

# **Comparison of Lamb Wave Interaction with High- and Low-Cycle Fatigue Cracks in Aluminum Plates**

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## ABSTRACT

Guided elastic (Lamb) waves have many properties that make them attractive for structural interrogation in active structural health monitoring applications. During the last two decades, a significant amount of research has focused on Lamb wave based techniques to detect, localize, and size various types of damage in plate-like structures. One area that appears to have received little attention in the literature is the degree to which differences in plastic zone size and residual stress levels around otherwise similar fatigue cracks can affect Lamb wave scattering behavior. This paper presents the results of a preliminary study on Lamb wave interaction with both low- and high-cycle fatigue cracks in aluminum plates. Wave field data are measured with a 3D laser Doppler vibrometer and processed using frequency-wavenumber domain filtering techniques. Quantitative results are presented in terms of wave transmission and reflection coefficients for both symmetric and asymmetric modes across multiple frequencies. Recommendations for additional analysis and future experiments are also provided.

## **INTRODUCTION**

Lamb waves can travel long distances in plate-like structures, have throughthickness interrogation capabilities, and are influenced by damage-related structural discontinuities such as cracks, corrosion, and delaminations. These features, combined with their relatively short wavelengths, make Lamb waves an attractive tool for active structural health monitoring (SHM) applications.

It is well-known that the propagation behavior of elastic waves, including Lamb



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Lamb waves, is affected by both the geometry of the waveguide and its material properties. Multiple researchers have investigated and characterized changes in wave phase and/or group velocities related to applied mechanical [1] and thermal [2] loads, residual stresses [3], and local plasticity around fatigue cracks [4, 5]. These variations in wave behavior further complicate the design and implementation of practical guided wave based SHM systems.

During a recent investigation on the application of commercial-off-the-shelf (COTS) SHM technologies to the detection of fatigue damage in aerospace structures, Davis *et al* [6] reported that a guided-wave based COTS SHM system demonstrated significant performance differences when used on a structure subjected to high load amplitudes (low-cycle fatigue) vs. one subjected to low amplitude loading (high-cycle fatigue). Despite both test structures developing cracks of similar lengths and in similar locations, the damage was detected by the COTS system much earlier in the low-cycle case than the high-cycle.

This paper presents the results of initial experiments to quantify the differences in Lamb wave scattering behavior between low- and high-cycle fatigue cracks in aluminum plates.

#### **EXPERIMENTAL METHODOLOGY**

#### **Test Articles**

Test specimens were 610 mm long by 305 mm wide by 3.175 mm thick 6061-T6 aluminum plates cut into a "dogbone." Test section width was 254 mm. A 4 mm diameter hole was drilled in the center of each specimen to represent a typical fastener hole and a partial depth notch (approximately 1 mm in length on either side of the hole) was etched with an Epilog FiberMark laser in order to facilitate fatigue crack growth. Two test specimens were prepared, each mounted in a set of mild steel grips using 12.7 mm diameter grade 8 bolts and loaded in a 500 kN Material Test Systems uniaxial fatigue test machine (Fig. 1(a)).

Test Article	Max/Min Load (kN)	Bulk Stress (% F <sub>ty</sub> )	Cycles (x1000)	Crack Length (mm)		
				Left	Right	Total (incl. hole)
DB1	53.4 / 5.34	28	324	46	44	94
DB2	133.5 / 13.35	70	15.4	44	45	93

Table 1. Fatigue Loading and Crack Parameters.

Both test articles were subjected to constant amplitude sinusoidal loading and developed cracks of approximately the same total length. Specific loading and crack length parameters are given in Table 1. Images of the cracks are shown in Figure 2 (fluorescent penetrant was used to improve crack visibility, which results in minor surface scratches appearing as short vertical lines). The XY axis origin was located at the center of the plates. A single 6.35 mm diameter by 0.254 mm thick PZT transducer was bonded to each plate using M-Bond 200 adhesive at (x,y) coordinates of (0,120 mm) and used for wave excitation (Fig. 1(b)).



Figure 1. (a) Dogbone specimen in MTS, (b) Dogbone Layout showing transducer location.

#### **Data Collection**

An Agilent 33120A arbitrary waveform generator was used to form the PZT excitation signal: 5-1/2 cycle sine bursts modulated with a Hamming window. Excitation burst and measurement timing were synchronized via an 80 Hz TTL square wave produced by the Polytec system's internal waveform generator. The excitation signal from the Agilent was sent through a Krohn-Hite model 7500 wideband power amplifier. This amplified signal (100 Vpp) was used to drive the PZT transducers. All data collections were performed with the plates in a zero-load condition.

