In-Situ Damage Detection of Composites Structures using Lamb Wave Methods

Seth S. Kessler[a], S. Mark Spearing[a] and Mauro J. Atalla[b]
[a]Massachusetts Institute of Technology
[b]United Technologies Research Center

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ABSTRACT

Cost-effective and reliable damage detection is critical for the utilization of composite materials. This paper describes part of an experimental and analytical survey of candidate methods for in-situ damage detection of composite materials. Optimal piezoceramic actuator geometry and driving parameters were developed from the Lamb wave equations. Results are then presented for the application of this Lamb wave technique to graphite/epoxy specimens containing representative damage modes. Linear wave scans were performed on narrow laminated specimen, sandwich beams, and built-up structures such as composite plates with stiffeners and a cylinder. Lamb wave techniques have been proven to provide more information about damage type, severity and location than previously tested methods (frequency response techniques), 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 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. Previous papers have focused on the

Seth S. Kessler, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
S. Mark Spearing, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
Mauro J. Atalla, United Technologies Research Center, East Hartford, Ct 06108, USA

application of modal analysis and Lamb wave techniques to narrow laminated coupons [2-4]. Lamb wave methods have recently re-emerged as a reliable way to locate damage in these materials [5-8]. These techniques have been implemented in a variety of fashions in the literature, which have been presented in previous papers. Much of the research presented in this paper follows work from the literature, extending it to various other types of damage, to built-up structures, and an attempt to optimize the testing parameters.

LAMB WAVE PROPAGATION PARAMETERS

Lamb waves are a form of elastic perturbation that can propagate in a solid plate with free boundaries [9, 10]. This type of wave phenomenon was first described in theory by Horace Lamb in 1917, however he never attempted to produce them [11]. The present work utilizes PZT piezoelectric patches to excite the first anti-symmetric Lamb wave (A0 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 [8]. 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, and each with some degree of arbitrariness. A major goal of the present research was to optimize the parameters used to propagate the Lamb waves based upon the various equations that describe their motion. In previous Lamb wave papers, a detailed derivation has been presented for the Lamb wave solutions to the wave equation, and the effects various variables had on the sensitivity of these methods to damage was discussed [3, 4]. The present work places these findings into selection guidelines to choose the appropriate actuating frequency, pulse shape, and sensor geometry for a particular Lamb wave application.

Frequency Selection

The first step in defining an appropriate Lamb wave damage detection solution is to select an appropriate driving frequency. This procedure commences by finding the Lamb solution for the wave equation, and plotting the dispersion curves for each section to be monitored. By entering the material properties (E, ν, and ρ) for a particular material, the resulting dispersion curves provide a range of potential wave velocities for the A_0 mode driven at different frequency-thickness products. For a given thickness, ideally one would like to choose the least dispersive driving frequency for the Lamb wave being generated, which generally exists where the slope of the phase velocity curve is equal to zero. This is because at low frequencies, the dispersion curves have steep slopes and thus are very sensitive to small variations in frequency making it difficult to maintain a constant velocity to predict the time of flight. The A_0 mode, however, follows a square root relationship with frequency until higher values, thus the frequency needs to be chosen by a different criteria. The higher the frequency the smaller the slope of the A_0 dispersion curve, although at a certain point other higher order Lamb waves begin to exist simultaneously and the signal becomes cluttered. The wave velocities are also much faster at higher frequencies, increasing data acquisition requirements

To balance these issues, the following procedure should be followed. First plot the dispersion curves for the material, and locate the frequencies at which the Rayleigh velocity is obtained and where the A_1 mode begins to be excited. If the Rayleigh velocity is below the point where the next anti-symmetric mode is generated (which normally is not true) then this is the critical frequency; otherwise it would be wise to choose a point about 10% below the A_1 origin point as the critical frequency. Next, it must be determined if the data acquisition capabilities are able to capture a wave traveling at this velocity. Typically, the data acquisition rate should be 10 times the frequency of the signal it is sampling, so the selected driving frequency may have to be lowered if the sampling rate is unobtainable. Also, with knowledge of the effects of various damage types on the stiffness of a particular material, the resolution of change for the resultant signal, or "observeability," can be predicted in order to determine the detection limitations with respect to flaw size for a given data acquisition capability.

