Time Reversal Health Monitoring of Composite Plates using Lamb waves

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Abstract

In this work, the use of time reversal technique along with Lamb wave active sensing is investigated for health monitoring of composite plate structures. Piezoelectric wafer active sensors (PWAS) were used for the actuation and reception of the Lamb wave modes in the composite plates. Experiments were conducted on glass-epoxy composite plates with different lay-up sequences to study the time reversal behavior of A_0 and S_0 Lamb wave modes. Damage in the form of delamination was simulated by inserting a Teflon release film between the sixth and seventh layer of the glass-epoxy composite plate. The change in the shape of the broad band Gaussian pulse under time reversal in the presence of delamination was studied experimentally. Time reversal experiments were further carried out on carbon-epoxy composite t-pull specimen and the specimen was subjected to a tensile loading in a universal testing machine. PWAS measurements were carried out for healthy and also during different stages of delamination due to tensile loading. Time reversal of A_0 and S_0 mode was applied for both healthy and delaminated composite specimens and change in shape of the time reversed Lamb wave was studied experimentally. This study aims in showing the effectiveness of Lamb wave time reversal as a baseline free technique for damage detection in composite plates.

1. INTRODUCTION

Composites are increasingly used in aerospace industry because of its superior properties like high specific stiffness and strength, improved fatigue resistance, tailorability etc. Unlike metals, the failure in composite is complex and the most common type of failure being due to delamination. The onset of delamination is barely visible to the naked eye and if left unchecked can lead to catastrophic failure. For damage detection in composite structures, commonly used health monitoring techniques are classified into global (vibration based) and local (wave based) approaches. In the present work, Lamb wave based damage detection method is used for interrogation of composite structures.

The ability of Lamb waves to interrogate large and complex structure quickly and the generation (and reception) of Lamb waves using embedded or surface bonded PZT wafers makes them suitable for Structural Health Monitoring (SHM) applications [1, 2]. Wang *et. al.* [3] employed an active Lamb wave diagnostic system to determine the location, size and orientation of the impact damage in carbon fiber reinforced composites. Paget *et. al.* [4] embedded PZT discs on composite laminates and used wavelet transform to study the interaction of Lamb waves with damages like sawcut, delamination and impact damage. Su *et. al.* [5] presented a comprehensive review on the generation and reception of Lamb waves in composites using various physical principles, mode selection for interrogation with damage, signal processing and wave based damage identification algorithms in plate structures.

In Lamb wave based methods, the existence of damage in a structure is generally traced by comparing the wave response of the structure at its present state with a base-line response. The presence of new peaks (scattered waves) compared to the baseline signal is correlated to the presence of damage in the structure. But the limitation is the sensitivity of baseline signals to environmental conditions like change in temperature, moisture affect the damage identification and lead to false predictions. Another major problem of employing Lamb waves for SHM is being multimodal and dispersive in nature which makes it more difficult to analyze and interpret the experimental signals. The effect of damage on the Lamb waves are small comparable to the effects due to geometry of the finite structure which causes dispersion and scattering of waves. To solve the dispersion problem, advanced signal processing techniques based on time-frequency analysis have been employed to extract the useful information from the Lamb waves [6]. But signal processing techniques post process the wave response and remove the dispersion effects. Therefore a new approach is required to make Lamb wave based damage detection method baseline free and also to reduce the dispersion effects of Lamb waves before applying signal processing techniques and one such method is the time reversal method.

2. LAMB WAVES IN COMPOSITES

Lamb waves are plain strain waves that propagate in a free plate guided by the lower and upper surface of the plate. For a given plate thickness and frequency, there are many propagation modes which are grouped into symmetrical and anti-symmetrical fundamental modes. This characteristic distinguishes Lamb waves from bulk waves. The dispersion relation obtained for the symmetric and anti-symmetric modes are referred as the Rayleigh-Lamb dispersion equations. Detailed theoretical and experimental work on Rayleigh and Lamb waves was conducted by Viktorov [7]. A comprehensive discussion on the Lamb wave propagation problem in anisotropic plates is given by Nayfeh [8] and Rose [9].

