Structural Health Monitoring in Composite Materials Using Lamb Wave Methods

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ASC-2001 #043

ABSTRACT

Cost-effective and reliable damage detection is critical for the utilization of composite materials. This paper presents part of an experimental and analytical survey of candidate methods for in-situ damage detection of composite materials. Experimental results are presented for the application of Lamb wave techniques to quasi-isotropic graphite/epoxy thin coupons and sandwich beams containing representative damage modes, including delamination, transverse ply cracks and through-holes. Optimization experiments provided a procedure capable of easily and accurately determining the presence of damage by monitoring the transmitted waves with piezoceramic sensors (PZT). Lamb wave techniques have been proven to provide more information about damage type, severity and location than previously tested methods, and may prove suitable for structural health monitoring applications since they travel long distances and can be applied with conformable piezoelectric actuators and sensors that require little power.

INTRODUCTION

Structural Health Monitoring (SHM) has been defined in the literature as the "acquisition, validation and analysis of technical data to facilitate life-cycle management decisions." [1] More generally, SHM denotes a system with the ability to detect and interpret adverse "changes" in a structure in order to improve reliability and reduce life-cycle costs. The greatest challenge in designing a SHM system is knowing what "changes" to look for and how to identify them. The characteristics of damage in a particular structure plays a key role in defining the

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architecture of the SHM system. The resulting "changes," or damage signature, will dictate the type of sensors that are required, which in-turn determines the requirements for the rest of the components in the system. The present research project focuses on the relationship between various sensors and their ability to detect "changes" in a structure's behavior.

Several techniques have been researched for detecting damage in composite materials, however Lamb wave methods have recently re-emerged as a reliable way to locate damage in these materials [2-4]. These techniques have been implemented in a variety of fashions in the literature, including the use of separate actuators and sensors to monitor transmitted waves and/or reflected waves, and multipurpose patches which both actuate and sense. Each of these techniques offers their own unique advantages in detecting certain types of damage with various levels of analytical complexity. Perhaps the earliest recognition of Lamb waves as a means of damage detection came in 1960 by Worlton of the General Electric Company [5]. His report investigated the dispersion curves of aluminum and zirconium to describe analytically the characteristics of the various modes that would pertain to nondestructive testing application. During the late 1980's and early 1990's work began on the applications of Lamb waves to composite materials. Research conducted at NASA by Saravanos demonstrated, both analytically and experimentally, the possibility of detecting delamination in composite beams using Lamb waves [6, 7]. Similar conclusions were drawn by Percival and Birt at the Defense & Evaluation Research Agency, UK, who began focusing their work on the two fundamental Lamb wave modes, which will be described further in the following section [8-10]. Work was also performed on composite sandwich plates subjected to impact damage by Osmont and Rose [11, 12].

The most successful work to date of using Lamb waves for damage detection has been performed by two separate groups at Imperial College. Since the mid-1990's, Cawley's group has been working to optimize the generation of directional Lamb waves [13, 14]. To allow the implementation of Lamb waves on a real structure, they have been developing flexible, cheap Polyvinylidenedifloride (PVDF) transducers in order to both generate and detect waves. Their work uses interdigital transducer leads to generate highly focused and directional waves without higher mode interference, and they have inspected various metallic specimens with encouraging results. Soutis's group in the Aeronautics department has focused more on the sensor placement and signal processing issues [15, 16]. They have chosen to use Lead-Zirconate-Titanate (PZT) actuators and sensors over PVDF since they require a factor of ten less voltage to generate Lamb waves, however they are not conformable. The most complete work from this group can be found in Valdez's PhD thesis [17]. During the course of his work he performed many experiments on quasi-isotropic graphite/epoxy composite specimens, pulsing them with Lamb waves in various configurations to detect delaminations. He also simulated the propagation of Lamb waves in plates using a finite element code. Much of the research presented in this paper follows Valdez's work, extending it to various other types of damage, to sandwich structures, and an attempt to optimize the testing procedure and setup. The following section will discuss the fundamentals and mathematics of Lamb wave propagation.

