it is possible to employ a buffer rod to maintain a safe operating temperature for the transducer.

ACKNOWLEDGEMENTS

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Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

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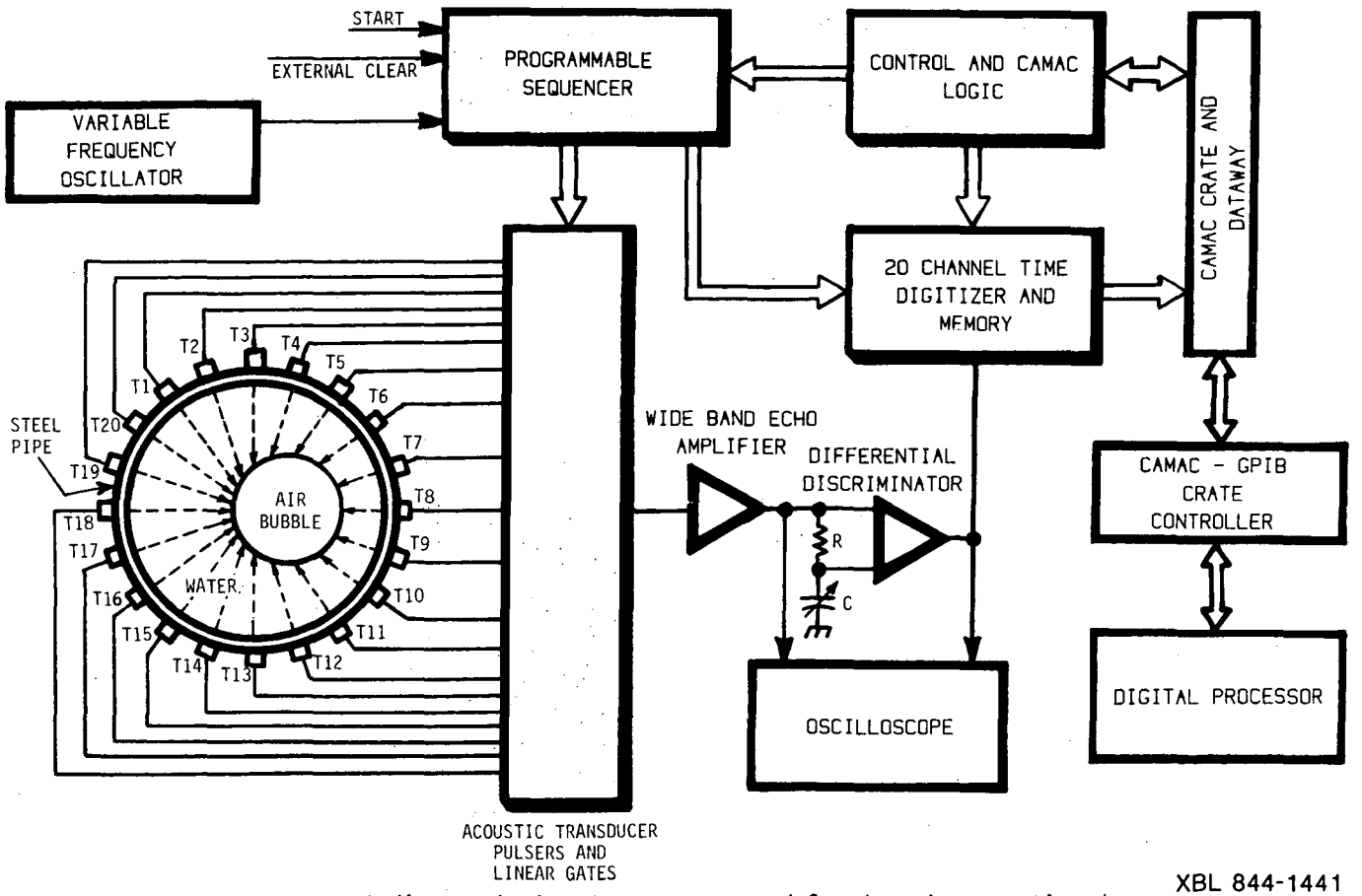