For a laminated composite structure (Fig. 1), the equation of motion for wave propagation is given by

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial x_j}. \tag{1}$$

Assuming a harmonic wave incident at the x_1–x_3 plane, the displacement field is expressed as,

$$u_j = U_j e^{ik(x_1 + \lambda x_3 - ct)}, \tag{2}$$

where U_j is the amplitude corresponding to different displacement components; $i = \sqrt{-1}$, k is the wave number corresponding to the x_1 direction, λ is the ratio of wave number along the x_3 direction over that of the x_1 direction and c is the phase velocity [8]. Substituting the displacement component u_j into the governing equation of motion (1), we get

$$\begin{aligned}
&\left(C_{11} + 2\lambda C_{15} + C_{55}\lambda^2 - \rho c^2\right)U_1 + \left(C_{16} + \lambda(C_{14} + C_{56}) + C_{54}\lambda^2\right)U_2 \\
&\qquad + \left(C_{15} + \lambda(C_{13} + C_{55}) + C_{53}\lambda^2\right)U_3 = 0 \\
&\left(C_{16} + \lambda(C_{14} + C_{56}) + C_{54}\lambda^2\right)U_1 + \left(C_{66} + \lambda(C_{46} + C_{56}) + C_{44}\lambda^2 - \rho c^2\right)U_2 \\
&\qquad + \left(C_{56} + \lambda(C_{36} + C_{45}) + C_{34}\lambda^2\right)U_3 = 0 \\
&\left(C_{15} + \lambda(C_{13} + C_{55}) + C_{53}\lambda^2\right)U_1 + \left(C_{56} + \lambda(C_{36} + C_{45}) + C_{34}\lambda^2\right)U_2 \\
&\qquad + \left(C_{55} + 2\lambda C_{35} + C_{33}\lambda^2 - \rho c^2\right)U_3 = 0,
\end{aligned} \tag{3}$$

where $C_{ij}(i,j = 1......6)$ is the stiffness matrix of the composite. Since U_1, U_2, U_3 cannot be all zero; the coefficient matrix should be singular and solving it leads to a sixth order polynomial equation in λ. By solving the polynomial equation, corresponding values of λ can be obtained. Therefore at each material point, a complete wave is the sum of six components of the wave and thus the total displacement is sum of them. Stresses can be calculated from the displacement components and applying the traction-free boundary conditions on the boundary, the governing equations for symmetric and anti-symmetric Lamb waves can be obtained. For an uni-directional glass-epoxy

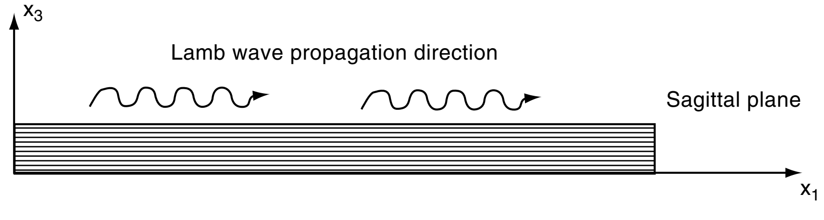

Figure 1. Schematic diagram of Lamb wave propagation in Composite laminate.