DESCRIPTION OF LAMB WAVES

Lamb waves are a form of elastic perturbation that can propagate in a solid plate with free boundaries, first described in theory by Horace Lamb in 1917 [18-20]. There are two groups of waves, symmetric and anti-symmetric as seen in **Figure 1**, that satisfy the wave equation and boundary conditions for this problem, and each can propagate independently of the other. The present work utilizes PZT piezoelectric patches to excite the first anti-symmetric Lamb wave (A_0 mode). This wave was chosen since it can propagate long distances with little dispersion, and no higher modes are present to clutter the resulting response waves [18]. The fundamental way to describe the propagation of Lamb waves in a material is with their dispersion curves, which plots the phase and group velocities versus the excitation frequency (often shown as a product with thickness). These curves are derived as solutions to the wave equation for the Lamb wave, and are often describe in terms of Lamé's constants. This equality must be solved numerically for a given set of constant material properties. Examples of dispersion curves can be found in several places in the literature, and will not be focused on in this paper [13-18].

EXPERIMENTAL PROCEDURE

Thin Coupon Testing

There is currently no standard or even a best-practice precedent for damage detection via Lamb wave testing. Several procedures have been developed in the literature, each with valuable characteristics. The preliminary goal of the present research was to determine the effects of various parameters such as actuation pulse and sensor geometry on the sensitivity of damage detecting. The results of this optimization study were used to conduct efficiently the following experimental procedure, and are the focus of a separate paper.

The first set of experiments was conducted on narrow composite coupons. The laminates used for the present research were manufactured during previous research that explored frequency response methods as a means of damage detection, and were re-used to compare directly the effectiveness of the two methods [21]. The specimens were 25 x 5 cm rectangular $[90/\pm45/0]_s$ quasi-isotropic laminates of the AS4/3501-6 graphite/epoxy system, which were clamped on one end to match the boundary conditions from the previous research. Three PZT piezoceramic patches were affixed to each specimen, as shown in **Figure 2**, using 3M ThermoBond™ thermoplastic tape so that they were firmly attached during testing, but could be removed afterwards to recover the specimens for future tests. The PZT was cut into 2 x 0.5 cm patches so that the longitudinal wave would be favored over the transverse one, and three patches were used on each specimen to actuate and accurately measure the transmitted and reflected waves. Both the actuation and the data acquisition were performed using a portable NI-Daqpad™ 6070E data acquisition board, and a laptop running Labview™ as a virtual controller. A Labview™ VI-file was created which would load an arbitrary waveform from Matlab™ and output it at the desired frequency and amplitude, while simultaneously acquiring data on four channels at 600,000 samples per second. The first channel, which served as the trigger for all of the channels, was connected to the output channel and actuating PZT, two others were connected to the sensing piezoceramic patches, and the final channel was connected to a PZT sensor not attached to the specimen to serve as a control channel to in order to zero out drift. A single pulse of the optimal signal found in the previous section, shown in **Figure 3**, was sent to the driving PZT patch to stimulate an A_0 mode Lamb wave, and concurrently the strain-induced voltage outputs of the other two patches were recorded for 1 ms to monitor the wave propagation.

The resulting data was then passed to Matlab™ where the drift was filtered out and the waveforms could be compared and analyzed within two specialized toolboxes. In the signal processing toolbox the waves could be easily superimposed, and a built-in peak detector was used to determine accurately the time of flight for each signal, and the delay in time of arrival between two specimens. Subsequently, in the wavelet toolbox a DB3 wavelet, which was selected due to its similarity to the input signal, was used to decompose the data into its frequency components. By plotting the magnitude of the wavelet coefficient at the peak driving frequency, the energy remaining from the inputted signal could be compared [22]. This procedure was carried out for two of each specimen type at the optimal driving frequency of 15 kHz.

As with the previous research on frequency response methods [21], various types of damage were introduced to the specimens. In the first group, 6.4 mm diameter holes were drilled into the center of each specimen. The next group was compressively loaded in a 4-point bending fixture until audible damage was heard, and the third was cyclically loaded in the same fixture for 2000 cycles at 80% of this load with an R ratio of –1. The next two groups of specimens were delamination specimens which were introduced by two methods: one used a thin utility blade to cut a 50 x 20 mm slot in one side, and the other with a Teflon strip cured into the center mid-plane of the laminate. After the damage was introduced into each specimen, an x-ray radiograph was taken using a die-penetrant to help document the type, degree and location of the damage as shown in **Figure 3**.

