ENHANCED DIFFERENTIAL METHODS FOR GUIDED WAVE PHASED ARRAY IMAGING USING SPATIALLY DISTRIBUTED PIEZOELECTRIC TRANSDUCERS

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ABSTRACT. A number of tomographic and phased-array methods have been proposed for generating two dimensional images of plate-like structures using sparse arrays of spatially distributed ultrasonic transducers. The phased array differential approach is considered here whereby pulse echo and through transmission signals are recorded before and after localized damaged is introduced, and differenced signals are combined using a focusing rule to produce an image of the plate. The application is structural health monitoring where the transducers are permanently bonded to the structure. The quality of the image is affected by many factors such as the number and location of the transducers, the characteristics of the damage, the signal-to-noise ratio, presence of edge reflections, and anything unrelated to damage that may perturb the ultrasonic signals such as temperature changes and transducer bonding variations. Two methods for enhancing image quality are implemented and then evaluated as to their effectiveness. In the first method, the windowing function is changed in width prior to phased signal addition to yield the best image quality. In the second method, signals are envelope-detected prior to phased signal addition to eliminate phasing artifacts. Results are reported for artificial defects introduced in aluminum plates.

Keywords: ultrasonics, guided waves, phased array imaging, structural health monitoring
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INTRODUCTION

Guided waves have been proposed by many researchers for structural health monitoring applications because of their ability to travel long distances in structures suitable for propagation of such wave modes. Recent work has shown much promise in terms of detecting, locating and characterizing defects in both plates and pipes [1,2]. Attached transducers have also been used to generate images for detecting and localizing damage in plate-like structures. Techniques used have been tomographic reconstruction [3,4] and compact phased array imaging [4,5,6]. Numbers of transducers have ranged from 11 to as many as 64 for compact phased array imaging, and from 8 to over 40 for tomographic reconstruction methods.

It is generally desirable to use as few transducers as possible to reduce the cost and complexity of the overall system. Very sparse arrays of only a few transducers have been
demonstrated to detect damage in structures [7], but localization can be more difficult. Many damage detection algorithms using fixed transducers rely on monitoring changes since the coupling and transducer variations common for nondestructive testing are no longer present [3,7,8,9]. Here we consider a sparse array of only four transducers, and demonstrate a phased signal addition algorithm for generating images of changes in the plate based upon differences in the received through transmission signals. The algorithm used is similar to that used by Wang et al. [9]; here two enhancements are described and results presented.

**MEASUREMENTS**

Measurements were made using a sparse array of four transducers bonded to two different 6061 aluminum plates using cyanoacrylate adhesive. The transducers were constructed at Georgia Tech with longitudinally polarized, 2.25 MHz PZT disks, 12.5 mm in diameter, and backed with epoxy. A conventional ultrasonic pulser receiver was used for spike mode transducer excitation and waveform amplification, and a multiplexer was used to switch between the four transducers on both transmit and receive. Waveforms were digitized with a sampling rate of 125 MHz using a Tektronix TDS5034 digital oscilloscope, and each recorded waveform was the average of 50 signals. All measurements were made at room temperature.

For both plates, six baseline waveforms were recorded in the undamaged condition, where the six waveforms correspond to the six possible through transmission pairs (1-2, 1-3, 1-4, 2-3, 2-4, 3-4). Defects were introduced in the form of drilled holes, and the same six waveforms were recorded after each hole was introduced. For specimen #1, two holes were drilled in two different locations. For specimen #2, a single hole was drilled and then enlarged to simulate a growing flaw. Plate dimensions, transducer locations and hole locations are summarized in Table 1.

Signals from transducer pair (3-4) of specimen #1 are shown in Figure 1 before and after the holes were drilled. The differences in the signals are not particularly evident from visual inspection of the raw signals of Fig. 1(a), (b) and (c), but the scattered echoes from the holes can be clearly seen in the differenced signals of Fig. 1(d), (e) and (f). These differenced signals are the ones used to construct images.

<table>
<thead>
<tr>
<th>Dimensions (mm)</th>
<th>Specimen #1 Thin Plate</th>
<th>Specimen #2 Thick Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Extent</td>
<td>610 x 605</td>
<td>610 x 610</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.79</td>
<td>4.76</td>
</tr>
<tr>
<td>Transducer #1 Coordinates</td>
<td>(170, 355)</td>
<td>(184, 338)</td>
</tr>
<tr>
<td>Transducer #2 Coordinates</td>
<td>(355, 430)</td>
<td>(379, 413)</td>
</tr>
<tr>
<td>Transducer #3 Coordinates</td>
<td>(430, 240)</td>
<td>(454, 225)</td>
</tr>
<tr>
<td>Transducer #4 Coordinates</td>
<td>(240, 165)</td>
<td>(264, 149)</td>
</tr>
<tr>
<td>Hole #1 Diameter(s)</td>
<td>6.35</td>
<td>3.18 and 6.35</td>
</tr>
<tr>
<td>Hole #1 Coordinates</td>
<td>(257, 273)</td>
<td>(297, 335)</td>
</tr>
<tr>
<td>Hole #2 Diameter</td>
<td>6.35</td>
<td>-----</td>
</tr>
<tr>
<td>Hole #2 Coordinates</td>
<td>(265, 390)</td>
<td>-----</td>
</tr>
</tbody>
</table>
FIGURE 1. Waveforms from transducer pair (3-4) of specimen #1. (a) Undamaged specimen, (b) after hole #1, (c) after hole #2, (d) difference between hole #1 and the undamaged specimen, (e) difference between hole #2 and the undamaged specimen, and (f) difference between hole #1 and hole #2.