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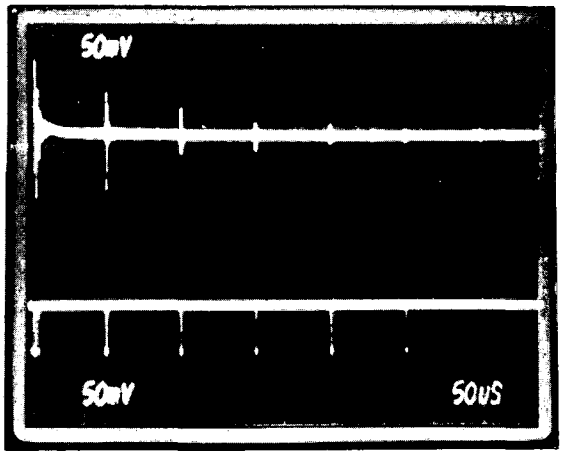
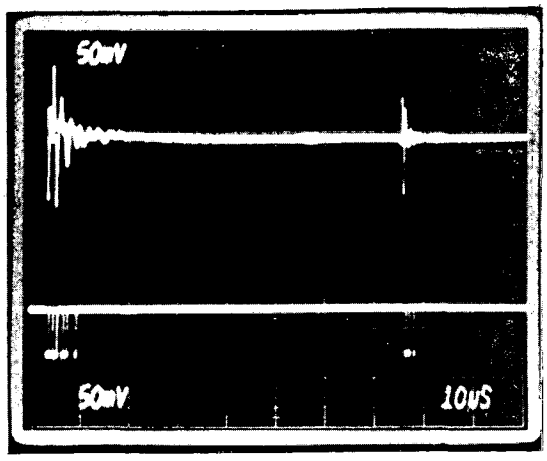
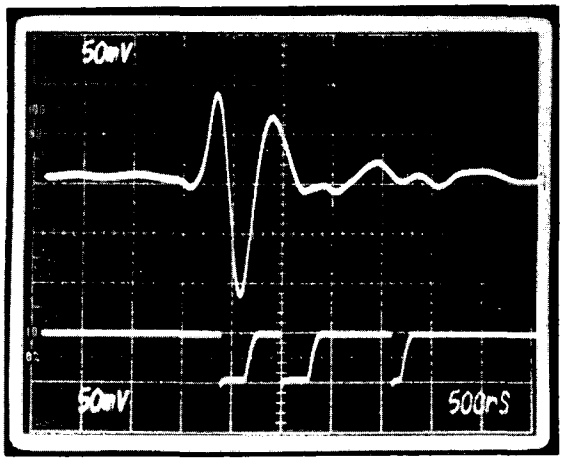
Fig. 1 Block diagram showing the apparatus used for observing acoustic echo signals and for obtaining digital information for image generation.



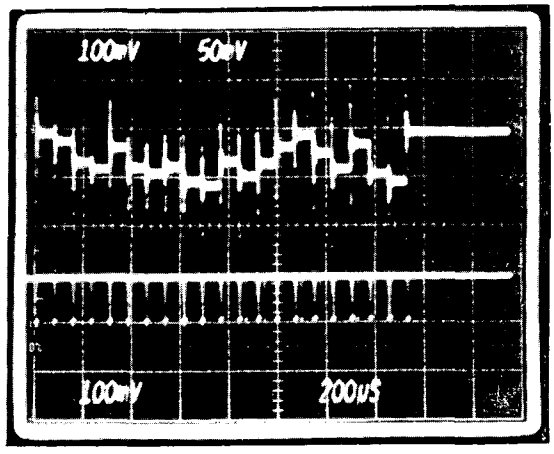
MULTIPLE REAR WALL ECHO SIGNALS
(a)



FIRST REAR WALL ECHO SIGNAL
(b)



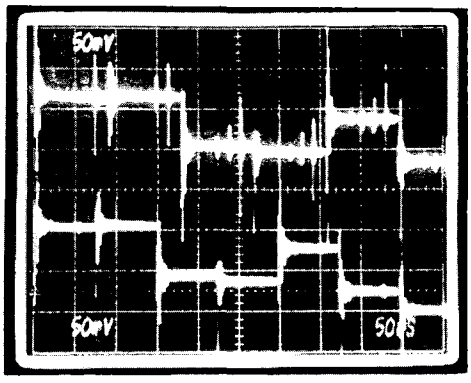
ECHO SIGNAL AT 42.0 V EXCITATION
(c)



ECHO SIGNAL AT 4.0 V EXCITATION
(d)

XBB 8310-8820

Fig. 2 Oscilloscope display showing rear wall echo signals and discriminator output for a single transducer.