Sandwich Coupon Tests

Analogous experiments were performed on sandwich coupons to that of the narrow laminates in order to test the effect of various types of core materials on the propagation of Lamb waves. Four different cores were used: low and high density (referred to as LD and HD) aluminum honeycomb, Nomex™, and Rohacell™. Each specimen contained two facesheets identical to the undamaged laminates in the previous section surrounding a 2 cm thick core, which were adhered using FM-123 film adhesive in a secondary curing process. Two controls and two damaged specimens of each type were manufactured for testing. In the damaged specimens, a 5 x 2.5 cm piece of Teflon was placed between the adhesive and the core in a central 2.5 cm region during the cure so that the facesheet would not bond to the honeycomb to simulate a delamination. An additional specimen was also manufactured with the high density aluminum core that had a 2 cm diameter circular piece of Teflon placed between the layers on either side so that it was indistinguishable from the controls by sight. This specimen was used for a "blind test" of the proposed Lamb wave damage detection method, where it was tested alongside the two control specimens to determine which had the artificial flaw. The test setup and data analysis procedure for the sandwich beam experiments were identical to that of the thin specimens with the exception of the driving frequency, which was determined to be optimized at 50 kHz for these tests.

RESULTS

Experimental Testing Results

There were two sets of results obtained for both groups of tests. The first set of results included the virgin time traces of voltage from the PZT sensor at the far end of the specimen. For the thin coupons, 1 ms of data was taken and the average peak voltage was around 20 mV. The time traces for one of each type of specimen along with a superimposed control specimen are shown in **Figure 5**. Similarly, 500 μs of data was taken for the sandwich beams with an average peak voltage of around 10 mV. For these specimens, time traces of each control beam are plotted against their delaminated complement in **Figure 7.** In each of these plots, a "bleed-through" portion of the sent signal leaking across the data acquisition board can be seen at the beginning of the time trace. Since the channels were all triggered at the 5V peak voltage, exactly half of the sent signal is visible so this became a convenient way to measure the time of flight. The second set of results for each specimen group was the outcome of the wavelet decomposition. For each specimen, the "bleed–through" portion of the signal was filtered out, and the wavelet coefficient magnitude of the dominant frequency (15 kHz for the thin coupons and 50 kHz for the beams) was plotted over time. For the thin coupons, **Figure 6** compares these coefficients, and thus the transmitted energy, for one of each type of specimen. Finally, **Figure 8** displays the coefficient magnitude results for the "blind test," comparing the two high density aluminum core control specimens with one known and one unknown damaged specimen.

DISCUSSION

Interpretation of Experimental Data

There are generally five goals for damage detection, each of which is gained with increasing difficulty and complexity. The first is the determination of the presence of damage in a specimen. The second is an estimation of the extent of severity of the damage. The third goal is to be able to differentiate between various different types of damage. The fourth is to be able to calculate where the damage is located. The final is to estimate the size of the damage. It appears that Lamb wave methods carry enough information potentially to meet all of these goals with a strategically placed array of sensors and suitable processing codes, however the current scope of this research focuses on the first two goals.

The results from the narrow coupon tests clearly show the presence of damage in all of the specimens. First of all, when the time traces of all of the control specimens were overlaid, there was a high degree of visible correlation, especially for the first half of the voltage time trace. The slight variation in the second half of the data can be attributed to the reflected signals returning from the far end of the specimen and passing under the PZT sensor again, which may encounter a slight cutting bias in the composite to cause a change in phase. Of the artificially damaged specimens, the Teflon-induced delamination was most easily quantified. When compared to the control specimens, these time traces appear at the same phase and frequency, only having been delayed about 55 μs due to the damage. For the other types of damage the frequency often remained the same, however there was a large reduction in amplitude, and a large and varying change in phase. This time trace was reproducible within a single specimen, although would not be consistent across multiple specimens with identical forms of damage. This is due to the scatter and reflecting of the waves on the various features of damage which may not be identical specimen to specimen, which makes a "damage signature" difficult to define. The most distinctly altered signal was that of the through-hole, having the same diameter as the actuator and sensor widths, which had the smallest voltage magnitude of all the specimens. The clearest method of distinguishing between damaged and undamaged specimens however is by regarding the wavelet decomposition plots. The control specimens retained over twice as much energy at the peak frequency as compared to all of the damaged specimens, and particularly contained more energy in the reflected waves. The loss of energy in the damaged specimens again is due to the dispersion caused by the micro-cracks within the laminate in the excitation of high-frequency local modes.

