Damage Detection in Stiffened Composite Panels Using Lamb Wave

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ABSTRACT

This paper presents a Lamb wave based methodology for damage detection in stiffened carbon-epoxy composite panel with stiffener de-bonding. The specimen considered encompasses most of the complexities that may be encountered in implementing a real-life Lamb wave based structural health monitoring (SHM) system. These complexities include multiple reflections from the stiffeners and edges, cluttering of wave modes, effect of variable thickness on time of flight and amplitude. Piezoelectric patches are used as transducers and only A_0 mode is excited through mode tuning. A damage index (DI) based on root mean square deviation (RMSD) is derived from the frequency spectra of the windowed A_0 mode of the Lamb wave response. The efficacy of the DI for predicting the presence of damage is tested experimentally for a specimen with known location of damage. In addition, a 2-D finite element (FE) simulation is carried out to validate the experimental results.

INTRODUCTION

Over the last one decade, substantial research, both experimental and theoretical, has been focussed on Lamb wave based damage detection in thin metallic and composite plates. This is primarily because of several advantages of Lamb wave

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based technique over conventional non-destructive methods and the potential of the former method to be implemented for online SHM. These advantages include larger area scanning, low attenuation, easy implementation using piezoelectric (PZT) transducers [1, 2]. Analysis of Lamb wave however possesses several challenges mainly due to their multi-modal characteristics, dispersive nature, and relatively higher speeds. These complexities have restricted the implementation of Lamb wave based SHM mainly to isotropic or composite plates of simple geometries, of relatively larger dimensions, and without many discontinuities like presence of stiffeners and joints.

Most of the existing works on Lamb waves have used changes in the amplitude, time of flight, and time reversal of wave packets to identify damage in both isotropic and composite plates where S_0/A_0 modes are well separated without cluttering and without merging of waves due to edge reflections. This is possible only in structures which are sufficiently large without any discontinuities in the path of the wave propagation. Aerospace structures however, have higher complexities in terms of stiffeners, joints, variable thickness, and other discontinuities.

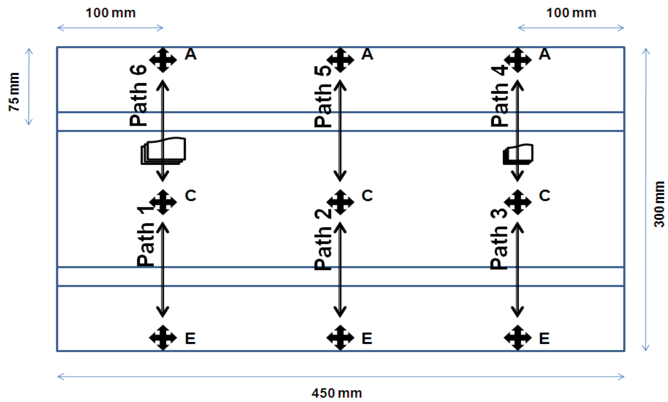
Compared to the extensive work done on Lamb wave based damage detection in flat metallic/composite panels, similar studies for stiffened panels are very few to the best of authors' knowledge. Studies conducted on the interaction of Lamb wave with geometric discontinuities (C Ramadas et al 2011 [3]) show the complexities involved quite clearly. Monnier (2006) [4] proposed a percentage damage index using frequency response of Lamb waves to identify delamination due to impact loads on a slightly curved carbon fibre reinforced plastic (CFRP) stiffened panel. Otherwise, complex techniques like outlier's analysis with neural networks (Z Su et al 2007 [5], Chetwynd et al 2008 [6]), correlation techniques (Ye Lu et al 2009) [7] and a comparative study of various damage indices (C Y Park et al 2007 [8]) were attempted on stiffened composite panels using time domain data to extract features indicating damage severity.