Pulse Shape Selection

The second set of variables explored was the actuation pulse parameters. These included the pulse shape, amplitude and number of cycles to be sent during each pulse period. Of the signal shapes that were analyzed and experimented, pure sinusoidal shapes appear to excite Lamb wave harmonics the most efficiently, and the application of a Hanning window helped to narrow the bandwidth further. For the present research, a signal of 3.5 sine waves under a Hanning window was used. The number of cycles of a periodic function desired to actuate the piezoelectric actuator is one of the more complicated decisions to be made for Lamb wave techniques. The fast Fourier transform (FFT) of a continuous sine wave would yield a single peak at the driving frequency, however for a few finite cycles, the FFT appears as a Gaussian curve with a peak at the driving frequency. Thus, the more waves sent into a driving pulse, the narrower the bandwidth and the less dispersion. The problem in a short specimen though, is the more waves in the pulse, the less time between the last signal sent and the first returning reflected signal, so the response is more difficult to interpret. An appropriate number of cycles can be determined by the maximum number of waves that can be sent in the time it takes for the lead wave to travel to the sensing PZT patch. It is also convenient to use intervals of half cycles so that the sent sinusoidal pulse becomes symmetric. Research from the literature has used signals varying from 3.5 to 13.5 cycles per actuating pulse [5-8].

Actuator Dimensions

PZT piezoceramic actuators were chosen for the present research due to their high force output at relatively low voltages, and their good response qualities at low frequencies. Waves propagate parallel to each edge of the actuator, i.e. longitudinally and transversely for a rectangular patch and circumferentially from a circular actuator. The width of the actuator in the propagation direction is not critical, however the wider it is, the more uniform the waveform created. As cited in the literature though, there is an important sinusoidal relationship between actuating frequency and actuator length [9]. In the direction of propagation the desired actuator length 2a for most efficient signal is:

$$2a = l\left(n + \frac{1}{2}\right) = \frac{c_p}{f}\left(n + \frac{1}{2}\right) \quad \text{for n} = 0, 1, 2, 3... \tag{1}$$

This value of 2a could either be a rectangular side length or the diameter of a circular actuator. This equation could also be used to determine actuator minimum dimensions, in order to inhibit waves from propagating in undesired directions. For the experimental procedures in the present research, PZT actuators of 1.5 cm x 0.75 cm were selected based upon this equation.

Sensor Spacing

Two important concepts to understand in wave propagation are dispersion and attenuation. Dispersion is the change in wavespeed in a material with respect to frequency, which was demonstrated graphically in the previous section. Since the group velocity is related to the rate of change of the phase velocity at a given frequency, the phase and group velocities are the same for a non-dispersive material. Attenuation is the change in amplitude of a traveling wave over a given distance. While propagating through the solid medium, energy is transferred back and forth between kinetic and elastic potential energy; when this transfer is not perfect, attenuation occurs. This loss in energy can be due to heat being generated, waves leaking into sideband frequencies or spreading into different propagation paths, restraints such as a bonded core, or in the case of composite materials, the fibers can provide reflecting surfaces, which would deteriorate the transmitted wave strength. These two concepts influence each other as well, as increased dispersion causes higher attenuation, and vice-versa. A mathematical approximation to this correlation from the literature that relates the attenuation as a function of propagation distance is:

$$A = \frac{1}{KL} \rightarrow \frac{1}{\sqrt{K_r L}} \tag{2}$$

where A is the attenuation factor, K is the wavenumber and L is the propagation distance. The attenuation tends to the slower Rayleigh attenuation value as the specimen becomes thicker. Analytical studies have also been performed to formulate the change in dispersion (and hence attenuation) in curved panels [9]. It was found that the phase velocity is changed by the relationship:

$$\bar{c}_p = \left(1 + \frac{c_p^2}{w^2 R^2}\right) c_p \tag{3}$$

where c_p is the original phase velocity and R is the radius of curvature. When the phase velocity dispersion curve is adjusted by this formula, the slight increase in dispersion is readily apparent. Using these two relationships, an approximation can be made to determine the appropriate spacing between the actuators and sensors on a structure based upon the acceptable signal loss for the voltage sensitivity of the data acquisition system. For the present research this was determined to be 25%, and the estimated actuator-sensor spacing was be calculated to be 0.5m.