The sandwich beam results were more difficult to interpret, due to the damping nature of the cores reducing the voltage generated by the PZT sensors. The high density aluminum core, which was the stiffest of the four tested, provided the clearest results; the other specimens yielded decreasing magnitude voltages as the stiffness decreased thus increasing the damping factor. There were two basic trends across all the specimens. The first was that the responses of the control specimens were larger than those that were delaminated for each core type. This is most likely due to the loss of energy of the wave in a local mode over the delaminated region. The second trend was the appearance of more reflected waves after the initial pulse in the time trace in the delaminated specimens, which again was probably due to other higher frequency modes being excited in the region of reduced thickness and dampening. Probably the most significant result of the present research was the "blind test." Four high density aluminum beam specimen were tested, one of which had a known delamination in its center, while of the remaining three specimens it was unknown which contained the circular disbond and which two were the undamaged controls. By comparing the four wavelet coefficient plots in **Figure 7**, one can easily deduce that the two control specimens are the ones with much more energy in the transmitted signals, while the third specimen (Control C) obviously has the flaw that reduces energy to a similar level to that of the known delaminated specimen. This test serves as a true testament to the viability of the Lamb Wave method being able to detect damage in at least simple structures.

Implementation of Lamb Wave Techniques in SHM System

Lamb wave techniques have good potential for implementation in a SHM system. These methods provide useful information about the presence, location, type size and extent of damage in composite materials, and can be applied to a structure with conformable piezoelectric devices. The major disadvantage of this method is that it is active; it requires a voltage supply and function generating signal to be supplied. This can be complicated in a large structure, especially if the SHM system is to be implemented wirelessly; it has been suggested in the literature however that PZT can be actuated remotely using radio frequency waves [17]. Another difficult requirement is the high data acquisition rate needed to gain useful signal resolution. If a system is sampling at 0.5 MHz from several sensors, a large volume of data will accumulate quickly. The data acquisition capabilities dictate the limitations of flaw size able to be resolved by a system using this method. A useful detection capability however arises from the fact that two different optimal driving frequencies were necessary for the thin laminates and the beam structures. This offers the possibility of having the ability to differentiate between damage within the laminate versus damage between the laminate and the core by discretely driving at two different frequencies. This procedure was not explored during the present research, however preliminary experimentation indicates that the potential of this procedure working exists.

CONCLUSIONS

This paper has explored the application of Lamb wave methods to damage detection in composite materials. Using an optimal procedure determined in prior research, several narrow graphite/epoxy specimens were tested with various forms of pre-existing damage. Similar tests were also performed on narrow sandwich beams using various cores. These tests demonstrated the feasibility of detecting several types of flaws in representative composite structures, and this method was validated successfully by a "blind test" of several beam specimens. Analytical modeling of these specimens yielded a similar conclusion. Lamb wave techniques have the potential to provide more information than previously tested methods such as frequency response methods since they are more sensitive to the local effects of damage to a material than the global response of a structure. The disadvantage of Lamb wave methods is that they require an active driving mechanism to propagate the waves, and the resulting data can be more complicated to interpret than for many other techniques. Overall however, Lamb wave methods have been found to be effective for the in-situ determination of the presence and severity of damage in composite materials. Future experimentation will be aimed at testing two-dimensional and built up structures using this technique, and the application of Lamb wave methods using a singe multi-purpose actuator and sensor. Structural heath monitoring systems will be an important component in future designs of air and spacecraft to increase the feasibility of their missions, and Lamb wave techniques will likely play a role in these systems.

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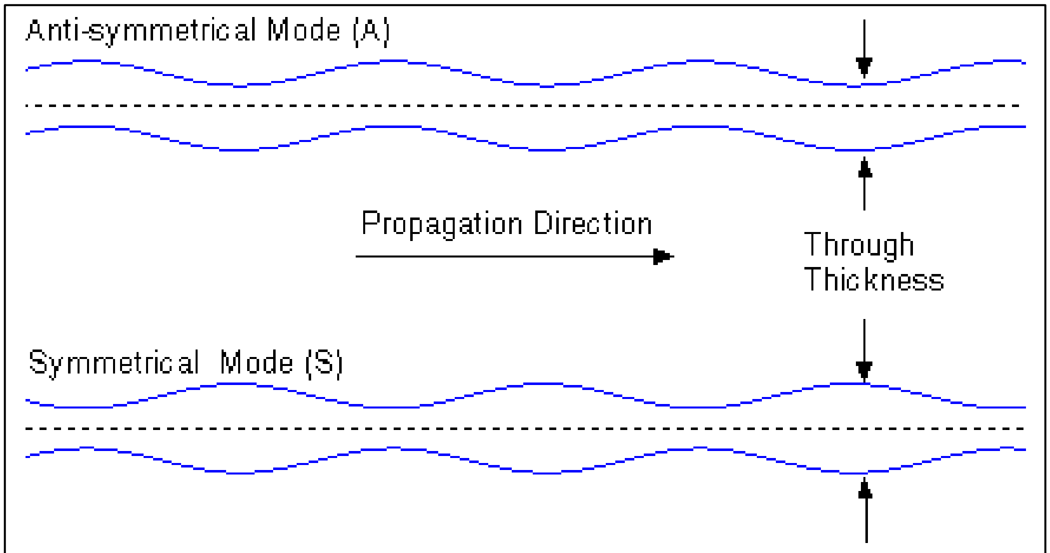

