EQUIVALENT FLAW TIME-OF-FLIGHT DIFFRACTION SIZING WITH ULTRASONIC PHASED ARRAYS

Brady J. Engle¹,², Lester W. Schmerr Jr¹,², and Alexander Sedov³

¹Center for Nondestructive Evaluation, Iowa State University, Ames, IA 50011
²Department of Aerospace Engineering, Iowa State University, Ames, IA 50011
³Department of Mechanical Engineering, Lakehead University, Thunder Bay, ON, Canada

ABSTRACT. Ultrasonic phased array transducers can be used to extend traditional time-of-flight diffraction (TOFD) crack sizing, resulting in more quantitative information about the crack being obtained. Traditional TOFD yields a single length parameter, while the equivalent flaw time-of-flight diffraction crack sizing method (EFTOFD) described here uses data from multiple look-angles to fit an equivalent degenerate ellipsoid to the crack. The size and orientation of the equivalent flaw can be used to estimate the actual crack size.

Keywords: Ultrasonics, Phased Arrays, Flaw Sizing, Time-of-Flight

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INTRODUCTION

Time-of-flight diffraction sizing (TOFD) was developed in the 1970s and is widely used to estimate crack lengths in welds. TOFD uses the time difference $\Delta t$ between scattered diffraction signals from the crack tips to estimate the length of the crack. Traditionally, the TOFD method is done in a pitch-catch arrangement using single element transducers. No detailed flaw geometry or orientation information is obtained through TOFD sizing, only a single length parameter [1].

A separate time-of-flight-based crack sizing method developed in the 1980s and 1990s used a multi-viewing transducer system, which was composed of multiple conventional transducers arranged conically, to inspect flaws from multiple incident wave directions, or look-angles [2]. A sizing algorithm used the $\Delta t$ data from different look-angles to estimate the crack size as a best-fit degenerate ellipsoid [3].

This work uses phased array transducers to extend traditional TOFD by incorporating the equivalent flaw sizing algorithm developed with the multi-viewing transducer system. This allows for a single array transducer in pulse-echo or a pair of array transducers in pitch-catch to estimate the size and orientation of a crack in what we will call the equivalent flaw time-of-flight diffraction sizing method, or EFTOFD. The EFTOFD method can be done in nearly the same amount of time as traditional TOFD by making a few more measurements and processing the data with a computationally inexpensive sizing algorithm.
CRACK SIZING ALGORITHM

Figure 1 depicts an immersion, pulse-echo interrogation of a horizontal elliptical crack with a phased array transducer. A coordinate system fixed with respect to the sample with axes $x$, $y$, and $z$ can be arbitrarily chosen, and the equivalent flaw size and orientation will be expressed in this coordinate system. To obtain an angle $\phi$, the sample can be rotated, or the incident beam can be rotated the same amount in the opposite direction. The beam rotation can be done either by mechanically rotating the transducer or electronically steering the beam. Incident waves from the transducer, with direction given by $e$, will result in a specularly scattered wave from the crack surface, and two diffracted signals from the crack edges. If the angle $\theta$ is such that the specularly reflected wave does not return to the transducer, only the diffracted signals will be seen. Figure 2 shows a simulated A-scan with well separated crack edge diffraction signals. The time difference $\Delta t$ is defined as the time between the largest peak of the first crack edge signal and the largest peak of the second edge signal. Obtaining a small number of these $\Delta t$ measurements from different incident vectors $e(\theta, \phi)$ and solving a linear least squares and eigenvalue problem will allow the determination of an equivalent ellipse.

Schmerr has shown that the $\Delta t$ data for each $e$ is related to the equivalent radius of the ellipse in the direction of $e$ [4]. This relationship is given by

$$r_e = c\Delta t / 4$$

and depicted graphically in Fig. 3. Figure 3 shows the incident vector $e$ and equivalent radius $r_e$, along with the semi-major and -minor axes $a_1$ and $a_2$ and their directions $u_1$ and $u_2$. The direction $u_3$ corresponds to the crack surface normal. Expressing the equivalent radius in
terms of the incident wave direction -e and the ellipsoid parameters \( a_1, a_2, a_3 \) and \( u_1, u_2, u_3 \) gives [4]

\[
r_e^2 = a_1^2 (e \cdot u_1)^2 + a_2^2 (e \cdot u_2)^2 + a_3^2 (e \cdot u_3)^2.
\]  

