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Title:

FATIGUE CRACK MONITORING WITH NONLINEAR ACOUSTICS

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Fatigue Crack Monitoring With Nonlinear Acoustics

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ABSTRACT
This paper presents a new application of piezoelectrically actuated Lamb waves in the structural health monitoring (SHM) of the riveted outer skin of commercial aircraft. Previous research has explored the linear response of Lamb wave propagation in thin plate structures. This project explores the ability of Lamb waves to excite and exploit the nonlinear response created by the presence of fatigue cracks in order to detect these cracks. Single plates with fatigue cracks emanating from a hole were initially considered. Piezoelectric transducers were bonded permanently to the plates to investigate various Lamb wave techniques for detecting the nonlinear response of the fatigue cracks. Impulses and continuous sine waves over a range of frequencies were considered. The most promising techniques were applied to a lap joint often seen on commercial aircraft.

I. Introduction

The detection of fatigue cracks in aerospace structures has always been of paramount importance. The cyclic loading (both thermal and mechanical) experienced by the aluminum skin, combined with stress concentrations caused by rivet holes, make fatigue cracks a primary source of failure. These cracks will grow if not found and repaired, and the structure will be considerably weakened if they span the distance between two rivets. Currently airplanes must undergo complicated and lengthy scheduled maintenances to ensure the absence of dangerous fatigue cracks. These lengthy downtimes increase costs for the aerospace industry [1]. The inefficiency of the scheduled maintenance required by these systems encourages the development of an embedded structural health monitoring system that could continuously monitor the structure and alert the user when repairs were necessary. Such a system would eliminate the need for aircraft deconstruction during inspection and the need for scheduled inspection and unnecessary downtime. Ultrasonic methods are thought to be the most promising for this type of system, and of these, Lamb waves are especially suited to the purpose because of their ability to propagate over long-distances and through the entire thickness of the plate [2].

Several methods of crack detection in plates using Lamb waves have been studied extensively. Giurgiutiu used piezoelectric wafers (often called PZTs) to excite Lamb waves in plates [3], and has also investigated the use of PZTs in laminated layers [4]. Alleyne and Cawley studied the optimal frequency selection for crack detection [5]. Grondel *et al.* examined the use of Lamb waves for damage detection in a riveted lap joint [2]. Fromme and Sayir investigated the scattering of Lamb waves caused by rivet holes with fatigue cracks [6]. Ikegami focused on issues with the use of Lamb waves for structural health monitoring in the aerospace industry [1]. All of these authors used wave attenuation and changes in wave-form to detect cracks.

An alternative method of detecting fatigue cracks uses the nonlinear responses of these cracks. These nonlinearities can be detected as harmonics, or sum and difference frequencies [7]. The nonlinear approach has the advantage of not requiring a baseline measurement as well as being more sensitive than methods currently available [8].

This paper explores the possibility of detecting nonlinearities from fatigue cracks in aluminum plates, similar to the skin of aircraft, using piezoelectric sensors and actuators. Initial tests considered three aluminum plates with holes at their centers. Two of these plates had fatigue cracks at the center hole generated by cyclic tensile loading, and the third was undamaged. These plates were excited using two PZTs, one at low frequency and one at high frequency, or one PZT at high frequency and acoustic bombardment at low frequency. Techniques developed on the small plates were also applied to a riveted lap joint from a commercial aircraft. The results from these experiments are discussed.

II. Theory

Damaged materials exhibit a nonlinear response because of wave distortion caused by the irregularities of the damage. This nonlinear response can manifest itself as the generation of harmonics or sum and difference frequencies. Harmonic generation occurs when a single frequency waveform is distorted. As the wave distorts, an increasing number of single frequency waves are needed to describe it. These additional frequencies appear as harmonics [7]. The displacement of an aluminum plate as it is excited acoustically can cause a fatigue crack to open and close, or chatter, which distorts the excitation wave and can result in harmonic generation. As a proof-of concept that instances of crack chatter can cause nonlinearities, an experiment was conducted in which a cantilevered plate would hit a mechanical stop when it was excited using acoustic bombardment as shown in Figure 1.