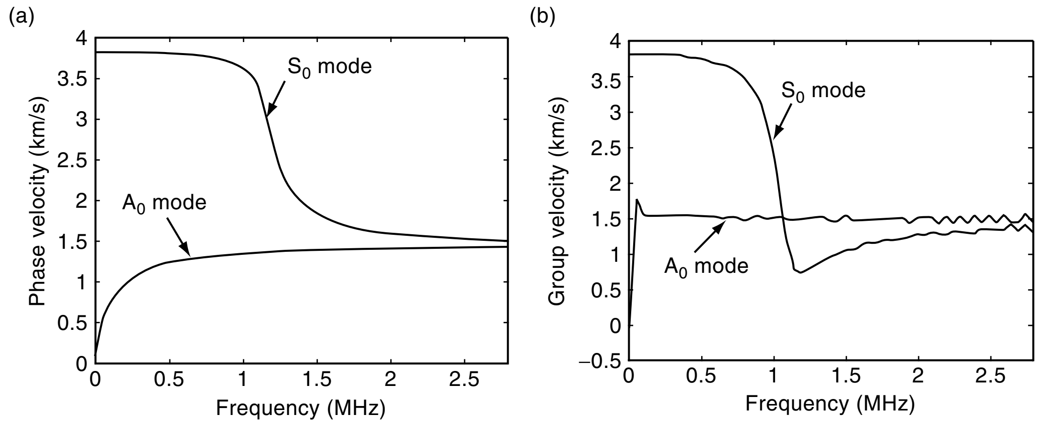

Figure 2. Dispersion curves for Uni-directional Glass/epoxy composite beam (a) Phase velocity vs. Frequency (b) Group velocity vs. Frequency.

composite lamina, the material properties used for calculations are: $E_1 = 30$ Gpa, $E_2 = E_3 = 10$ Gpa, $G_{12} = G_{13} = 4.7$ Gpa, $G_{23} = 3.2$ Gpa, $\gamma_{12} = \gamma_{13} = 0.254$, $\gamma_{23} = 0.428$, $\rho = 2100$ Kg/m^3 and were used to compute the stiffness coefficients C_{ij}. The dispersion curves are computed and shown in Fig. 2. The phase velocity and group velocity of the Lamb wave modes change with the frequency-thickness product and there exit at least two modes for a frequency-thickness product, i.e., they are multi-modal. It is therefore important to take into account both the influence of dispersion and multi-modality in analyzing Lamb waves. Also the dispersion curves give us an idea of selecting the frequency at which a mode propagates with less dispersion.

3. TIME REVERSAL TECHNIQUE

The time invariance and spatial reciprocity form of the acoustic waves propagating in any medium is the main principle behind time reversal technique [10]. For every burst of sound diverging from a source and possibly reflected, refracted, or scattered by any propagation media, there exists in theory a set of waves that precisely retraces all of these complex paths and converges in synchrony, at the original source, as if time were going backward. Time reversal mirror (TRM) uses the above principle for detection of an anomaly, especially in medical imaging. In TRM, one part of the array generates a brief pulse to illuminate the region of interest through any medium [11]. If the region contains a defect, the reflected wave front is selected by means of a temporal window and then the acquired information is time-reversed and reemitted. The reemitted wave front refocuses on the target through the medium. It compensates also for unknown deformation of the mirror array. Although this self-focusing technique is highly effective, it requires the presence of a reflecting target in the medium. Much of the work using time reversal were based on non dispersive waves for medical imaging and very few work has been reported on the use of time reversed Lamb waves for damage detection.

The idea behind Lamb wave time reversal is the shape of the time reversed signal breaks in the presence of a nonlinearity caused by damage. And, this deviation from the original input tone burst signal helps in determining the presence of damage in the structure without requiring the baseline signal for comparison. Time reversal of Lamb waves also helps in spatial and temporal recompression of the wave response and improves the signal to noise ratio. Another advantage of time reversal is the enhancement of the amplitude of the reflected wave from the defect and reduces the spurious reflection effects from the boundaries of the finite structure. Ing *et. al* [12] used time reversal mirror to compensate the dispersion effects of Lamb waves. The authors used TRM in the pulse echo mode to focus and detect flaws in large metallic plate structures. Wang *et. al*. [13] combined time reversal and synthetic aperture technique for imaging the defect in the structure. The authors also shown that it is not possible to reconstruct the original tone burst excitation due to the dispersive nature of the Lamb waves makes. Xu *et. al*. [14] studied single mode tuning effects on Lamb wave time reversal for health monitoring application. They proposed a theoretical model which includes the PWAS model for studying the Lamb wave time reversal behavior in single mode, two modes (S_0, A_0) and verified it experimentally. However the authors did not discuss about the interaction of time reversed Lamb waves with defects in the structure. Gangadharan *et. al*. [15] showed that shape of the time reversed Lamb waves did not change in the presence notch like defect in the aluminum plate. Sohn *et. al*. [16] proposed an enhanced time reversal method for damage detection in composite structures. They employed wavelet transform to improve the time reversibility of Lamb waves. Through the experimental results they showed that the time reversibility breaks in the presence of delamination [17]. However the information regarding the amplitude and dispersion of the time reversed waves due to the presence of damage is not clearly reported. In the present work, the use of time reversed Lamb waves is investigated for SHM applications. Experiments were conducted on glass-epoxy composite plates to study the time reversal behavior of A_0 and S_0 Lamb wave modes. Experiments were also conducted to study the change in shape of the time reversed Lamb wave modes in the presence of delamination type of damage in the composite structure.

