In-situ ultrasonic monitoring of crack growth under static and dynamic loading conditions

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ABSTRACT

Successful in-situ monitoring of crack initiation and growth is a necessary prerequisite for applying ultrasonic methods to structural health monitoring. For conventional ultrasonic testing methods, a focused beam may be used to directly image the crack tip; however, this method is difficult to apply during fatigue testing because of access limitations and couplant contamination issues. However, ultrasonic sensors can be permanently attached to a specimen to detect signal changes due to crack initiation and growth if the wave path is properly directed through the area of critical defect formation. The dynamics of cracks opening and closing during the fatigue process modulate the amplitude of ultrasonic waves propagating across these crack interfaces. Thus, even very small cracks can be reliably detected using permanently mounted sensors if the ultrasonic response can be measured as a function of load. A methodology is presented here that uses this behavior to detect and monitor crack formation and growth. This methodology may also be applied to structures subjected to unknown dynamic loads by using the ultrasonic signal to both estimate the instantaneous dynamic load and interrogate the integrity of the structure. Essential to the success of this method is an initial calibration on the undamaged structure where ultrasonic response is measured as a function of known static load. Results are presented from several aluminum specimens undergoing low cycle fatigue tests, and the dynamic loading results are shown to be comparable to the static ones in terms of the response of the ultrasonic signal to crack progression.

Keywords: Ultrasonic, Crack Detection, Fatigue Monitoring

1. INTRODUCTION

The purpose of this paper is to develop an ultrasonics-based SHM technique for detecting initiation and growth of cracks emerging from rivet holes during fatigue loading. Furthermore, the objective has been to devise a method which can be used while the specimen is being fatigued; i.e., measurements are made in-situ without interrupting the fatigue test. The eventual field application of this method might be the monitoring of “hot spots” on structures subjected to externally applied loads, for which it would not be possible or practical to interrupt service in order to make ultrasonic measurements.

Ultrasonics has been extensively applied in nondestructive evaluation (NDE), and it is one of the few NDE techniques suitable for use in a structure-integrated damage monitoring system\(^1\). In structures made of ductile alloys that are subjected to fatigue failure, a large part of the service life is spent in crack initiation and the presence of very small cracks\(^2\). One of the major concerns with metallic aircraft in general is fatigue cracking\(^3\). Thus, monitoring the onset and growth of cracks in critical structures has been a research area of great interest in the field of structural health monitoring (SHM).

Early research efforts on characterizing cracks ultrasonically were mainly for NDE purposes. Diffraction techniques have been used for bulk crack detection and sizing\(^4,5\). Surface wave scattering\(^6,7\) and imaging\(^8\) have been used to detect surface breaking cracks. Guided Lamb waves have been studied in the laboratory for detecting cracks in plate structures\(^9\). The guided wave technique requires knowledge of wave modes for the structure in order to design the inspection system and to interpret the results, and thus are limited to simple structures\(^10,11\). Recently work has begun on the development of ultrasonic methods for in-situ monitoring of structural health. Some examples include using an array
of surface-mounted PZT wafer elements for monitoring crack growth in a specimen exposed to uniaxial cyclic loading\textsuperscript{12}, surface acoustic wave modulation to monitor growing cracks\textsuperscript{13}, and vibration modal analysis for characterizing fatigue cracks\textsuperscript{14}.

This paper reports on data obtained from rectangular specimens with two rivet holes using attached miniature angle beam ultrasonic transducers to detect and size cracks. Cracks open up under tension loads, and open cracks block and/or scatter a greater portion of ultrasonic energy than do closed cracks. This observation has led to development of an energy ratio method to detect and estimate crack size as previously reported by the authors.\textsuperscript{15} This energy ratio method was calculated from ultrasonic waveforms obtained by interrupting the fatigue test to take the measurements. This paper describes a dynamic measurement method where this same energy ratio can be computed from ultrasonic measurements recorded while the specimen is being fatigue loaded; i.e., without interrupting the fatigue test. The dynamic method described in this paper uses the arrival time of various shear wave components to calculate the effective load associated with each dynamically recorded waveform. Once the loads are known, then the energy ratio between zero-load and a specified axial load can be calculated. We show here that the energy ratios obtained from dynamic measurements agree very well with the static method.

2. EXPERIMENTAL PROCEDURE

2.1. Fatigue Testing

The specimen used for fatigue testing was an aluminum alloy, 7075-T7351, and the specimen geometry is shown in Figure 1. Rivet holes are simulated by two through holes in the middle of the specimen.

![Figure 1. Aluminum alloy (7075-T7351) specimen. Specimen dimensions are in mm.](image)

The specimen was fatigued with a uniaxial load until failure using a cyclic rate of 5 Hz. The loading spectrum was aperiodic as illustrated in Figure 2 to simulate the variable loads on a structure during field use. The maximum load value in the spectrum; i.e., the 100 percent value, was 17,000 lb, which represents approximately 75 percent of the yield point for this material. The load cycles were grouped into blocks of 2640 cycles each, and typical time to failure was between 15 and 20 blocks.

