MODEL-BASED ITERATIVE FLAW SIZING FOR THICK COMPOSITES

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INTRODUCTION

Ultrasonic inspection of thick composites has been plagued by many problems such as the high degree of anisotropy and difficulties in achieving sufficient signal penetration. The dependency of wave speed to propagation direction causes beam skewing and excess beam divergence in certain directions, leading in turn to distortion of beam profile. Consequently, the beam distortion generates false indication of size and location of a flaw. This distortion of the beam in thick composites depends on several factors such as fiber layout of the material, size and frequency of the transducer used, etc.

Last year we reported on some preliminary results that were obtained in sizing circular simulated delaminations in the form of Teflon films imbedded inside [0/90] graphite/epoxy matting sample [1]. In that study, a numerical method was developed to use the ultrasonic reflected amplitude from a delamination versus transducer position, and estimate the size of the delamination. In this paper we are extending our flaw sizing technique to unidirectional composites which produce the most severe beam distortion and hence the greatest error in the delamination size. Also, we examined the effect of depth on delamination sizing.

The main thrust of our numerical computation is to calculate the displacement field at any point inside the composites. To achieve this, an approximate Gauss-Hermite beam model was used. The Gauss-Hermite model [2] can treat the propagation of sound fields through homogeneous, isotropic and anisotropic materials. This model has the advantage of being computationally fast and can be adapted to a wide variety of materials with different symmetry. The Gauss-Hermite model requires some parameters to describe the transducers and some parameters to characterize the composite material. To find the parameters for the composite, the elastic constants of the material must be known. In this paper we shall describe an iterative method by which the delamination size can be obtained from experimental data in the form of ultrasonic echo amplitude versus transducer position.

THE APPARENT SIZE OF A DELAMINATION

A simple way to measure the size of a delamination is to move a transducer over the delamination and record the amplitude of the reflected echo as a function of distance. The apparent size of the delamination is obtained using some simple criterion such as the
full-width-at-half maximum (FWHM), that is, the distance between the 50% points of the maximum signal. However, this apparent size can be quite different from the actual size of the delamination due to beam distortion. An important parameter in sizing a delamination ultrasonically is the width of the beam at the plane of the delamination. There are three beam width regimes relative to the size of a delamination.

**The Size of the Delamination is Much Larger than the Width of the Beam**

In this case, sizing the delamination is relatively easy. As the beam approaches the delamination, the reflected signal increases; it then remains constant as long as the beam is directly over the delamination. Finally, the reflected signal decreases as the beam passes over the delamination. The region over which the signal is constant can usually be interpreted as the extent of the delamination.

**The Size of the Delamination is much Smaller than the Width of the Beam**

In this case, the result of a c-scan will show the beam profile of the transducer instead of the flaw shape and size. Small changes in the delamination size will not affect the shape of the scan. Therefore, the estimation of the delamination size will be quite difficult in this case; in fact, the small flaw size will make the detection difficult as well.

**The Size of the Delamination is of the Same Order as the Beam Width**

This case will be the main focus of this study. The shape of line scan over a delamination in this situation is sensitive to the size of the delamination and the apparent size found in this case depends on several factors. One of these factors is the frequency of the transducer used to map the delamination. Usually the high frequency transducers have a narrower beam width and can give a better measure of the apparent size. However, due to the attenuative nature of thick composites, the high frequencies do not penetrate far into the material, and the signal-to-noise ratio of a deep flaw is usually very poor. Therefore there is a trade-off between resolution and penetration. Figure 1 shows a line scan over a delamination using the same broadband transducer but the signal amplitude at two different frequencies is plotted. As can be seen, the apparent width of the curve is smaller at the higher frequency.

![Graph showing amplitude vs. X-coordinate for 2 MHz and 4 MHz frequencies](image-url)

**Figure 1** Results obtained from 2 and 4 MHz component of a 5 MHz, 0.5 inch diameter transducer scanned along fibers over a 0.25 inch delamination embedded 2.72 cm in a unidirectional graphite/epoxy composite.
Another factor that affects the apparent size of a delamination is the fiber layout. The ultrasonic beam spreads faster in the direction of fibers; hence the beam is wider in that direction. Figure 2 shows the results of a line scan over a delamination when the transducer is scanned along the fibers and normal to the fiber direction. Finally, the distance of the transducer from the delamination can also affect the apparent size of the delamination. As the beam travels further, it gets wider; especially inside the composite materials. Figure 3 shows this effect.

**Figure 2** Results obtained from scans along fibers and normal to fibers over a 0.25 inch delamination embedded 2.72 cm inside a unidirectional graphite/epoxy composite. Plotted are the 2 MHz component of an echo obtained with a 2.25 MHz, 0.5 inch diameter transducer.

