Nondestructive flaw characterization has keen research interests throughout industry. The nuclear industry is no exception. Identifying the size, shape, orientation, type and position of material flaws in nuclear reactor pressure vessels has a top priority. Under a contract with the Electric Power Research Institute of Palo Alto, California, Battelle-Northwest is developing a demonstration model of a sequentially pulsed phased linear array system for ultrasonic inspection of reactor vessels. This program employs the linear array in both pulse echo and holographic modes and provides near real time images of the weld zone volume. The objectives of the program are to develop a rapid and accurate means for sizing subsurface defects in heavy section steel members. This article outlines the first six months effort on the two year program.

The first objective of this program is to design, develop and evaluate a breadboard ultrasonic imaging system which can provide a rapid and accurate means for evaluating ultrasonic reflectors in nuclear reactor pressure vessels. To meet this objective, Battelle-Northwest will use a multielement linear ultrasonic array which, in conjunction with appropriate electronic, ultrasonic, computer, mechanical and display subsystems, can provide either pulse echo or holographic mode evaluations. The pulse echo mode operation will be designed for high speed scanning to detect and locate subsurface indications. The holographic mode operation will be designed to characterize and record the detail of subsurface defects.

ASME Section XI Codes are the control documents for in-service inspection of nuclear reactor pressure vessels. Present in-service inspection requirements are written around pulse echo ultrasonic techniques which employ discrete transducers operating within specific operating conditions. Use of advanced concepts such as ultrasonic arrays or holography are allowed under present codes, provided equivalence of performance can be established. Holographic techniques are not yet recognized under the codes requirements; however, research and laboratory experimentation has shown the potential that this approach can provide the characterization desired.

A second objective of the program, therefore, is to establish the capability of the high speed scanning and evaluations using the multielement linear array and demonstrate that the concept can meet and exceed the ability of present inspection techniques. As presently envisioned, one goal is to show that the ultrasonic array pulse echo system can provide a much faster inspection. A second goal is to demonstrate the capability of the ultrasonic array used in holographic imaging, thus potentially providing the basis for incorporating holographic interpretations into future appropriate ASME Code requirements.

A final objective of the program is to build an operating demonstration model of the advanced imaging system that can be used to establish the potential for multielement ultrasonic arrays in the examination of reactor pressure vessel welds. The program is aimed at developing a system for inspection of welds in reactor vessels from the outside surface.

Background

Ultrasonic inspection of welds in accordance with 1974 ASME Section XI BPVC Codes requires examination of 0°, 45° and 60° sound beam viewing from both sides of the weld. Current testing systems used to inspect pressure vessels from the outside surface employ quasi-contact techniques to couple the ultrasonic energy from a multiple transducer head into the surface of the part. These transducer heads are moved across the weld and the data are recorded on magnetic tape, CRT display, pen recorder or a combination of displays. The systems are relatively slow and require several minutes to cover a 1 ft section of weld. Interpretation of recorded data requires detailed examination and is subject to human interpretation to develop dimensional size information.

Acoustic holography has been successfully used to characterize known defects; however, present single surface holographic techniques are quite slow (typically 5-10 minutes per 1/sq ft) and many holograms are required to develop an accurate interpretation of the ultrasonic reflector.

Ultrasonic arrays are being used with great success in the medical ultrasonic diagnostic field (pulse echo techniques). The use of arrays has been proposed for industrial applications, but while several concepts have been researched and validated, no system has been developed. The use of ultrasonic arrays for holographic imaging has also been researched and validated, but technology has not been carried to demonstration instrumentation. The system proposed by Battelle-Northwest has high versatility and should be capable of clearly demonstrating the ability of the ultrasonic arrays. Using the combined technology of pulse echo and holographic imaging and incorporating the latest advances in multielement ultrasonic arrays can provide a substantial improvement in the speed of inspection and the accuracy of detailing the characteristics of subsurface defects.

SYSTEM CONCEPT

Basic System

An artist's concept of the demonstrated model to be developed under Phase II of the program is shown in Fig. 1. The system components include the computer, ultrasonic array, pulse echo and holographic electronics, pulse echo and holographic.
displays, and the transducer scanning bridge. The key element in the system is the ultrasonic transducer array which, under control from the computer and electronic steering circuitry, will produce a steerable ultrasonic sound beam that can cover various angles from -70° through zero to +70°. The array itself is approximately 7 in. long and is made up of 240 individual transducer elements. The mechanical scanning bridge will move the array over the weld zone in a pattern designed to give full coverage to both sides of the weld.