Fatigue testing was halted between blocks to take "static" measurements of ultrasonic response versus load. Ultrasonic measurements were also recorded during the fatigue process, and these measurements are referred to as the "dynamic" measurements. The dynamic measurements were taken at random times so that the actual load associated with each waveform was not known, but a sufficient number of waveforms were recorded to assure that waveforms were obtained throughout the entire load range.
2.2. Ultrasonic Measurements

Two pairs of 10 MHz, 70° shear wave angle beam transducers, Panametrics Model A5054, were attached to the two-hole rectangular specimen as shown in Figure 3. The shear wave path was aligned with the holes by peaking ultrasonic pulse/echo signals. Transducers were also positioned axially to obtain two balanced echoes, one from the top corner and the other from the bottom corner of the hole as shown in Figure 4. This final position places the center of the refracted shear wave near the center of the hole, with the echoes from the corners being visible because of beam spread.

![Image](image1.png)

Figure 3. Two-hole rectangular specimen with two pairs of angle beam transducers. (a) Schematic of transducer configuration and shear wave propagation paths, (b) picture of actual specimen and transducers.

![Image](image2.png)

Figure 4. Typical pulse/echo signal with two balanced echoes from top and bottom of the hole.
Both static and dynamic ultrasonic measurements were performed during the fatigue test. For the static measurements loads were applied from 0 lb to 10,000 lb in 1000 lb increments. Dynamic measurements were taken at random times near the beginning of each block of fatigue cycles. All measurements were made using a Panametrics 5072PR pulser receiver, and were recorded using a Tektronix TDS5034 digital oscilloscope operating at a digitizer frequency of 125 MHz.

3. DATA ANALYSIS

3.1. Typical Signals
When both angle beam transducers in the pair are aligned as described, the through transmission ultrasonic signals have two leading wave arrivals as shown in Figure 5. The first wave is the single V arrival and the second the double V arrival. The single and double V wave paths are illustrated in Figure 3.

These signals change in two ways during fatigue loading. First, the amplitudes of both signals vary with load and the damage condition, and second, the signals shift slightly in time with increasing load as shown in Figure 6. A 1.0 μs time window was used to gate each of the individual signal components as shown in Figure 5 for analysis step which follow.

![Figure 5](image_url)  
**Figure 5.** Typical through-transmission ultrasonic signal received by the angle beam transducers with two arrival pulses identified.

3.2. Energy Ratio Calculations
The authors have previously reported on a method for monitoring of the onset of fatigue crack initiation and subsequent crack growth using through transmission ultrasonic measurements from attached shear angle beam transducers\(^{15}\). A normalized energy ratio method proved to be a robust self-calibrating method for crack monitoring. The first step in calculating the energy ratio is to calculate an energy value for a windowed portion of the recorded ultrasonic waveform under zero axial load and under 5000 lb of load:

\[
E_{\text{NoLoad}} = \int_{TTU} x_{\text{NoLoad}}^2 (t) dt
\]

\[
E_{5000\text{lbs}} = \int_{TTU} x_{5000\text{lbs}}^2 (t) dt
\]

Next, a ratio is formed of these two energy values. In the previous work, the fatigue test was interrupted to apply a static load and make these measurements.
Finally, the energy ratio is normalized by the energy ratio value obtained before the fatigue loading was initiated, i.e., the no-damage condition.

\[
R_{\text{NORM}} = \frac{R}{R_{\text{INITIAL}}}
\]  

For the work reported here, static ultrasonic measurements were made and energy ratios were calculated at the end of each block of fatigue cycles. These energy ratios are the ones used as benchmarks for comparison with those obtained from the dynamic measurements.

3.3. Time Shift under Axial Loading

The relative time shift between various recorded waveforms is referred to here as the relative time-of-flight (ΔTOF), and is computed using a cross correlation method. The inherent resolution of the position of the cross correlation peak is the period of the digitizer clock, which is 8 nsec. To improve the accuracy of the ΔTOF calculations, interpolation methods were used to fit a cubic spline to the cross correlation peaks. The resultant accuracy of the ΔTOF calculations is approximately 0.8 nsec.

Calculated values of ΔTOF versus applied load are shown in Figure 7 for one specimen which failed in the 17th block of fatigue cycles. For this specimen static measurements were recorded for the initial zero-load, no-damage condition, and after each block of fatigue cycles. Figures 7(a) and 7(b) are the single V path results, and 7(c) and 7(d) are the double V path results. Figures 7(a) and 7(c) show the ΔTOF measurements referenced to the initial zero-load, no-damage state. Note that there is a progressively increasing offset of the curves as fatigue progresses. It is believed that this offset is due to permanent deformation of the specimen, which thereby increases the shear wave path lengths. Figures 7(b) and Figure 7(d) show the ΔTOF measurements referenced to the zero-load values at the beginning of each block, and these are the curves which will serve as a calibration for analyzing the dynamic measurement results.