This paper presents a Lamb wave based technique for damage detection in a T-stiffened carbon-epoxy composite panel of relatively smaller dimensions. Lamb waves are generated and recorded using PZT patches as transducers. A_0 Lamb wave mode is excited through mode tuning by aligning two PZT patches. A DI is derived from the frequency spectra of windowed A_0 mode of the Lamb wave response. The DI formulated is later used to predict damage from experimentally measured response of the stiffened panel with stiffener de-bonding. A parallel theoretical study using FE simulation is presented to validate the experimental study.

EXPERIMENTAL SETUP

The specimen used for the experiments is shown in Figure 1(a). It is made from T300/914 carbon epoxy pre-preg. The panel dimensions are 450 mm x 300 mm x 2.4 mm with two stiffeners placed symmetrically with respect to the centreline at a distance 150 mm apart along the longer side of the plate. As mentioned earlier, the specimen exhibits several complexities of an aircraft composite panel; the smaller size of the plate brings in wave mode merging and interference with edge reflections. The base plate has a 16 layer symmetric layup sequence $[45/-45/0/45/0/-45/0/90]_s$ and that of the T-stiffeners is [45/-45/0/45/0/-45/0/90] placed back to back. 7mm x 5 mm x 0.47 mm, Lead Zirconate Titanate (PZT) patches (type SP-5A) are used as actuators and sensors. The rectangular patches are glued to the structure with a standard epoxy adhesive.

(a)



(b)

Figure 1. (a) Carbon-epoxy stiffened panel under investigation (b) Sensor positions and damage location

The CFRP composite panel contains two small regions of stiffener de-bonding roughly 2 cm^2 and 1 cm^2 respectively, at the inner edge of one of the stiffener flange, as shown in Figure 1(a) (hash marking) and 1(b). Nine active PZT patches are bonded at the locations shown in Figure 1(b), forming six wave propagation paths across the stiffeners. Two of these actuator-sensor paths pass through the de-bond regions in the specimen. The sensors at ‘A’ and ‘E’ are deliberately positioned very close to the edge of the plate to avoid complications arising from longer edge reflections.

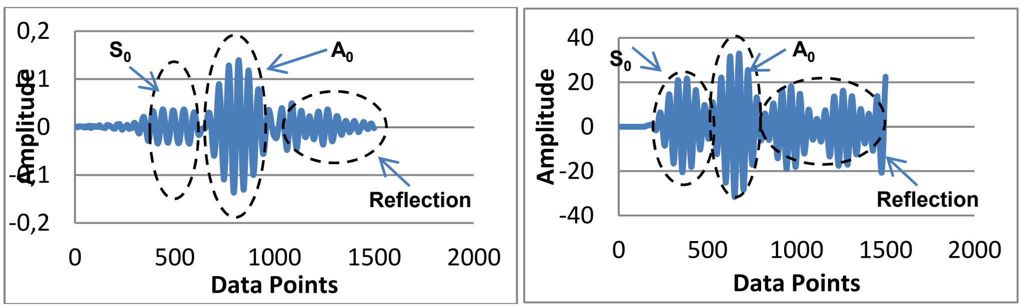
The excitation source for the PZT actuators was an eight cycle Hanning window modulated tone burst generated by a Tektronix AFG3021B multifunction generator. The Lamb wave response was measured by the PZT sensors through a Tektronix TDS 1002B two channel oscilloscope. The test was conducted at a central frequency of 92 kHz and 100 kHz. To reduce the effects of high frequency electro-magnetic noise, the recorded signals are filtered using an eighth order low pass Butterworth filter with inbuilt MATLAB codes.

Lamb wave simulation was also undertaken in ANSYS© 13 using 2-D cross sectional plate model [9, 10] of the specimen to understand Lamb wave response and damage assessment performance for various degrees of de-bonding and delamination. The geometric model is meshed using 2-D eight-noded plane183 elements in ANSYS© 13 under plane strain conditions. Free meshing is done using fine discretization of 0.4e-3m to capture the Lamb wave modes accurately. A pin force model simulated the actuation and sensing using transient analysis with a time step of 2e-7s.

