MULTIVIEWING ULTRASONIC TRANSDUCER SYSTEM FOR FLAW RECONSTRUCTION

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INTRODUCTION

The characterization of failure-initiating flaws in materials and components is an important task in the assurance of structural integrity. Based on ultrasonic signals scattered from the flaw in a number of directions, inverse scattering algorithms may be used to reconstruct the size, shape and orientation of the flaw. One of the more successful methods for elastic wave inverse scattering and flaw sizing has been the inverse Born algorithm in the long and intermediate wavelength regime.

At Ames Laboratory, multi-transducer ultrasonic instrumentation, as well as the associated data acquisition and signal processing algorithms, have been developed for the utilization and advancement of flaw reconstruction methodologies [1]. One-dimensional inverse Born flaw sizing and ellipsoidal-based reconstruction have been performed on spheroid-like flaws with considerable success. The reliability problem in the reconstruction of arbitrarily oriented flaws was studied in detail and an angular scan plan was developed to optimize the data acquisition configuration and to improve the reconstruction reliability [2]. The angular scan plan was first implemented manually and its usefulness verified, the multiviewing transducer instrument was then extensively redesigned so that automated scans may be made. The scan results are used to determine the data acquisition angles for the transducers that provide the best coverage of the flaw surface and the highest signal-to-noise ratio. In this paper details of the "second generation" instrumentation are described and results of an example reconstruction are shown.

The expanded instrumentation has a large number of degrees of freedom and serves as an ideal research and testing tool for flaw characterization. Several new topics are being pursued and two will be briefly discussed here. First, the signal amplitude contour is obtained for an arbitrarily oriented general ellipsoid. The result is then compared qualitatively to the predicted contour based on the flaw geometry. Second, the multiview ultrasonic system is applied to flat crack-like flaws much larger than a wavelength. Angular scans are made to reveal the crack-like nature (as opposed to volumetric) and to determine the orientation of the flaw. The size of the crack is then estimated from the time delay of the two tip diffraction signals observed in a line scan across the face of the crack.

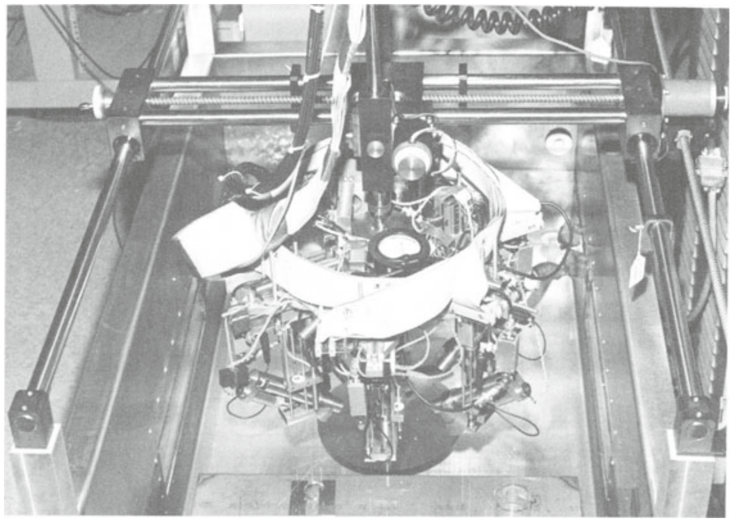

Fig. 1. Multiviewing transducer apparatus positioned in an immersion tank.

DESCRIPTION OF THE NEW MULTIVIEW TRANSDUCER SYSTEM

The first generation of the multiview transducer assembly, as reported in Ref. 1, consisted of six peripheral transducers and a center transducer. The six transducers were held in a gimbaled mount on a 2" diameter ring. They were coupled to a common drive so that all six transducers were set to the same angle of incidence, up to 30° in water. As a result, the instrument was limited to a configuration in which the axis of the transducer assembly must be held perpendicular to the flat surface of the part so that all transducers focused onto the flaw. This design has been substantially expanded in the second generation apparatus in order to implement the angular scans for better reconstruction reliability.

