Ultrasonic guided wave imaging for damage characterization
James S. Hall, Paul Fromme, and Jennifer E. Michaels

Abstract

Guided wave imaging with a sparse array of inexpensive transducers offers a fast, reliable, and cost-efficient means for damage detection and localization in plate-like structures such as aircraft and spacecraft skins. As such, this technology is a natural choice for inclusion in condition-based maintenance and integrated structural health management programs. One of the implementation challenges results from the complex interaction of propagating ultrasonic waves with both the interrogation structure and potential defects or damage. For example, a guided wave interacts with a surface or sub-surface defect differently depending on the angle of incidence, defect orientation, and ultrasonic frequency. Fortunately, however, this complex interaction also provides a mechanism for guided wave imaging algorithms to perform damage characterization in addition to damage detection and localization. Damage characterization provides a mechanism to help discriminate between actual damage (e.g. fatigue cracks) and benign changes, and can be used with crack propagation models to characterize the stress state. This work proposes the combined use of two guided wave imaging techniques to perform both damage localization and characterization. The robustness of conventional delay-and-sum imaging to errors in \textit{a priori} assumptions make it ideal for use in locating potential damage locations. Minimum variance imaging, which is highly sensitive to errors in \textit{a priori} assumptions, can then be leveraged to characterize the potential damage location by determining which scattering assumptions best match the measured data. Scattering assumptions are obtained through finite element modeling (FEM). Experimental data from an \textit{in situ} sparse array are used to demonstrate feasibility of this approach using two through-thickness notches of different orientations, one inside and one outside the array bounds, to simulate damage in an aluminum plate.

I. INTRODUCTION

Ultrasonic guided waves are capable of quickly interrogating large plate-like structures and are sensitive to both surface and subsurface features [1]. As such, significant efforts have recently been expended to use them for damage detection and localization in structures such as aircraft skins [2]. Since inexpensive piezoelectric transducers can both generate and respond to guided waves, permanently attached sparse arrays of these transducers offer a cost-effective \textit{in situ} structural health monitoring (SHM) solution for both aging aircraft and new aerospace designs.

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In situ monitoring does not require the system to be taken out-of-service for inspection, so inspections cost a fraction of current NDE methods and can be performed much more frequently, decreasing the inspection cost of condition-based obsolescence schedules and increasing safety margins.

To date, sparse arrays of piezoelectric transducers have already been demonstrated to be capable of detecting and locating damage [3]. Damage detection is typically performed through a simple differencing and threshold operation. A set of baseline signals is recorded during a known good condition and compared to signals recorded after some service period. If the difference between these two signals exceeds a predetermined threshold, then the interrogation system indicates that damage may be present. Damage localization is performed with the same differenced signals through guided wave imaging techniques. Several guided wave imaging methods are in use, including tomographic [4], hyperbolic [5], and elliptical imaging algorithms [3], [6], [7]. These imaging methods all produce an intensity map that corresponds to the interrogation structure, with the brightest pixels indicating the most likely damage location(s).

In addition to damage localization, elliptical guided wave imaging algorithms also offer the potential to perform damage characterization. The geometric structure of a damage site or defect, such as size, orientation, etc., has a profound impact on the scattering behavior. Significant efforts have been conducted to characterize and experimentally validate the scattering behavior of guided waves for through and partial through-thickness holes [8]–[12], notches [13], [14], and cracks [15], [16]. Since guided wave imaging algorithms have the ability to incorporate the anticipated scattering behavior of potential defects, these imaging algorithms can be used to distinguish between defect types. This approach is similar to that used by Zhang et. al [17] for damage detection using bulk waves.

