CHARACTERIZATION OF FLAW SHAPE AND ORIENTATION USING ULTRASONIC ANGULAR SCANS

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INTRODUCTION

To exploit theoretical advances in elastic wave inverse scattering, an automated multiviewing ultrasonic transducer system and the associated signal processing algorithms have been developed at the Ames Laboratory for the reconstruction of the size, shape, and orientation of volumetric flaws [1]. The flaw sizing algorithm is based on elastic wave inverse scattering theories in the long and intermediate wavelength regime [2,3] and the three-dimensional reconstruction algorithm finds the equivalent ellipsoid that best fits the flaw sizes in the various viewing directions [4,5]. The original multiprobe system consists of six peripheral transducers equally spaced in a circle surrounding one transducer at the center. The peripheral transducers may be tilted at an angle toward the center to increase the aperture and can also be translated along their respective axes to allow an equilization of the acoustic propagation time. The axis of the aperture cone is normally placed perpendicular to the part surface. The flaw sizing procedure was a one-dimensional inverse Born algorithm to determine the flaw's centroid-to-tangent plane distances for a number (normally 13 or 19) of pulse-echo or pitch-catch scattering directions within a finite aperture cone. The flaw sizes are then used as inputs to a nonlinear least squares regression program to yield a complete geometric reconstruction in the form of three semi-axes and three Euler angles of the best-fit ellipsoid. Using this system, successful reconstructions have been obtained for both oblate spheroidal (disk-like) and prolate spheroidal (rod-like) inclusions and voids. The readers are referred to a complete description of the system in Ref. 1.

Recently, efforts have been devoted to the assessment of the reconstruction reliability as a function of the aperture size and the signal-to-noise ratio of the flaw waveforms [6]. Of particular interest is the effects of flaw orientation on the reconstruction reliability [7]. Computer simulations of the reconstruction errors were made for flaws untilted and tilted with respect to the viewing aperture. For the same aperture size, the reconstruction errors were much greater for a tilted flaw, consistent with experimental observations. With the viewing aperture situated normal to the part surface, a flaw tilted with respect to the surface may afford a very low leverage for reconstruction due to limited surface area coverage by the wavefront tangent planes, small signal-to-noise ratio, and possibly also the presence of flash point interferences.
in the scattering amplitude spectrum. Examples are edge-on views of a disk-like flaw or end-on views of a rod-like flaw. As a result, a larger aperture containing the same number of scattering directions (kept as a constant for speed considerations) may not be sufficient in improving the reconstruction reliability. Besides, the aperture size has practical limits in a single-side access inspection situation. A more advantageous approach is to tilt the interrogation aperture to compensate for the particular flaw orientation and to restore the leverage for a reliable reconstruction. To do so, some prior knowledge about the flaw shape and orientation is required. In this work an angular scan method is developed in which the flaw shape and orientation are estimated from azimuthal and polar scans of the flaw signal amplitude. Based on such preliminary determination of flaw shape and orientation, an aperture orientation may then be chosen so that the aperture axis is perpendicular to the flaw surface where the total curvature is a minimum. The angular scans and the judicious choice of the aperture configuration for data acquisition have several advantages: the signal-to-noise ratios of the flaw waveforms are improved, the flash point interference phenomena are avoided, and the symmetry planes determined in the angular scans allow two-dimensional cross-sectional reconstructions in the principal planes of the ellipsoid-like flaws.

RECONSTRUCTION OF TILTED FLAWS

To assess the reconstruction reliability for tilted flaws using the multiviewing transducer system, two flaws were studied: a short section of copper wire (160\(\mu\)m dia. x 400\(\mu\)m) tilted 45° in a thermoplastic host and a 400 x 200\(\mu\)m oblate spheroidal void in titanium tilted 30°. Using a data acquisition aperture perpendicular to the part surface, the usual reconstruction procedure failed to yield good results for both tilted flaws. However, when the aperture was tilted to compensate the flaw orientation, excellent reconstructions were obtained for these tilted flaws. These experiments clearly demonstrated the advantages of conducting the construction with an aperture perpendicular to the flattest part of the flaw surface. Because the orientation of the flaw under investigation is generally unknown, an angular scan plan was developed to obtain this information.