In the new instrument, shown in Fig. 1, a total of six transducers are used. The fixed diameter ring is eliminated and each transducer can move radially up to 5" from the central axis. Two of the transducers can be moved to the center in the search mode. The increased diameter of the apparatus makes possible the evaluation of flaws up to 4" deep in common metals. Each transducer can be tilted to a maximum angle of 60° and translated along its axis over a distance of 2", as shown in Fig. 2. The three independent degrees of freedom of the six transducers, together with the x,y,z and θ motions of the whole apparatus, give the multiviewing system a total of 22 possible adjustments. All the translational and angular motions of the transducers are controlled and monitored by a computer. High precision is achieved by the use of linear voltage differential transformers (LVDT). The new apparatus is therefore capable of carrying out the angular scan plan to optimize the data acquisition aperture for an arbitrarily oriented flaw.

The transducers are a matched set of commercial immersion probes with a nominal center frequency of 10MHz and a diameter of 1/4". The spread in their spectral amplitudes is within 2-3 dB. The transducers can be driven by either a spike voltage or a step function voltage (for unipolar pulse generation). The various pulse-echo and pitch-catch combinations are selected through a high speed electronic switch. The detected flaw signals are transmitted to a common receiver through 20dB preamplifiers connected to each transducer. The time domain flaw signals are digitized and averaged in a Tektronix 7912 programmable digitizer and stored in a MicroVax computer for further processing.

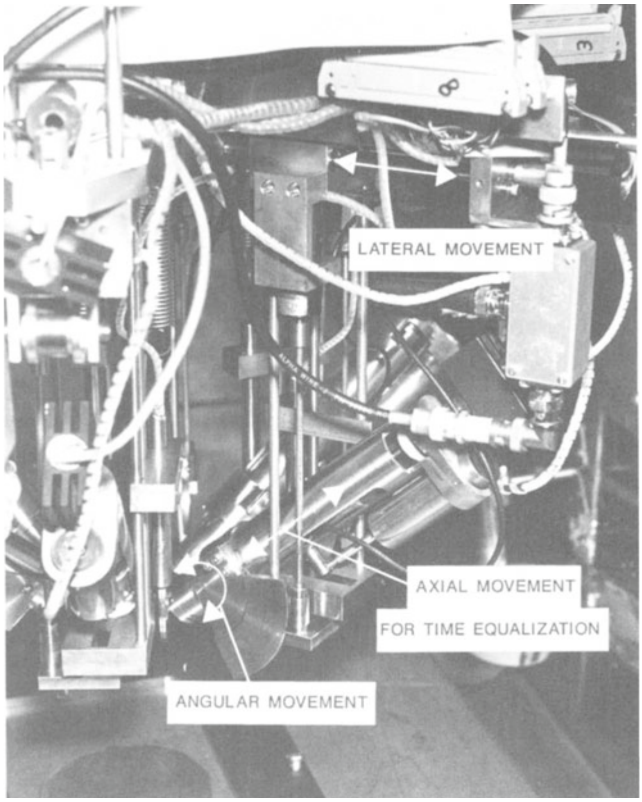

Fig. 2. Close-up photograph showing the three movements of one of the six transducers.

To obtain the absolute scattering amplitudes, the raw flaw signals are processed with a "measurement model" software [3] that removes system responses. The flaw sizes (center to tangent plane distances) in the various directions are obtained by using the 1-D inverse Born algorithm, as described in Refs. [4,5]. Finally the flaw sizes in different directions are used in a best-fit-ellipsoid reconstruction of the flaw [1,5]. Details of these flaw reconstruction procedures have been given in previous publications and will not be repeated here.

AUTOMATED FLAW RECONSTRUCTION WITH MULTIVIEW APPARATUS

When a flaw of arbitrary orientation is situated below a flat part surface, a multiviewing aperture with its axis perpendicular to the surface may not be the optimum configuration for data acquisition in terms of signal-to-noise ratio and insonification of the flaw surface. It was demonstrated previously[2] that angular scans can be used in finding the optimum data acquisition configuration. With manual angular scans, excellent reconstruction results were obtained on a tilted copper inclusion in a thermoplastic sample. With the new multiviewing apparatus, it is now possible to carry out the entire flaw reconstruction sequence automatically; from the angular scan that determines the optimum data acquisition aperture for the particular flaw encountered to the iteration that leads to the best-fit-ellipsoid. The automated sequence was performed on the same copper inclusion and the results compared with those obtained manually. The copper inclusion is a short section of copper wire 80 μm in radius and approximately 400 μm long. To approximate this flaw as a prolate ellipsoid, the parameters a_x = 200 μm, a_y = a_z = 80 μm are used.

