# Experimental Application of Optimized Lamb Wave Actuating/Sensing Patches for Health Monitoring of Composite Structures

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## ABSTRACT

In an ongoing effort to evaluate the effectiveness of Lamb wave methods for the health monitoring of composite structures, this paper presents the conclusions of an experimental study applying optimized piezoelectric actuating/sensing patches and new algorithms to composite laminates and sandwich structures. During the first part of this NRO funded research program, several piezoelectric materials, conductive electrodes and adhesives were analyzed to produce the highest actuation force to sensor resolution sensor ratio at the lowest voltage. Algorithms were designed to filter and decompose the resulting signals to more efficiently interpret damage information. The present research utilized linear wave scans on thin laminates and sandwich structures to validate the test procedure and algorithms, monitoring both the transmitted and reflected waves. A software product was also demonstrated, using refined algorithms to provide automated data interpretation. Lamb wave techniques have proven to provide accurate and useful data about the state of composite structures, and can be applied with low power and conformable piezoelectric actuators and sensors, making them suitable for SHM applications.

## INTRODUCTION

The benefits of composite materials in modern air and spacecraft are well known: compared to metals, composites can have lighter weight, superior structural properties, and the capability to be readily formed into custom shapes to meet unique requirements. Non-destructive evaluation (NDE) techniques, however, have been problematic to employ. Heritage techniques such as the "tap-test", commonly used to check fiberglass payload fairings, were extremely technician-sensitive and statistically unreliable. Currently successful laboratory non-destructive testing methods, such as X-radiographic detection and C-scans, are impractical for service

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inspection of large integrated subsystems. Other techniques such as acoustic emission and optical fiber measurements are not easy to employ due to the complexity of the support equipment required [1]. The principal problem is determining the extent and nature of suspected structural anomalies in composite structure when visual inspections may not suffice, and more perceptive NDE techniques are not practical. These structural anomalies may include delaminations, "kissing debonds", fiber fractures, or matrix cracks caused by misuse, impacts or cyclic fatigue. It is clear that new approaches for inspection of composites need to be developed [2]. To resolve this issue, Metis Design Corporation (MDC) have been working with MIT and the NRO to developed a structural health monitoring (SHM) system for damage detection in composite materials, using Lamb waves driven and received by piezoelectric wafers.

Previous research by the present authors has investigated several potential NDE methods for detecting damage use in composite materials [3]. More detailed research into the propagation of Lamb waves by the present authors can be found in several journals and conference proceedings [4-11]. The conclusion of this research was that Lamb waves offered the best resolution to range ratios for the detection of damage in large composite structures. Lamb waves are a form of elastic perturbation that can propagate in a solid plate with free boundaries [12-14]. The present work utilizes piezoelectric patches to excite the first anti-symmetric Lamb wave ($A_0$ mode). Using Lamb wave methods, preliminary results have been presented for applications to quasi-isotropic graphite/epoxy laminate and sandwich panel specimens containing representative damage modes, including delaminations, transverse ply cracks and through-holes. By comparing energy content and arrival times within wavelet plots, damaged specimens have been easily discernable.

Now that Lamb wave techniques have been demonstrated successfully for composite materials, recent research has focused on analytically and experimentally investigating Lamb wave infrastructure. The purpose of this research program was to optimize the actuation force and sensed signals while utilizing the lowest power level for efficient and accurate results. The components investigated included the piezoelectric sensors and actuators, the mechanical and electrical connections and the configuration necessary to integrate them. New algorithms have also been written to yield less subjective interpretation of the compiled data. This paper presents results of these optimized test methods and algorithms as applied to composite plates and sandwich structures with matrix crack and delamination.

## TESTING CONFIGURATION

At the conclusion of the previous optimization research, a final overall testing configuration was selected based upon a series of analytical models for the application of Lamb wave methods to composite specimens [15]. PZT-5A was selected as both the actuating and sensing material due to its high force output at low voltages and temperature stability. In place of side-by-side actuator/sensors or self-sensing circuits, a PZT disk circumscribed by a PZT ring was used for an actuating and sensing scheme for the present research. All four combinations were experimentally tested (disk-disk, ring-ring, ring-disk, and disk-ring) and it was determined that the best signal was obtained by using the rings as the actuator and the disks on either side of the damage as the sensors. The disk had a 12mm diameter as calculated for optimal sensing, and the ring had an overall diameter of 25mm with a true width of 6mm. The PZT wafers were bonded to the brass shim electrode using the 3M electrically conductive tape with a small separation between them. This thermoplastic tape requires no heat for adhesion, and just a small amount of uniform pressure. This assembly was then bonded to the structure using a similar 3M tape that was not conductive. Lastly, the electrical connections were made by soldering BNC cables to the nickel electrode on top of each PZT and a tab on the brass shim, forming a common ground. A schematic of this set-up can be seen in **Figure 1** and a photograph of the assembly as tested in **Figure 2**. Initial results have shown that this overall setup has increased the signal strength by nearly a factor of four over the previous configurations. With system power increasing with the square of voltage, this setup has the potential to decrease the system power requirements by $^{1}/_{16}$. The results collected using this setup were then decomposed using the algorithms presented in the following section.