Equation (2) can be rewritten as

\[
r_e^2(C, e) = C_{xx} e_x^2 + C_{yy} e_y^2 + C_{zz} e_z^2 + C_{xy} e_x e_y + C_{xz} e_x e_z + C_{yz} e_y e_z
\]  

where

\[
C_{xx} = a_1^2 u_{1x}^2 + a_2^2 u_{2x}^2 + a_3^2 u_{3x}^2 \quad C_{yy} = 2(a_1^2 u_{1y} u_{1y} + a_2^2 u_{2y} u_{2y} + a_3^2 u_{3y} u_{3y})
\]

\[
C_{yx} = a_1^2 u_{1y} u_{1x} + a_2^2 u_{2y} u_{2x} + a_3^2 u_{3y} u_{3x}
\]

\[
C_{zz} = a_1^2 u_{1z}^2 + a_2^2 u_{2z}^2 + a_3^2 u_{3z}^2 \quad C_{zz} = 2(a_1^2 u_{1z} u_{1z} + a_2^2 u_{2z} u_{2z} + a_3^2 u_{3z} u_{3z})
\]

Using Eqs. (1) and (3) we can define a function, \( F_m \), and error function for \( M \) measurements where \( \Delta t_m \) and -e \(_m\) are the \( m\)th time difference and incident wave direction, respectively.

\[
F_m = \left( \frac{c \Delta t_m}{4} \right)^2 - r_e^2(C, e_m)
\]

\[
E(C) = \sum_{m=1}^{M} F_m^2
\]

Minimizing the error function, i.e.

\[
\frac{\partial E}{\partial C_{ij}} = 0 \quad (i, j = 1, 2, 3),
\]

yields a system of linear equations for the \( C \) parameters, which can then be used to solve the eigenvalue problem

\[
\sum_{j=1}^{3} (C_{ij} - \lambda \delta_{ij}) l_j \quad (i = 1, 2, 3).
\]

It can be shown that the eigenvalues of \( C \) are just the lengths of the semi-major axes of the equivalent ellipsoid and the eigenvectors are the corresponding directions:

\[
\lambda = \begin{pmatrix} a_1^2 \\ a_2^2 \\ a_3^2 \end{pmatrix} \quad l = (u_1, u_2, u_3).
\]
MODEL-BASED BANDWIDTH ERROR CORRECTION

Small $\Delta t$ measurements are subject to large errors due to the finite bandwidth of the ultrasonic system. These errors can be corrected by using modeling to generate an error correction curve [3], as shown in Fig. 4. The ideal, infinite bandwidth crack edge diffraction signals are modeled using the scattering amplitude given by the Kirchhoff approximation. The exact $\Delta t$ values, shown as $\Delta t_e$ in Fig. 4, are taken to be the time differences between these modeled signals. Convoluting the Kirchhoff scattering amplitude with a Gaussian distribution, which represents the limited bandwidth of the system, results in a band-limited representation of the diffraction signals. The time differences between peaks of these limited bandwidth signals are taken to be the band-limited $\Delta t$ values, shown as $\Delta t_b$ in Fig. 4.

EXPERIMENTAL RESULTS

The experimental setup used is depicted in Fig. 1. Two flaws were used: the first was a #5 flat bottom hole (FBH) with a 1.984 mm diameter in 7075-T651 aluminum, and the second was an elliptical shaped isolated crack-like flaw that was manufactured in a diffusion-bonded titanium sample [5,6]. The elliptical crack was designed to have a semi-major axis of 2.5 mm and a semi-minor axis of 0.6 mm. These flaws are suitable for simulating crack responses because they both exhibit strong edge diffraction signals. The flaws were oriented during

