SIZING DEFECTS USING ANNULAR ARRAY TECHNIQUES WITH AN AUTOMATIC ULTRASONIC DATA ACQUISITION SYSTEM

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INTRODUCTION

Present state of the art sizing measurements of defects by ultrasonic techniques has been inadequate, especially in support of a quantitative fracture mechanical analysis of the strength of a material. Present capabilities of defect sizing in some cases do not allow an accept/reject decision to be made. Currently, ultrasonic imaging systems including phased array, synthetic aperture, and wavefront reconstruction systems are being developed to quantitatively measure defect sizes. Also, in the medical field phased array systems have been developed for imaging purposes. This work describes an annular phased array system which is being developed for general NDE applications on metal and ceramic materials. The main usefulness of phased array techniques is the ability of electronically changing the focus of the acoustic beam radiating from a phased array transducer or reflecting from a defect in a solid material.

GENERAL COMPUTERIZED ULTRASONIC DATA ACQUISITION SYSTEM

The annular phased array system is part of a general purpose ultrasonic data acquisition and display system. A block diagram of this system is shown in Figure 1. The design of the system is such that a quick change from phased array operation to conventional single transducer operation is possible. As seen in Figure 1, the scanning motion of a single transducer or a multielement annular array transducer is under complete computer control. A detected A-scan output of the ultrasonic receiver is obtained from the pulse echo waveform of a single transducer or the pulse echo summed waveform of a phased array transducer.
Fig. 1. Block diagram of the ultrasonic data acquisition system

The ultrasonic A-scan interface digitizes the time-of-flight delays and amplitudes of up to four consecutive echoes appearing on a single A-scan trace. A detailed description of the ultrasonic A-scan interface, its operation, and schematics have been given by Stoker. The digitized ultrasonic data is passed to the host computer as soon as it is recorded along with the position coordinates of the transducer through a pair of DR11-C interfaces. Data is accepted or rejected under computer control and saved in a buffer area of core memory. When the buffer area is filled, the data is stored permanently on disc and displayed in a B-scan and C-scan format on the display terminal for quick evaluation.

For single transducer operation, the pulsing of the transducer is done asynchronously as the transducer traverses the target material. In the phased array operation scanning is accomplished in a similar way. However, the programmable phased array controller is continuously updated by the host computer at the end of a data taking interval in order to set a new electronic focus of the annular array transducer.
SIZING DEFECTS USING ANNULAR ARRAY TECHNIQUES

HOST PDP 11/34
DRI1-C INTERFACE
DATA OUTPUT CONTROL
INTERNAL TIMING AND INTERFACE LOGIC
PULSER CONTROL
HI-SPEED RAM
256 X 18 BITS
RECEIVER CONTROL
ANALOG TAPPED DELAY LINES (5 NS/STEP)

EXTERNAL OPERATE SYNC
SUMMED OUTPUT TO A-SCAN INTERFACE

PHASED ARRAY TRANSDUCER UP TO 16 ELEMENTS

Fig. 2. Block diagram of the programmable phased array controller.

Generating one A-scan for each electronic focus at each external sync pulse maximizes the speed of data acquisition under dynamic focusing operation. The digitized time-of-flight delay of the echo can be checked by software against the intended time delay of the electronic focus. If it is not within acceptable limits, it is rejected as spurious data. The speed of the transducer is adjusted to adequately scan the thickness of the target block while in the dynamic focus mode.

A block diagram of the programmable phased array controller is shown in Figure 2. The controller has 16 individual pulser/receiver modules. The firing order of each pulser is controlled by the 256 x 16 bit high speed RAM (Fairchild Type 93L422). Execution of both pulser and receiver controls is triggered by an external sync pulse which starts sequencing the RAM by clock pulses applied to the address counter. Each bit set in the RAM address fires the corresponding pulser of the phased array element. Operation at 50 nanosecond steps is the maximum rate the RAM can be addressed.
The preamplified echo signal of each transducer element is delayed at the receiver control using analog tapped delay lines. Programmed delays in increments of 5 nanoseconds up to 225 nanoseconds are possible with the present tapped delay configuration. All delayed receiver outputs are summed and applied to the basic ultrasonic receiver where the detected A-scan signal is formed.

Pre-programming of the RAM and the tapped delay lines at regular intervals is accomplished by the host computer through the internal timing and interface logic module. Control lines establish the code for passing data from the host computer to the pulser control module, the receiver control module, and set the internal logic for an external sync execute command. The system configuration allows fast, real time machine language programming of the pulser/receiver delays just prior to reception of the sync pulse of the external timer.

ANNULAR ARRAY DESIGN

The annular array transducers were constructed of segmented concentric rings of equal widths and spacings. The width, spacing, and number of elements were chosen so that at a one inch distance along the center line of the transducer in water the sound pressure due to a segment of the outer most element would be only -3dB lower than the segments maximum pressure. Calculations were made assuming the angular response of a single element segment is of the form

\[ P(\theta) = \frac{P_o \sin (\frac{\pi a}{\lambda} \sin \theta)}{\pi a/\lambda \sin \theta} \]  

(1)

where \( P_o \) is the maximum pressure, \( a \) is the element width, and \( \lambda \) is the wavelength of the acoustic wave. Table 1 lists the annular array parameters of the two phased array transducers used in this study.

Table 1. Annular Array Parameters for Transducer Elements of K-81 Lead Metaniobate

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Width</th>
<th>Spacing</th>
<th>Max. Radius</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MHz</td>
<td>0.020 inch</td>
<td>0.03 inch</td>
<td>0.26 inch</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>0.014</td>
<td>0.02</td>
<td>0.21</td>
<td>9</td>
</tr>
</tbody>
</table>


Fig. 3. Illustration of the focusing geometry with the Nth element of an annular array at a water to metal interface.