## ALGORITHMS

To interpret the data generated from these Lamb wave tests, a series of algorithms were developed and compiled into a piece of software called METIS_v1 within MATLAB™. The software was divided into several subroutines to initialize the variable value, then filter the data and pass it through several types of damage prediction algorithms followed by a reporting section. First, each series of collected data was filtered using a custom Butterworth bandpass filter. This filter was designed to eliminate drift and mechanical vibrations below 5 kHz and electrical noise above 50 kHz, while preserving the waveform characteristics of the actuated 15 kHz signal. Next, a wavelet decomposition was performed. Wavelet analysis is perhaps the most important factor that has allowed Lamb wave techniques to flourish recently. Wavelet decomposition is similar to the Fourier decomposition, however instead of using sine waves, complex “mother wavelets” are used to break down the signal [16]. During the present research, a modified Morlet mother wavelet was used to decompose the signals, with a shape designed to be close to the actuated pulse shape, making the processing more accurate and efficient.

Following the filtering and wavelet decomposition, a series of algorithms were used to compare the potentially damaged signal with known undamaged ones. The first algorithm compared the integrated voltage over time for the undamaged and damaged signals, yielding a metric for the total received energy. By setting an energy-loss threshold, the presence of damage could be indicated, and furthermore the severity of damage could be judged since the worse the damage mode, the more energy that would become dispersed and attenuated. The second algorithm calculated the actuation peak and arrival times at the near and far sensors using the normalized wavelet energy for the driving frequency of 15 kHz. By setting a time-lag threshold, the presence of damage could again be indicated. The third algorithm compared the normalized energy received across the entire wavelet spectrum for both the undamaged and damaged signals to help determine type of damage. While propagating even through an undamaged structure, a Lamb wave disperses thereby contributing to a small bandwidth of frequencies around the driving frequency. Various types of damage would have different effects on the wavelet spectrum energy, either shifting the central peak, widening the bandwidth or perhaps even causing a secondary peak. A band-shift threshold was put in place to further verify the presence of damage. By using three separate algorithms based on different yet related physical principals—energy, time and frequency—the presence of damage can be predicted reliably, minimizing false positives and missed negatives.

In order to determine the location and size of damage, a fourth algorithm based on wavelet waterfall cross-section plots was used. The waterfall plot is a three-dimensional figure with axes of time, frequency and magnitude. By taking a cross sectional cut of this plot at a threshold value (set to eliminate signal noise), a very accurate measure of waveform peaks and hence time of flight could be measured. By comparing this data for by both the transmitted and reflected measurements from either side of the damage, an estimate of damage position and geometry could be deduced. As larger volumes of data are collected, these algorithms are continually refined, mostly by adjusting various threshold levels, to produce more accurate and consistent results. Each of these algorithms has been coded within MATLAB™ as the backbone of an automated piece of software, which takes the raw sensor voltage data as its input, and outputs a report of the damage presence, severity, type, location and size. Using this software, results are presented in the next section for the application of Lamb waves to composite laminates and sandwich structures.

## RESULTS

To validate the test setup and algorithms, several composite specimens were manufactured. The first specimens were thin quasi-isotropic 8-ply laminates of AS4/3501-6. Three of each laminate type was manufactured, including specimens with matrix microcrack regions, delaminations and undamaged laminates. The second specimens were composite sandwich panels. These too used quasi-isotropic 8-ply laminates of AS4/3501-6 each face sheet, using high and low density aluminum honeycomb, Nomex, Rohacell and solid and sheet aluminum as core materials. For each type of core material, both debonded and undamaged specimens were manufactured. Impacted facesheets and core gaps were also introduced into the high density aluminum specimens. A few specimens with multiple core types were also produced for advanced testing. Six of the actuator/sensor pairs described previously were adhered along the perimeter of parallel sides each specimen, and the tests were performed using an HP arbitrary function generator and oscilloscope. Once the data was collected, the METIS_v1 software described in the previous section was used to interpret the data and determine the state of damage present in each specimen.