4. EXPERIMENTAL STUDY

The experimental setup (Fig. 3) consisted of set of PWAS for actuation and reception of Lamb waves, a NI-PXI 6115 data acquisition card and a voltage amplifier. Using the analog output channel of the NI-DAQ card, a tone burst signal was generated and then amplified using the voltage amplifier to actuate the PZT wafers. The signal picked up by the receiver PZT sensor was filtered using Labview software and transferred to the computer via the NI-DAQ card. The PWAS used were 10 mm in diameter and 1mm in thickness. The sensors were bonded to the surface of the structure using Phenyl-salicylate salt. In this work, all the composite laminates were prepared using hand lay-up stacking of an E-glass unidirectional fiber and epoxy resin. The composites were cured under room temperature for 12 hours at 1bar vacuum pressure. All the glass-epoxy composite plate specimens used for experimental study have dimensions of 360 mm × 360 mm × 2.4 mm.

4.1. Time reversal of Lamb wave modes

The experiments were carried out on a unidirectional glass-epoxy composite plate ($[0_{12}]$) for both broadband and narrowband excitations. The schematic diagram of the composite plate specimen and the location of the PWAS's are shown in Fig. 4. A broadband Gaussian pulse was used to actuate the PZT sensor A and the response picked up by sensor B is shown in Fig. 5a. The Fig. 5a clearly shows that only the A_0 mode was picked up by the sensor and has undergone dispersion resulting in broadening of the pulse. The signal was then time reversed, amplified and re-emitted from the sensor B. The time reversed response was picked up by the sensor A and the reconstructed signal is shown in Fig. 5b. It is noted that, although wave recompression took place as the wave travels towards transducer A, the recompressed wave is not the same as the original Gaussian pulse and this behavior is due to the frequency dependence of the time reversal operation. Nevertheless, these results confirm temporal focusing of the time reversed waves and also enhances the signal to noise ratio.

Next, narrow band hanning window tone burst signal centered at 50 KHz was used for exciting the PZT wafer. The flexural mode was generated in the structure and picked up by the sensor B. The signal

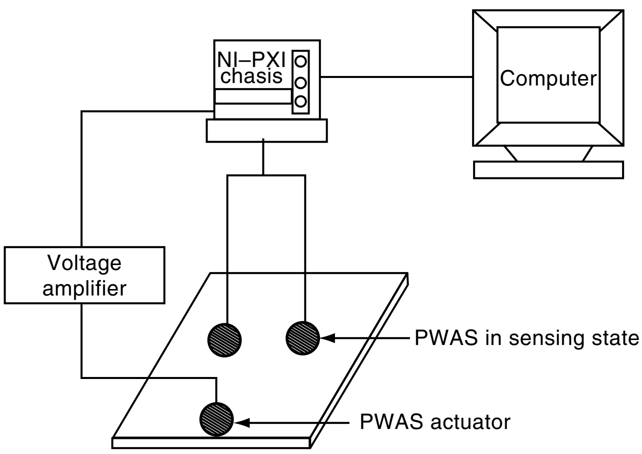

Figure 3. Schematic diagram of the experimental setup.

is then filtered using the Labview tool to remove the noise. A rectangular window function was chosen to retain only the A_0 mode and remove the reflections and other modes present in the signal. This signal is then time reversed, amplified and fed into the NI-DAQ card to actuate the sensor B. The time reversed wave was picked up by the sensor A. The Fig. 6a shows the reconstructed A_0 mode and clearly shows that experimental result closely matches with the time-reversed original tone burst.