RESULTS AND DISCUSSIONS

Time Domain Analysis

Figure 2(a) presents the experimental Lamb wave response of the stiffened CFRP plate across path number 3. Simulated Lamb wave response of a clean base plate having lay-up sequence and dimension similar to the stiffened panel is shown in Figure 2(b) for comparison. The plate dimension along the wave propagation direction is only 300 mm. Hence adequate time is not available for the A_0 and S_0modes to separate out completely. Therefore, A_0, S_0 and the edge reflections tend to clutter with each other for both the clean base plate and stiffened plate. In addition, for the stiffened plate, the S_0 mode and the edge reflections are distorted substantially due to the presence of additional wave packets from the stiffener. Thus, presence of a stiffener in the path of the Lamb wave shows additional wave forms reflected from the stiffener end, rejoining the wave propagating through the base plate, modulating the response and transforming the characteristics.



(a) (b)

Figure 2. (a) Experimental Lamb wave response of Path 3 in stiffened plate (b) Simulated Lamb wave response on a similar clean base plate without stiffener

However, the effects of cluttering are less prominent for A_0. Thus, it can be observed from Figure 2(a) & (b) that in addition to the distortion due to merging of reflections from edges, the presence of stiffeners distorts the time domain Lamb wave responses to a large extent, and presence of waves resulting from damage if any will be camouflaged by the reflections from the stiffeners. The second observation from this and similar experimental results is that the presence of stiffener strongly attenuates the amplitude of S_0 mode unlike A_0 mode amplitude. This suggests that tracking the A_0 mode may be more useful to detect the effects of damage.

Though, as mentioned earlier the effects of stiffeners are less prominent for A_0 mode the amplitude of the mode is nevertheless attenuated by the presence of stiffener which is highlighted by the following experiments. Figure 3 shows comparison of Lamb wave responses recorded along path 1 and 6 by inducing excitation at transducer E and capturing responses experimentally at transducer C and A, one after first stiffener and the other after both stiffeners respectively.

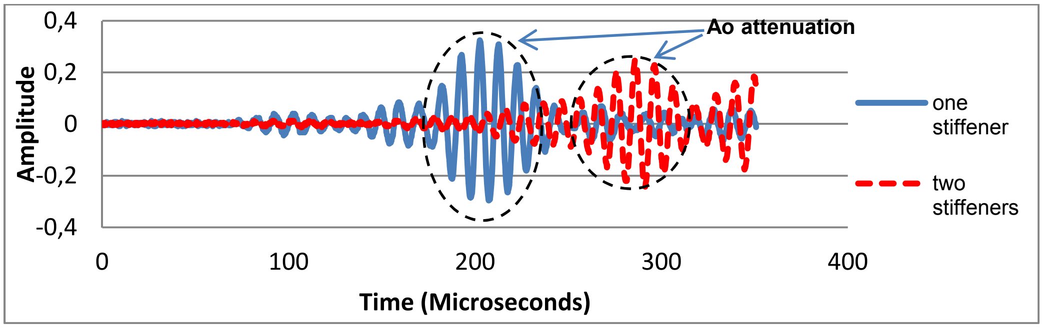


Figure 3. Experimental Lamb wave response showing attenuation of A_0 mode after one and both the stiffeners

The response clearly indicates step by step reduction in the amplitude of A_0 signal across each stiffener. Hence, adequate amplification of the signal is required for analysis. The reference form the last two examples can be summarised as follows,

- The presence of stiffeners results in several reflected waves which clutter A_0 and S_0 and can hide the waves arising from the damage.
- The amplitude of S_0 is drastically reduced as it travels through the stiffener
- A_0 mode is comparatively less attenuated while it travels through the stiffeners, though there may be need to enhance its amplitude
- Identifying S_0/A_0 mode with wave speed is not possible as the wave speed varies considerably due to the inherent complexities. Hence, a mode selection approach is adopted wherein a desired mode can be enhanced and the other unwanted modes can be suppressed.

