# Structural Damage Identification in Stiffened Plate Fatigue Specimens Using Piezoelectric Active Sensing

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## ABSTRACT

This paper presents a guided wave structural health monitoring (SHM) technique, based on the use of piezoelectric active-sensors, used to determine the structural integrity of stiffened aluminum plates. For damage detection, the transmitted power between piezoelectric transducers used for Lamb wave propagation is utilized to analyze the extent of damage in the structure. Damage initiation and propagation were successfully monitored with the guided wave technique. Overall, these methods yielded sufficient damage detection capability to warrant further investigation into field deployment. This paper summarizes considerations needed to design such SHM systems, experimental procedures and results, and recommendations that can be used as guidelines for future investigations.

## INTRODUCTION

Recently, the use of aluminum has been incorporated into the design and fabrication of marine and naval vessels with increasing regularity. Many of the naval applications for aluminum include high speed and high performance vessels. While aluminum is a natural material choice for these ships due to its lightweight properties, the use of aluminum comes with several challenges including limited performance knowledge of the materials, aluminum sensitization, structural fatigue performance, and strength of welded aluminum structures. With these challenging areas, the desire for a comprehensive naval structural health monitoring (SHM) system has been an area of great interest [1- 5].

One area of concern in aluminum structures is the head-affected zone (HAZ) generated as a result of the aluminum welding process [6-7]. Unlike welding in steel, where nearly all tensile strength is retained, welding in aluminum can leave localized weakness in the base material near the weld, known as the heat-affected zone, due to heat generated from welding. In some aluminum alloys, up to a 50% reduction in

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tensile strength is possible due to the HAZ. Despite these major differences between steel and aluminum, most current structural analysis and design procedures of an aluminum ship are still based on data and knowledge of designing a steel ship. As a result, the welds and surrounding HAZ can act as crack initiation sites due to operational cyclic loading.

In this paper, a representative welded aluminum test specimen is monitored via guided wave SHM while undergoing cyclic fatigue loading. Lamb waves have been extensively utilized as a highly effective SHM technique for many types of structures [8]. Advantages include the ability of guided waves to travel long distances in plates as well as the ability to both excite and record wave propagation with piezoelectric transducers. The use of piezoelectric materials as actuators and sensors also allows for the combination of Lamb wave methods with other SHM techniques such as the impedance method [5]. A description of the test structure, the applied monitoring techniques, and results and conclusions will be presented in the following sections.

## FATIGUE SPECIMENS

In this study, the test structures are aluminum fatigue specimens constructed with typical Navy ship design details (Figure 1). Each of these medium sized specimens consists of a single stiffened plate at the location of an intersecting stiffened bulkhead, which provides stress concentration, and therefore crack initiation, sites. All connections are welded. The base plate and bulkhead material consist of 3/8 and 1/4 inch thick 5083-H116 aluminum, while the stiffeners are made of extruded 6061-T6 aluminum. Thick end plates are welded to the specimen to allow for placement of the plate in a tensile fatigue machine. Using the fatigue machine, different loading profiles are applied to groups of specimens in an effort to characterize the S/N curve for this type of plate intersection. The results from monitoring one of these stiffened plate specimens are presented in this paper. Sixteen strain gauges were applied to the specimen to assist in balancing the structure in the fatigue machine, as well as monitor the loading through the fatigue process.

## EXPERIMENTAL PROCEDURE

The specimen under investigation was secured and balanced in a 550 kip MTS machine. Fully reversed (R = -1), constant amplitude loading was applied to the specimen at a rate of 5 Hz. The average stress range of this loading was +/- 5 ksi. Cycling was continued until the presence of a crack was detected. Generally, crack initiation would be considered a failure of the specimen. However, the crack was allowed to grow further in this case, and cycling continued until the crack propagated through one side of the plate.

As seen in Figure 1, four piezoelectric transducers were bonded to the surface of the base plate. Each transducer is a 0.5 inch diameter, 0.02 inch thick disc made of 851 material from APC, International and was bonded to the plate with Vishay Micro-Measurements M-Bond 200 adhesive. An Acellent Technologies Inc. Smart Suitcase Lamb wave data acquisition system was used to actuate each piezo and record the response at each of the three other piezos in order to measure all the propagation paths between the transducers.  A Krohn-Hite 7602M wideband amplifier is used to amplify the excitation signals from the DAQ system.  The excitation signal consisted of 5 cycles of a Hanning-windowed sine wave.  Data were recorded for 20,000 samples at a rate of 25 MHz and averaged 20 times.