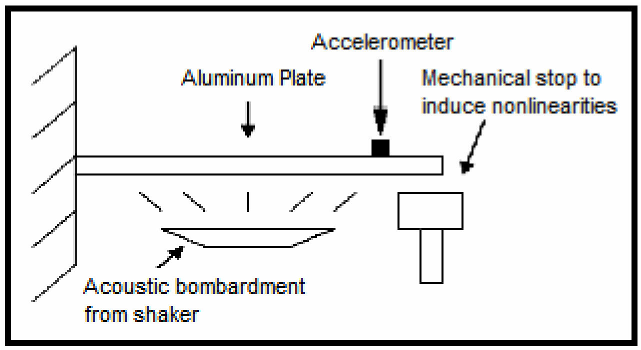


Figure 1. Experimental configuration to show harmonic generation

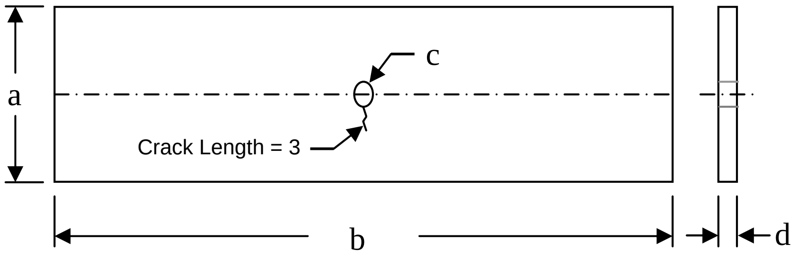
The mechanical stop causes the frequency spectra to include the excitation frequency, the frequency at which the plate hits the mechanical stop, and harmonics of this frequency. The experiment confirmed the nonlinear behavior of the impact, and harmonics should be expected if crack chatter is initiated.

Sum and difference frequencies, or sidebands, are another source of nonlinearity. When two frequencies are excited the sums and differences of these frequencies can also be excited in a nonlinear system. The mechanism of the production of sidebands is not understood but have been consistently observed in damaged materials [8,9]. Both sum and difference frequencies and harmonics require a large amplitude response in order to be excited.

III. Small Plate Experiments

An initial exploration of the techniques needed to excite the nonlinear response of fatigue cracks considered three aluminum plates, two cracked (P39 and P40) and one uncracked. The test specimens were made available by the Federal Aviation Administration's Airworthiness Assurance NDI Validation Center (FAA-AANC) operated by Sandia National Laboratories, where they were cyclically loaded more than 100,000 cycles at 138.9MPa until a fatigue crack was initiated. A single four millimeter diameter rivet hole was body centered on each plate, and a 3 millimeter fatigue crack extended from the hole towards the outer surface of each cracked plate. The geometry of the plates is shown in Figure 2. There was some variance in the sizes of the plates which affected resonant frequencies and time domain response. However, it was assumed that this variance should not affect the nonlinear response of the fatigue cracks and its features. Therefore, no differentiation was made between the two cracked plates, and the uncracked plate was assumed to be suitable for comparisons.

The cracked and uncracked plates were instrumented with three, one half inch omni-directional PZTs (American Piezo, Mackeyville, PA) as shown in Figure 3. A fourth, quarter inch PZT, was bonded in closer to the crack for additional sensitivity. The aluminum plates were suspended from a rigid frame structure with one strand of fishing line looped through the rivet hole.



(a)

Dimension	Cracked		Uncracked
	P39	P40	
a	40.0	40.0	38.5
b	204	201	204
c	4.00	4.00	4.00
d	1.00	1.00	1.00
All dimensions in millimeters			

(b)

Figure 2. (a) Geometry of three aluminum plate test specimens (not to scale) (b) Dimensions of cracked (P39 and P40) and uncracked plates

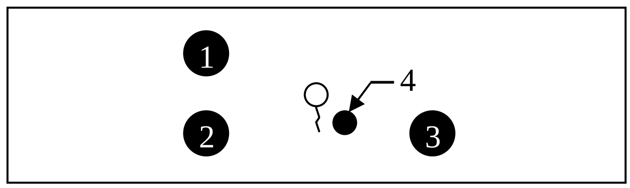


Figure 3. Location of PZTs relative to rivet hole on all test specimens.

The equipment used to drive the PZTs and the shaker remained the same for all tests. All PZTs used in single frequency excitation tests were excited by a Compugen 1100 v2.1 analog waveform generator and amplified through a Krohn-Hite Corporation (Brockton, MA) model 7602M wide band amplifier. Signals were sent through a CYTEC (Penfield, NY) 8-009-1 actuator relay board and received through a sensor relay board of the same type and model. Any additional PZT excitation to the system was output by a LabVIEW sinusoidal signal generator through a National Instruments PXI-4461 board and amplified by an AV Instrumentation 790 series power amplifier. The shaker used in all tests was a Labworks Inc. ET-132-2 shaker powered by a Labworks Inc. pa-138 linear amplifier receiving a signal from the National Instruments PXI-4461 board. The data acquisition system used for all tests was a Gage Compuscope 1250, 12 bit, 50 MS/s. A MATLAB user interface for the data acquisition system was used for all tests.