ANGULAR SCAN METHOD

In the high frequency regime the principles of geometrical optics apply and the amplitude of the ultrasonic signal backscattered from a flaw should be proportional to \(\rho_1 \rho_2\) where \(\rho_1\) and \(\rho_2\) are the principal radii of curvature at the point where the wavefront makes contact with the flaw surface. The high frequency regime is characterized by \(ka \gg 1\), where \(k\) is the wavevector and \(a\) is some characteristic size of the flaw. The product \(\rho_1 \rho_2\) is referred to as the total curvature (or Gaussian curvature) of the flaw surface at the contact point. For an ellipsoid it can be shown that \(\rho_1 \rho_2 = A_x A_y A_z / r_e^2\) where \(A_x\), \(A_y\) and \(A_z\) are the semiaxes of the ellipsoid and \(r_e\) is the center-to-tangent plane distance for the scattering direction [8]. The value of \(r_e\) depends on the sizes of the semiaxes as well as the orientation of the flaw [5]. (The signal amplitude also depends on the impedance mismatch between the flaw and host material; but, for a given flaw, it is simply a constant multiplicative factor.) Based on this, one would expect that flaw shape and orientation information can be deduced from the angular dependence of the backscattered flaw signal amplitude in the large \(ka\) limit. We shall first describe the angular scan method and then discuss its applicability in the comparison with the experimental data.
To illustrate the flaw shape and orientation estimation, we computed the high frequency signal amplitude \( \frac{A_x A_y A_z}{r^2} \) for a prolate spheroid with \( A_x=A_z=80\, \mu m, A_y=250\, \mu m \), and with the major axis of the prolate pointed at an azimuthal angle of 120° and a polar angle of 45° in the laboratory coordinates fixed on the sample. Figure 1 shows azimuthal scans at five polar angles: 0, 15, 30, 45, and 60°. The distance from the origin to a point on the curve represents the amplitude of the computed flaw signal. As can be seen, a plane of mirror symmetry exists at an azimuthal angle of 120° (or 300°). A polar scan at this azimuthal angle, shown in Fig. 2(a), shows a peak at \( \alpha=45° \) and \( \beta=300° \); thus revealing the tilt angle of the prolate flaw. Here we use the notations \( \alpha \) and \( \beta \) for the polar and azimuthal angles, respectively. A second scan in a plane containing the direction of maximum signal (\( \alpha=45°, \beta=300° \)) and perpendicular to the plane of mirror symmetry is shown in Fig. 2(b). (The second scan requires changing the polar angle \( \alpha \) and the azimuthal angle \( \beta \) simultaneously). The second scan shows a constant signal amplitude; thus confirming the prolate spheroidal shape of the flaw. For the convenience of discussion, we shall call the plane of mirror symmetry containing the normal to the part surface the vertical sagittal plane (or VSP). The VSP bisects the flaw and is normal to the part surface. The plane of the second scan perpendicular to the VSP and also bisecting the flaw, is called the perpendicular sagittal plane (or PSP), as shown in Fig. 3.

The angular scan pattern of a general ellipsoid characterized by semi-axes \( A_x=400\, \mu m, A_y=200\, \mu m, A_z=100\, \mu m \) and Euler angles \( \theta=37°, \phi=54°, \psi=0° \) is shown in Fig. 4. Pictorially, the long axis of the ellipsoid lies along an azimuthal angle of 144° (or 324°) and the tip in the second quadrant is tilted out of the figure. The symmetry of the pattern in Fig. 4 shows that the VSP is at an azimuthal angle of 144° (or 324°). The VSP and PSP scans are shown respectively in Figs. 5a and b. As can be seen, the VSP curve shows a peak at the expected 37° and, because

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**Fig. 1.** Computed signal amplitude of a tilted prolate flaw as a function of azimuthal angle at five different polar angles. \( A_x, A_y, \) and \( A_z \) are the semi-axes and \( \theta, \phi, \) and \( \psi \) are the Euler angles specifying the flaw orientation.
AX = 88
AY = 250
AZ = 88
THETA = 45
PHI = 30
PSI = 0

Fig. 2. a) Scan in the vertical sagittal plane revealing the 45° tilt angle of the flaw. b) Scan in the perpendicular sagittal plane revealing the prolate shape of the flaw.

Fig. 3. yz plane is the vertical sagittal plane (containing the normal to the part surface). xz plane is the perpendicular sagittal plane.

$A_x > A_y$, the width of the VSP peak is broader than the PSP peak. If this were an oblate spheroid with $A_x = A_y > A_z$, then the widths of the VSP peak and the PSP peak would have been equal.
Fig. 4. Computed angular scan pattern of a general ellipsoid.

Fig. 5. a) VSP scan showing a broader peak at a polar angle of 37°.
    b) PSP scan showing a narrower peak because $A_x > A_y$. 
Using computer simulation, the angular scans of a large number of flaw shapes and orientations have been studied. It was noticed that spheroidal flaws of any orientation always have a VSP. A VSP also exists for general ellipsoids if the third Euler angle $\psi$ is zero. The angular scan of a general ellipsoid with a nonzero $\psi$ possesses no mirror symmetry. Further investigations are needed to extract its orientation information and to distinguish it from nonellipsoidal flaws. Based on this rather extensive simulation study, a flow chart, as shown in Table 1, has been made for characterizing the shape and orientation of ellipsoidal flaws.