Figure 6. Time shift of ultrasonic signals with axial load. (a) Before crack initiation the signal is stretched, but the amplitude is not strongly affected. (b) After the crack initiation, the signal is stretched in time and its amplitude decreases with load.
The $\Delta$TOF curves for the single V shear wave component exhibit nonlinear behavior when a large crack exists near the rivet hole. This is seen as a departure from linearity after a static load of about 2000 lb. We believe that the crack begins to open at about 2000 lb, and is completely open after about 5000 lb, based upon these results and visual observations when the static measurements were made.

The double V path is less affected by the presence of a large crack near the rivet hole than the single V path; therefore, $\Delta$TOF curves from the shear wave double V path are best suited to be the calibration curve for deducing actual loads from the recorded dynamic waveforms. This is because the transducer attachment geometry favors the double V signal, as the amplitude of the through transmission signal from the double V path is about four times the amplitude of the single V signal.

As shown in Figure 7, axial loading exerted on the specimen shifts the ultrasonic signals linearly about 4 nsec per 1000 lb for the single V path signal, and about 8 nsec per 1000 lb for the double V signal. The two dominating factors that cause the signal to shift are specimen elongation and the variation of shear wave propagation velocity with stress; i.e., acoustoelasticity effects. It is well known that both of these contributions result in a linear time shift with applied load, but detailed analysis of these effects is beyond the scope of this paper.
3.4. Load Mapping

A linear curve fit was used to calculate the effective applied load for both the single V and double V shear wave components from the data shown in Figures 7(b) and 7(d). Results are shown in Figure 8 for using both the single V and double V calibration data; note that both calibrations agree very well. However, as mentioned previously, the double V ΔTOF curve is least affected by the presence of cracks emerging from the rivet holes and thus is more accurate near the end of fatigue life. The double V calibration curve was used for the energy ratio calculations from the recorded dynamic measurements.

![Figure 8. Load estimated from TOF for 50 dynamic measurements during block 10.](image)

3.5. Energy Ratio Calculations from Dynamic Measurements

Waveforms were collected during fatigue loading, and these are referred to as the dynamic measurements. These waveforms exhibited subtle changes in wave arrival times as a function of the applied axial load. These changes are consistent with the time shifts observed statically. Thus, the ΔTOF curves obtained from the static calibration can be used to assign an axial load value to the dynamically collected waveforms. The specific steps used for calculating the energy ratios from the dynamic measurements were as follows:

1. Ultrasonic waveforms were randomly recorded during fatigue loading.
2. The ΔTOF curves obtained from static calibrations were used to assign an effective axial load value to each waveform.
3. The waveform closest to an axial load of 5000 lb was selected.
4. The waveform closest to an axial load of 1000 lb was selected.
5. The energy ratio was computed using these selected waveforms as per Eq. (3).
6. The energy ratio obtained at the beginning of block 1, i.e., at the beginning of the fatigue test, was used to calculate the relative energy ratio as per Eq. (4).

4. DISCUSSION OF RESULTS

Results are presented in Figure 9 for static and dynamic calculations of the normalized energy ratio for two specimens. Specimen S3-0001 failed after 16 blocks, and Specimen S4-0030 was halted prior to failure after 15 blocks. For Specimen S3-0001 the energy ratio began to drop after block 10 and decreased to a ratio of approximately 0.25 just prior to failure. Both the static and dynamic methods yielded essentially the same results, as the energy ratio curves overlap.
throughout the entire range of fatigue life. The energy ratio curves for Specimen S4-0030 also show excellent agreement between the static and dynamic methods.

![Graphs showing energy ratio comparison for two specimens.](image)

**Figure 9.** Energy ratio comparison from two specimens.

5. SUMMARY AND CONCLUSIONS

An ultrasonic method has been developed to monitor initiation and growth of fatigue cracks emerging from rivet holes in thin plate specimens of 7075-T7351 Aluminum. This method uses permanently mounted miniature angle beam transducers, which transmit ultrasonic shear waves through a region near a rivet hole that is targeted for monitoring. It was shown in previous work that energy of the ultrasonic waves transmitted through the affected region is reduced due to the presence of cracks and further, that this energy is modulated by the applied load during fatigue due to opening and closing of the crack. This led to the development of an energy ratio method as a robust metric for monitoring changes in crack size. The method required measurements of ultrasonic waveform energies as a function of applied static load, for which the fatigue test was interrupted.

The work reported here shows results from development of a new method, referred to as "dynamic" measurements, which are made during fatiguing without interrupting the test. Waveforms are obtained at random, and subtle shifts in the arrival times of various shear wave components are used to calculate the uniaxial load associated with each waveform. This provides sufficient data to calculate an energy ratio that agrees well with values obtained from the static measurements.

The eventual application of this method might be in-situ ultrasonic monitoring of crack initiation and growth near "hot spots" in service critical structures. The opening and closing of cracks under applied load modulate the ultrasonic energy that can be transmitted through a crack. In order to properly interpret results under variable field load conditions, it will be necessary to know the actual stress conditions near the crack, and the TOF method demonstrated in this paper is expected to play a key role.

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REFERENCES