For developing the pulse echo images the ultrasonic sound beam will scan the volume under inspection at discrete angles in accordance with code requirements. Each traverse of the array will provide a 6 in. wide inspection path and, since only a few seconds are needed for each traverse, a high speed inspection of the volume of the weld can be accomplished (e.g., 12 in. lineal distance per minute). Figure 2 shows the volume of the weld that is evaluated with the array for the pulse echo inspection. Figure 3 shows the projection of the image that is planned for the high speed pulse echo B-scan isometric display. Approximately 2 ft of the weld will appear on the display at one time, and each of the ultrasonic reflectors which exceed the established threshold will be displayed. The pulse echo data will be displayed both on the conventional A-scan monitor used in standard ultrasonic flaw detectors and on A-scan converter used as the B-scan isometric display monitor. Ultrasonic reflectors which show on the monitors will be further evaluated with the holographic system.

To develop the hologram the electronic system is switched to the holographic mode of operation. While the computer controls both the pulse echo and the holographic operations, the computer performs more functions in holographic mode. Once the suspect zone has been identified and the transducer is positioned over the zone, the computer is used to control the sound beam angle and the protocol followed during the development of the hologram. The hologram aperture is about 6 in. x 6 in. Approximately five seconds are required to complete each scan. The 'viewing' angle can be adjusted to obtain multiple views of the ultrasonic reflector under investigation.

System Operation

The host computer (PDP 11-34) has sufficient memory to handle the command functions, the pulse echo functions, the holographic mode and correction functions, and all future interface requirements projected for the program.
On computer command the mechanical scanning bridge initiates its scan. The scanning bridge microcomputer defines all standard X and Y movements of the array, selects the speed of travel and maintains exact position information for locking the transducer coordinates to the image display. The scanning bridge may be controlled by the microcomputer, the host computer, or manually by joystick control. Under pulse echo search scan conditions the array will travel across the carriage in approximately ten seconds and index to the next scan position in approximately five seconds. An entire 2 x 4 ft area can be covered in about two minutes.

Ultrasonic Array

The array consists of 120 transmitter and 120 receiver elements. The piezoelectric material is PZT 5, which has been acoustically damped with a moderate backing to achieve an intermediate Q. As a range resolution is not a major factor and since it is desirable to have both holographic and pulse echo operation from a single array, the damping characteristics are of secondary consideration. The center-to-center spacing of the individual elements is 0.058 in. with an element-to-element separation of 0.008 in. The unit is designed with the positive electrode on the rear of the crystal. An epoxy-aluminum oxide matrix is used as the backing. The operating frequency is 2.3 MHz. Since the shear velocity of sound in steel is approximately 1.25 x 10^5 in./sec, the element center-to-center spacing provides \( \lambda \) separation for shear mode and \( \lambda/2 \) spacing for longitudinal mode operation. Final evaluation of the design has not been completed; however, the zero degree experiments have shown the desired gaussian beam pattern.

Transmit Electronics

The transmit steering electronics, as controlled by the host computer, selects the mode of operation (pulse echo or holographic), the array elements to be used, the beam angle, and the sequence of pulsing. Each element in the 120 element array has a separate pulser. The time delay established between elements determines the propagation angle of the sound beam. In the present system a 37 MHz oscillator is used as the reference clock. The basic time period between clock pulses is \( 1/f \) or 27 nanoseconds. Thus the transmit delay periods between elements are a function of \( f(t) = n \times 27 \) nanoseconds as established by the \( n \) divide counter. The 16 bit shift register provides the delay time inputs to the switching matrix which in turn selects the pulsers that will be used to launch the ultrasonic beam. The basic frequency of the waveform driving the pulsers is 2.3 MHz as determined by the clock frequency divided by 16 through a counter. The number of cycles applied to the pulsers (or elements) is determined by the divide-"m" counter. For pulse echo mode the pulser is excited for 2-4 cycles. For holographic mode the pulser is excited for longer periods ranging from ten to two-hundred-fifty cycles.

The switching matrix can establish either positive or negative beam angles in either the pulse echo or holographic modes. The available delays provide a total of 49 selectable angles, including 15 shear mode, 9 longitudinal mode, in both positive and negative directions, plus the zero mode.

Sixteen elements are used for the pulse echo mode providing a sound beam that is about the same as obtained from a 1 in. square crystal. The scan across the array is achieved by sequencing successive blocks of sixteen elements. Under normal operation the zero degree beam sequences through its series followed by the 45 degree beam and then the 60 degree beam (see Fig. 4). Upon completion of the sequence the cycle is repeated over and over. The pulse rate of the system is based on the longest path length (60° shear beam) while the speed of the travel of the array is established to maintain a minimum of 50% indexing of the sound beam in both the X and Y scan directions. Elements 1-16 are used to generate the sound beam for the first pulse. The second pulse utilizes elements 8-24, and so forth, until the entire 120 element array is scanned.