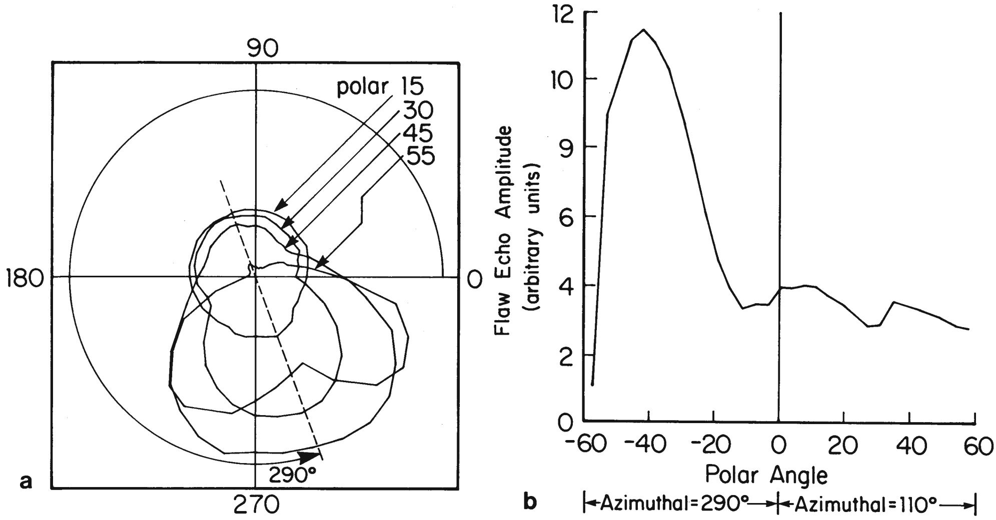

Fig. 3. (a) Azimuthal scan at four polar angles. Distance from the center to a point on the curve represents the flaw echo amplitude. (b) Polar scan in the bisecting symmetry plane of 290° obtained from (a).

Figure 3 shows the results of the automated angular scans; 3(a) is the flaw signal amplitude pattern obtained in azimuthal scans at four polar angles (15, 30, 45 and 55°). This pattern revealed a plane of symmetry (the vertical sagittal plane of the flaw) at an azimuthal angle of 290°. A polar scan in the sagittal plane produced the result shown in Fig. 3(b) and revealed the tilt angle of the prolate inclusion at 42°, quite close to the actual tilt of 45°. Based on the angular scan results, a data acquisition pattern consisting of 13 back-scattering directions centered about (polar = 42°, azimuth = 290°) was selected, as shown in Fig. 4. The acquired scattering data, after processing through the procedures described previously, yielded the automated reconstruction results listed in Table 1. Manual reconstruction results of the same flaw are also listed in Table 1 as a comparison. As can be seen, the automated reconstruction was very successful. The largest error in sizing again occurred in the length of the inclusion because the flaw shape is a short cylinder and not a prolate ellipsoid.

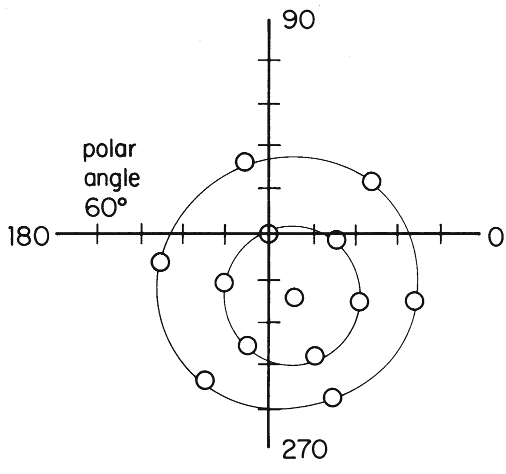

Fig. 4. Data acquisition aperture based on angular scan results. Azimuthal angles are shown every 90° and polar angles are shown from the origin in 15° increments. The two circles are drawn to aid the eye in visualizing the transducer positions of the tilted data acquisition aperture.

Table 1 Reconstruction results using the automated multiview apparatus.

	ACTUAL VALUES	AUTOMATED RECONSTRUCTION*	MANUAL RECONSTRUCTION*
a_x	200 μm	250 μm	257 μm
a_y	80 μm	89 μm	87 μm
a_z	80 μ	84 μm	81 μm

* Approximating the flaw shape with a prolate ellipsoid.