Single Frequency Tests: Harmonics

Initial tests considered a single frequency excitation in a pitch-catch configuration involving PZTs 1 and 4 as an actuator and sensor respectively. Finite Element (FE) models of the plates were used to find the flexural and longitudinal modes that were most influenced by the cracks. These frequencies were used as a starting point for identifying the driving frequencies for the single frequency tests.

The actuating PZTs used a sine wave at a frequency of 123 kHz. The frequency response of the cracked plate is shown in Figure 4. The second and third harmonics of the driving frequency, f_1, are visible in the response verifying that nonlinearities are present. The Fast Fourier Transform (FFT) of the uncracked plate is shown in Figure 5. The second harmonic (369 kHz) is barely seen above the noise floor while the first harmonic (246 kHz) is clearly visible. Although a difference between the cracked and uncracked plate responses is apparent, nonlinearities, attributed to the electronic equipment, are present in each. Similar observations were made for a variety of frequencies.

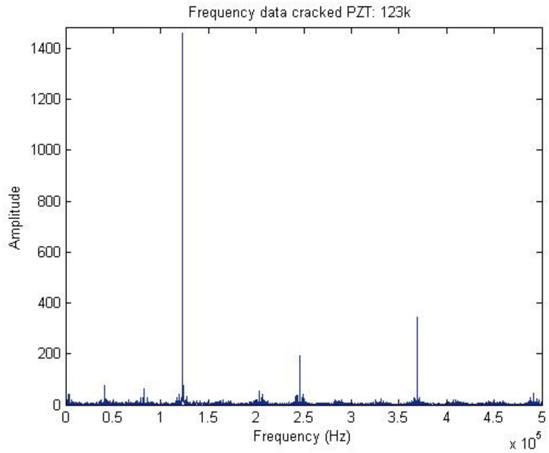


Figure 4. FFT of cracked plate

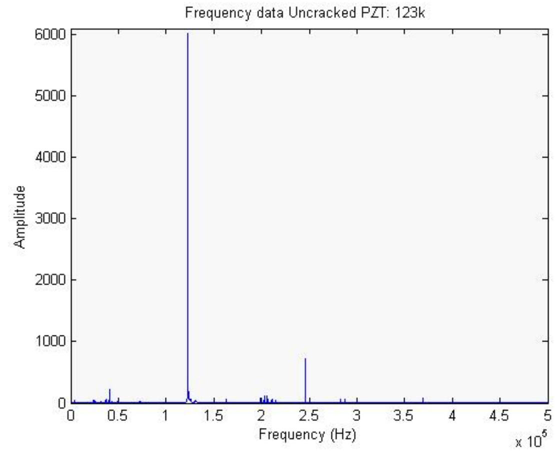


Figure 5. FFT of uncracked plate

Two Frequency Tests: Sum and Difference Frequencies

Sum and difference frequencies from the electronic equipment are less common, so further testing with two actuating frequencies was performed. Two experimental configurations were considered for inputting two frequencies into the plates. The first configuration used a shaker, acoustically coupled to the plate, to input the low frequency excitation, and a PZT to input the high frequency. The setup was similar to that in Figure 1 but with the addition of two PZTs for actuating and one for sensing in place of the accelerometer. The second configuration, as shown in Figure 3, used PZT 2 as a replacement for the low frequency excitation of the shaker. Both configurations used PZT 1 to input the high frequency excitation and PZT 4 for sensing.

Several combinations of high and low frequencies were considered with the shaker configuration. In one trial, the low frequency, f_1, was excited at 130 Hz, and the high frequency, f_2, was excited at 123 kHz. These frequencies were picked because the first was near a bending mode, and the second was near a longitudinal mode. The FFT of the response measured from the cracked plate is shown in Figure 6, and both driving frequencies as well as the first and second harmonics of the f_2 frequency ($2f_2$ and $3f_2$) are clearly represented. A zoomed view of Figure 6, shown in Figure 7, reveals what appear to be sum and difference frequencies mirrored about the second driving frequency, f_2. Both the harmonics and the sum and difference frequencies are indicative of nonlinearities in the response of the cracked plate.