Selected plots generated as output by the software for the thin laminates can be seen in **Figures 1-4**. The control laminate results are very reproducible, and were used to calibrate threshold levels for each of the algorithms. As seen in **Figure 1**, delamination causes a large time lag in the far sensor signal, as well as several reflections in the near sensor in **Figure 2** with little change to frequency bandwidth. The waterfall cross-section plot was used, as seen in **Figure 3,** to calculate the delamination location. In this case the damage reflection was found at 510 microseconds, corresponding to 121 mm, with the actual damage at 122 mm. Specimens with matrix cracking present yielded frequency changes with some reflections, as seen in **Figure 4**. Here the damage location was predicted to be at 120 mm. Comparable plots were generated for each combination of actuators and sensors affixed onto each of the specimen types.

Identical results were collected for each of the sandwich structure specimens. Each type of damage was easily predicted in all of the high density aluminum core specimens. The wavelet cross-section plots for a debonded specimen can be seen in **Figure 5**, where the damage was correctly predicted to begin at 121 mm. Similarly, **Figure 6** displays the results for a debonded low density aluminum core specimens, whose signal was slightly damped with a predicted damage location of 111 mm. The Nomex and Rohacell core specimens were more difficult to interpret since they provided additional damping, however reasonable results were still obtained. Lastly, the solid and sheet aluminum cores greatly accelerated the waves, however also provided the clearest signals and hence damage locations because of the homogeneity of the material and the cleanness of the bond-lines. The final specimens tested were the mixed sandwich structures. Identical plots were also produced for each of these advanced tests to examine the effect of core interfaces and additionally to predict the location of debonded regions. First, **Figure 7** displays the wavelet cross-section plot for a high density aluminum core specimen with a gap between the core running down the center. This gap is easily differentiated from disbond by the results, and is predicted to be at 150 mm, with the true gap commencing at 140 mm. Specimens were also tested alternating high density aluminum core with solid aluminum. This interface produced a large reflected wave at the interface, however, as seen in **Figure 8**, did not prevent the software from locating a debonded region over the interface. This disbond was predicted to be at 120 mm and was actually located at 121 mm.

## CONCLUSIONS

This paper describes the experimental application of an optimized actuator and sensor configuration for Lamb wave methods to composite laminates and sandwich structures. Theoretical calculations were performed during previous research to select the appropriate piezoceramic material types and their geometries, as well as for the necessary mechanical and electrical connections. Using this setup along with newly developed algorithms to decompose and interpret the collected Lamb wave data, testing was performed on several composite thin laminates and sandwich structures. These tests proved that Lamb wave methods are an effective method for the in-situ determination of the presence, location and type of damage in simple composite specimens. Future work on the software will be directed at refining threshold values to improve accuracy. Integrated reliable SHM systems in composite structure will be an important component in future designs of air and spacecraft, and Lamb wave techniques will likely play a key role in their success.

## ACKNOWLEDGEMENTS

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**Figure 1:** Far sensor plots for thin laminate with central delaminatoin

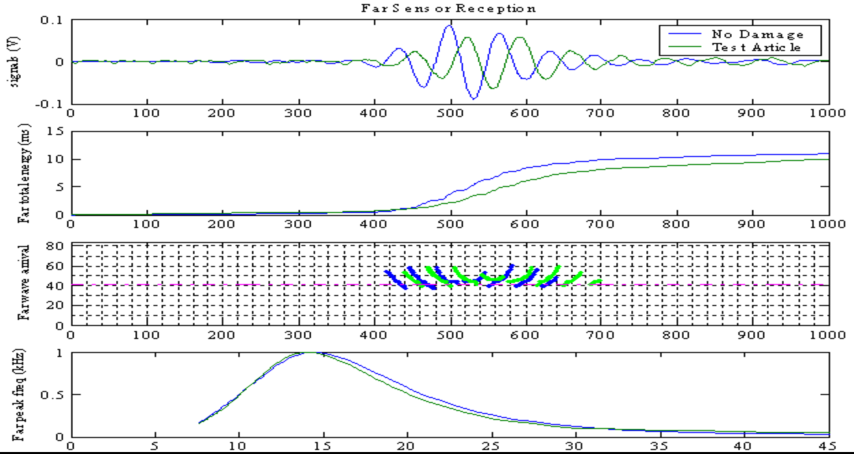
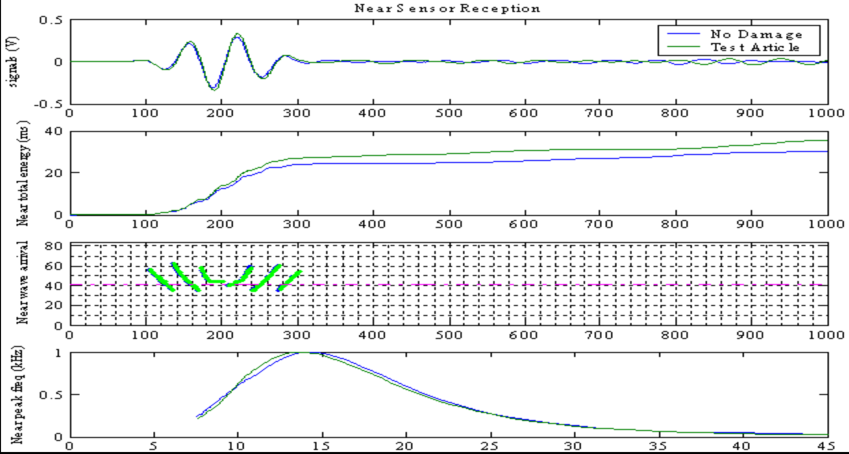