This paper proposes the use to two elliptical guided wave imaging algorithms for damage localization and characterization. Conventional delay-and-sum imaging has already been shown to be robust to errors in a priori assumptions, such as scattering behavior, but is susceptible to large imaging artifacts. Therefore, conventional imaging is an ideal first-pass mechanism for identifying potential damage locations. Minimum variance imaging, on the other hand, is highly sensitive to a priori assumptions. This sensitivity can be leveraged to characterize the potential damage locations identified with conventional imaging. Damage characterization is performed by generating minimum variance images for various scattering assumptions and determining which image contains the strongest response at the potential damage location. The damage characteristics corresponding to scattering assumptions that cause the strongest response are taken to be the characteristics of the defect or damage.

This paper is organized as follows. Elliptical guided wave imaging and its use for damage localization and characterization is discussed in section II. Section III describes the experimental setup and testing procedure and section IV provides details about the finite element modeling (FEM) used to generate potential scattering fields. Experimental results are then presented in section V, which is followed by a brief summary.

II. ELLIPTICAL IMAGING

This section provides a brief introduction to elliptical guided wave imaging, including both conventional delay-and-sum imaging as well as minimum variance imaging. The reader is referred to [7] and [18] for a more in depth
When performing guided wave imaging for structural health monitoring, differenced signals are typically used. Differenced signals are obtained by subtracting a known good, or baseline signal, from the test signal. This operation, referred to as baseline subtraction, isolates any changes between the two signals. For guided wave imaging to produce meaningful results, it is important that any differences between these two signals correspond to scattering from defects or damage. In reality, however, there are a number of factors that can produce significant changes in the signals that are unrelated to damage, including changes in temperature, humidity, pressure, and loading. If uncompensated, the imaging artifacts that result from these factors can both mask legitimate damage and cause false positives.

Elliptical imaging is performed by computing each pixel based on the differenced signals. If damage is present at pixel location \((x,y)\), then each differenced signal should contain some scattered energy at time \(\tau_{ixy}\), defined as:

\[
\tau_{ixy} = \frac{d_{ixy}}{c_g},
\]

where \(i\) indicates a specific transducer pair, \(xy\) identifies the \((x,y)\) coordinate, \(d_{ixy}\) is the total propagation distance from transmitter to pixel location \((x,y)\) to receiver for the \(i\)th transducer pair, and \(c_g\) is the propagation speed. Since the differenced signal from the \(i\)th transducer pair contains scattered energy at time \(\tau_{ixy}\), then the following equation for pixel intensity, \(P_{xy}\), is non-zero when damage is present:

\[
P_{xy} = \sum_{i=1}^{N} |w_{ixy} r_i (\tau_{ixy})|^2,
\]

where \(r_i(t)\) is the differenced signal for the \(i\)th transducer pair and \(w_{ixy}\) is a weighting coefficient that is specific to both transducer pair and pixel location. For simplicity, the above equation can be rewritten in matrix format:

\[
P_{xy} = \mathbf{w}_{xy}^H \mathbf{R}_{xy} \mathbf{w}_{xy},
\]

where “\(H\)” indicates a Hermetian transpose operation, \(\mathbf{w}_{xy}\) is a vector of weighting coefficients, and \(\mathbf{R}_{xy}\) is a singular autocorrelation matrix defined as \(\mathbf{R}_{xy} = \mathbf{r}_{xy} \mathbf{r}_{xy}^H\). The measurement vectors, \(\mathbf{r}_{xy}\), used to define \(\mathbf{R}_{xy}\) are composed of the \(r_i(\tau_{ixy})\) values from Eq. (2).