COMPARISON WITH EXPERIMENTS

To compare with the predicted signal amplitude contours in angular scans, we obtained experimental data on a tilted oblate spheroidal void in titanium. The sizes of the flaw are $A_x=A_y=400\mu$m and $A_z=200\mu$m. The azimuthal and polar angles of its $z$-axis (normal to the "flat" surface) are respectively 255° and 30°. Experimental data in Fig. 6(a) show that the VSP occurs near the expected azimuthal angle of 255° and that the signal amplitude at this azimuth first increases with polar angle and then decreases after the polar angle exceeds the tilt angle 30° of the oblate flaw. The frequency spectrum of the transducer used in the angular scans is such that $ka$ ranges approximately from 0.5 to 3. As a comparison, the computed high frequency limit signal amplitude contours are shown in Fig. 6b. Although the computed results are made for the large $ka$ limit, they clearly display qualitatively the same features as the experimental results. It should also be noted that the experimental data represent the raw flaw signal amplitude without correcting for diffraction and interface refraction effects, except

![Fig. 6. a) Experimental angular scan results for an oblate spheroidal void in titanium tilted 30° with respect to the part surface. b) Computed signal amplitude contours for the titled oblate spheroid.](image-url)
Table 1. Flow chart for flaw shape characterization based on angular scans of the flaw signal amplitude.

Note: Abbreviated notations in this table are: VSP-vertical sagittal plane, PSP = perpendicular sagittal plane, $\psi$ is the third Euler angle, $\alpha$ is the polar angle, $xyz$ is the laboratory system of coordinates, and $z$ is perpendicular to the part surface.
that the acoustic propagation time was equalized for the various look angles. The important conclusion to be drawn from this comparison is that the symmetry and Gaussian curvature of the flaw surface are such strong features that they are observable even in the intermediate frequency regime. Furthermore, the flaw signal amplitude is dominated by the front surface $\delta$-function of the impulse response, which contains most of the high frequency components.

To investigate the angular dependence of the flaw signal amplitude (the front surface echo strength) more quantitatively, a polar scan was made in the VSP of the 2:1 oblate and the results are shown in Fig. 7. The experimental flaw signal was processed with the measurement model algorithm [9] to correct for diffraction and refraction effects in order to extract the front surface echo strength of the impulse response function the experimental results are shown in Fig. 7 as crosses. As a comparison, the dashed line in Fig. 7 represents Opsal's calculated results [10] bandlimited by the transducer response used in the experiment. Although the experiment and the calculation show some discrepancy, the trend supports the conclusion reached above.

In Fig. 8 we compare the experimental and computed angular scan contours of a copper wire inclusion tilted 45°. The experimental amplitude contours clearly differ from the computed results by having a bulge in the second quadrant. This difference, in fact, was caused by a strongly

![Fig. 7. Comparisons of experimental front surface echo strength for the 2:1 oblate spheroidal void and the computed results with transducer band limiting effects included.](image-url)
reflecting flat facet on one end of the copper wire (cut by a wire cutter, see micrograph inset). This shows that the angular scan contours are sensitive to detailed surface features of the flaw. A PSP scan perpendicular to the axis of the wire section is shown in Fig. 9. As expected, the signal amplitude is a constant. In contrast, the PSP scan of the oblate spheroid tilted 30° (also shown in Fig 9) shows a peak.

CONCLUSIONS

We have demonstrated that angular scans of the flaw signal amplitude cannot only reveal considerable flaw shape and orientation information, but also may be used to position the finite aperture of the multiviewing apparatus for a spatial data acquisition pattern that greatly improves the reconstruction reliability. The angular scan method has therefore provided an alternative approach for flaw reconstruction using the multiviewing transducer system. Instead of determining the full flaw characterization (size, shape, and orientation) by relying on the iterative fitting of the sizing data to the best-fit ellipsoid, the approximate shape and orientation of the flaw may be first determined with angular scans of the flaw echo amplitude prior to any sizing measurements. It should be stressed that the angular scan method is not limited to any particular flaw sizing inversion algorithm. Instead, it is a preliminary step that provides useful information to make the subsequent sizing and reconstruction more stable and reliable. Future work will be directed toward extracting more quantitative information such as aspect ratios and developing reconstruction methods based on the Gaussian curvature of the flaw surface.

Fig. 8. a) Experimental angular scan contours of a copper wire section tilted 45°. b) Computed angular scan contours for the same flaw.
Fig. 9. PSP scans of the copper wire inclusion and the oblate spheroidal void in titanium. Here $\theta$ is the angle measured from the maximum signal direction.

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