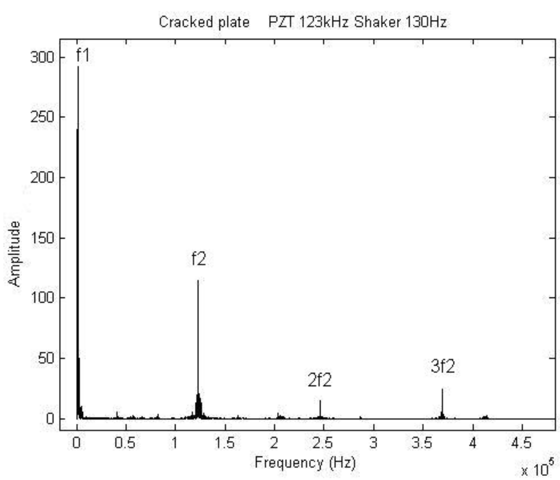


Figure 6. FFT of cracked plate

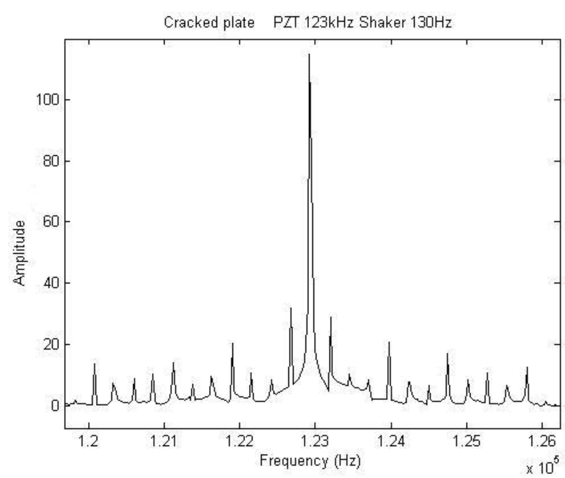


Figure 7. Close up of Figure 6

Repeating the test on the uncracked plate revealed the frequency response shown in Figure 8. The first harmonic of the higher driving frequency is clear, and a zoomed view of the f_2 frequency, shown in Figure 9, reveals sum and difference frequencies. Again, the nonlinear response is observed in both the cracked and uncracked plates, implying that a portion of the nonlinearities were caused by the electronic equipment and other factors not associated with the fatigue cracks.

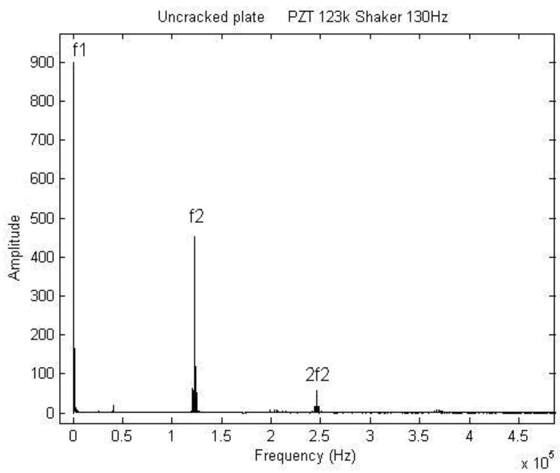


Figure 8. FFT of uncracked plate

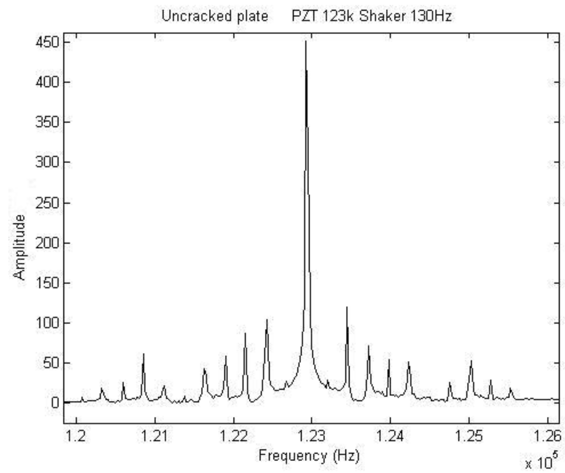


Figure 9. Close up of Figure 8

Driving frequencies for the second test configuration were selected such that the sum and difference frequencies were more defined. The low frequency, f_1, was driven by PZT 1 at 5 kHz, and the high frequency, f_2, was driven by PZT 2 at 150 kHz. Results of the second configuration resembled the first, as harmonics and sum and difference frequencies appeared in the responses for both cracked and uncracked plates. The frequency response of the cracked plate is shown in Figures 10 and 11, followed by the response of the uncracked plate in Figures 12 and 13.