The choice of weighting coefficients, \(\mathbf{w}_{xy}\), plays a fundamental role in imaging performance. As implemented here, the weighting coefficients for conventional delay-and-sum elliptical imaging, referred to as conventional imaging throughout this paper, are scaled to produce a unit vector that maximizes the pixel value, \(P_{xy}\), if damage is present. When damage is present, each element of the measurement vector, \(\mathbf{r}_{xy}\), will be related to the others as:

\[
\mathbf{r}_{xy} = \begin{bmatrix}
 r_1 (\tau_{1xy}) \\
 \vdots \\
 r_N (\tau_{Nxy})
\end{bmatrix}^T,
\]

\[
x_0 \begin{bmatrix}
 \psi_{1xy} \\
 \vdots \\
 \psi_{Nxy}
\end{bmatrix}
\]

where \(x_0\) is the excitation signal at time \(t = 0\), \(d_{ixy}^\infty\) is the propagation distance from transmitter to pixel location \((x,y)\) multiplied by the propagation distance from pixel location \((x,y)\) to receiver for the \(i\)th transducer pair, and \(\psi_{ixy}\) corresponds to the scattering behavior of the damage or defect at pixel location \((x,y)\) for the \(i\)th transducer pair.
pair. Note that the multiplication of propagation distances in $d_{ixy}$ is appropriate since geometric loss will occur in two distinct stages. Since $\vec{w}_{xy}$ is constrained to be a unit vector, the pixel value, $P_{xy}$ defined in Eq. (3), will be maximized when $\vec{w}_{xy}$ is proportional to $\vec{r}_{xy}$, as defined in Eq. (4), therefore the weighting vector for conventional imaging is defined as:

$$\vec{w}_{CV} \propto \frac{\psi_{1xy}}{\sqrt{d_{1xy}}} \ldots \frac{\psi_{Nxy}}{\sqrt{d_{Nxy}}}^T. \quad (5)$$

Conventional imaging has been shown to be capable of performing reasonably well, even in the absence of $a priori$ information about potential scatterers (i.e. $\psi_{ixy}$ is not known and is therefore assigned an arbitrary constant value). However, it is susceptible to significant imaging artifacts that can mask the presence of damage or cause false positives. As such, minimum variance distortionless reponse (MVDR) has been incorporated into the algorithm to reduce imaging artifacts and improve imaging resolution.

In addition to maximizing the pixel value when damage is present, as is the case for conventional imaging, minimum variance imaging also attempts to minimize the pixel value when damage is absent. Rather than defining the weighting vectors as in Eq. (5), the weighting vectors in minimum variance imaging are chosen to satisfy the following constrained optimization problem:

$$P_{xy} = \min_{\vec{w}} \vec{w}^HR_{xy}\vec{w}, \text{ such that } \vec{w}^H\vec{e}_{xy} = 1,$$

where $\vec{e}_{xy}$ is a unit norm vector referred to as the “steering vector” and is analogous to $\vec{w}_{CV}$ for conventional imaging. The constrained optimization problem can be solved through the use of a Lagrange multiplier. The value of $\vec{w}$ that satisfies Eq. (6) is:

$$\vec{w}_{MV} = \frac{R_{xy}^{-1}\vec{e}_{xy}}{\vec{e}_{xy}^H R_{xy}^{-1} \vec{e}_{xy}}, \quad (7)$$

where the “$-1$” superscript indicates a matrix inverse. Since $R_{xy}$ is known to be a singular matrix, the inversion process is regularized through diagonal loading. For all imaging presented in this paper, the weight of the diagonal loading is 0.1 times the squared magnitude of $\vec{r}_{xy}$. It should be noted that additional optimizations exist to reduce computation time and for the cases considered in this paper, minimum variance imaging can be computed without performing a complete matrix inversion, which allows the imaging process to complete in a comparable amount of time as conventional imaging. Details about implementation optimizations can be found in [18].

The fundamental assumption with minimum variance imaging is that if damage is present, then the measurement vector, $\vec{r}_{xy}$, will behave according to Eq. (4). If this assumption does not hold, then the minimum variance imaging algorithm will attempt to minimize the pixel value, which may result in missed detection. As such, although minimum variance imaging is capable of significantly reducing imaging artifacts, the trade-off is sensitivity to $a priori$ information.