<table>
<thead>
<tr>
<th>$\theta$ (deg)</th>
<th>$\phi$ (deg)</th>
<th>Meas. $\Delta t$ ($\mu$s)</th>
<th>Meas. $\Delta t$ ($\mu$s) with BW Corr.</th>
<th>Exact $\Delta t$ ($\mu$s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>0</td>
<td>0.49</td>
<td>0.513</td>
<td>0.5160</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>0.45</td>
<td>0.473</td>
<td>0.4826</td>
</tr>
<tr>
<td>45</td>
<td>0</td>
<td>0.41</td>
<td>0.433</td>
<td>0.4455</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>0.35</td>
<td>0.373</td>
<td>0.4049</td>
</tr>
<tr>
<td>40</td>
<td>45</td>
<td>0.36</td>
<td>0.383</td>
<td>0.4049</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
<td>0.40</td>
<td>0.423</td>
<td>0.4455</td>
</tr>
<tr>
<td>50</td>
<td>45</td>
<td>0.46</td>
<td>0.483</td>
<td>0.4826</td>
</tr>
<tr>
<td>55</td>
<td>45</td>
<td>0.50</td>
<td>0.523</td>
<td>0.5160</td>
</tr>
<tr>
<td>55</td>
<td>60</td>
<td>0.50</td>
<td>0.523</td>
<td>0.5160</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
<td>0.46</td>
<td>0.483</td>
<td>0.4826</td>
</tr>
<tr>
<td>45</td>
<td>60</td>
<td>0.41</td>
<td>0.433</td>
<td>0.4455</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>0.35</td>
<td>0.373</td>
<td>0.4049</td>
</tr>
</tbody>
</table>
TABLE 2. Data table for 5x1.2 mm (major x minor axes) elliptical crack.

<table>
<thead>
<tr>
<th>θ (deg)</th>
<th>φ (deg)</th>
<th>Meas. Δτ (μs)</th>
<th>Meas. Δτ (μs) with BW Corr.</th>
<th>Exact Δτ (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>90</td>
<td>0.34</td>
<td>0.362</td>
<td>0.3194</td>
</tr>
<tr>
<td>50</td>
<td>90</td>
<td>0.31</td>
<td>0.332</td>
<td>0.2987</td>
</tr>
<tr>
<td>45</td>
<td>90</td>
<td>0.26</td>
<td>0.282</td>
<td>0.2757</td>
</tr>
<tr>
<td>40</td>
<td>90</td>
<td>0.23</td>
<td>0.252</td>
<td>0.2506</td>
</tr>
<tr>
<td>55</td>
<td>60</td>
<td>0.69</td>
<td>0.713</td>
<td>0.7205</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
<td>0.63</td>
<td>0.653</td>
<td>0.6738</td>
</tr>
<tr>
<td>45</td>
<td>60</td>
<td>0.58</td>
<td>0.603</td>
<td>0.6220</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>0.51</td>
<td>0.533</td>
<td>0.5654</td>
</tr>
<tr>
<td>40</td>
<td>45</td>
<td>0.66</td>
<td>0.683</td>
<td>0.7593</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
<td>0.76</td>
<td>0.783</td>
<td>0.8353</td>
</tr>
<tr>
<td>50</td>
<td>45</td>
<td>0.83</td>
<td>0.853</td>
<td>0.9049</td>
</tr>
<tr>
<td>55</td>
<td>45</td>
<td>0.93</td>
<td>0.953</td>
<td>0.9676</td>
</tr>
</tbody>
</table>

inspection such that the crack surface normal \( \mathbf{u}_3 \) was in the \( z \)-direction, and the elliptical flaw had the semi-major and -minor axes \( \mathbf{u}_1 \) and \( \mathbf{u}_2 \) in the \( x \)- and \( y \)-directions respectively.

A 32 element, 10 MHz linear array transducer with a 0.36 mm pitch was used to carry out the inspection. The array was used to change the angle \( \theta \) electronically, while the samples were rotated to change the angle \( \phi \). Note that the use of a 2-D array would allow both angles to be changed electronically. Twelve look-angles were used for each flaw, and the \( \phi \) values were rotated to change the angle \( \phi \) during the inspection such that the crack surface normal \( \mathbf{u}_3 \) was in the \( z \)-direction, and the elliptical flaw had the semi-major and -minor axes \( \mathbf{u}_1 \) and \( \mathbf{u}_2 \) in the \( x \)- and \( y \)-directions respectively.

Equation (10) shows the exact results for the FBH, Eq. (11) shows the EFTOFD results with the bandwidth correction, and Eq. (12) shows the EFTOFD results with the bandwidth correction.

\[
\begin{pmatrix}
a_1 \\ a_2 \\ a_3
\end{pmatrix} =
\begin{pmatrix}
0.992 \\ 0.992 \\ 0
\end{pmatrix}
\begin{pmatrix}
u_{1x} & u_{2x} & u_{3x} \\ v_{1y} & v_{2y} & v_{3y} \\ v_{1z} & v_{2z} & v_{3z}
\end{pmatrix} =
\begin{pmatrix}
\cdots & 0 \\ 0 & 0 & 0
\end{pmatrix}
\]

Equation (11) shows the EFTOFD results with the bandwidth correction.