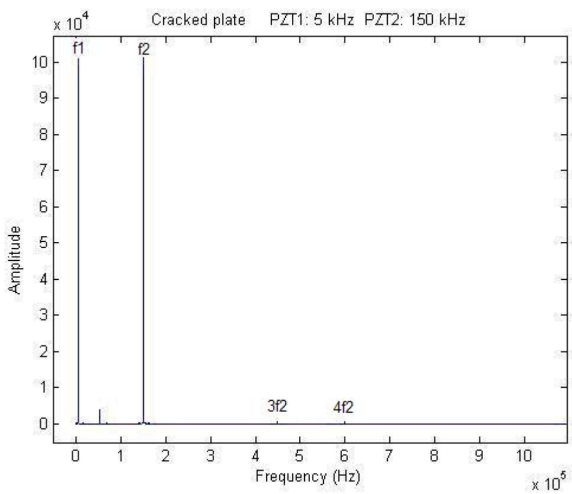


Figure 10. FFT of cracked plate

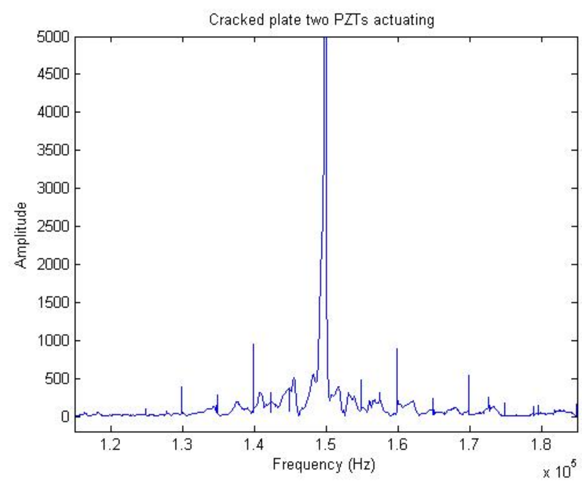


Figure 11. Close up of Figure 10

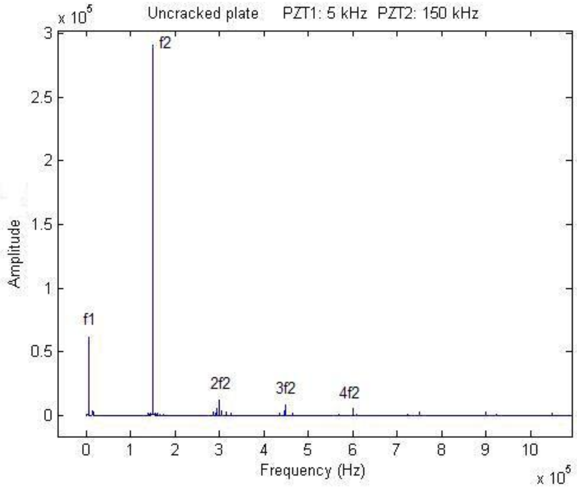


Figure 12. FFT of uncracked plate

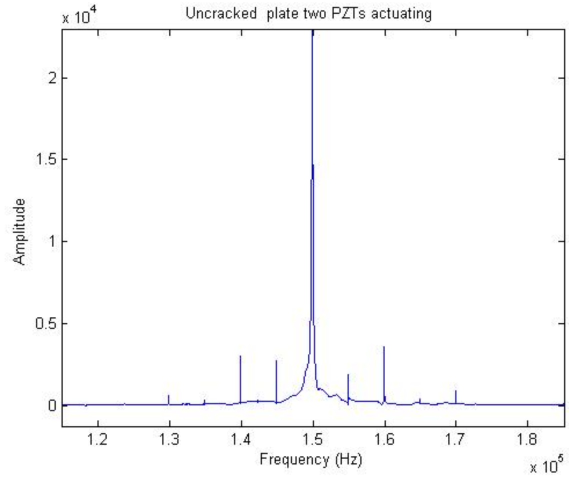


Figure 13. Close up of Figure 12

IV. Lap-Joint Experiments

With no clear conclusions about the best techniques for detecting the nonlinear response of fatigue cracks, similar experiments were performed on a representative axial lap-joint section from a Boeing 737. This specimen was also made available by the FAA-AANC, and it contained two large fatigue cracks, 10 mm and 12 mm, on either side of one rivet hole as shown in Figure 14. It was hoped that the larger fatigue cracks would more readily generate a nonlinear response than the 3 mm cracks found in the small plates. Three other fatigue cracks existed in the lap-joint. However, their sizes were two millimeters or less, so the assumption was made that their effects were negligible compared to those caused by the 10 and 12 millimeter cracks. The lap joint has many other contacting surfaces (plate to plate, rivet to plate) that also have the potential for producing a nonlinear response. An uncracked lap joint was unavailable, so sensor placement was used to try to distinguish between the nonlinear response of the cracks and the nonlinear response from other sources.

Seven PZTs were use to instrument the lap-joint for testing, and their placement is shown in Figure 14. Five locations were chosen in a straight line to the left of the severely cracked rivet hole, and two locations were chosen to the right. The same experimental setup was used on the lap joint for exciting and receiving the acoustic signals as was used on the small plates. The lap joint was hung by fishing line from holes in the corners of the plate to simulate a free-free condition.