EXPERIMENTAL PROCEDURE

The first set of experiments were conducted on narrow composite coupons, and was presented in a previous paper. The laminates were 25 x 5 cm rectangular $[90/\pm45/0]_s$ quasi-isotropic laminates of the AS4/3501-6 graphite/epoxy system with various forms of damage introduced to them, including matrix-cracks, delaminations and through-holes. PZT piezoceramic patches were affixed to each specimen using 3M ThermoBond™ thermoplastic tape. 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 single pulse of the optimal signal found in the previous section was sent to the driving PZT at 15 kHz 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 results were compared by performing a wavelet decomposition using the Morlet wavelet, and plotting the magnitude of the coefficients at the driving frequency [12].

This procedure was also carried out for beam specimens with various cores at a driving frequency of 50 kHz. Further experimentation examined damage in more complex built-up specimens. Laminated plates were tested with ribs that were bonded across the center of each plate using Cytec™ FM-123 film adhesive. Different configurations included 25 mm wide aluminum C-channel rib and a composite doubler with and without a center delamination, both using a driving frequency of 15 kHz. Next a sandwich construction cylinder with a 40 cm diameter and length of 120 cm was tested. It had two facesheets of similar layup as the other tested specimens, and a 25 mm thick low-density aluminum honeycomb bonded between them. Piezoceramic patches were placed down the length of the cylinder every 10 cm for 60 cm in several control regions as well as in a region with visible impact damage. The driving frequency for this test was 40 kHz because of the honeycomb core and slightly different layup.

EXPERIMENTAL RESULTS

Detailed results for each of the experiments described can be found in previous papers focusing on Lamb wave experimentation [3, 4]. A few key results are shown in this paper that demonstrate the utility of the presented parameter optimization procedures for the application of Lamb wave testing. Results from the narrow coupon tests clearly showed the presence of damage in all of the specimens. The most obvious method to distinguish between damaged and undamaged specimens was by regarding the wavelet decomposition plots, show in **Figure 1,** where the control specimens retained over twice as much energy at the peak frequency as compared to all of the damaged specimens. The loss of energy in the damaged specimens was due to reflection energy, and dispersion caused by the micro-cracks within the laminate in the excitation of high-frequency local modes. Probably the most significant result of the present research was the “blind test.” Four high density aluminum-core 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 2**, 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 testament to the viability of the Lamb Wave method being able to detect damage in at least simple structures. Similar effects of damage were observed in each of the built-up composite structure cases. By comparing the stiffened plates results, a reproducible signal was transmitted across each of the intact portions of the composite stiffeners while it was obvious that the signal traveling through the delaminated region was propagating at a different speed. Finally, by comparing the axial wave propagation in the control and damaged regions of the cylinder, it could be seen that the impacted region caused severe dispersion, which attenuated the received signal at each sensor further down the tube. For all of the tested specimens, damage was easily perceived by comparing the wavelet coefficient magnitudes for the control versus damaged signal.

IMPLEMENTATION OF LAMB WAVE METHODS IN AN SHM SYSTEM

Lamb wave techniques have good potential for implementation in a SHM system. These methods provide useful information about the presence and extent of damage in composite materials, and holds the potential to detect the location of damage in a structure. It 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. Another difficult requirement is the high data acquisition rate needed to gain useful signal resolution. In order to conserve power and data storage space, the Lamb wave method should most likely be placed into a SHM system in conjunction with another passive detection method, such as a frequency response method. Three to four piezoelectric multi-functioning actuator/sensor patches would be placed in the same vicinity in order to be able to triangulate damage location based upon reciprocal times of flight and reflected waves. Another possible scheme could rely on long strips of piezoelectric material, which would be able to send and receive large uniform Lamb waves, and integrate the received and reflected energy in order to determine the state of the material between them. The detailed specifications of the Lamb wave driving parameters to be used for a particular application would be designed by the procedure described in the optimization section.