To balance the features and drawbacks of both conventional imaging and minimum variance imaging, the authors propose the use of both algorithms to perform damage characterization. Conventional imaging is a robust imaging algorithm that can be performed without $a priori$ information. Therefore, it can be used to perform a preliminary assessment of damage, identifying potential damage locations that require additional analysis. The sensitivity of
Fig. 1. Experimental setup. A distributed sparse array of six transducers were attached to a 914 mm × 914 mm × 3.18 mm aluminum plate. Two notches at ±45° were introduced at the indicated locations to simulate damage.

minimum variance imaging can then be leveraged to characterize the potential damage locations identified by conventional imaging. The use of these two imaging algorithms combines the robustness of conventional imaging with the sensitivity of minimum variance imaging and can be performed with a single set of differenced signals.

III. EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup is illustrated in Figure 1. Six piezoelectric transducers are attached in a randomized pattern to a 914 mm × 914 mm × 3.18 mm aluminum 6061 plate, simulating a large plate-like structure that will be interrogated for damage. Although realistic structures are likely to have more complex geometries, the setup employed here is intended to provide a proof-of-concept, allowing damage characterization to be demonstrated without the additional complications introduced by a more complex structure.

The plate is interrogated with a 7-cycle Hamming-windowed sinusoid with a center frequency of 300 kHz. The frequency was selected because it maximizes the energy ratio of $S_0$ to $A_0$ and is below the cutoff frequency of higher-order modes. Although the SH$_0$ mode is also present in the recorded data, the amplitude is negligible compared to both $S_0$ and $A_0$. At these frequencies, the $S_0$ mode is highly dispersive, meaning that the propagation velocity of the guided wave varies with frequency. Therefore, a narrow-bandwidth tone-burst was used to minimize these effects.

A dataset is composed of signals from each unique transducer pair obtained in a round-robin fashion (1→2, 1→3, ..., 5→6). For the six-transducer array considered here, this produces 15 recorded signals. Reciprocal signals (2→1,3→1, etc.) are not recorded in the interest of time since they do not contain additional information.

The experiment is conducted as follows. First, a dataset is recorded under known good conditions with no simulated damage present. The recorded data will be referred to as the damage-free signals. A 15 mm × 2 mm × 3.18 mm notch oriented 45° from horizontal is introduced to simulate damage, labeled Notch-1 in Figure 1(b). A second set
of signals, referred to as notch-1 data, is then recorded. At that point, a second 15 mm × 2 mm × 3.18 mm notch is introduced at the site labeled Notch-2 in Figure 1(b), this time oriented -45° from horizontal. A third set of data, notch-2 data, is then obtained, completing the experimental data acquisition.

Since the experiment was not climate-controlled, minor temperature, humidity, and pressure changes were present during data acquisition. These changes were manifested in the recorded data as variations in the transducer transfer functions as well as the dispersive properties of the material. To minimize these changes, a method referred to as baseline signal stretch (BSS) was employed. Although the details of these pre-processing steps are beyond the scope of this paper, readers are referred to [19]. It should be noted that the BSS algorithm did not require any additional measurements or a priori information.

The three datasets are then post-processed to detect, locate, and characterize the two simulated damage sites.

IV. Finite Element Modeling

As discussed in section II, the performance of minimum variance imaging is dependent on the similarity of the steering vector, $\mathbf{e}_{xy}$, used to calculate the pixel value and the measurement vector, $\mathbf{r}_{xy}$. Since the steering vectors are largely defined by the scattering coefficients, $\psi_{ixy}$, accurate knowledge of scattering coefficients is necessary to maximize imaging performance.