By appropriately placing PZT patches one can make zero order modes to interact in such a fashion that only desired A_0 or S_0 is seen. Since, it is required to generate only the A_0 mode in the Lamb wave responses in the experiments, two PZT patches are fixed one over the other on the host structure and excited out of phase simultaneously [1]. This sort of arrangement gives out responses dominated by A_0 mode helping in identifying the A_0 mode in the Lamb wave responses obtained from the stiffened composite specimen.

Figure 4 presents the tuned and unturned Lamb wave response of the stiffened panel. It can be seen that the A_0 mode is enhanced substantially with S_0 being reduced. Both the S_0 and A_0 mode are sensitive to structural damage, however, A_0 mode shows higher sensitivity to surface damage [1]. Thus, A_0 mode is considered more suitable for identifying de-bonding on the surface of the CFRP base plate.

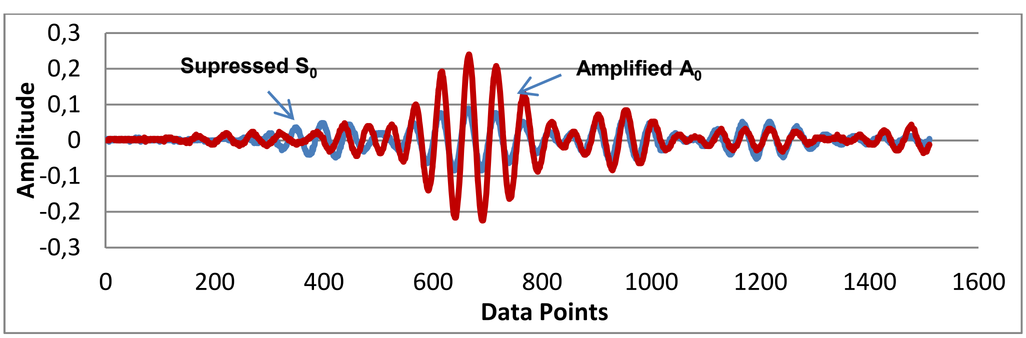


Figure 4. Comparison of tuned and un-tuned Lamb wave response along Path 2

Frequency Domain Analysis for Damage Assessment

Though, Figure 4 shows that the tuned Lamb wave response primarily containing A_0 is much clearer with less cluttering, it may not be used directly for damage identification. In this study, first these responses are converted into frequency domain through FFT and the frequency spectrum of the Lamb wave responses across de-bond is compared with responses through the path without damage. Figure 5(a), (b) & (c) shows a comparison between a pair of frequency spectra of a path with damage and a path without damage i.e. paths 1 & 6, paths 3 & 4 and paths 2 & 5 respectively. The entire time window with 2500 sampling points of the response is considered for obtaining the frequency spectra, i.e. without resorting to mode tuning, filtering or mode selection. The plot clearly indicates presence of change in the frequency spectra between damage free and damaged path. The spectra of the three damage free paths shows considerable variation which can be attributed to the in-homogeneity of the structural geometry and the unknown behaviour of the unidentified modes affecting particularly S_0.