Figure 1: Graphical representation of *A* and *S* Lamb wave shapes

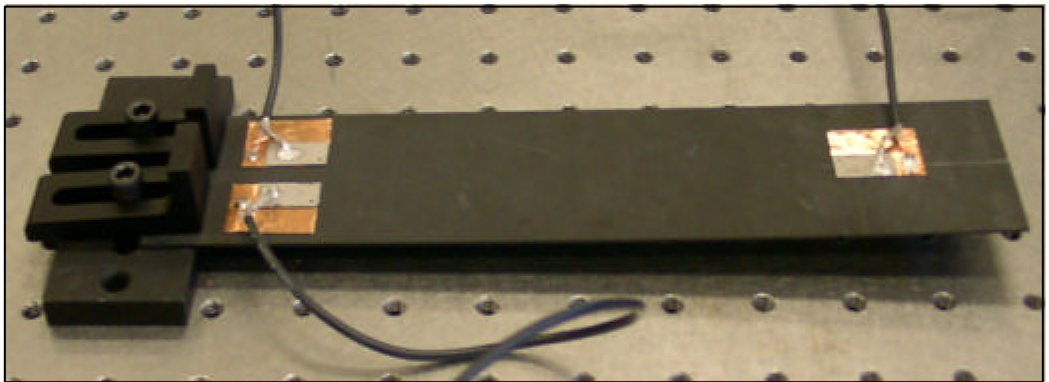

Figure 2: CFRP specimen (250mm x 50mm) with piezoceramic actuator and sensors

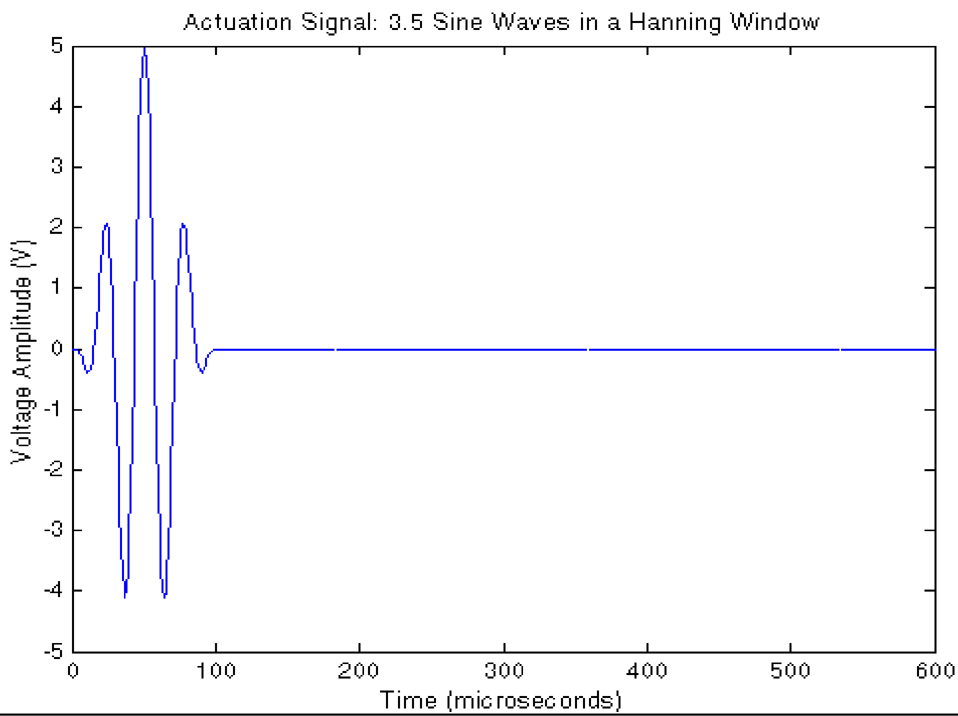

Figure 3: Actuation signal used to generate Ao Lamb mode, 3.5 sine waves at 15 kHz