Three dimensional finite element modeling (FEM) with the ABAQUS® software suite was performed to generate anticipated scattering fields for the simulated damage using nominal 6061 aluminum material properties. The FEM simulation used explicit time integration, with linear brick elements of 1.25 mm in the direction along the notch, 1 mm in the direction of the notch thickness, and 0.795 mm through the plate thickness. Excitation of the $S_0$ mode was performed using opposing out-of-plane point-sources located at the top and bottom edges of the plate with a 5-cycle Hamming-windowed toneburst at 400 kHz. Out-of-plane measurements were obtained from one surface of the plate on a 49 mm × 61.25 mm grid centered at the notch. Since both the excitation and the notch are symmetric about the center of the plate and out-of-plane measurements are used, recorded data were assumed to contain pure $S_0$. Because notches scatter energy differently depending on incident angle, the FEM simulations were repeated for incident waves over a 90° range at 5° increments. The symmetries of a through-thickness notch allow the scattering behavior for the remaining incident angles to be inferred from these simulations.

Scattering behavior was estimated using the same baseline subtraction technique as used for guided wave imaging described in section II. A complete FEM simulation was first performed without a notch and then repeated with a notch. Data from the two simulations were then differenced to isolate the effects of the notch. Differenced information from the rectangular grid was spatially interpolated to obtain measurements located at 1° increments along a circle of radius 24 mm centered at the notch location. To better match the frequency content of the experimental data, the interpolated signals were deconvolved with the excitation function (5-cycle Hamming-windowed toneburst at 400 kHz) and filtered with a 12-cycle Hamming-windowed toneburst at 300 kHz. Each of these 359 signals was then converted to the frequency domain and the magnitude and phase of the signal at 300 kHz was used to determine anticipated scattering behavior. All scattering behavior estimates were normalized
Incident Angle (degrees)

Scattered Angle (degrees)

−180
−90
0
90
180

−180
−90
0
90
180

0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

(a)

(b)

Fig. 2. S₀ scattering behavior of a 15 mm long notch perpendicular to an incident S₀ wave at 0° shown for (a) all incident and scattered angles and (b) for incident angles of 0°, -45°, and -90°. Arrows indicate the direction of the incident wave relative to the center of the polar plot.

to have a magnitude of 1 if the differenced signal is the same amplitude and phase as a direct arrival that has propagated the same distance.

Figure 2 shows the S₀ scattering behavior observed from FEM simulations for a 15 mm × 2 mm × 3.18 mm notch oriented perpendicular to an incident S₀ wave at 0°. Figure 2(a) depicts the magnitude of the differenced signal as a function of both incident and scattered angle for all angles. Figure 2(b) represents the same information, displayed as a polar plot for incident angles of 0°, -45°, and -90°. The color-coded arrows depict the incident wave propagation direction. These figures show that for the 0° incident wave, the signal is largely reflected back towards the source, producing two large lobes. The lobe in the forward (0°) direction corresponds to the lack of signal that will be evident in the differenced signal due to the “shadowing” effect of the notch, while the lobe in the backward (180°) direction corresponds to the reflected wave. Figure 2 highlights the directionally dependent nature of the scatterer, with dependencies both on the incident and scattered angle.

V. EXPERIMENTAL RESULTS

After collecting the notch-1 dataset, the differenced signals are obtained by subtracting the damage-free dataset. Figure 3(a) shows the conventional imaging results, without any assumptions about scattering behavior (e.g., the scattering field is assumed to be uniform). The effects of Notch-1 can be clearly observed in the lower right corner of the plate.

Figure 4 illustrates damage characterization results when conventional imaging is used to evaluate the damage site. Each subfigure of Figure 4 was generated with scattering assumptions corresponding to a 15 mm notch with orientations ranging from -75° to +90° in 15° increments. All scattering assumptions were based on FEM simulations described in section IV. The use of conventional imaging for damage characterization leaves some ambiguity as to the notch orientation, as significant peaks can be observed in the lower right corner for Figures 4(a), (e), and (h)-(j). One can identify consistent imaging artifacts visible between transducer pairs 1-6, 2-3, 2-6, 3-4, and 3-5 throughout Figure 4. These artifacts are characteristic of poor baseline subtraction and are likely due to temperature
changes that occurred during data acquisition.

