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Load-differential imaging for detection and localization of fatigue cracks using Lamb waves

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A B S T R A C T

Fatigue cracks are common and potentially critical defects in metallic plate-like structures, and ultrasonic guided wave methods provide an efficient and relatively low-cost means of crack detection and monitoring. However, widely used baseline subtraction methods may fail under mismatched environmental and operational conditions. In particular, varying applied loads change not only the contact state of a crack but also specimen dimensions and wave speeds, which affect the ultrasonic signal response. The load dependence of crack opening provides a possibility for enhanced crack detection, which is well-known for higher frequency bulk waves. A load-differential method is proposed in this paper whereby guided wave signals obtained at different loads under the same damage state are compared without utilizing previously recorded damage-free data. To demonstrate this method, a fatigue test was performed on an aluminum plate specimen instrumented with a sparse array of piezoelectric transducers. Signal changes due to crack opening effects caused by increasing tensile loads are visualized using delay-and-sum imaging. The results show that the load-differential method is capable of detecting cracks and visualizing their locations.

1. Introduction

Compared to current nondestructive evaluation (NDE) approaches, structural health monitoring (SHM) methods are widely regarded as being able to significantly reduce inspection time and maintenance costs. For plate-like structures, an SHM system based on Lamb wave propagation offers promise for damage detection in large structures because of the ability of such waves to travel long distances with less amplitude loss than bulk waves [1–3]. Research on sensor array design and signal processing as applied to this approach has been undertaken within recent years. Also relevant to this present work are studies on the interaction of guided waves with cracks and notches, and the *in situ* detection and characterization of fatigue cracks using both bulk and guided waves.

Different sensor array geometries have been proposed to implement guided wave NDE and SHM systems. Zhao et al. [4] compared circular, rectangular and parallel linear arrays for Lamb wave tomography. Yu and Giurgiutiu [5] constructed five different 2-D compact phased arrays and applied beamforming to compare the damage detection capabilities of the five geometries. One limitation of the above tomographic and compact array approaches is the requirement of a relatively large number of transducers. A sparse (i.e., spatially distributed) array geometry was initially proposed by Wang et al. [6] and later used by Michaels [7] and Clarke et al. [8] to achieve detection and localization of discrete damage using fewer transducers than are typically required for the tomographic and compact array approaches. Another advantage of the sparse array geometry is that imaging algorithms can take advantage of the so-called shadowing effect, or forward scattering, whereby forward propagating waves are partially blocked by damage. For some defects of interest, backscattered waves may be significantly smaller in amplitude than these forward scattering effects [9].

The idea of baseline comparison plays a key role in many SHM methods. Ideally, by subtracting baseline signals recorded from the damage-free structure from current test signals, a residual signal, which is assumed to arise from damage, is obtained. A variety of signal processing algorithms can be applied to these residual signals for damage detection, localization and characterization. However, such a process is strongly affected by mismatched environmental and operational conditions. Lu and Michaels [10] and Konstantinidis et al. [11] both addressed the temperature mismatch problem by optimal baseline selection, where a number of baselines were recorded at different temperatures and the optimal baseline that minimized the residual signal was selected. The signal stretch method, which was introduced in [10] and since used by others [12,13], adjusts the optimal baseline by stretching to better match it to the current test

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signals; essential to this method are homogeneity and isotropy of both the material and the temperature change. Another common environmental condition, surface wetting, has not been as fully investigated as temperature, but results to date indicate that even small amounts of surface wetting can adversely affect the performance of guided wave SHM systems [14–16].

The effects of loads on properties of guided waves in cables and rail structures were investigated via the finite element method by Chen and Wilcox [17]. Michaels et al. [18] examined the effects of applied uniaxial loads on guided wave signals for both early time regimes where specific echoes can be identified and later time regimes where signals are composed of multiple interfering echoes. Results indicated that damage detection methods based upon signal changes were likely to fail in the presence of loading variations. There have been several studies to both theoretically and experimentally investigate the effects of applied loads on guided waves [19,20], but they have not addressed the impact on guided wave SHM systems.

Fatigue cracks are one of the most common defect types in metallic plate structures and frequently initiate from fastener holes. Notches are commonly used to simulate cracks, and a number of studies have been reported on the interactions of guided waves with notches and cracks [1,21,22]. One of the major differences between the two interactions is the load dependence of crack closure. It is well known that closed cracks are hard to detect with conventional ultrasonic testing methods because ultrasound can propagate through a tightly closed crack [23,24]. Applied loads can open such cracks and make them easier to detect, whereas loads have minimal effects on finite width notches. Research on load modulation of ultrasound with fatigue cracks can be traced back to the 1970s and has been the subject of a number of investigations. Frandsen et al. [23] used acoustic techniques to estimate the area over which closure occurred. Kim et al. [25] investigated closed fatigue cracks using surface acoustic waves and suggested that modulation of loading about a low mean static load was able to enhance the detection of small closed cracks. Mi et al. [26] used the bulk wave energy transmitted through the region of a fastener hole to dynamically monitor the initiation and growth of fatigue cracks. Connolly and Rokhlin [27] analyzed the backscattered ultrasonic response to fatigue cracking as a function of transit time, fatigue life, and applied load to visualize and identify specific echoes scattered from geometrical features of the specimen and crack. Ohara et al. [28] recently introduced a nonlinear ultrasonic imaging method whereby a phased array was used to create linear and subharmonic images. Images obtained at different applied loads were subtracted to better visualize fatigue cracks.