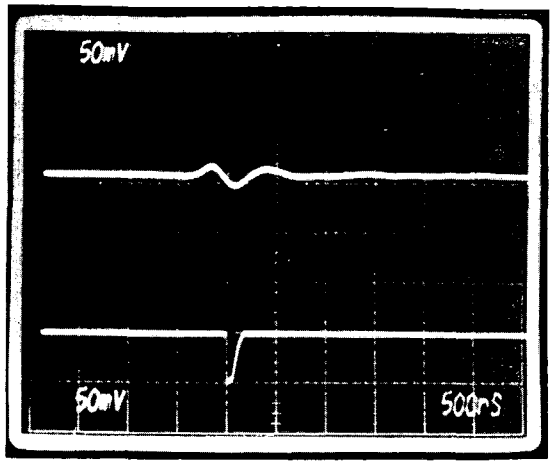


CLOCK FREQ.
11.7 MHz

CLOCK FREQ.
13.4 MHz

XBB 8310-8821A

Fig. 3 Echo signals for multiple channel detection at differing clock frequencies. Channels 1 through 6 are shown.



XBB 8310-8822

Fig. 4 Echo and discriminator output signals for entire 20 channel sequence.

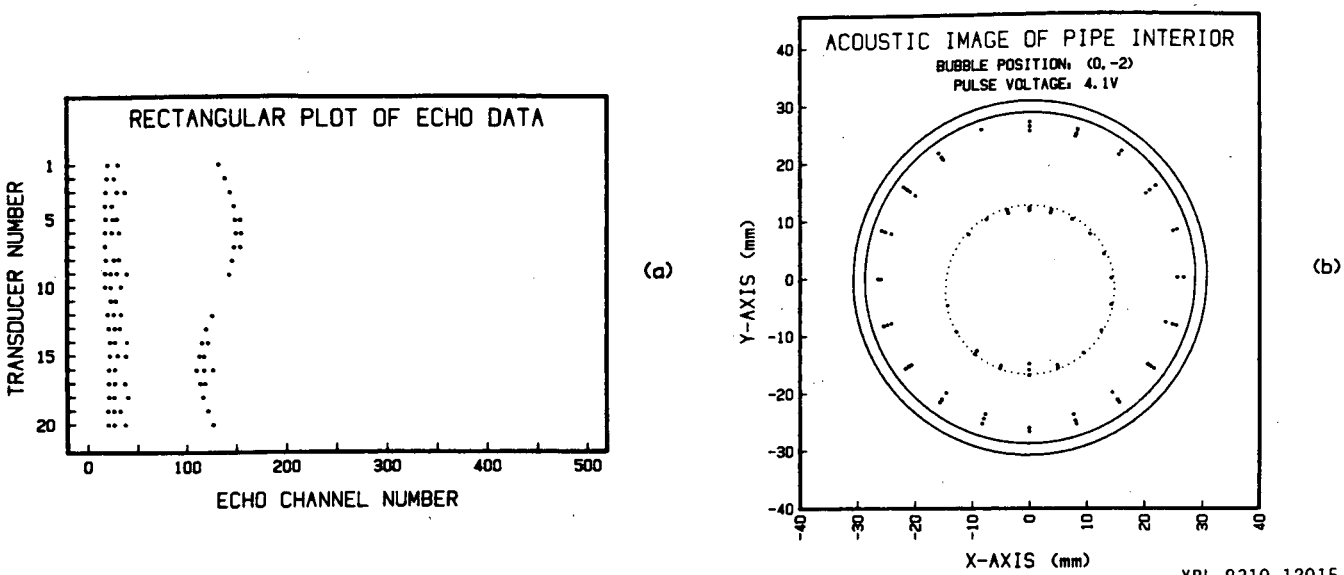


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Fig. 5 Acoustic image of spherical reflector of diameter 29.5 mm positioned at coordinates (0, -2) mm generated with a pulse amplitude of 4.1V (a) rectangular display, (b) polar display.