SIGNAL AMPLITUDE CONTOUR OF ARBITRARILY ORIENTED GENERAL ELLIPSOID

The signal amplitude contours generated in angular scans reveal considerable information about the flaw's shape and orientation. In the regime of geometric acoustics, the echo amplitude is proportional to $(r_1r_2)^{1/2}$ where r_1 and r_2 are the principal radii of curvature at the point where the wavefront makes contact with the flaw surface. A large number of cases were studied in an earlier paper [6]. For spheroidal flaws under a flat part surface, there is always a vertical bisecting plane and hence a plane of symmetry in the signal amplitude contour. However, general ellipsoids ($a_x \neq a_y \neq a_z$) with a nonzero ψ will not exhibit a plane of symmetry in the scanned amplitude contour. (Here ψ is the third Euler angle according to the convention of Ref. 7).

In this work, a thin rectangular plate copper inclusion imbedded in a thermoplastic disk is used as an approximation to a general ellipsoid. The "semiaxes" of the plate are 200 μm, 470 μm and 26 μm. The plate is oriented with the Euler angles equal to $\theta = -18°, \phi = 10°$ and $\psi = 20°$. Figure 5 shows the experimentally obtained signal amplitude contour and the computed contour. Azimuthal scans are made at polar angles of 15, 24, 33 and 42°. The resemblance between the two figures is obvious and the differences are mainly due to the difference in shape between a rectangular plate and an ellipsoid.

The lack of symmetry planes in the signal amplitude contours of arbitrarily oriented general ellipsoids makes it more difficult to extract information about the flaw shape and orientation. This "inverse problem" is yet to be solved.

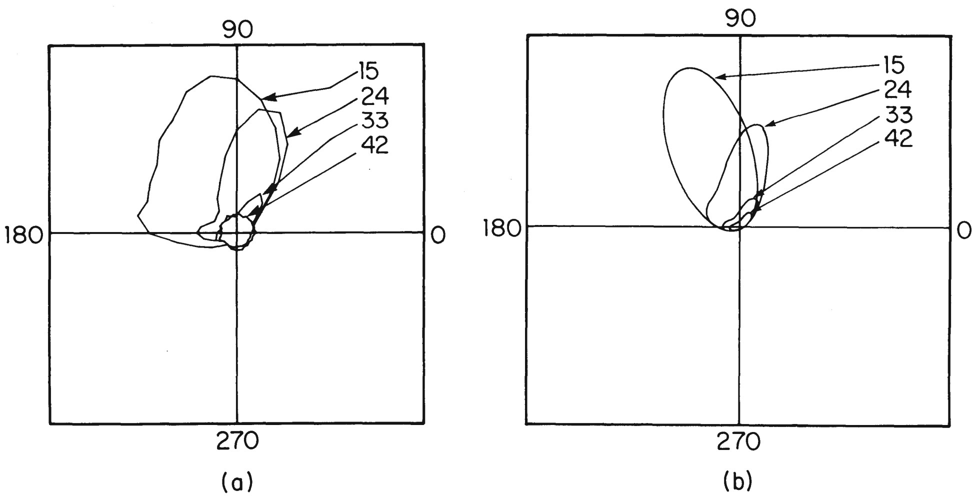

Fig. 5. (a) Experimental flaw signal amplitude of a rectangular inclusion, the small circle at the origin is the noise level, (b) Calculated signal amplitude contours based on ellipsoidal assumption. In both figures, azimuthal angles are marked every 90° and the polar angles are 15, 24, 33 and 42°.

ANGULAR SCAN AND SIZING OF A CRACK

The reflection of ultrasonic waves from a crack is highly directional. The signal amplitude is a maximum when the waves impinge on the crack perpendicularly and the amplitude drops off extremely rapidly as the angle deviates from the normal. Using a powder metallurgy iron sample containing an interior circular crack[8] with a diameter of 1/8 inch, angular scans were performed. The results easily determined the actual orientation angles of the crack (azimuth = 180° and polar = 42°). Figure 6 shows the experimental and calculated amplitude contours for the crack in azimuthal scans. The circles at the center of the experimental data (Fig. 6(a)) represent the noise floor of the flaw signal. The calculated results (Fig. 6(b)) were obtained for a diameter/thickness ratio of 7, even though the actual ratio was much greater, in order to avoid the entire contour degenerating into a single line. The calculation of the amplitude contour was for an ideal case of high frequency plane waves and did not include multi-frequency and diffraction effects.