This paper builds upon previous work by the authors [29–31] in which the basic delay-and-sum imaging method is applied in conjunction with varying external loads. In contrast to the work described in [28], signals rather than images are differenced, and these differenced signals are used for detection and localization of fatigue cracks. By calculating residual signals at varying loads at the same state of damage, fatigue cracks can be assessed without requiring baseline data recorded from the undamaged specimen.

The paper is organized as follows: Section 2 describes the fatigue testing and data acquisition protocols. Section 3 reviews the delay-and-sum imaging algorithm. Section 4 discusses the effects of applied loads on baseline subtraction imaging. Section 5 introduces the load-differential method and demonstrates performance on fatigue test data, and Section 6 contains concluding remarks.

2. Experiment

Fatigue cracks were initiated and grown in a 6061-T6 aluminum alloy plate of dimensions 305 mm × 610 mm × 3.18 mm. As can be seen in Fig. 1, an array of six piezoelectric transducers was affixed to one side of the plate using two-component epoxy, and each transducer was further backed with a bubble-filled epoxy protection layer. The surface mounted transducers were fabricated from 300 kHz, radial mode PZT disks (7 mm in diameter and 0.5 mm thick).

The aluminum specimen was then mounted in a servo-hydraulic test machine running in load control mode. A National Instrument PXI-5412 waveform generator was used to generate a linear chirp excitation sweeping from 50 to 500 kHz with a duration of 0.2 ms. A Panametrics 5072PR pulser-receiver was used to amplify the received signals, and a custom multiplexer switched between the 15 unique transmit–receive pairs. The received signals were then digitized by a National Instrument PXIe-5122 14-bit digitizer at a sampling frequency of 20 MHz. For each acquisition, 20 waveforms were averaged to improve the signal-to-noise ratio.

The broadband chirp excitation resulted in multiple Lamb wave modes propagating in the plate. Received signals were filtered to yield the equivalent narrow-band tone burst response as described in [32]. A 3-cycle Hanning windowed tone burst response centered at 100 kHz was selected primarily because of

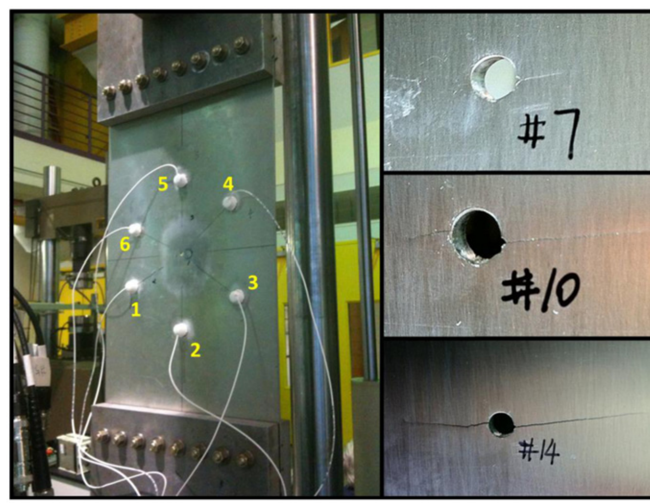

Fig. 1. Aluminum plate with attached transducers (numbered 1–6) mounted in the testing machine prior to fatiguing (left), and photographs of fatigue cracks corresponding to data sets 7, 10 and 14 (right). The front of the plate is the transducer side; crack photos are from the back of the plate.

Table 1
Summary of data sets acquired, fatigue cycles, and cracks.

Data set	Fatigue cycles	Notes/max. crack length at surface	
		Left	Right
1	0	Baseline, no hole, no notch	
2	0	5.1 mm diameter hole drilled	
3	0	Starter notch cut (left, front of hole)	
4	5000	No visible cracks	
5	8000	1.6 mm	–
6	10,000	3.6 mm	–
7	12,500	5.4 mm	–
8	15,500	7.7 mm	–
9	17,000	9.9 mm	–
10	18,500	13.4 mm	4.7 mm
11	19,500	16.8 mm	8.4 mm
12	20,000	19.5 mm	11.5 mm
13	20,400	22.7 mm	15.6 mm
14	20,600	25.2 mm	18.8 mm