\[
\begin{pmatrix}
a_1 \\ a_2 \\ a_3
\end{pmatrix} =
\begin{pmatrix}
1.0173 \\ 0.9577 \\ 0.4887i
\end{pmatrix}
\begin{pmatrix}
u_{1x} & u_{2x} & u_{3x} \\ v_{1y} & v_{2y} & v_{3y} \\ v_{1z} & v_{2z} & v_{3z}
\end{pmatrix} =
\begin{pmatrix}
-0.1500 & -0.9817 & -0.1173 \\ -0.9887 & 0.1481 & 0.0244 \\ 0.0066 & -0.1197 & 0.9928
\end{pmatrix}
\]

Equation (12) shows the exact results for the elliptical crack, and Eqs. (14) and (15) show the EFTOFD results without and with the bandwidth correction, respectively.

\[
\begin{pmatrix}
a_1 \\ a_2 \\ a_3
\end{pmatrix} =
\begin{pmatrix}
2.5 \\ 0.6 \\ 0
\end{pmatrix}
\begin{pmatrix}
u_{1x} & u_{2x} & u_{3x} \\ v_{1y} & v_{2y} & v_{3y} \\ v_{1z} & v_{2z} & v_{3z}
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1
\end{pmatrix}
\]
\[
\begin{pmatrix}
a_1 \\
a_2 \\
a_3
\end{pmatrix} = \begin{pmatrix}
2.4594 \\
0.6255 \\
0.6928i
\end{pmatrix}
\quad \begin{pmatrix}
u_{1x} & v_{2x} & v_{3x} \\
u_{1y} & v_{2y} & v_{3y} \\
u_{1z} & v_{2z} & v_{3z}
\end{pmatrix} = \begin{pmatrix}
-0.9821 & -0.0473 & 0.1822 \\
-0.1184 & 0.9076 & -0.4029 \\
0.1463 & 0.4173 & 0.8969
\end{pmatrix} \quad (14)
\]

\[
\begin{pmatrix}
a_1 \\
a_2 \\
a_3
\end{pmatrix} = \begin{pmatrix}
2.4886 \\
0.6556 \\
0.6647i
\end{pmatrix}
\quad \begin{pmatrix}
u_{1x} & v_{2x} & v_{3x} \\
u_{1y} & v_{2y} & v_{3y} \\
u_{1z} & v_{2z} & v_{3z}
\end{pmatrix} = \begin{pmatrix}
-0.9834 & -0.0581 & 0.1717 \\
-0.1219 & 0.9131 & -0.3890 \\
0.1342 & 0.4035 & 0.9051
\end{pmatrix} \quad (15)
\]

The \(a_3\) values in Eqs. (11), (12), (14), and (15) are imaginary because the \(a_3^2\) values returned by the eigenvalue problem are small, often negative numbers. Taking the square root of a negative value of \(a_3^2\) results in an imaginary \(a_3\). The \(a_1\) and \(a_2\) values for both flaws are estimated to within 10% of their actual values, and the orientation results show good agreement with the expected values. The crack surface normal \(u_3\) for both flaws is estimated as primarily in the \(z\)-direction, as expected. Equations (14) and (15) shows that for the elliptical crack the semi-major and -minor axes \(u_1\) and \(u_2\) are predominately along the \(x\)- and \(y\)-directions, respectively, which was also expected.

The sizing results for these flaws only differ slightly when the bandwidth correction is applied. This is due to most of the \(\Delta t\) values being large enough so that the errors are relatively small. Figure 4 shows that the errors for many of the \(\Delta t\) values encountered are only a few percent. The bandwidth correction becomes more important for smaller flaws, whose smaller \(\Delta t\) values would have much larger errors. However, Table 1 shows that, for the FBH, the \(\Delta t\) values with the bandwidth correction are all closer to the exact values than the \(\Delta t\) values without the correction. Table 2 shows that 10 of the 12 \(\Delta t\) measurements are closer to the exact values with the bandwidth correction than without for the elliptical crack. This trend indicates that the bandwidth correction is removing some systematic error and resulting in more accurate sizing results.

**CONCLUSION**

The equivalent flaw time-of-flight diffraction (EFTOFD) sizing method has been shown to accurately determine the size and orientation of crack-like flaws using equipment already used for standard TOFD sizing. The inclusion of a few more measurements and a computationally inexpensive processing algorithm allows the EFTOFD method to obtain more quantitative information about the flaw than traditional TOFD sizing. This additional information can be directly used in fracture mechanics studies to determine the significance of the crack from a safety and reliability standpoint.

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