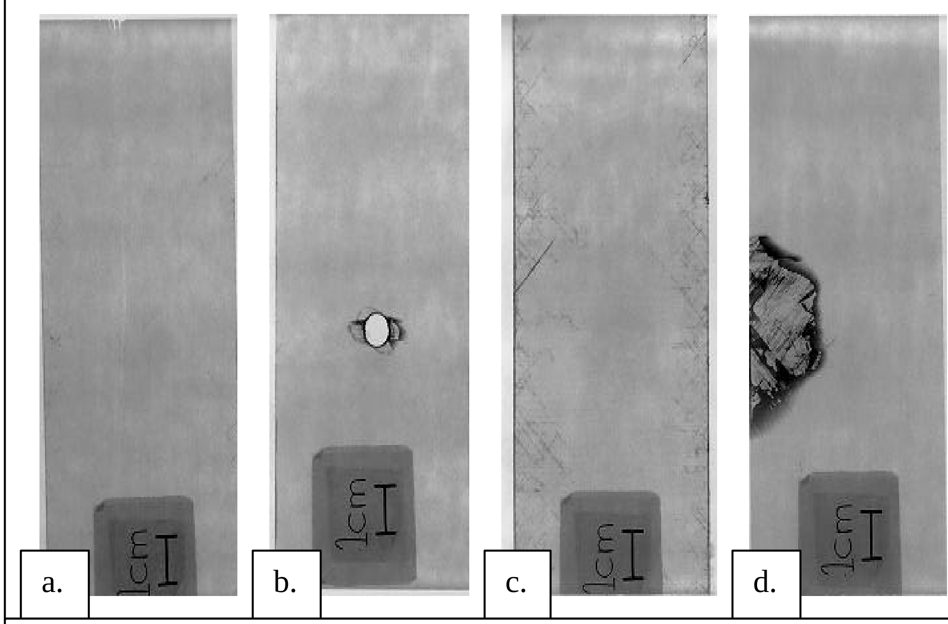

Figure 4: X-Radiographs of damaged specimens:

a. Control specimen with no damage present
b. Stress concentration specimen with drilled through-hole
c. Matrix-crack specimen with fatigue induced damage
d. Delamination specimen cut with a thin utility knife at the mid-plane