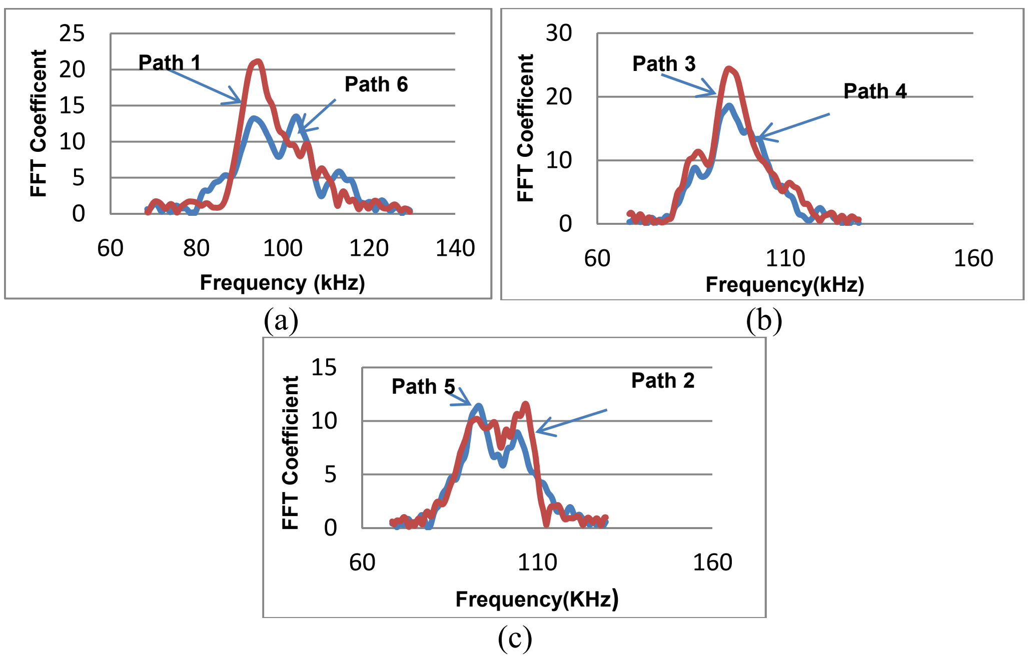


Figure 5. (a) FFT plot for path 1 & 6 (b) FFT plot for path 3 & 4 (c) FFT plot for path 2 & 5

The idea behind this work is to obtain an index that can identify and quantify the damage facilitating automation and in-situ SHM. The RMSD damage index (DI) obtains the difference between two frequency spectra of their respective Lamb wave responses,

$$DI_{RMSD} = \sqrt{\frac{\left(\sum_{i=1}^{n}(x_i - y_i)^2\right)}{\left(\sum_{i=1}^{n}(y_i)^2\right)}} \quad (1)$$

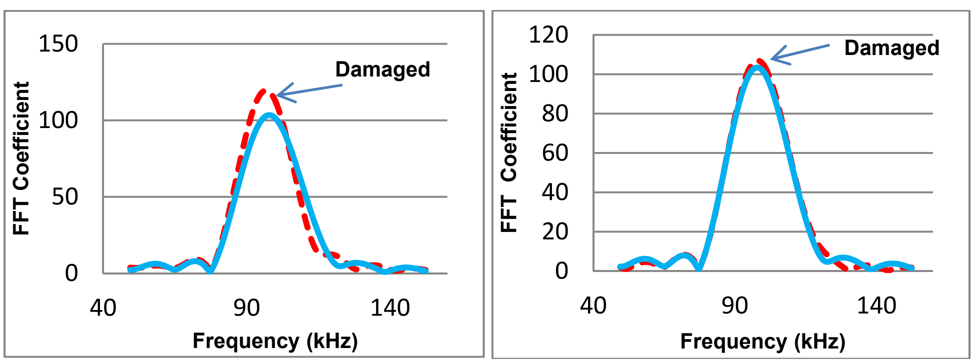
Where, x_i and y_i are the Fourier coefficients of the time domain data of interest for damaged and undamaged conditions respectively. The DI is a measure of the similarity between the two frequency spectra in terms of the error between the damaged and undamaged signal [11]. Thus, it gives the overall difference between the frequencies spectra's of two signals. The DI calculated for different frequency ranges, are tabulated in Table 1.