![Sequentially pulsed phased linear array diagram](image)

Figure 4. Sequentially pulsed phased linear array

For the holographic mode an analogous sequencing scan is made; however, the number of elements is reduced to develop a divergent sound beam. Our present research indicates that three to five elements can project an adequate beam. To develop a beam that is symmetrical in the X and Y directions involves selection of an appropriate number of transmitter elements and the use of a mechanical shutter which is placed over the face of the array to develop a square configuration. Beam steering (as required) is again developed by selecting the time delay.
triggering the individual pulsers. The array sequencing is different from the pulse echo case in that the index is advanced by a single element for each pulse (e.g., 1-2-3, 2-3-4, 3-4-5, etc.). Other functions of the transmit circuitry are common for the two operational modes.

Receiver Electronics

For the pulse echo operation, eight receiver elements are used for each sixteen block of transmitter elements. As an example, receiver elements 1, 3, 5, 7, 9, 11, 13, and 15 are used when transmitter elements 1-16 are pulsed. Since the receiver delays are the reciprocal of those of the transmitter, the electronic circuitry must handle the received signals in a different manner. For zero degree beam naturally there are no delays. For any angle beam operation the signals impressed on the receiver elements are amplified and input to an A to D converter. The digitized signals are then delayed by an appropriate amount, converted to analog waveforms and summed to reconstruct the signal. The response speed of the electronic switching, delay circuitry, and the A to D and D to A converters controls the number of receiver elements that can be conveniently used. Our present design uses eight receiver elements for the pulse echo mode. Once the signals are summed, the signal is input to the display system for further processing and imaging.

In the holographic mode, only a single receiver element is used. The switching electronics selects the center element adjacent to the transmitter group as the receiver. The sequence is a simple progression - 2, 3, 4, 5, etc. across the array. As the complete sequence requires 150-200 milliseconds, the entire 6 in. x 6 in. aperture area can be covered in a few seconds. The holographic signal is amplified and input to the holographic electronic circuit.

Display Electronics and Monitor

Four monitors are planned for the demonstration system; two for pulse echo and two for holographic.

The A-scan display is a commercial flaw detector used as a calibration, setup and single trace monitor. The electronic gates and distance amplitude compensator (DAC) of this instrument will be used as part of the operating system. Additional electronics are being developed to convert the ultrasonic signals for display on the scan converter monitor. The image displayed on the scan converter is an isometric projection buildup of the multiple B-scan signals from the ultrasonic reflectors. The front and back surfaces of the reflections (zero degree beam) are electronically suppressed to show as a light shade of gray. The signals from internal reflectors are brightness enhanced and displayed in their correct positions.

The computer maintains coordinate position information to accurately trace the 0.45 degree and 60 degree sound beams so that the B-scan overlays are correctly positioned on the monitor. The isometric display is a buildup of all reflector information in the electronic gates and the picture is developed as the weld zone is scanned. Since the scan converter displays the peak signal from any ultrasonic reflector, the brightness of the signal is indicative of the amplitude of the echo. The scan converter is designed to hold the image until erased allowing time for visual interpretation of the signals displayed. When the mechanical scan is complete a two-foot length of the volume of the weld will be displayed.

Recall that the pulse echo system is designed as a high speed search and locate scan. Reflectors which exceed the established threshold are to be evaluated using holographic techniques to provide more accurate archival records which detail the suspected flaw.

In the holographic mode the signals from the ultrasonic reflector are input through amplifiers and gates in the A-scan flaw detector to the holographic electronics. Here the phase of the ultrasonic signals is compared to the reference oscillator and the quadrature components (real and imaging) are developed. These quadrature signals are input to the host computer for compensation of distortions which result from the holographic process and from geometrical boundary conditions. Signal distortions due to aberrations (spherical, astigmatism, field curvature, etc.) and from the curvature of the entry surface must be corrected before accurate holograms can be generated. Many of these distortions can be predicted and computer corrections can be input to the quadrature components before the signals are presented to the holographic display section.