CONCLUSIONS

This paper has explored the optimization of Lamb wave methods for damage detection in composite materials. A collection of equations is presented to determine the driving parameters and actuator dimensions for testing. With these tools, an optimal configuration was selected and several narrow graphite/epoxy specimens were tested with various forms of damage. Similar tests were performed on sandwich beams and built-up composite structures such as stiffened plates and curved structures. Lamb wave methods 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 in 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 the most effective for the in-situ determination of the presence and severity of damage in composite materials of the methods examined in this research project. 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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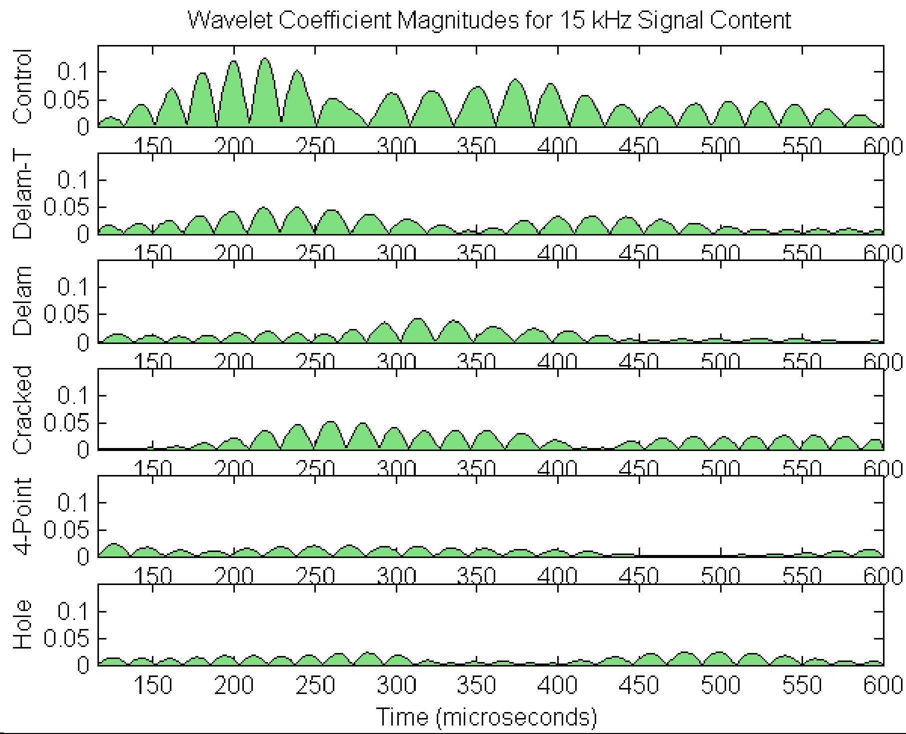

Figure 1: Wavelet coefficients for thin coupons; compares 15 kHz energy content

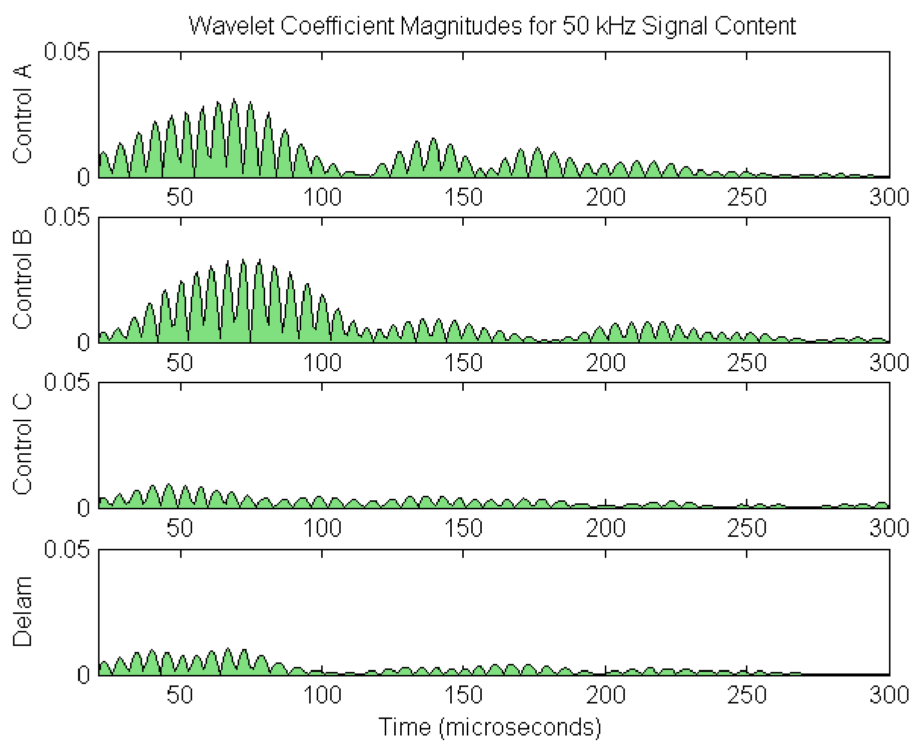

Figure 2: Wavelet coefficients for beam "blind test"; compares 50 kHz energy content