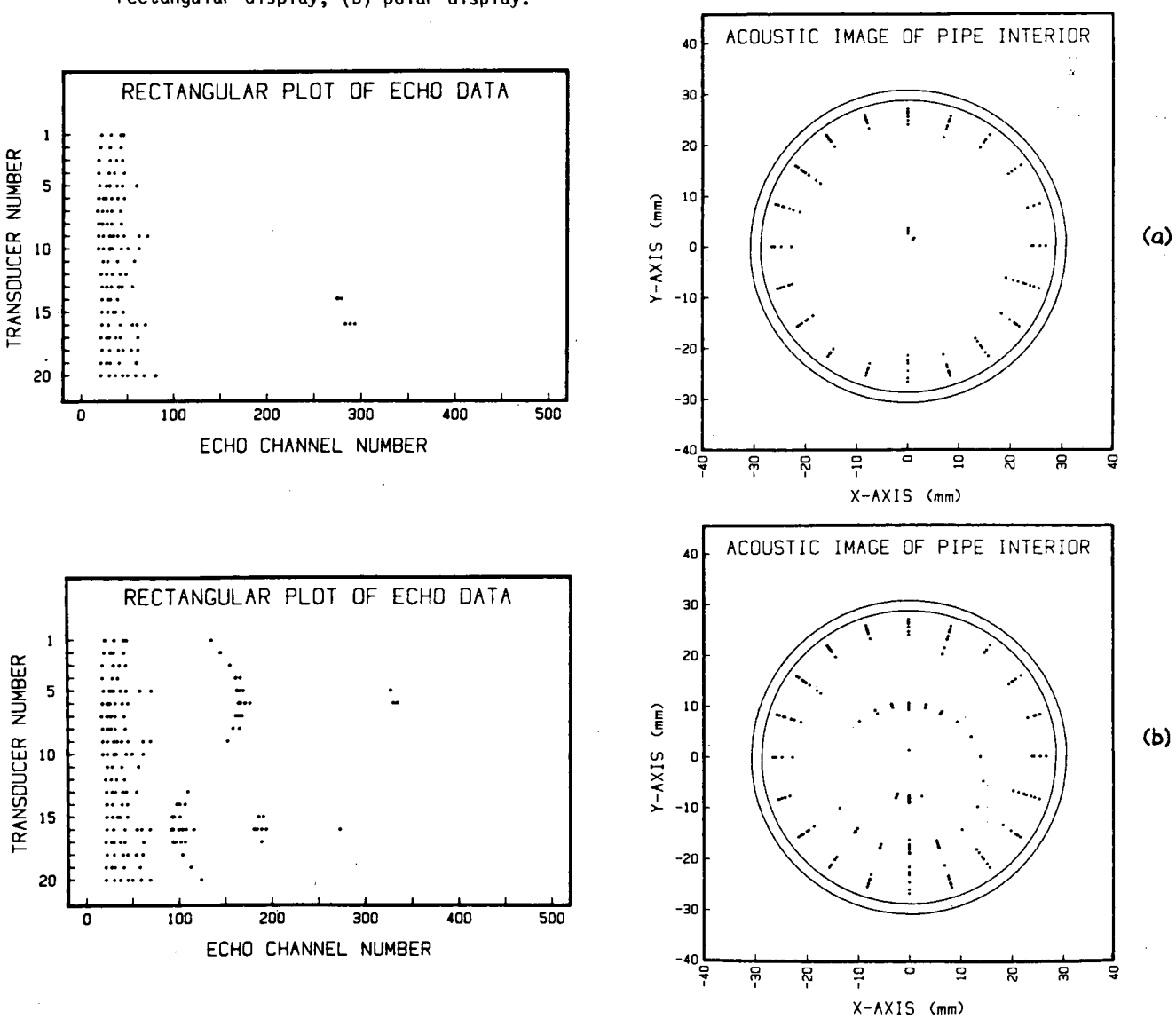

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Fig. 6 Rectangular and polar display of unprocessed echo data. (a) reference pattern with bubble removed. (b) sample pattern for 29.5 mm diameter bubble at (0, -4) mm.

