Understanding and Exploiting Applied Loads for Guided Wave Structural Health Monitoring

School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, 30332-0250, USA
*Phone: 1-404-894-2994, *Email: jennifer.michaels@ece.gatech.edu

Abstract – A challenging goal of aircraft structural health monitoring (SHM) systems is to provide continuous assessment of structural integrity during flight. It is now widely recognized that variable environmental and operational conditions can compromise results and thus lead to erroneous maintenance and usage decisions. This issue is particularly evident for SHM systems utilizing ultrasonic guided waves because of their known sensitivity to these variable conditions. Much attention has been given to the effect of temperature variations because they are both unavoidable and readily investigated in the laboratory. More recently, the effects of applied loads on SHM systems have been considered. On the one hand, loads affect both wave speeds and propagation distances similarly to temperature changes, but the anisotropic nature of such changes can compromise SHM techniques that require baseline comparisons. On the other hand, applied loads can open cracks and thus enhance their detectability. Here these loading effects are considered along with their impact on detection and localization of damage via guided wave imaging with a spatially distributed array. A new approach is investigated whereby the load-dependent behavior of the guided wave signals is used for improved damage detection and localization without requiring baseline data from the damage free structure. Experimental results are shown from fatigue tests performed on an aluminum plate specimen that was instrumented with a sparse array of ultrasonic guided wave transducers.

Keywords: Structural health monitoring, sparse arrays, damage detection, damage localization, array imaging.

INTRODUCTION

Ultrasonic guided waves are being evaluated for structural health monitoring (SHM) systems because of their ability to propagate relatively long distances in structures of engineering interest [1,2]. Their actual efficacy in terms of damage detection and localization depends upon both their sensitivity to damage and their selectivity in the presence of operational and environmental variations. A spatially distributed array of discrete transducers is considered here where each transducer transmits in turn and all remaining transducers receive. This configuration, where all pitch-catch transducer pairs are considered, has been shown to be sensitive to damage, particularly because it takes advantage of forward scattering, or the shadowing effect of damage on forward propagated waves [3,4].

A significant obstacle to field implementation of such arrays is the sensitivity of received signals to environmental and operational conditions. Temperature and applied loads have been identified as two of the most critical since they are unavoidable under realistic conditions. Homogeneous temperature changes have been thoroughly investigated by several researchers [5-8], primarily because even the small changes present under typical laboratory conditions can adversely affect SHM systems. The effects of applied loads on guided wave propagation in homogeneous media, which are caused by both dimensional changes and the acoustoelastic effect, are relatively well understood [9,10]. Implications for SHM systems have also been investigated [11,12], but the situation is more complicated than for temperature because loads also cause structural effects such as cracks opening and boundary conditions changing [13,14].

This paper specifically considers the effects of applied uniaxial loads on an SHM system consisting of a spatially distributed array of guided wave transducers.

EXPERIMENTS

A 6061 aluminum plate measuring 305 mm × 610 mm × 3.18 mm was instrumented with an array of six piezoelectric transducers fabricated from 7 mm diameter, 300 kHz, radial mode PZT discs. The discs were backed with bubble-filled epoxy for protection and bonded to the plate with epoxy. Transducers were excited with a 50-500 kHz chirp excitation using an arbitrary waveform generator, and signals were received via a commercial ultrasonic instrument (Panametrics 5072PR). A custom multiplexer switched between the 15 unique transmit-receive pairs. Signals were digitized at a frequency of 20 MHz and a resolution of 14 bits, and 20 waveforms were averaged for each acquisition.

Because of the broadband chirp excitation, multiple Lamb wave modes are generated in the plate. Signals were filtered to yield the equivalent response to a 5-cycle tone burst at 100 kHz [16], and it was observed that the A0 guided wave mode was dominant. The group velocity was measured to be 2609.8 m/s.

The plate was machined with appropriate features to enable mounting in an MTS machine as shown in Figure 1. Ultrasonic data sets were recorded as a function of applied tensile load from 0 to 115 MPa in steps of 11.5 MPa, for a total of 11 loading values per data set. After the specimen was mounted, a 5.1 mm diameter through hole was drilled in

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Figure 1. Photographs of plate specimen mounted in testing machine.

the center of the specimen, and a small starter notch was introduced on one side of the hole to serve as a site for initiation of crack growth. The plate was fatigued using a sinusoidal tension-tension profile ranging from 16.5 to 165 MPa at a frequency of 3 Hz. Data were recorded at intervals throughout the fatiguing process as summarized in Table 1, and fatiguing was terminated when crack lengths on both sides of the hole exceeded approximately 18 mm.

Table 1. Summary of Fatiguimg Schedule and Data Acquired

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Fatigue Cycles</th>
<th>Notes / Crack Lengths at Surface (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left Front</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Baseline, no hole, no notch</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>5.1 mm diameter hole drilled</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>Starter notch cut (left, front of hole)</td>
</tr>
<tr>
<td>4</td>
<td>5,000</td>
<td>No visible cracks</td>
</tr>
<tr>
<td>5</td>
<td>8,000</td>
<td>1.7</td>
</tr>
<tr>
<td>6</td>
<td>10,000</td>
<td>3.6</td>
</tr>
<tr>
<td>7</td>
<td>12,500</td>
<td>5.4</td>
</tr>
<tr>
<td>8</td>
<td>15,500</td>
<td>7.6</td>
</tr>
<tr>
<td>9</td>
<td>17,000</td>
<td>9.9</td>
</tr>
<tr>
<td>10</td>
<td>18,500</td>
<td>13.5</td>
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<tr>
<td>11</td>
<td>19,500</td>
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<tr>
<td>12</td>
<td>20,000</td>
<td>19.5</td>
</tr>
<tr>
<td>13</td>
<td>20,400</td>
<td>22.7</td>
</tr>
<tr>
<td>14</td>
<td>20,600</td>
<td>25.2</td>
</tr>
</tbody>
</table>

