Load-Enhanced Imaging of Fatigue Cracks Via Sparse Guided Wave Arrays

J. E. MICHAELS, S. J. LEE, X. CHEN and T. E. MICHAELS

ABSTRACT

Detection and localization of fatigue cracks originating from fastener holes is an important application of proposed systems for structural health monitoring (SHM). However, detection of even large fatigue cracks using ultrasonic guided waves can be challenging when cracks are tightly closed, which is common in the absence of applied tensile loads. It can also be problematic to detect fatigue cracks using baseline comparison methods if the baseline data are not recorded under the same environmental and operational conditions as the current signals of interest. Work presented here considers guided wave signals recorded from a spatially distributed array of PZT discs bonded to an aluminum plate. A hole was drilled in the center of the plate to simulate a fastener hole, and cracks were grown via low cycle tension-tension fatigue. At intervals during the fatigue test, signals were recorded as a function of static tensile load from all transmit-receive transducer pairs. Data were first analyzed by comparing current signals to baselines recorded from the undamaged specimen at different loads. Results indicate that load mismatch can significantly degrade images, and cracks may be invisible if loads are not applied. Data were next analyzed by comparing signals at one load to those at another load at the same damage state, and results show that cracks can be effectively detected and localized without using baseline data from the undamaged state. This load-dependent but baseline-free approach could thus enable robust monitoring of fatigue cracks in the presence of varying loads.

INTRODUCTION

Ultrasonic guided waves are a frequently considered candidate for structural health monitoring (SHM) systems because they are mechanical waves whose propagation is directly affected by damage. Furthermore, they travel relatively long distances in plate-like structures of engineering interest while still maintaining sufficient energy to detect damage. Guided wave sensors can be arranged in a variety of configurations, including linear [1], circular [2], and spatially distributed [3,4]. The spatially distributed, or sparse, configuration can take advantage of increased

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sensitivity to damage by forward scattering [5], also called the shadowing effect, whereas compact linear and circular configurations must rely solely on backscattering. However, a disadvantage of the sparse configuration is that analysis methods generally must incorporate baseline signal subtraction so that direct arrivals can be removed from the signals. As many researchers have shown, baseline subtraction without appropriate compensation for varying environmental and operational conditions is problematic because large residual signals may either obscure damage or result in excessive false alarms.

In this paper we consider the varying operational condition of quasi-static and quasi-homogeneous applied loads such as arise during normal operation of a structure. The effects of such loads on propagation of both bulk and guided ultrasonic waves in homogeneous media are generally well understood [6,7]. As is also the case for temperature variations [8,9], applied loads change both structural dimensions and wave speeds. Unlike temperature, applied loads can also enhance the detectability of defects, such as when a tensile load opens a tight crack. Here we motivate, define and demonstrate load differential imaging, whereby images are generated from differences in sparse array signals caused by small loading variations. We show that such images are very effective in detecting and locating fatigue cracks that may otherwise be tightly closed and thus not visible to interrogating guided ultrasonic waves.

**IMAGING METHOD**

The imaging method used here is based upon signal changes, and is thus a differential method. Consider sets of signals recorded at two different times from all possible pairs of a sparse array consisting of $N$ transducers. For example, these two times may correspond to before and after introduction of damage, or before and after a change in operational conditions. For convenience, we refer to the first set as baseline signals, and to the second set as current signals; note that the term “baseline” does not necessarily mean “damage-free.” A set of residual signals is calculated by simply subtracting the baseline signals from the current signals. These residual signals are analyzed via delay-and-sum imaging whereby they are back propagated and summed at each pixel location using an appropriate delay law [4], and the pixel intensity is computed as the square of the summed values:

$$E(x, y) = \left[ \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} s_{ij}(t_{ij}(x, y)) \right]^2.$$  

(1)

In this equation $s_{ij}(t)$ is the residual signal from sensor pair $ij$, and $t_{ij}$ is the delay time that corresponds to the time of propagation from the transmitter to the pixel location to the receiver. If the $i$th transducer (the transmitter) is located at $(x_i, y_i)$, the $j$th transducer (the receiver) is located at $(x_j, y_j)$, and the pixel location is $(x, y)$, then $t_{ij}$ is,

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

(2)

where $c_g$ is the group velocity. Although the residual signal in Eq. (1) 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 from all transducer pairs.
EXPERIMENTAL SETUP

An aluminum plate specimen was instrumented with an array of six piezoelectric transducers and subjected to fatigue loading to investigate loading effects on guided wave SHM. The plate, made of 6061 aluminum and machined to enable mounting in an MTS machine, measured 305 mm × 610 mm × 3.18 mm and is shown in Figure 1. Transducers, which are also shown in the figure, were fabricated from 7 mm diameter, 300 kHz, radial mode PZT discs that were attached to the plate with epoxy and further protected with a backing of bubble-filled epoxy.