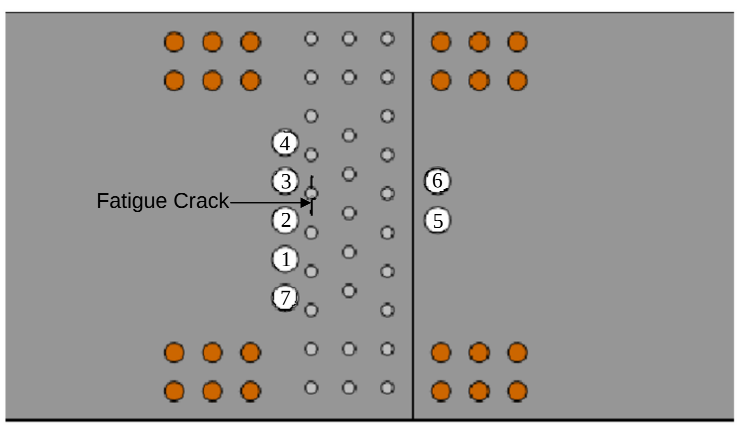


Figure 14. Location of PZTs relative to cracked rivet hole on lap-joint.

The fatigue cracks extended into certain paths between actuator and sensing PZTs, so it was theorized that the harmonics seen in the frequency response of plate would vary in magnitude depending on which PZTs pairs were actuating and which were sensing. In an effort to view these harmonics, a series of tests were completed in which one PZT in the row of 5 PZTs was used as an actuator, and the remaining PZTs on the plate were used to sense the joint response.

The first set of experiments on the fuselage used a PZT to excite a frequency while a second PZT received the signal. The actuating frequency, f_1, was a continuous sine wave at a frequency of 150 kHz. The FFT of the time domain response with PZT 2 as the actuator and PZT 3 as the sensor can be seen in Figure 15. All possible path combinations were used, and harmonics of the f_1 frequency were present in all the frequency responses. The lap-joint severely attenuated the signals received by PZTs 5 and 6, that data from those channels was not used.

A trend that certain actuator/sensor paths had more pronounced harmonics than others arose in the resulting FFT data. The path data gathered between PZT 2 and PZT 3 had more well-defined harmonics than other paths irregardless of which PZT was sensing or actuating. The fatigue cracks were present between PZT 2 and 3, so it was inferred that the more pronounced harmonics could be caused by the fatigue crack's location. Expanding on this theory, development of an algorithm to identify crack location by comparing the various PZT paths began.