**Figure 3** Results obtained from scans over two 0.25 inch delaminations at depths of 2.72 cm and 1.07 cm inside a unidirectional graphite/epoxy composite. Plotted are the 2 MHz component of an echo obtained with a 2.25 MHz, 0.5 inch diameter transducer.
THEORETICAL BACKGROUND OF BEAM MODEL-BASED FLAW SIZING METHOD

Gauss-Hermite Beam Model

The Gauss-Hermite model has been developed to predict the sound field radiated into both isotropic and anisotropic materials by focused and unfocused transducers [2]. This model uses the Fresnel approximation, which assumes that the beam profile varies sufficiently slowly in the vicinity of the propagation direction. Thus, the slowness near the propagation direction can be expanded as a Taylor series.

\[
\left( \frac{k}{\omega} \right) = S_0 + A \left( \frac{k_x}{\omega} \right) + B \left( \frac{k_y}{\omega} \right) + C \left( \frac{k_x}{\omega} \right)^2 + D \left( \frac{k_x}{\omega} \right) \left( \frac{k_y}{\omega} \right) + E \left( \frac{k_y}{\omega} \right)^2
\]

where \( S_0 \) is the slowness along the propagation direction. To find the constants \( A, B, C, D, \) and \( E \), the derivative of \( (k/\omega) \) has to be taken with respect to each component of the slowness \( (k_x/\omega), (k_y/\omega), \) and \( (k_z/\omega) \). Usually the expression for slowness is quite tedious, and it is much easier to try to match a parabola with slowness surface at the vicinity of the propagation direction. It has been observed that the range of slowness surface to be used for the approximation of the parabola depends on the frequency and size of the transducer [3]. Therefore, it is beneficial to first try to map the beam through the material experimentally, and compare the beam profile with the Gauss-Hermite calculation. By doing so, the best values of the constants that can match the experimental profile can be found. This procedure increases the accuracy of the flaw sizing technique.

Delamination Sizing Technique

Several assumptions have been made for the sizing technique. First, it is assumed that the delamination has a constant reflectivity over its area and has a very small thickness. Also, it is assumed that the delamination has a circular shape. For other noncircular and somewhat irregular delaminations, the sizing technique will yield the radius of a circle which has the same area as the delamination. Finally, the delamination is approximated by a finite number of area elements.

The beam from the transducer will propagate to the delamination and, if the pulse/echo inspection method is used, a portion of the incident field is reflected back by the delamination to the transducer. By using Auld’s reciprocity relationship together with a Kirchoff approximation, the response \( \Gamma_S \) received by the transducer can be written approximately as

\[
\Gamma_S = K \int_S u^2 \cdot n \, dS
\]

where \( u \) is the displacement field on the delamination, \( n \) is the normal unit vector to the delamination surface \( S \), and \( dS \) is an area element of the delamination surface which encloses a point with displacement field \( u \). \( K \) is a constant for a particular experimental setup. Now, if we had the size and shape of the delamination, and could find the displacement field on each point on the delamination, we could predict the received signal. The displacement field \( u \) at any point can be calculated by using the Gauss-Hermite beam model.

The experimental procedure for estimating the size of a delamination is as follows. First, a transducer is scanned over the delamination and at each point of the scan the Fourier transform of the received signal is obtained and the amplitude of selected frequencies are stored. By making an initial guess for the radius of the delamination, the Gauss-Hermite solution is used to calculate the displacement field \( u \). Then, the square of the displacement field for the same frequency used in experimental results is integrated over the assumed delamination area. This calculation is repeated for every point of the scan. To compare the
Figure 4  Schematic diagram showing the steps of the iterative sizing of delamination in thick composites.

Figure 5  The experimental setup for sizing delamination at different depths.
experimental and calculated results, both results are normalized to a maximum amplitude of unity. The difference between the experimental results and calculated results now can be obtained and recorded. The theoretical calculation is repeated for different delamination sizes, and its difference with experimental results is again observed. Finally, by minimizing the difference between the experimental and the theoretical results, an estimate of the size of the delamination is arrived at. Figure 4 shows the process of sizing a delamination schematically. The optimization routine used for minimizing the difference between the measured and calculated results is the Fibonacci search with Golden section.

EXPERIMENTAL PROCEDURES AND RESULTS

A plate of unidirectional graphite/epoxy composite laminate with three delaminations was used in this study. Each delamination was a 0.25 inch Teflon implant embedded at the midplane of the composite. In order to simulate flaw sizing in a "thick" composite, the plate was placed under a thicker plate of unidirectional graphite/epoxy composite which had three different thicknesses. In this way we could also simulate the delamination at different depths. Figure 5 shows the experimental setup used for sizing the delaminations.