ANALYSIS

Images are constructed of the entire plate based upon the six differenced signals between the current state and the nominally undamaged state. If a flaw is the only change that has occurred since the baseline signal was recorded, then the differenced signal will contain only information due to scattering from the flaw. Figure 2 illustrates the geometry of two transducers and a single flaw. If the coordinates \((x_i, y_i)\) are those of transmitting transducer \(i\), \((x_j, y_j)\) are those of receiving transducer \(j\), and \((x_f, y_f)\) are those of a flaw, then the received signal will consist of both a direct arrival from transducer \(i\) to transducer \(j\) as well as a scattered signal from transducer \(i\) to the flaw and then to transducer \(j\). Not shown are multiply scattered signal paths between the flaw and plate boundaries.

If we assume that only a single guided wave mode is propagating in the structure, then the group velocity of the mode can be calculated from the time of the direct arrival, and this group velocity can be used to calculate the time of a scattered signal from a flaw at a specified location,

\[
c_g = \sqrt{\frac{(x_i - x_j)^2 + (y_i - y_j)^2}{t_{ij}}},
\]

\[
t_{ij}' = \frac{\sqrt{(x_i - x_f)^2 + (y_i - y_f)^2 + \sqrt{(x_f - x_j)^2 + (y_f - y_j)^2}}}{c_g}
\]

In these equations, \(c_g\) is the group velocity, \(t_{ij}\) is the time for the direct arrival from transducer \(i\) to transducer \(j\), and \(t_{ij}'\) is the time from transducer \(i\) to the flaw and then to transducer \(j\).
If we think of \((x_f, y_f)\) as the coordinates of a potential flaw location, then the scattered signals from all possible transducer pairs due to this potential flaw will arrive at the various times calculated as per Eq. (2). If \(d_{ij}(t)\) is the differenced signal from transducer pair \((i-j)\), then each of these signals can be windowed about the calculated arrival time for that transducer pair. If there really is a flaw at \((x_f, y_f)\), then each of these windows should contain a scattered echo from the flaw, and they can be summed to yield a composite result,

\[
s_{xy}(t) = \frac{1}{N} \sum_{i,j=1}^{N} d_{ij}(t - t_{ij})w(t - t_{ij}).
\]

In this equation \(w(t)\) is a windowing function. An image of the plate can then be formed where the pixel value of the image at the point \((x, y)\) is the energy of the composite scattered signal \(s_{xy}(t)\).

Figure 3 illustrates this approach where the various differenced signals are shown for specimen #1. The point considered is an actual flaw location, and the windows indicated by vertical lines on each signal are determined by the computed time for the specified transducer pair and flaw location. Note that the signals in these windows, which are the scattered signals from the flaw, are all aligned in time and have the same phase.

**FIGURE 2.** Geometry of direct and scattered echo arrivals for two transducers and one flaw.

**FIGURE 3.** Differenced signals from all transducer pairs illustrating alignment of the scattered signal from a flaw at \(X=259 \text{ mm}, Y=273 \text{ mm}\). The windows shown in the figure correspond to hole #1 of specimen #1.
This phased array signal addition algorithm assumes that the signals are not only from a single mode but that they are non-dispersive with the phase velocity equal to the group velocity. This assumption is usually not the case for Lamb waves, and can result in phase cancellation in Eq. (3) even if the signal envelopes are in alignment. If the differenced signals are envelope detected before summation, then phase cancellations due to dispersion will no longer result. The envelope of the signal is determined by taking the magnitude of the analytic signal after obtaining the imaginary part via the Hilbert transform.

RESULTS

The signals from the undamaged thin plate (specimen #1) were analyzed to identify the envelope of the first arrival for each transducer pair and calculate the group velocity as the average value from the six pairs. The calculated group velocity is 5.56 mm/µs, which corresponds to the S₀ Lamb wave mode in the plate [10]. The measured center frequency is 210 kHz, and the frequency-thickness product is 0.17 MHz-mm. The S₀ mode is non-dispersive at this operating point, which can be seen in the received signals by comparing the phase of the first arrivals from the different transducer pairs. The differenced signal between the current state and the baseline state was calculated by simple subtraction, and these differenced signals were then used to construct images of the plate as per Eq. (3).