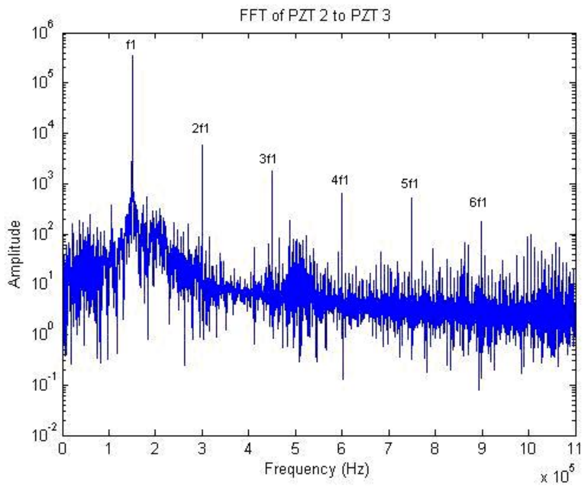


Figure 15. Frequency response of PZT 2 and 3 on the lap joint

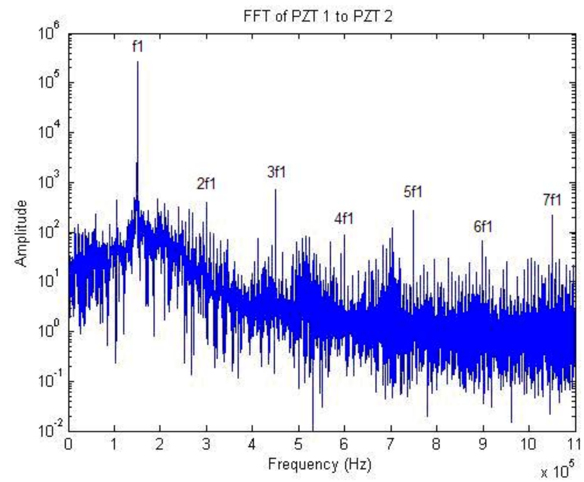


Figure 16. Frequency response of PZT 1 and 2 on the lap joint

The first algorithm developed involved taking the ratio of the driving frequency, f_1, and its second harmonic, $3f_1$, with respect to amplitudes of the frequency response. Results from the initial algorithm used to detect the fatigue crack located between PZT 2 and PZT 3 are shown in Figures 17 and 18. The legend on the right of each figure shows the individual PZT paths with the first and second numbers referring to the actuating and sensing PZTs respectively. Figure 18 includes additional data gathered after PZT 7 was added to the lap joint.

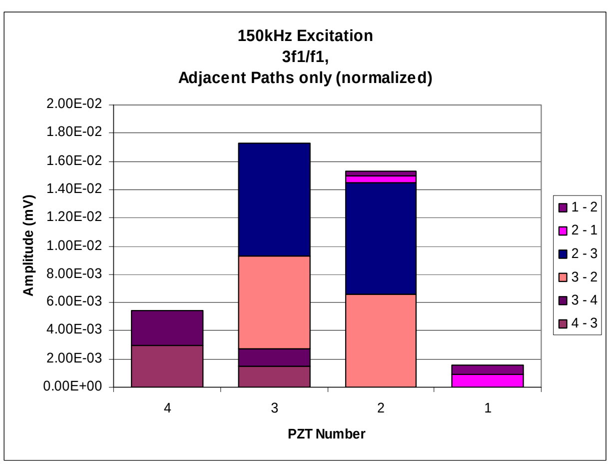


Figure 17. Algorithm to detect fatigue cracks

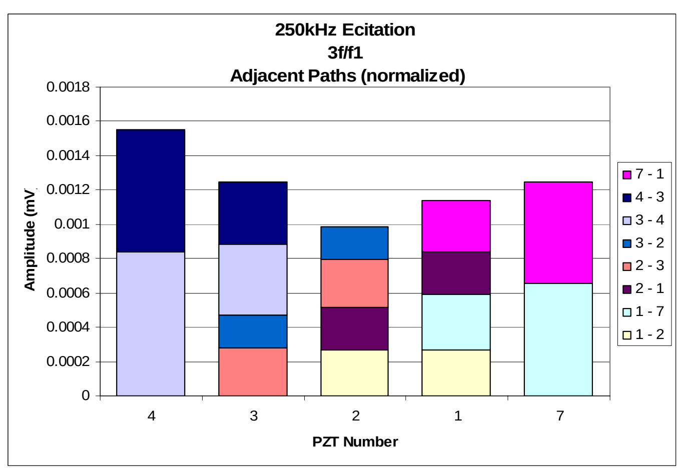


Figure 18. Algorithm to detect fatigue cracks

Data for Figure 17 was collected using a driving frequency of 150 kHz. The results indicate greater amplitude responses of PZTs 2 and 3 when compared with PZTs 1 and 4, possibly indicating a fatigue crack in path 2-3. However, results were not repeatable when using a driving frequency of 250 kHz which can be seen in Figure 18.

Additional analysis of the data used to produce Figures 19 and 20 was completed by slightly changing the original crack location algorithm. For each data set, the ratio was taken between the amplitude summations of the first ten harmonics to its third harmonic, $3f_1$. The varied method was unsuccessful at consistently identifying the crack location path.