Table 1. DI values obtained considering both S_0 & A_0

	Frequency Range (kHz)		
	80-100	**90-100**	**95-100**
Path 1 & 6	0.38365	0.36485	0.35346
Path 2 & 5	0.17168	0.17013	0.22804
Path 3 & 4	0.23709	0.23191	0.25669

The higher value of DI for path 1 & 6 in comparison with path 3 & 4 shows that there is a potential to identify and quantify the severity of the damage as path 6 contains larger de-bonding as shown in Figure 1(b). However, the DI value obtained for paths 2 & 5 (damage free paths) indicate that there is significant difference between the spectra of two damage free paths too. Thus, it is intuitive to say that though comparing Lamb wave responses before and after damage occurrence in the same path will give an indication of the damage and the DI value will show a considerable variation with different paths of wave propagation. To reduce thresholds and improve the accuracy of the obtained DI analysing specific mode response is considered next.

Now, Lamb wave responses are truncated and only the predominant A_0signal responses are considered for transformation into the frequency domain as shown in Figures 6(a) & (b). This figure shows the comparison of frequency



(a) (b)

Figure 6. (a) Comparison of A_0 mode frequency spectra of path 2 & 6 (b) Comparison of A_0 mode frequency spectra of path 2 & 4

spectra of paths 2 & 6 and paths 2 & 4 at 92 kHz considering only the A_0 mode Narrowing down to the use of only A_0mode has brought down the threshold from 0.17 to 0.15 (Figure 7). The experimental DI values obtained through usage of only A_0 mode clearly indicate the presence of damage in path 4 and 6 and the value difference also indicates the severity of the damage accurately. ANSYS© simulation of Lamb wave responses for de-bonding of the stiffener shows that the Lamb wave response gradually move towards base plate configuration with increase in the length of de-bond along the Lamb wave propagation path.

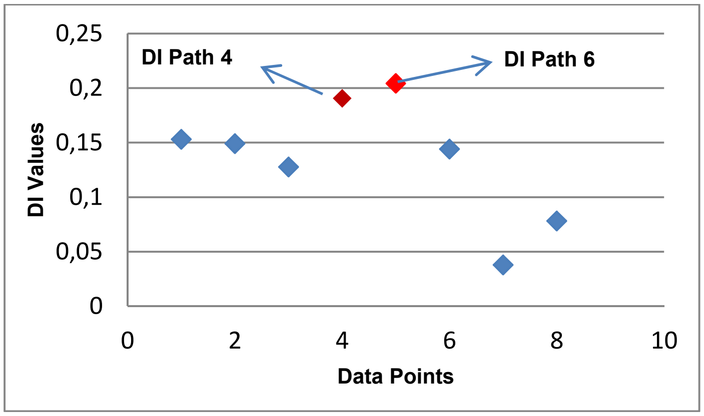


Figure 7. DI values obtained experimentally considering A_0 response

Thus, larger de-bond (75.8 mm in depth) along the Lamb wave propagation path tends to distort A_0 considerably. The DI value obtained through simulation (at 100 kHz) was 0.306799 showing similar characteristics achieved through experiments. Thus, both simulation and experiment indicate the potential of the damage index based on frequency spectra for damage detection. This paper only indicates the potential of frequency spectra information useful for damage detection. The experiment is conducted in a controlled laboratory environment, hence influence of external factors like temperature is not considered in this work. Simulation requires no threshold selection but due to a number of variables in a real time structure intensive work would be required to characterise the whole structure under investigation to set up thresholds for implementation of a real time SHM.

CONCLUSION

An experimental and simulation study has been worked out to explore the potential of frequency spectra of Lamb wave responses to identify damages in real world structures. Experiments are conducted on flat aluminium and composite plates before attempting the DI based on frequency spectra on stiffened composite panel. Simulation is also undertaken in different mediums to understand the potential of frequency spectra for damage detection. Though simulation results show consistent increase in DI value with increasing degree of damage, implementation of the same to real time structure is far more challenging due to a number of variables like in-homogeneity in geometry, external factors etc. This is unavoidable but this can be overcome by characterising the structure and setting up thresholds when implementation of a real time SHM. This is an exploratory work to explain the potential of using frequency spectra for damage detection. The experimental and simulation results show promising results indicating possibility of developing a reliable real time SHM for thin walled composite structures of higher complexities.

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