The holographic display is being developed by the Holosonic Corporation under separate contract with the Electric Power Research Institute. Their system consists of a 128 x 128 element solid state memory, a hologram recording monitor and a real time image display monitor which incorporates a Ruticon™ solid state device developed by the Xerox Corporation. The solid state memory stores the hologram data output from the computer. The data stored in the memory is displayed continually on the hologram monitor. The image on this monitor provides a continuous updated hologram which can be photographed for future use. The image from the hologram monitor is imaged onto the Ruticon to provide a means for real time reconstruction of the hologram thus replacing the holographic film used in present scan holographic systems. The Ruticon devices will temporarily store an input image as a surface deformation pattern on an elastomer layer. These devices consist of a transparent conductive substrate, a photoconductive layer, an elastomer...
layer and a means for applying voltages across the two layers. A light image impressed on the photo-conductor layer changes the voltage distribution across the layer which in turn changes the electric field across the elastomer layer. The resulting forces cause a surface deformation on the elastomer layer which corresponds to the light image. By scanning the surface with a laser and optically reconstructing the ordered diffractions, the hologram image can be displayed on an image plane. The vidicon used to view the image plane develops the image for display on a TV monitor. The Ruticon display provides real time images of the hologram stored in the memory and displayed on the hologram monitor.

Summary

Flaw characterization is a most critical requirement for developing a means for evaluating the severity of defects in structural or fracture critical components. Ultrasonic imaging techniques offer promise of providing detail of subsurface defects that is difficult to obtain by conventional means. The versatility of the sequentially pulsed phase linear arrays indicated that isometric projections of the volume of material surrounding the weld in a nuclear reactor pressure vessel can provide a detailed image which can accurately describe subsurface defects. The aim of Battelle-Northwest's program is to establish the capability of the linear array and demonstrate the practicality of imaging subsurface defects. While only limited performance data has been generated to date, no technological limits have developed which pose a limit to the system. Initial results from both pulse echo and holographic results look most promising.

REFERENCES


2. The holographic data developed by the ultrasonic array and electronic systems being developed by Battelle is to be interfaced to a digital memory device and display system being designed by the Holosonics Corporation of Richland, Washington, under a separate contract from EPRI.

3. Typical systems in use today operate at 2.25 MHz and use transducers with crystal elements from 3/4 in. to 1 1/2 in.


DISCUSSION

DR. EMANUEL PAPADAKIS (Ford Motor Company): Any questions? Yes?

DR. ROBERT SANDERS (Acoustic Emission Corporation): First, I'd like to mention that I think we're over-seek ing small flaws in a rather large structure, so I'd like to ask how you're comparing this with probes in space and as to its positional accuracy and also, do you have a positional error feedback signal since, obviously, the scanning area is of a critical nature on that large of a structure?

MR. POSAKONY: To answer your last question first, yes, we do have the corrections--we have a very accurate location within plus or minus 0.001 of an inch recall on the position of the array with respect to the structure. This gives us a positive position for the start of the ultrasonic beam. We've also provided corrections for the geometrical distortions on the surface of the structure so we can correct those in time.

Your other question had to do with--would you restate it, please?

DR. SANDERS: I think it's probably covered. I started to bring out the point that our company is working with a similar system that G.E. has, which is on the market, in which a rather unique use of acoustical emission occurs in that we pulse at the ultrasonic carriage, and by acoustical triangulation attain a continuous error signal as to the location of the ultrasonic scanning carriage. Is your carriage magnetically attached to the--

MR. POSAKONY: No, sir, it is not. It is mechanically placed on the surface of the structure and scanned from there. The G.E. development is a magnetic crawler. We could apply the very same technique, but essentially what we're doing is saying we have an array contained in a very sophisticated mechanical scanning bridge. The mechanical scanning bridge has a tolerance of plus or minus 0.002 inches over a distance of (vibration tolerance) one foot, giving us pretty good assurance that we're not going to get phase distortion from our holographic reconstruction. We are only requiring a 6 inch span. We do have very accurate recall as to the position of the array. So, we think we've covered most of the problems one way or another. We also can put back into the computer a correction function for anything that we need to have before it is displayed. Our concern, of course, is not necessarily in pulse echo. We can have distortion there and not be overly concerned because that's the search and locate device. But the hologram itself has to be very carefully controlled.
MR. ROY S. SHARPE (Harwell Labs): Can you comment on how the variability in the cladding is going to degrade your image?

MR. POSAKONY: Yes, it certainly will. If you notice, I avoided the use of the inside system. We are going to the outside to prove in principle that the concept is valid. We do not know what we would do for I.D. inspection through the clad. The clad is a very rough, undulating surface; it is not smooth. Sometimes you'll have as much as 1/16 of an inch variation peak to valley, and its going to be a real bearcat to do holographic reconstruction in that aspect, but many, many of the new reactors going on plan now are inspectable from the O.D., and, of course, BWR's are only inspectable from the O.D.