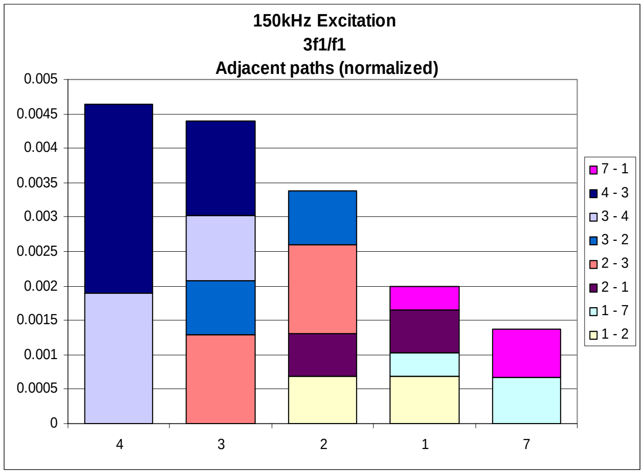


Figure 19. Algorithm to detect fatigue cracks

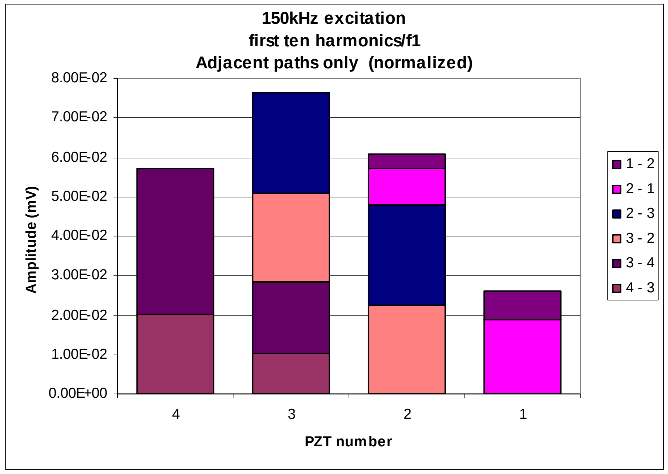


Figure 20. Algorithm to detect fatigue cracks

The fuselage also underwent testing with two PZTs driving two frequencies and one PZT receiving. Strategies were employed using different driving frequencies. Other approaches to vary the actuating and sensing PZTs were also attempted. The results yielded no sum and difference frequencies above the threshold of the noise floor.

V. Discussion and Conclusion

Damage identification through observation of nonlinear content in system frequency responses was unsuccessful because a nonlinear response was evident in both cracked and uncracked plate experimental results. The additional nonlinearities, though possibly contributed from any number of external sources, were likely caused by nonlinearities in the electronics.

It was noticed during testing that an increase of either frequency in the “two frequency” experiments resulted in initially linear responses that, past a threshold, became nonlinear. Thus, the content was linked directly to the preamplifier and/or the data acquisition board. Some of the nonlinearities could have been avoided by bypassing the preamplifier all together and acquiring sensor responses directly with the data acquisition board. This would have allowed higher voltage outputs and removed any nonlinear response associated with the preamplifier.

The research was conducted by applying equipment designed to output both low amplitude, low energy signals, towards experiments requiring signals of high amplitude and energy, and clipping was a serious concern. Prior to testing, time responses resulting from various frequency inputs and amplitudes were observed. At several settings, time responses were clipped, introducing harmonics into the frequency response. Thus, before final data was recorded, amplifier gain settings as well as input voltage settings were adjusted to maximize the actuating PZT excitation while preventing clipping of the response voltages within the acquisition software. Though every attempt to identify clipping occurrences was made, it is possible that certain instances were missed, adding nonlinear content to a responses where it was not expected. In the future, this can be avoided by acquiring test equipment suited for the necessary high frequency, high energy inputs.

Despite the nonlinear response of the fatigue cracks being indistinguishable from electronic nonlinearities, the increased harmonic response in the spectrograms and frequency spectra of the cracked plates suggest that nonlinear response of fatigue cracks was excited. This is supported by laser vibrometer measurements taken near the near the hole of the small plates. Analysis of the vibrometer data reveals many higher order harmonics in the cracked plate contrasted by only two higher order harmonics in the uncracked plate. Therefore, the success of future studies in discerning fatigue crack nonlinearities from general electronic nonlinearities is directly related to the magnitude of energy input to the system and the assurance that the response is within the acquisition systems linear range of sensing.

Acknowledgments
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