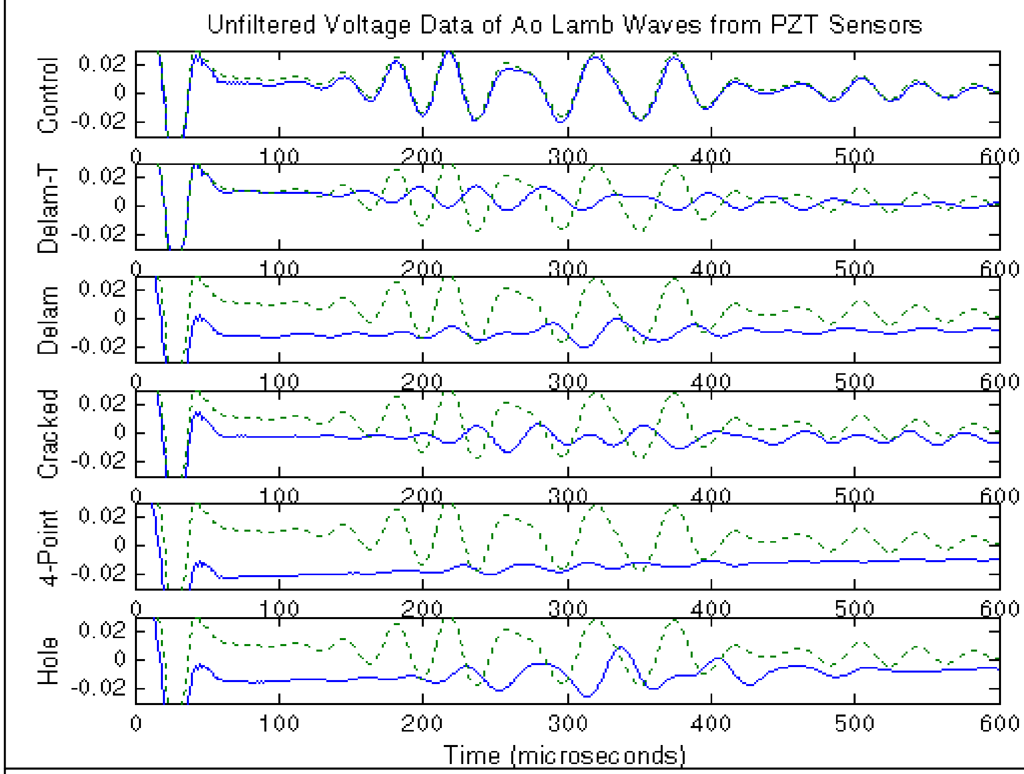

Figure 4: Time-trace of voltage signal from PZT sensor 20 cm from actuator, 15 kHz signal
Solid lines are damaged specimens; control is superimposed as a dashed line

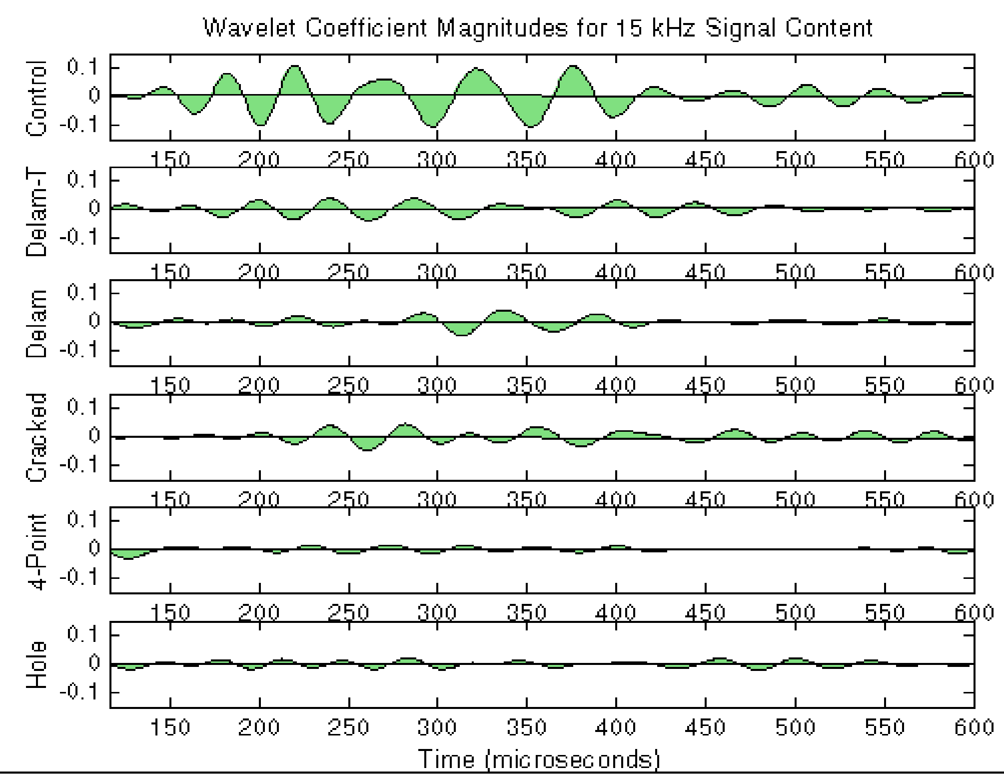

Figure 5: Wavelet coefficient plots for thin coupons; compares 15 kHz energy content