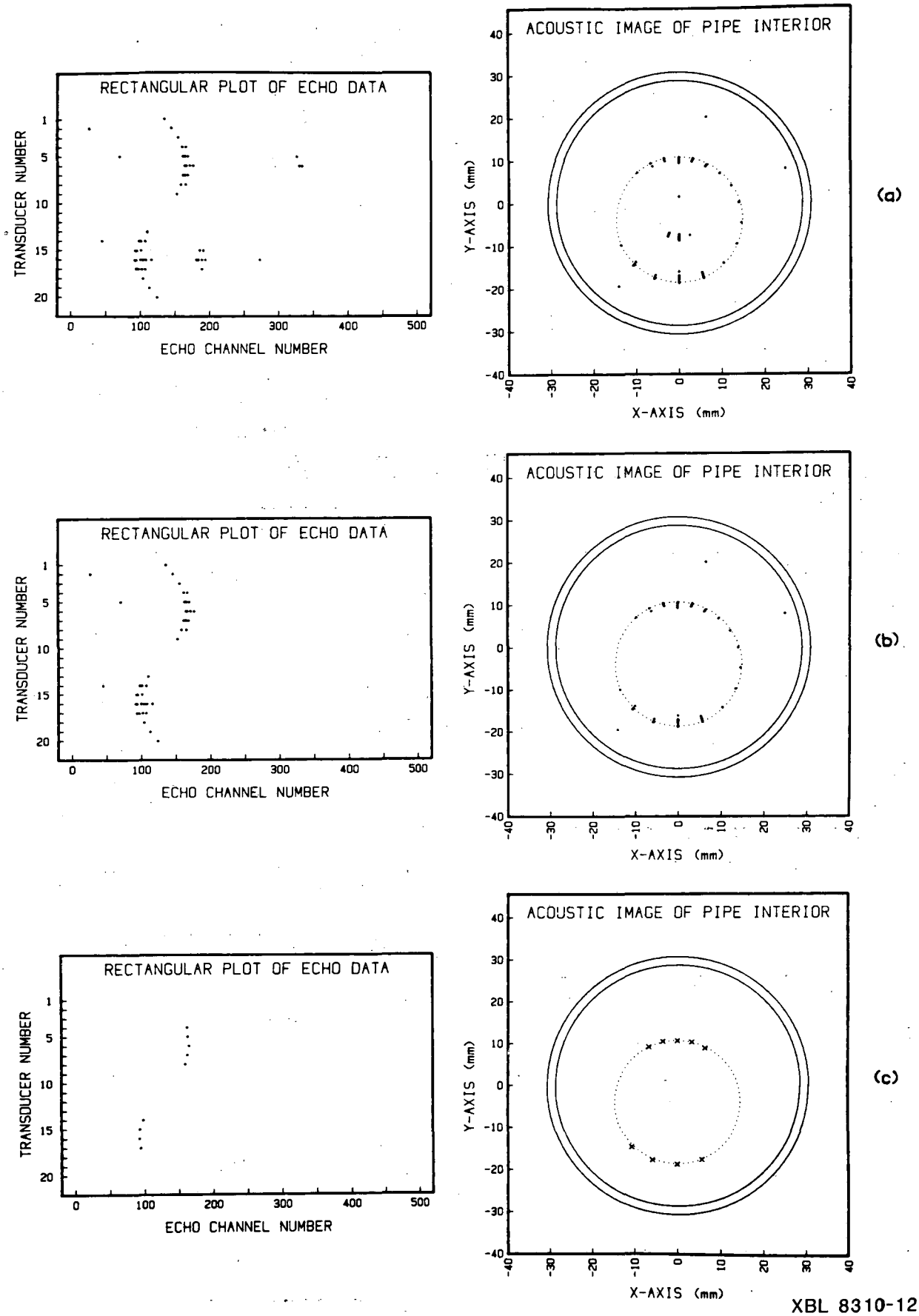

Fig. 7 Illustration showing application of data reduction techniques to image shown in Fig. 6. (a) background removal, (b) harmonic echo suppression, (c) pair retention and truncation.