**Figure 2:** Near sensor plots for thin laminate with central delaminatoin



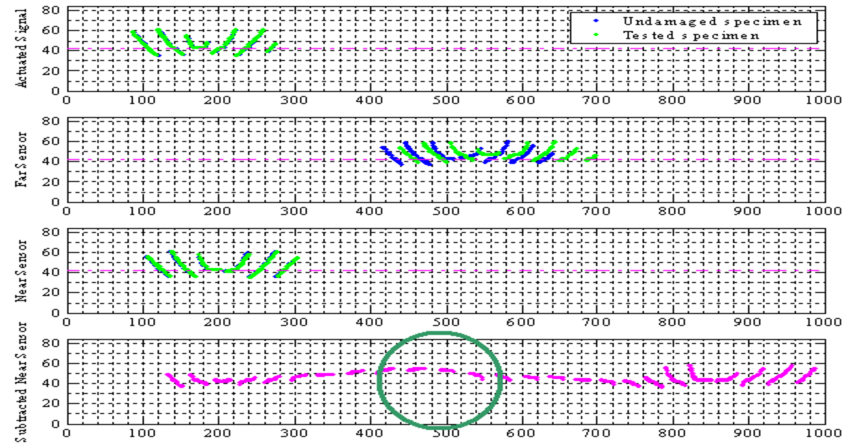


**Figure 3:** Wavelet cross-section plot for thin laminate with center delamination

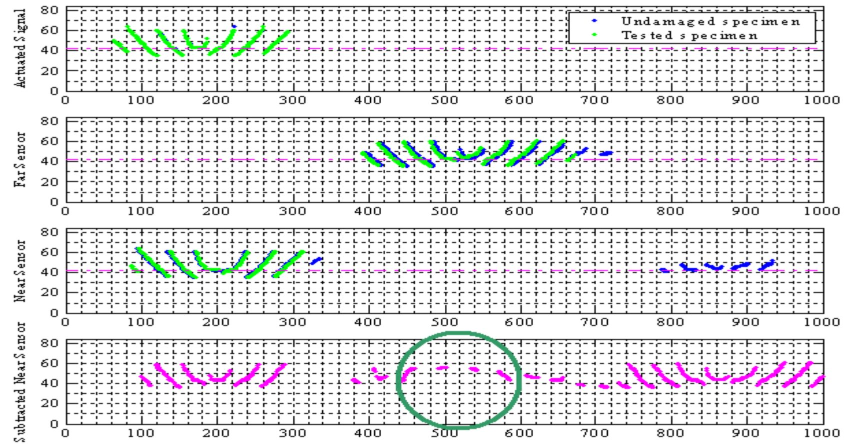


**Figure 4:** Wavelet cross-section plot for thin laminate with matrix cracks

**Figure 5:** Wavelet cross-section plot for high density Al core with debond

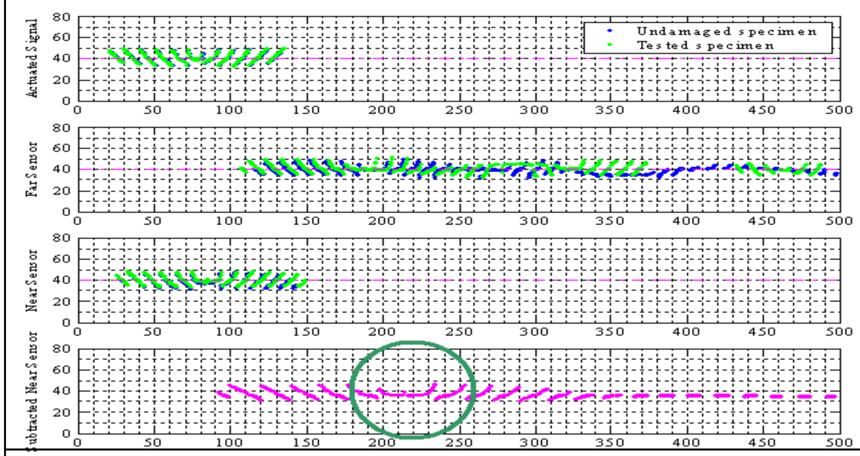