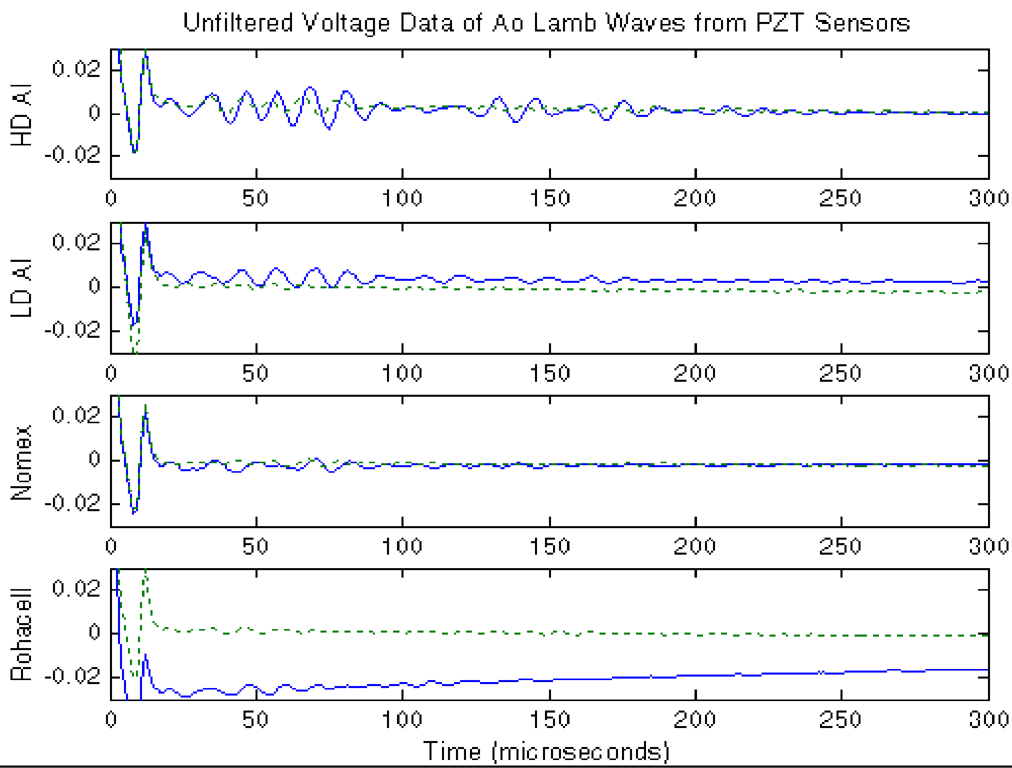

Figure 6: Time-trace of voltage signal from PZT sensor 20 cm from actuator, 50 kHz signal Solid lines are undamaged beam controls, debonded specimens

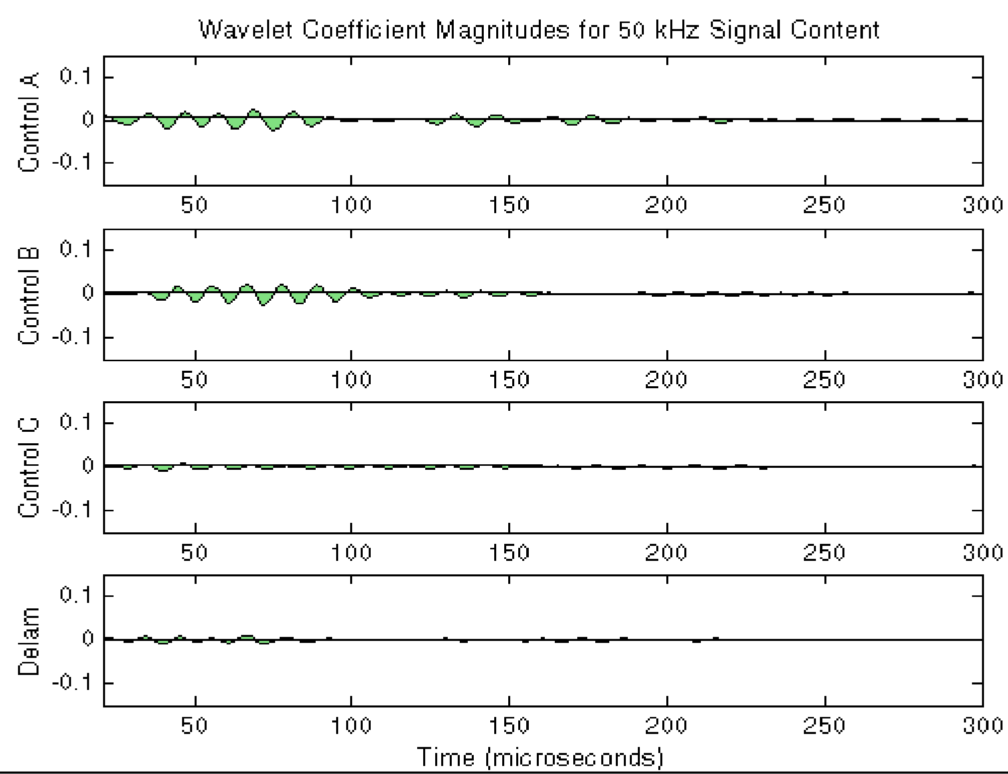

Figure 7: Wavelet coefficient plots for beam "blind test"; compares 50 kHz energy content