In all the experiments presented here, the pulse/echo method is used. This method is preferred over transmission because a single-side access is more practical for the ultrasonic inspection of large composite parts. To be consistent, one of the delaminations was chosen and all measurements were made on the same delamination. This delamination was placed under each step of the upper plate and it was scanned both along the fibers and normal to fiber direction. Four different transducers were used over each step. The amplitude of a frequency component, chosen within the bandwidth of the reflected signal, was then plotted against the position. By measuring the full-width-at-half-maximum amplitudes (FWHM), the apparent sizes were obtained for each scan. The experimental scan results were then used in the iterative determination of the delamination size according to the scheme shown in Figure 4. An example of the iteration results is shown in Figure 6.

![Figure 6](image)

Figure 6 Theoretical and experimental results of the 2 MHz component of an echo reflected from a delamination, using a 2.25 MHz, 0.5 inch diameter transducer. Experimental result is obtained from a line scan over a 0.25" diameter circular Teflon implant through a total thickness of 2.72 cm of unidirectional graphite/epoxy composite.
Here line scans, both along the fibers and normal to the fibers, were made over a circular delamination embedded in a unidirectional graphite/epoxy composite. The matching of the calculated amplitude-versus-position curves based on the beam model with the experimental data yielded the results shown in the inset table in Figure 6. It should be noted that the apparent size obtained from the two scans differed by 30% whereas the iterated sizes, not only much closer to the nominal actual size, differed only by 7% in the two directions.

Using the iterative scheme, the 0.25" diameter simulated delamination was sized for a variety of experimental conditions. The parameters varied included the depth, the frequency, the transducer size, and the focal length. In most cases a planar transducer was used, but a 0.75" diameter, 4" focal length (in water) transducer was used in some of the scan and the iteratively determined flaw sizes were also satisfactory.

Tables 1 and 2 summarize some of the sizing results. An obvious trend was that the apparent size by FWHM suffered increasing overestimation with increasing flaw depth. The discrepancy between the apparent sizes in the two scan direction was also greater at larger depth. The iteratively determined sizes, on the other hand, were in reasonable agreement with the actual size and showed much better agreement for the two scan directions.

Table 1. Apparent and computed results using the 2 MHz component of a 2.25 MHz, 0.5 inch diameter transducer. The delamination is a circular 0.25 inch diameter Teflon implant in a unidirectional graphite/epoxy composite.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Scan Direction</th>
<th>Sizing Method</th>
<th>Along Fiber Direction</th>
<th>Normal to Fiber Direction</th>
<th>Percentage Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.07 cm</td>
<td>Apparent Size</td>
<td>0.303&quot;</td>
<td>0.272&quot;</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Computed Size</td>
<td>0.289</td>
<td>0.278&quot;</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>1.92 cm</td>
<td>Apparent Size</td>
<td>0.325&quot;</td>
<td>0.270&quot;</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Computed Size</td>
<td>0.274&quot;</td>
<td>0.272&quot;</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2.72 cm</td>
<td>Apparent Size</td>
<td>0.382&quot;</td>
<td>0.285&quot;</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Computed Size</td>
<td>0.272&quot;</td>
<td>0.253&quot;</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Apparent and computed results using the 4 MHz component of a 5 MHz, 0.5 inch diameter transducer. The delamination is a circular 0.25 inch diameter Teflon implant in a unidirectional graphite/epoxy composite.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Scan Direction</th>
<th>Sizing Method</th>
<th>Along Fiber Direction</th>
<th>Normal to Fiber Direction</th>
<th>Percentage Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.07 cm</td>
<td>Apparent Size</td>
<td>0.274&quot;</td>
<td>0.297&quot;</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Computed Size</td>
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<td>0.307&quot;</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>1.92 cm</td>
<td>Apparent Size</td>
<td>0.343&quot;</td>
<td>0.299&quot;</td>
<td>14</td>
<td></td>
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<tr>
<td></td>
<td>Computed Size</td>
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<td>0.242&quot;</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>2.72 cm</td>
<td>Apparent Size</td>
<td>0.324&quot;</td>
<td>0.261&quot;</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Computed Size</td>
<td>0.258&quot;</td>
<td>0.252&quot;</td>
<td>3</td>
<td></td>
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</tbody>
</table>
CONCLUSION

We have investigated the problem of sizing delaminations in thick composites and developed an iterative sizing method based on the line scan echo-amplitude data and Gauss-Hermite beam model. Attention was given to the case where the delamination size and beam width are comparable. The sizing method was tested experimentally on simulated delaminations in a unidirectional graphite/epoxy composite where the elastic anisotropy is the greatest. The method represents a considerable improvement over the apparent size based on the full width at the half maximum amplitude.

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REFERENCES


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