ANALYSIS

Signals were analyzed via delay-and-sum imaging whereby differenced signals from all transducer pairs are summed using an appropriate delay law [3,15]. The delay law for a spatially distributed array is formulated by considering sensor pair $ij$ where the $i$th transducer, located at $(x_i, y_i)$, is the transmitter and the $j$th transducer, located at $(x_j, y_j)$, is the receiver. If a scatterer is introduced at $(x, y)$, the arrival time of the scattered signal at the receiver is,

$$t_g(x, y) = \sqrt{(x_i - x)^2 + (y_i - y)^2} + \sqrt{(x_j - x)^2 + (y_j - y)^2},$$

where $c_e$ is the group velocity. Let $s_g(t)$ be the differenced signal from sensor pair $ij$; that is, the difference between the current signal of interest and a baseline signal. Then $s_g(t_g(x, y))$ corresponds to the amplitude of the signal scattered from the point $(x, y)$. The image value at $(x, y)$ is calculated as,

$$E(x, y) = \left[ \sum_{i=1}^{N} \sum_{j=1}^{N} s_g(t_g(x, y)) \right]^2.$$  

Note that $s_g(t)$ can be either the raw (RF) signal, or the envelope-detected (rectified) signal; here we use only the envelope-detected signals. The group velocity is estimated from the times of the first arrivals for all transducer pairs.

RESULTS

Data were first analyzed by comparing current signals to no-damage baseline signals from data set 3 (acquired after the starter notch was cut). Images were generated as described in [15] using the envelope-detected scattered signals calculated from data set 7 (i.e., signals after subtraction of baselines). As previously reported, the baseline signals must be well-matched to the current signals in terms of temperature. Figure 2 shows images generated with signals acquired at the same load (left figure) and at different loads (right figure). Temperature data were not recorded so it is not known how closely the temperatures were matched, although the data were recorded under the same nominal conditions.

Figure 2. Images generated from data set 7 (~5 mm crack length) using the no-damage baselines of data set 3. The images are plotted on the same 10 dB scale. Left: Signals and baselines were both recorded at 115 MPa. Right: Baselines were recorded at zero load and signals were recorded at 115 MPa.

The image on the right shows significant degradation of defect localization performance since applied loads were not the same for signals of interest and baselines. As is the case for temperature changes, when imaging using no-damage baselines, the baseline data for all possible loading conditions should be acquired to ensure best imaging performance.
As an alternative approach that does not require baseline data to be recorded from the undamaged structure, we consider the effects of applied loads on recorded signals. Figure 3(a) shows signals from transducer pair 2-5 (i.e., transmitting on 2 and receiving on 5) as a function of load. The shape of the signals does not change significantly with load, although the first arrival decreases as the load is increased from 0 to 10%. To more clearly see signal changes with load, Figure 3(b) shows differential signals where each signal is the difference of two signals recorded at adjacent loads (e.g., signal at 40% minus signal at 30%). It is clear that there is an initial large change in the first arrival as the crack on one side of the hole opens up and blocks the direct wave. At about 70% load it appears that the crack on the other side of the hole opens up, causing a further decrease in signal amplitude.

The load differential signals of Figure 3(b) can be used as the scattered (i.e., differenced) signals $s_i(t)$ in Eq. (2) to construct load differential images. Ten images are formed per data set, which correspond to differential loads increasing from 0-10% to 90-100%. Figure 4 shows these images for data sets 3, 7, 10 and 14, which correspond to no damage, a single crack on one side of the hole, two cracks with one on each side of the hole, and the two cracks at their final sizes after fatiguing was terminated.

The images of Figure 4 clearly show the effects of the various cracks opening under load. For data set 3, there are no cracks, and all ten images are very similar. For data set 7, the single crack on one side of the hole is fully open at about 60% load. For data set 10, the crack on one side of the hole opens up when the load is first applied, whereas the second crack on the other side of the hole opens up much later in the loading process; both cracks are fully opened at about 90% load. By data set 14 both cracks are very large, but there is still some evidence that they do not open simultaneously; they are fully opened at about 80% load.
The imaging algorithm can also discriminate between the two cracks on either side of the hole. Figure 5 shows two images from data set 10, one at 10% load and the other at 70% load. It is clear from these images that the 10% load opens the crack on the left side of the hole whereas the 70% load opens the crack on the right side.

![Figure 5](image_url)  
Figure 5. Load differential images generated from data set 10. Each image is shown on a 10 dB scale relative to the max value of the image. Left: 10% load. Right: 70% load.

**SUMMARY AND CONCLUSION**

This study shows that applied loads can adversely affect damage localization images created from differenced signals if loading conditions applied to baselines are significantly different than those applied to signals of interest; this result is similar to that obtained for temperature variations. However, the results shown here also demonstrate that applied loads can be successfully exploited to enable baseline-free imaging of fatigue cracks by using load differential signals. The success of the method is due to the cracks opening under load combined with the sensitivity of the guided waves to these load-induced changes. Rather than generating a single image, the method generates a series of images that shows the load-dependent response. With these multiple images it is possible to obtain greater confidence in detection of damage and thus reduce the possibility of false alarms. An additional benefit is the ability to identify multiple cracks as they open at different loads. Although the temperature was not varied for the results shown here, an advantage of the load differential method is that it is not dependent on temperature or other environmental conditions as long as they do not change significantly in between load steps.

**REFERENCES**