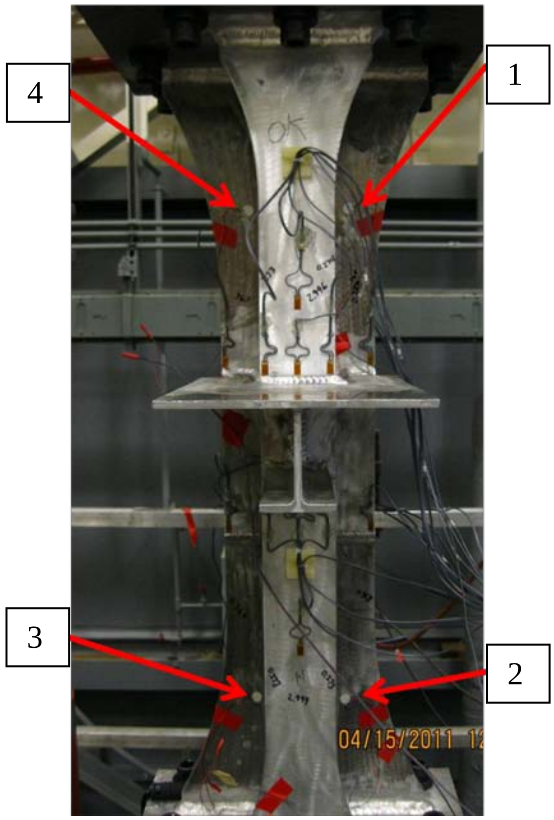


Figure 1.  The front of the specimen is shown and the four piezoelectric discs bonded to the plate are labeled.

As the specimen was fatigued, the MTS machine was periodically paused to allow for guided wave signals to be recorded at specific cycle counts.  Before the fatigue testing started, Lamb wave signals were generated and recorded at 50, 75, 100, and 150 kHz.  Once fatigue testing began, two measurements were acquired at each of these excitation frequencies.  These measurements were taken at the specific cycle counts presented in Table 1 as the test was paused.

As the fatigue test progressed, a crack was initially observed at 167,300 cycles.  The crack was located in the heat-affected zone adjacent to the main plate butt weld.  The crack started in the center of the plate, directly under the rathole in the stiffener.  A rathole feature (seen in Figure 2) allows for the stiffener to be welded to the plate without having to grind the butt well flush with the plate surface.  As previously mentioned, the test was not terminated due to the initiation of a crack, but allowed to continue.  The crack grew through the plate thickness to the back of the specimen, and then along the butt weld towards the free edges of the test specimen.  Figure 3 shows the crack in the back of the plate with the length of the crack indentified at different cycle counts.  Eventually, the crack extended completely to the edge (right side of

Figure 1) in one direction, and was less than an inch away from the other edge. The crack length described at the Lamb wave measurement cycle counts is described in Table 1.

Figure 2. The front of the specimen shows the butt weld and rathole where crack initiation occurs.

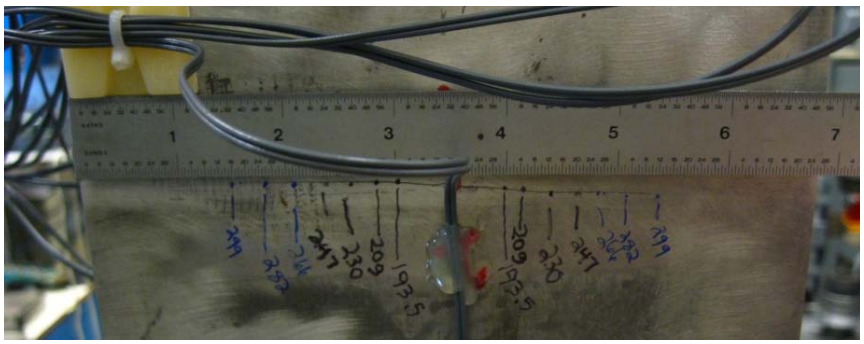


Figure 3. The crack, with propagated length labeled at fatigue cycle counts (in thousands), is visible on the back of the specimen (butt weld covered by ruler).

TABLE I. MEASUREMENT SUMMARY WITH DAMAGE DESCRIPTIONS

| **Cycles** | **Specimen Temp** | **Visually Observed Damage** |
|---|---|---|
| none | 70° F | none |
| 1k | 69° F | none observed |
| 60,826 | 69° F | none observed |
| 110,452 | 69° F | none observed |
| 185,601 | 69° F | crack detected |
| 217,727 | 70° F | around 1.5" crack |
| 232,008 | 66° F | 2" crack |
| 251,709 | 68° F | growing |
| 268,276 | 68° F | growing |
| 299,296 | 70° F | 4" crack |
| 314,728 | 70° F | growing |
| 325,365 | 65° F | crack extended through left edge of specimen (between PZTs 1&2), less than 1" from edge on other side |

## DATA ANALYSIS

As a Lamb wave travels through a structure, any defect in the path of the wave can potentially alter the wave propagation. Depending on the type of defect, orientation, and excitation frequency of the waves, the waveform can be altered in several ways including attenuation of the waveform amplitude, scattering of the waves, or distortion of the waveform (including phase delays). In this study, we will use a technique based on the power spectral density (PSD) to take advantage of the wave scattering and attenuation features [9]. The idea behind this method is that as a crack propagates through the structure, it will act as a wave scattering source and decrease the amount of energy that reaches a sensor. As the crack grows, the energy transfer between a particular actuator-sensor path will decrease.