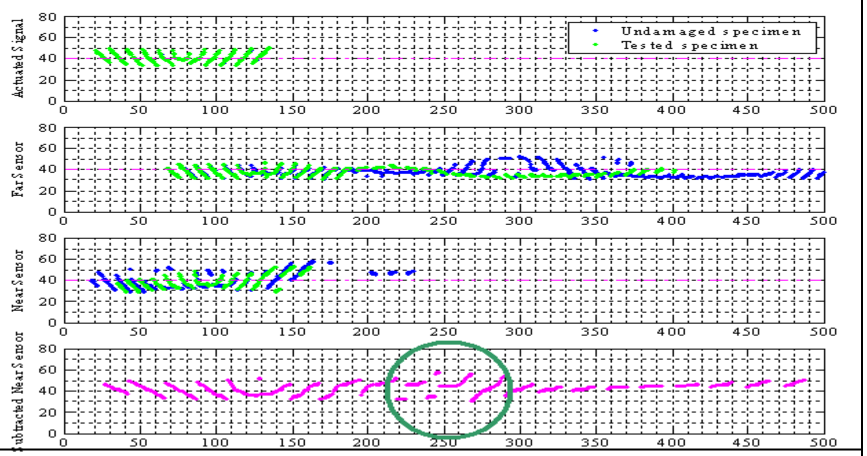


**Figure 6:** Wavelet cross-section plot for low density Al core with debond



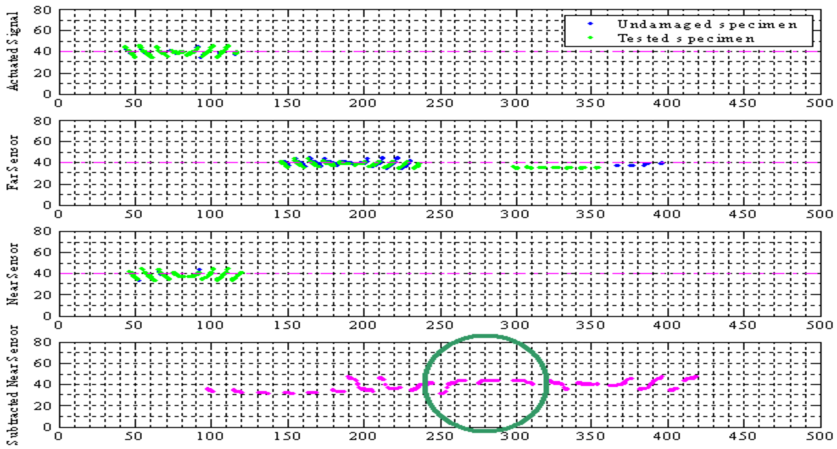


**Figure 7:** Wavelet cross-section plot for high density Al core with gap

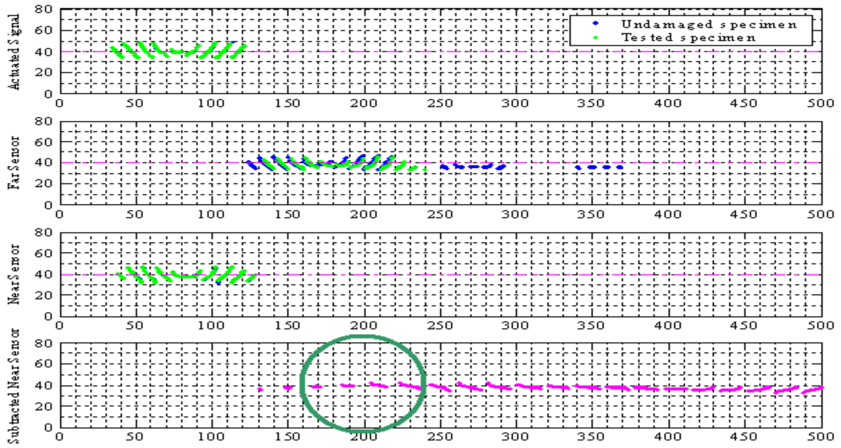


**Figure 8:** Wavelet cross-section plot for high density/solid core with debond