Figure 5 illustrates damage characterization results using minimum variance imaging and the same data as used for Figure 4. Note that although the baseline subtraction artifacts from Figure 4 have been significantly reduced for many of the angles, the artifacts are still problematic in some of the images, particularly Figure 5(k). These artifacts, however, are not co-located with the damage location identified with conventional imaging in Figure 3(a), and are therefore not problematic for this example. Since Figure 5(i) clearly has the strongest response in the area of interest, the notch can be correctly discerned to be oriented at +45°. Figures 3(a) and 5 demonstrate that the proposed approach is capable of performing damage characterization.

Figure 3(b) shows conventional imaging results when the notch-1 dataset is subtracted from the notch-2 dataset, effectively isolating changes due to Notch-2. As with Figure 3(a), the location of the damage site is clearly visible, even in the absence of any scattering assumptions. Figure 6 depicts minimum variance imaging results for scattering assumptions corresponding to a 15 mm notch oriented from -75° to 90° in 15° increments, similar to Figure 5. Based on Figure 6, one would conclude that the notch is oriented at -30°, rather than the actual orientation of -45°. The orientation error is likely due to the previously mentioned baseline subtraction error, which is evident in the consistent artifacts observed between transducer pairs 1-4, 2-6, and 3-6 in both Figure 3(b) and 6. Even with the baseline subtraction error, however, the minimum variance images in Figure 6 provide a clear indication of the general orientation, within 15°, of the notch based on the observed scattering behavior from just six transducers.

The experimental results shown in Figures 3(a), 5, 3(b) and 6, demonstrate that guided wave imaging is capable of characterizing the orientation of simulated damage. Figures 3(a) and 3(b) show that conventional imaging is capable of identifying the damage location of highly directional scatterers, both inside and outside the array bounds, without a priori information about the scatterer. Minimum variance imaging can then be used to characterize the damage observed at these locations using the same dataset as that for conventional imaging. The approach demonstrated here for discerning notch orientation can be reasonably expected to successfully characterize other damage features as well, including type, size, depth, and shape.
Fig. 4. Comparison of conventional imaging results generated with notch-1 data and anticipated scattering behavior based on FEM simulations of a 15 mm through-thickness notch. (a)-(l) correspond to notch angles -75° to +90° in 15° increments. The white square indicates the area of interest based on conventional imaging.
Fig. 5. Comparison of minimum variance imaging results generated with notch-1 data and anticipated scattering behavior based on FEM simulations of a 15 mm through-thickness notch. (a)-(l) correspond to notch angles -75° to +90° in 15° increments. The white square indicates the area of interest based on conventional imaging.
Fig. 6. Comparison of minimum variance imaging results generated with notch-2 data and anticipated scattering behavior based on FEM simulations of a 15 mm through-thickness notch. (a)-(l) correspond to notch angles -75° to +90° in 15° increments. The white square indicates the area of interest based on conventional imaging.
VI. Summary

The proposed algorithm uses conventional imaging to locate a potential defect without assumptions about scattering behavior. Minimum variance imaging is then applied to the same dataset using various scattering assumptions, which are obtained with FEM simulation. The damage characteristics that create the strongest pixel value at the potential defect location are taken to be those of the damage site or defect. The approach was shown to be effective with experimental data for 15 mm notches located both inside and outside the array polygon, in two different orientations.

This paper has demonstrated that damage characterization can be performed in SHM systems using guided waves excited and recorded from a sparse array of inexpensive transducers. Sparse array SHM systems offer a cost-effective option for quickly and reliably interrogating large, plate-like structures, such as aircraft skins. The ability to extract information about potential defects, such as size, depth, and orientation, can be used to discern between actual damage and benign changes and provide supporting information for decisions regarding stress state, remaining life, and/or the need for additional inspection, repair, or replacement. Such decisions lie at the core of condition-based maintenance schedules, which are critical to aircraft airworthiness and sustainment.

REFERENCES