The first choice for a time window was a rectangular window, 10.94 µs in width, which is the average width of the six first arrivals and corresponds to approximately two cycles. Figure 4(a) is the image constructed based upon this window using the signal from the undamaged plate as a baseline and the signal after the first hole was drilled as the current state. The four white “X” symbols indicate the transducer locations, and the center of the white square is the location of the hole. The grey scale for this and subsequent figures is nonlinear to enhance the smaller amplitude details of the various images. In Figure 4(a), notice the patterns near the image of the hole. These are phasing artifacts due to periodic reinforcement of different cycles in the scattered signal from the hole, and are due to the finite bandwidth of the signals. Note also the artifacts in the image outside the area bounded by the transducers; particularly evident are multiple artifacts that appear in an arc in the bottom of the image. These artifacts are caused by multiple scattering between the flaw and the plate boundaries. The rectangular windowing function was decreased to 1 µs in width to reduce these artifacts, and the resulting image is shown in Figure 4(b). Both types of artifacts are clearly lower in amplitude relative to that of the flaw.

An image was also generated using the envelope of the differenced signal and is shown in Figure 4(c). The phasing artifacts are removed but at the expense of considerable blurring of the defect image and smearing of the multiply scattering artifacts. Note the various elliptical patterns that are evident with pairs of transducers as foci; the scattered arrivals for each pair contribute to the image as ellipses as per Eq. (2).

The image of Figure 4(d) is based upon the differenced signal but after hole #2 was drilled; both holes are clearly evident. Figures 4(e) and 4(f) are based upon the difference between hole #2 and hole #1 with 4(f) generated from the envelope of the differenced signal. Hole #2 is clearly visible in both images with hole #1 completely removed.

Data for the thick plate were similarly analyzed with results shown in Figure 5. The main difference is that many more Lamb wave modes were present due to the broad band excitation, and the signals were filtered to retain information below about 400 kHz. The S₀ mode, at 245 kHz, was again the dominant mode, and its wave speed was measured to be 5.02 mm/µs. The frequency-thickness product was 1.17 MHz-mm, indicating that this mode should exhibit dispersion [10]. The average width of the first arrival was measured to be 18.09 µs, also indicating increased dispersion compared to the thin plate.
FIGURE 4. Images from specimen #1. (a) Hole #1 relative to baseline, full 10.94 us window, (b) hole #1 relative to baseline, 1 us window, (c) hole #1 relative to baseline, 1 us window and envelope detected signals, (d) hole #2 relative to baseline, 1 us window, (e) hole #2 relative to hole #1, 1 us window, and (f) hole #2 relative to hole #1, envelope detected signals. White “X” symbols denote transducer locations and the white squares denote locations of drilled holes.
Figures 5(a) and (b) are images of the hole at its two diameters of 3.18 mm and 6.35 mm using a rectangular window of 1 µs. The hole is clearly visible but the phasing artifacts are much more pronounced than in the images from the thin plate. This result is not unexpected because the larger pulse widths offer more opportunities for periodic reinforcement, and the imaging algorithm does not include any dispersion compensation.

Figures 5(c) and (d) are the corresponding images generated from the envelope detected signals. Results are similar to those obtained from the thin plate with removal of phasing artifacts at the expense of general image blurring and smearing of multiple scattering artifacts between the defect and the plate boundaries.

Despite the presence of image artifacts, the damage is well-localized for both the thin plate and the thick plate. The largest amplitude phasing artifacts are in the immediate vicinity of the actual damage, and the multiple scattering artifacts are not well-localized, particularly in the envelope detected images; these characteristics enable damage to be recognized and distinguished from imaging artifacts.

FIGURE 5. Images from specimen #2. (a) 3.18 mm diameter hole, 1 us window, (b) 6.35 mm diameter hole, 1 us window, (c) 3.18 mm diameter hole, 1 us window and envelope detected signals, and (d) 6.35 mm diameter hole, 1 us window and envelope detected signals. White “X” symbols denote transducer locations and the white squares denote locations of drilled holes.
SUMMARY AND CONCLUSIONS

Presented here are images constructed from a very few number of signals obtained from a sparse array of transducers; they are based upon phased addition of scattered signals before and after damage. Signals from as few as four transducers have been shown to be sufficient to localize damage in plates, including damage at multiple sites in the presence of boundary reflections. Artifacts in the images consist of phasing artifacts due to periodic reinforcement of multiple cycles, and multiple scattering artifacts between defects and boundaries and also between multiple defects. Both types of artifacts can be reduced by proper selection of the windowing function, and phasing artifacts can be eliminated at the expense of image blurring by first envelope detecting the scattered signals.

This imaging method shows particular promise for localizing damage after it has been detected. Using more transducers should reduce artifacts further, with the addition of even one or two transducers having the potential to offer significant improvement in image quality. Future work should address improved signal and image processing including dispersion compensation and incorporating information from multiple Lamb wave modes.

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REFERENCES