![Figure 1. Aluminum plate specimen mounted in the testing machine prior to fatiguing. A close-up of one of the transducers is shown in the inset photograph.](image)

An arbitrary waveform generator was programmed to apply a 50-to-500 kHz linear chirp excitation to the transducers, a commercial ultrasonic instrument acted as a receive amplifier, and a multiplexer switched between the 15 unique transmit-receive pairs. Signals were digitized at a sampling rate of 20 MHz at a resolution of 14 bits, and 20 waveforms were averaged for each acquisition to reduce incoherent noise. Because of the length and bandwidth of the chirp excitation, signals are difficult to interpret in the time domain. Thus, signals were filtered during a post-processing step to obtain the equivalent response to a 5-cycle tone burst at 100 kHz [10]. It was observed that the $A_0$ guided wave mode was dominant, and the corresponding group velocity was measured to be 2609.8 m/s.

The plate was fatigued with a 3 Hz sinusoidal tension-tension loading profile from 16.5 to 165 MPa. Fatiguing was periodically paused to record ultrasonic data as a function of applied tensile load starting at 0 MPa and ending at 115 MPa in steps of
11.5 MPa, resulting in a total of 11 unique loads for each data set. After the first such data set was recorded prior to initiation of fatiguing, a 5.1 mm diameter through hole was drilled in the center of the specimen. A small starter notch was subsequently inscribed on one side of the hole to act as a site for initiation of a fatigue crack. Data were recorded as summarized in Table 1, and fatiguing was terminated prior to failure when the largest crack was about 25 mm in length.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Fatigue Cycles</th>
<th>Observations / 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>No-damage baseline (no hole, no notch)</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>No-damage baseline (5.1 mm diameter hole drilled)</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>No-damage baseline (starter notch cut at 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>
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<tr>
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<td>22.7</td>
</tr>
<tr>
<td>14</td>
<td>20,600</td>
<td>25.2</td>
</tr>
</tbody>
</table>

**IMAGING WITH DAMAGE-FREE BASELINES**

The previously described imaging method is first applied by comparing current signals to damage-free baselines. As an example, we first consider images constructed between data sets 1 and 2, which would be expected to show the 5.1 mm hole that was drilled in between these two data sets. Figure 2 shows three such images, which correspond to matched loads of 0%, 50% and 100% (0 MPa, 57.5 MPa and 115 MPa); i.e., signals and baselines were recorded at the same load. As expected, the three images are very similar since the hole is only very slightly affected by the applied tensile load.

The situation is much different when the loads are not matched. Figure 3 shows three images, also constructed from data sets 1 and 2, but with the baselines (data set 1) recorded at zero load and the current signals recorded at 20%, 60% and 100% loads (23 MPa, 69 MPa and 115 MPa). The image of Figure 3(a), which has only a 23 MPa mismatch, is not significantly degraded from those of Figure 2. However, the image of Figure 3(b), with a 60 MPa mismatch, is obviously degraded, and that of Figure 3(c), with a 115 MPa mismatch, is degraded to a degree that the hole is no longer detectable.
The reason for the degradation of images when loads are mismatched can best be understood by considering the effects of applied loads on guided wave propagation. As has been previously shown [7], there are two primary effects: (1) dimensional changes; i.e., strains, and (2) changes in wave speed due to the acoustoelastic effect. To first order, both of these changes perturb times of arrival of echoes but in an anisotropic manner. Thus, there will be significant residual energy in differenced signals caused solely by load changes regardless of whether damage has also been introduced. In the case of Figure 3(c), this energy dominates the residual energy resulting from introduction of the through-hole.