To perform the PSD method, the first arrival of the $A_O$ mode is isolated in the time history. The PSD, which defined as the distribution of the power of a signal with respect to frequency, is calculated for the asymmetric mode, and appears as a peak around the excitation frequency in the frequency domain. Welch's averaged, modified periodogram method is used to calculate the PSD. A rectangular window is used for the estimation with no overlapping samples. Once the PSD estimate is obtained for the $A_O$ mode, the area under the PSD curve is calculated using trapezoidal integration to yield the average power of the wave. As the crack grows, the average power received at sensors along a particular path should decrease.

## RESULTS

As mentioned in the previous section, the PSD analysis was applied to the first arrival of the first asymmetric mode. In Figure 4, the $A_O$ mode is isolated in the time domain for 100 kHz excitation generated at piezo 1 and measured at piezo 2. As the crack grows across the stiffened plate, changes to the waveform can be visually observed. The signal with the largest amplitude was acquired before any fatigue testing began. By 185,601 fully reversed cycles, attenuation of the curve is clearly noticeable. After 299,296 fatigue cycles, there is a significant difference in amplitude as well as a phase delay.

After applying the PSD analysis to the waves seen in Figure 4 (as well as the rest of the data described in Table 1), charts were generated to describe the average recorded signal power as a function of the number of fatigue cycles. Figure 5 displays one of these bar graphs for 100 kHz excitation measured on the path from piezo 1 to piezo 2. Each bar represents an average power calculation, and two measurements are shown for each of the data sets described in Table 1 (i.e. the first two bars correspond to the measurements acquired with no cycling, the next two correspond to 1,000 cycles, and so on).

As seen in Figure 5, there are two distinct energy levels that happen along this path from 1 to 2. At the measurement taken at 110,452 cycles, there is a significant decrease in the signal power. This power level generally remains constant until 299,296 cycles when there is another large decrease in signal power (as visually observed in Figure 4). These dramatic power reductions at the sensor are likely caused by two distinct fatigue stages of the specimen. As previously mentioned, the crack was first visually observed at 167,300 cycles. This Lamb wave technique is likely showing changes in energy at the onset of cracking before it can be felt or visually detected, indicating the presence of imminent damage. By 299,296 cycles, the crack was near four inches in length and directly in the path between piezos 1 and 2, thus severely limiting the amount energy transfer along that path. The PSD average power calculated along path 3 to 4 shows similar results.

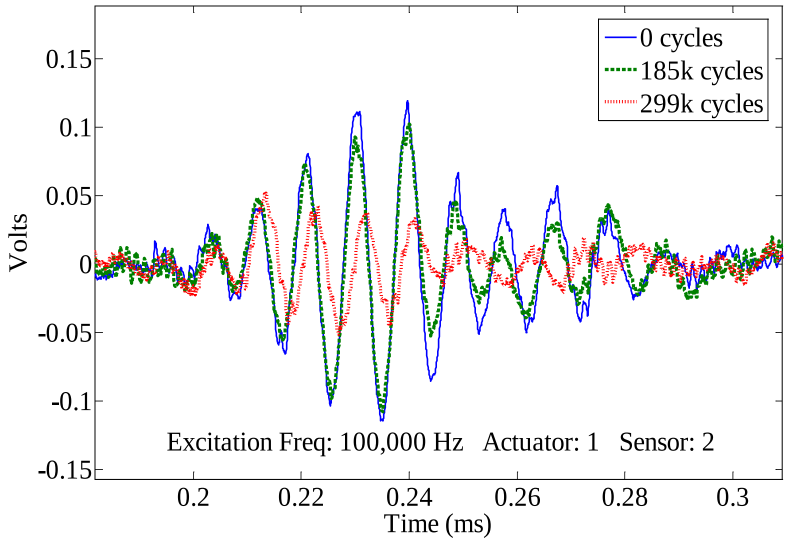


Figure 4. The isolated $A_O$ mode first arrival, recorded at PZT 2, is shown at 3 different fatigue levels.