Data collection was performed using a Polytec PSV-400-3D-M scanning laser Doppler vibrometer. This system is designed for full-field vibration measurements at frequencies up to 1 MHz. System components include a motorized tripod supporting 3 separate sensor heads, a high-resolution digital camera, rack-mounted sensor control units, data collection computer, etc. The system makes surface velocity measurements by evaluating the Doppler frequency shift of reflected laser energy. Because each sensor head can only measure velocity along the axis of its beam, the raw velocity data from all three heads are combined in software with alignment and beam angle data to resolve the velocity data onto an orthogonal 3D coordinate system. In this manner, the system allows for fast, precise, non-contact 3D surface velocity measurements. In order to maximize return laser energy to each sensor head, retro-reflective film was applied to each of the test articles.



Figure 2. (a) High- and (b) low-cycle fatigue cracks.

Each plate was scanned at approximately 20,000 points with a nominal spacing of 0.8 mm in both the X and Y directions. The scan grid was a rectangle measuring 160 mm  $\times$  80 mm (X  $\times$  Y) centered at (0,0). Data was collected at a sample rate of 2.56 MHz for 400 µsec, producing 1024 point time histories. In order to improve signal-to-noise ratio (SNR), each data point was averaged 40 times and band pass filtered via the Polytec software suite. In all cases, the pass band was 100 kHz wide and centered at the excitation frequency. Four excitation frequencies were used: 100, 250, 300, and 400 kHz.

#### RESULTS

Measurement data was converted to the frequency-wavenumber domain via a two-dimensional Fourier transform to facilitate separation of incident, transmitted, and reflected waves by direction of travel. These techniques will not be described in detail here as they are relatively common in the SHM community, have been in use for some time [7], and are well covered in relevant SHM textbooks [8]. Based on the geometry of the test articles, the predominant wave propagation direction in the region of interest was parallel to the y-axis, with incident waves propagating in the negative y-direction. Wave energy with a negative y-wavenumber  $(k_y)$  was considered as either incident or transmitted, while wave energy with a positive  $k_y$  was considered to be reflected.

Composite frequency-wavenumber contour plots were generated using all scan points in the grid. Figure 3 includes plots for both out-of-plane  $(V_z)$  and in-plane  $(V_y)$  velocity components across all excitation frequencies for each test article. Analytical dispersion curves for both  $S_0$  and  $A_0$  wave modes are included. Comparing the high- vs. low-cycle data, the low-cycle plots appear to have higher peaks in the quadrants representing reflected signals (positive  $k_y$ ). However, the most noticeable difference between plots is the change in  $S_0$  mode amplitude when comparing in-plane and out-of-plane velocity data. Because symmetric modes are predominantly an in-plane phenomenon (longitudinal waves), this result is expected.



The data were filtered (windowed by quadrant) and transformed back to the time-spatial domain. The reflection and transmission coefficients (RC and TC) were calculated via the Hilbert transform following a technique presented by Lu, *et al* [9, 10]. The filtered data from four lines of scan points (each parallel to the y-axis but at a different x-coordinate value) were processed via the Hilbert transform, the absolute value of which represents the time-varying magnitude envelope of the velocity time signal (Fig. 4). The maximum values of the different wave components were averaged along each line of data, and the RC and TC were calculated as ratios. The results are presented in Figure 5.



Figure 4. Hilbert Transform of a Scan Point at 100 KHz Excitation.



Figure 5. Reflection and Transmission Coefficients.

In general, the RC were highest near the center of both cracks and decreased towards the crack tips. RC also tended to decrease with increasing excitation frequency, though additional data is required to determine how well these factors are correlated. As would be expected, trends for TC were in the opposite direction of RC. RC for the low-cycle crack were consistently higher than those of the high-cycle crack. Based on wave field images of both test articles, it appears the center portion of the crack in DB2 (low-cycle test article) may be slightly open (Fig. 6), and a partially open crack would be expected to reflect more wave energy than a similar closed crack.

#### **CONCLUSIONS**

This paper presented the results of a preliminary study of Lamb wave interaction with low- and high-cycle fatigue cracks in aluminum plates. Initial results indicate that a low-cycle fatigue crack reflects more wave energy than a similar sized high-cycle crack. However, additional investigation is required to determine the cause of this behavior. Logical causes include the larger plastic zone and higher residual stresses in the material surrounding a low-cycle crack, differing contact conditions between the crack faces, etc. Further experimental research is planned and will include variations in loading level and crack length. Additionally, more robust signal processing and data reduction algorithms may be required to better characterize variations in wave speed and scattering behavior in the vicinity of different cracks.



(a)  $V_z$  (300 kHz excitation, t = 55.9 µs)



(b) 
$$V_z$$
 (300 kHz, t = 55.9 µs)

Figure 6. Lamb wave interaction with (a) high- and (b) low-cycle fatigue cracks.

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