**PHASED ARRAY DELAY TIME SCHEDULING**

The focal point position of an array is a function of the firing and summing delays of the individual elements. Figure 3 shows a diagram of ray traces from a single annular element which correspond to a water focus at \( F_w \) and a metal focus at \( F_k \) in a target material. \( D \) is the distance the annular array is above the target material. To focus at \( F_k \) a time-of-flight difference between the outermost annulus \( N \) and any inner annulus \( n \) is given by

\[
\Delta T_n = T_N - T_n = \frac{W_n - W_{n-1}}{V_1} - \frac{P_n - P_{n-1}}{V_2}
\]  

where \( W \) is the water path, \( P \) is the metal path, and \( V \) is the corresponding acoustic velocity of each medium. From the diagram, the focus \( F_k \) is given by

\[
F_k = \frac{R_n}{P_w} (F_w - D) \cot \theta_2
\]  

where
\[
\cot \theta_2 = \left[ 1 - \frac{V_2}{V_1} \sin \theta_1 \right]^{1/2} \frac{V_2}{V_1} \sin \theta_1 \quad (4)
\]
and
\[
\sin \theta_1 = R_n \left[ R_n + F_w \right]^{-1/2} \quad (5)
\]

To determine \( \Delta T \) for a specific focus \( F_k \), \( \theta_1 \) and \( \theta_2 \) must be determined in order to calculate \( W \) and \( P \). \( \theta_1 \) and \( \theta_2 \) can be found iteratively by starting with \( F_w = D + (V_2/V_1)F_k^2 \), using equations (4) and (5), and adjusting \( F_k \) until equation (3) is satisfied.

The host computer was used to prepare a pulser and receiver delay schedule data array \( A(K,I) \) where \( K \) is the focus number and locations \( I \) contain receiver delay information and bit patterns for the RAM for each focus number. \( A(K,I) \) is used for fast loading into the phased array controller during dynamic focusing and automatic scanning of the target block. A flow chart of the computer code for setting up \( A(K, I) \) is shown in Figure 4.

**PHASED ARRAY DATA ACQUISITION**

The flow chart of the computer code for rapid scanning of a target under dynamic focusing of the phased array transducer is shown in Figure 5. After initiation of the system, data acquisition, storage, and display of all acceptable echoes proceeds automatically. Accumulative real time plots of the data are made during scans in order to allow the operator a preview of the data collected. For each echo received within an acceptable focus window, the echo amplitude in one dB increments for one to 15 dB, the time-of-flight of the echo in increments of 25 nanoseconds, and the X, Y transducer position to within \( \pm 0.05 \) mm are all recorded and saved. When scanning of the target material is complete, appropriate B-scan and C-scan plots of the data at given threshold amplitudes can be made.

**EXPERIMENTAL RESULTS**

The actual geometry of an aluminum target block with machined flat bottom holes is compared in Figure 6 with the C-scan and B-scan plots of the block using a 10 MHz annular array transducer and a 10 MHz 0.25 inch diameter flat transducer. FBH diameters of 0.0625 and
Fig. 4. Flow chart of computer code used to prepare a data array \( A(K,I) \) for fast loading of the phased array controller.

Fig. 5. Flow chart of computer code for automatic scanning and data acquisition with dynamic focusing of the phased array transducer.
0.125 inch were machined at 0.25, 0.5, and 0.75 inch depths. From Figure 6 it is seen that good resolution and sizing of the FBH's is accomplished at all depths with the annular array technique and, as expected, both over and under sizing is evident for the flat transducer.

Quantitative sizing results for the FBH's are shown in Figure 7 for the 10 MHz annular array transducer. The plotted data in Figure 7 illustrates the results of sizing the FBH's as directly measured from the C-scan plots at threshold amplitudes in 2 dB increments. Note that an adequate size of both the 0.0625 and the 0.125 inch diameter FBH is given at 11 to 13 dB for all depths. Similar graphs of sizing the same FBH's for the 5 MHz, 8 element annular array is shown in Figure 8a. Figure 8b and 8c gives the sizing results using a 10 MHz 1.2 inch water focus transducer. As seen in Figure 8, the sizing with the conventional flat and focused
transducer is much more amplitude dependent. Figure 9 illustrates the sizing versus depth capabilities of the annular array technique in comparison to the flat and focused transducers.

An adequate sizing with the flat transducer can only be given at one depth for a given amplitude threshold. In order to approach the correct sizing at all depth for the flat transducer, one must use either an artificially constructed DAC curve for data reduction or an electronic time corrected gain curve employed during data acquisition. Both of these methods only estimate the correct size and do not measure it directly. The focused transducer allows sizing at one depth only (0.50 inch depth in Figure 8). Sizing at other depths can be achieved by changing the water path distance and rescanning the target block. This alternative greatly increases the inspection time to scan the total volume of the target block.
Fig. 8. Quantitative sizing results of FBH targets. (A) for 5 MHz annular array; (B) for 10 MHz flat transducer; and (C) for 10 MHz focused transducer.
Fig. 9. Comparison of measured size versus depth using the phased array technique, flat, and focused transducers at the optimum threshold amplitude.
CONCLUSION

An annular array technique of sizing defects in metals and ceramics employing electronic focusing of the array while automatic scanning of a target has been described. C-scan plots of threshold amplitudes renders sizing capabilities by the annular array technique to be largely independent of defect depth and system gain.

Improvements in the programmable phased array controller are still possible. These may include faster RAM devices and improved techniques of delaying the receiver waveforms. The tapped delay line technique was found to be limited in bandwidth and it generated undesirable internal reflection characteristics. Further work is planned to improve these techniques which should be beneficial for general NDE applications.

REFERENCES