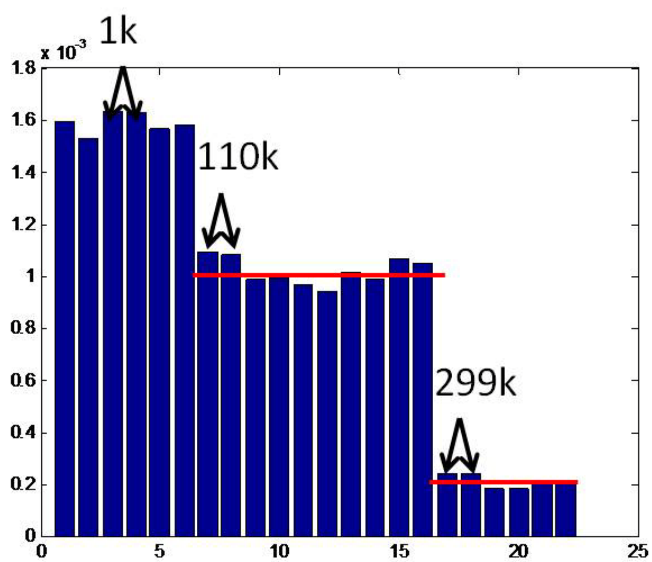


Figure 5. The area under the PSD curve, calculated twice at each fatigue level, is shown for the path from piezo 1 to 2 at an excitation of 100 kHz.

While the 100 kHz results provide an indicator for the onset and extension of damage, the frequency was not able to track the crack growth. However, a higher frequency should be more sensitive to smaller changes in the amount of damage. Presented in Figure 6 are the average powers calculated for paths 1 to 2 and 3 to 4 at an excitation of 150 kHz. At this frequency, the onset of damage is again indicated at the measurements taken at 110,452 cycles (except for path 3 to 4). However, instead of a constant power level until the crack extends to directly between the transducers, the energy gradually decreases as the crack grows. With this higher frequency, the growth of the crack can be consistently tracked by monitoring the signal power.

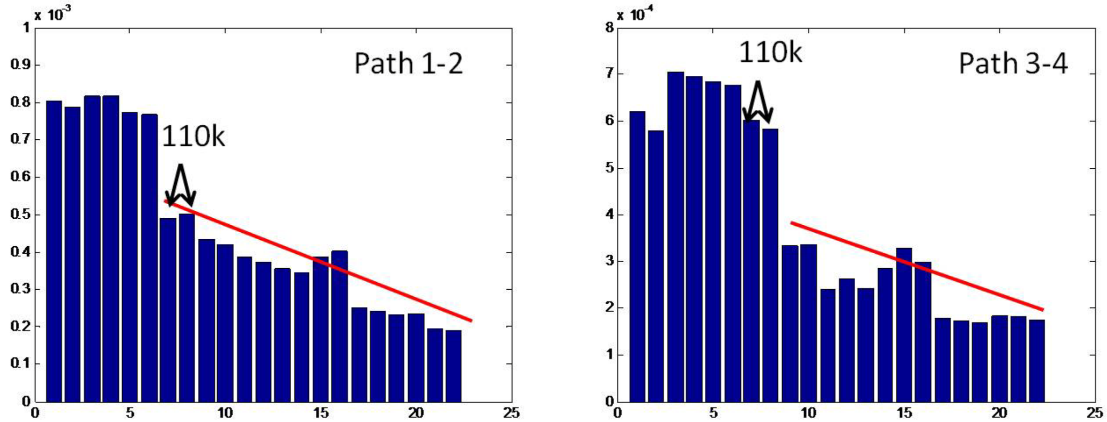


Figure 6. The area under the PSD curve displayed for the paths between PZT 1 to 2 (left) and 3 to 4 (right) at an excitation of 150 kHz.

## CONCLUSIONS AND FUTURE WORK

The study presented in this paper support that wave propagation can be efficiently used for detecting fatigue crack initiation and monitoring the growth of cracks as they propagate through a structure. A stiffened plate fatigue specimen was instrumented with piezoelectric transducers to allow for guided wave SHM implementation during fatigue testing. An energy analysis technique based on the power spectral density allowed for the monitoring of transmitted energy along sensor paths. The use of excitation frequencies above 100 kHz is preferable in identifying the severity of any identified damage. The most important result of this study is that structural changes due to fatigue were identified using Lamb waves prior to any visually observed cracking.

The specimen presented here is one of many (30 to 35) identical fatigue samples. Each of these specimens will be fatigued to failure with different levels of loading profiles (both constant and random amplitude) and stress levels. A number of the specimens will be observed with various SHM techniques. In addition to Lamb waves, the impedance method for SHM will be used via the piezoelectric transducers already bonded to the specimen. Additionally, monitoring the influence of fatigue damage on global modes will be observed using modal analysis techniques.

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