Now consider a similar series of images obtained from data sets 3 (baseline signals) and 7 (current signals) where the primary difference between the data sets is a single fatigue crack that is about 5 mm in length. Figure 4 shows the resulting images, which are quite different from those of Figure 2 for the through-hole. In particular, the fatigue crack is not detectable at zero load because the crack is tightly closed, whereas at loads of 57.5 MPa and 115 MPa it is clearly visible, more so at the higher load because it is more completely opened.
Figure 4. Images constructed between data set 3 (baseline signals) and data set 7 (current signals) from matched loads. (a) 0 MPa, (b) 57.5 MPa, and (c) 115 MPa. All three images are shown on the same 10 dB color scale.

Figure 5. Images constructed between data set 3 (baseline signals) and data set 7 (current signals) from mismatched loads. (a) 0-to-23 MPa, (b) 0-to-69 MPa, and (c) 0-to-115 MPa. The images are shown on separate 10 dB color scales where each is normalized to its peak value.

Figure 5 shows images from data sets 3 and 7 for mismatched loads; this figure corresponds to Figure 3 for data sets 1 and 2. None of these images is satisfactory in the sense that it can unambiguously detect the fatigue crack. A comparison of Figures 4 and 5 indicates that the fatigue crack is adequately imaged only when loads are both well-matched between current signals and baselines and of sufficient magnitude to open the crack. These results clearly show the possible pitfalls when imaging fatigue cracks (as opposed to holes and notches) in the presence of applied loads. If the loads are too small, cracks may be tightly closed and thus undetectable. If loads are mismatched, then they may either obscure small cracks or result in false alarms.

**IMAGING WITH LOAD-DIFFERENTIAL BASELINES**

The results of the previous section motivate a different approach to imaging of fatigue cracks – the load-differential method. In this method “baseline signals” are recorded at one load, and “current signals” are recorded at the same damage state but at a slightly increased tensile load. Differences between the signals are thus caused by a combination of crack opening effects and loading effects. The image of Figure 3(a), which is of the through hole with a 23 MPa load mismatch, clearly shows the hole with only a few additional artifacts as compared to the images of Figure 2. This
comparison suggests that load differences of 23 MPa and smaller may not adversely affect imaging, at least for this specific specimen and transducer arrangement.

Figure 6 shows six load-differential images for data set 7 to validate this idea. The difference in loads is 23 MPa for each image, and the baseline loads start at 0 MPa and increment by 11.5 MPa. The remaining three images in the sequence are not shown because they contain nothing of interest on the dB scale used (i.e., they are uniformly dark). It can be deduced from these images that the crack does not begin to open until the load is about 35 MPa, and that it is fully open at about 80 MPa. The images also indicate that the crack is on the left side of the hole, which is correct.

Figure 6. Load-differential images constructed from data set 7 where current signals and baseline signals are recorded at different loads. (a) 0-to-23 MPa, (b) 11.5-to-34.5 MPa, (c) 23-to-46 MPa, (d) 34.5-to-57.5 MPa, (e) 46-to-69 MPa, and (f) 57.5-to-80.5 MPa. All six images are shown on the same 10 dB color scale.

A composite image can readily be generated for each data set by averaging a series of load-differential images. This composite image, while perhaps not as useful for locating individual cracks as a single load-differential image, does capture in one image the cumulative effects of the applied loads. Figure 7 shows a collage of composite images from all data sets that were generated by averaging the five load-differential images computed from non-overlapping loads separated by 23 MPa (e.g., 0-to-23, 23-to-46, 46-to-69, 69-to-92 and 92-to-115). Note that the first three composite images are from data sets recorded prior to fatiguing but with differing structural conditions (i.e., no hole, hole, hole plus notch). It can be seen from these images that the fatigue crack is perhaps barely visible by data set 6 and is clearly evident at data set 7. Cracking is obviously increasing as fatiguing progresses.
SUMMARY AND CONCLUSIONS

A load-enhanced imaging method for detecting and locating fatigue cracks has been developed and successfully demonstrated. This method is based on the fact that a small tensile load can open a crack but does not otherwise significantly change received signals. These results are significant because not only does the method provide a means of imaging fatigue cracks in the presence of variable loads, it takes advantage of the positive effects of loading to enable such imaging without relying on baselines recorded from the damage-free structure.

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REFERENCES