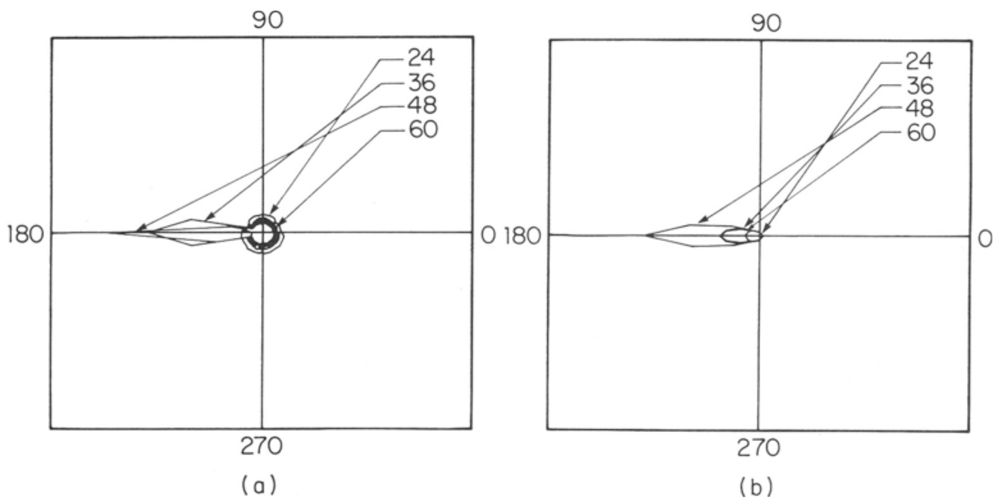

Fig. 6. Experimental (a) and calculated (b) flaw signal amplitude contours for an interior crack. In both figures azimuthal angles are marked every 90° and the polar angles are 24, 36, 48, and 60°.

Once the orientation of the crack is known, the crack size may be estimated from the time delay of the tip diffracted echoes when the transducer is scanned in the vertical (perpendicular to the part surface) bisecting plane. Figure 7 shows a side-view of the crack and the scanning path of the transducer parallel to the part surface. The time delay Δt between the two tip diffracted echoes of opposite polarity may be used in the determination of the crack diameter D. A brief analysis of the geometry leads to a formula for the crack diameter:

$$D = (\Delta t)V[\sin(90-\Theta)]/(2\sin\gamma) \quad (1)$$

where V is the speed of sound in the solid, Θ is the angle of incidence in the solid and γ is the tilt angle of the crack with respect to the part surface. (The incident beam is in general not perpendicular to the crack surface.)

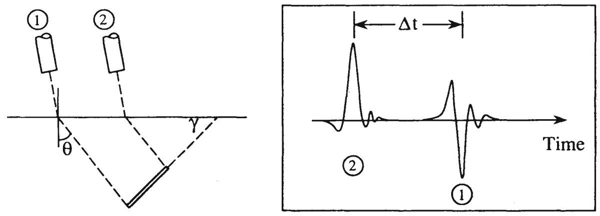

Fig. 7. Sizing a crack diameter by scanning the transducer parallel to the part surface in the vertical bisecting plane.

Table 2 Crack sizing by time delay of tip diffraction echoes.

θ	$\Delta t(us)$	Measured D (in)	Actual D (in)
15°	0.80	0.114	0.125
19°	0.82	0.114	"
23°	0.83	0.114	"
27°	0.84	0.110	"

Using Eq. (1), the size of the 1/8" diameter crack in powder metallurgy iron was measured ultrasonically. The results are shown in Table 2. The estimated sizes are within about 10% of the actual value.

CONCLUSION

This work represents a "coming together" of the various components of the multiviewing flaw reconstruction technique in the long and intermediate wavelength regime using ultrasonic inverse scattering algorithm. It was demonstrated that the apparatus automatically performs the angular scans to optimize the data acquisition configuration for the flaw encountered, acquires and processes the data, and carries out the iteration to find the best-fit ellipsoid to the flaw. The apparatus is also used in the evaluation of non-ellipsoidal flaws and cracks. For complex shaped flaws the future direction for utilizing the multiviewing system is in the development of 2-D and 3-D tomographic reconstructions.

ACKNOWLEDGEMENT

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