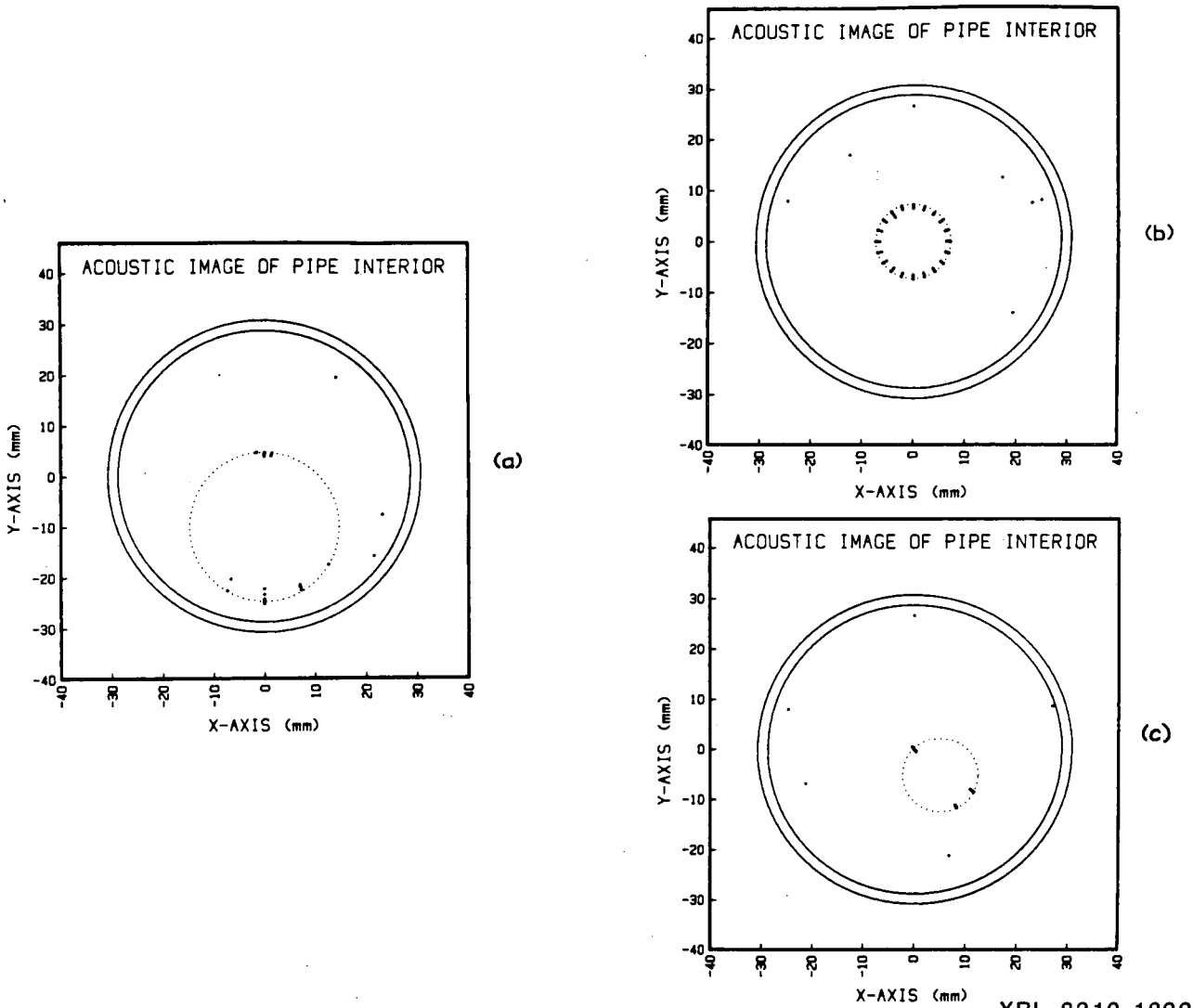

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Fig. 8 Sample images of spherical reflectors positioned in pipe after data reduction (a) 29.5 mm diameter at (0, -10) mm, (b) 14.7 mm diameter at (0, 0) mm and (c) 14.7 mm diameter at (5, -5) mm.

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