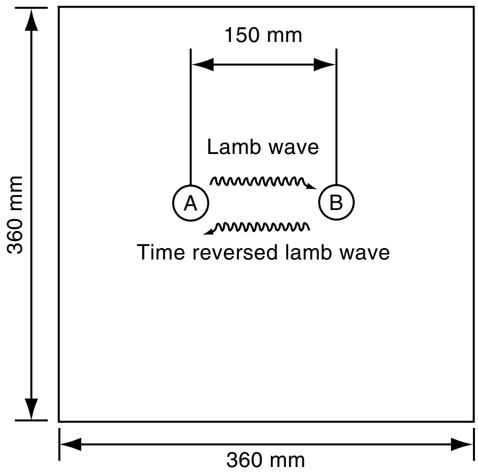

Figure 4. Schematic diagram of the composite plate with PZT sensors.

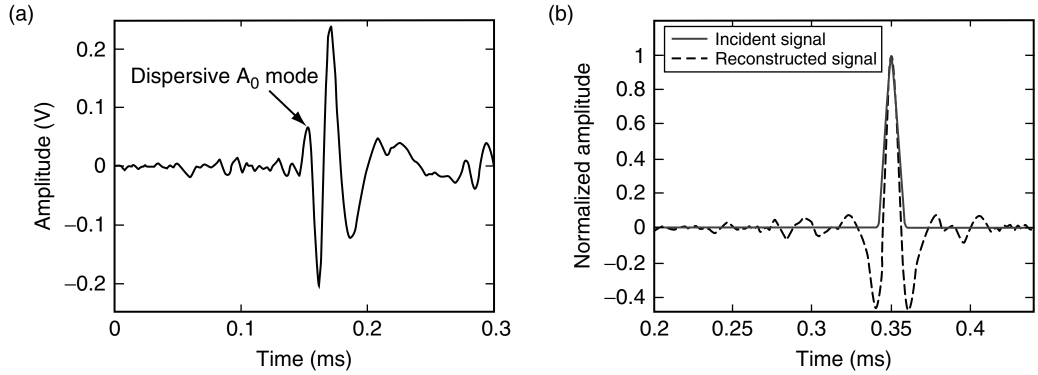

Figure 5. Unidirectional glass-epoxy composite (a) Signal picked up by sensor B under Gaussian pulse (b) Reconstructed signal at sensor A.

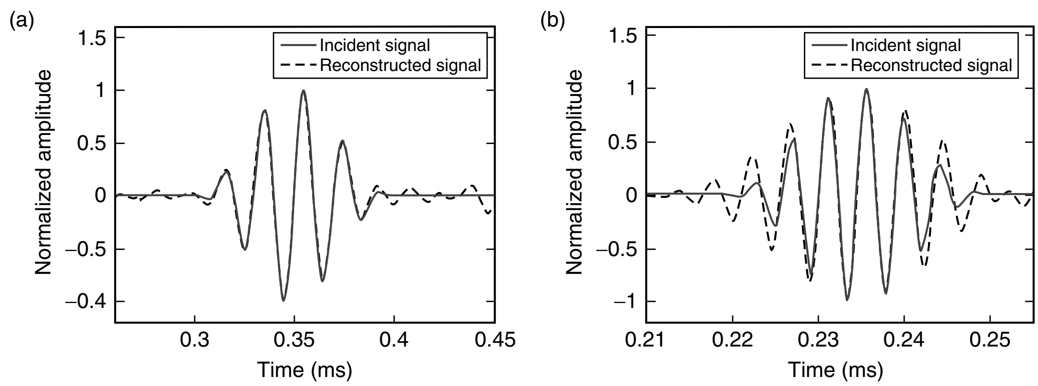

Figure 6. Unidirectional glass-epoxy composite: Time reversed signal picked up by sensor A (a) A_0 mode (b) S_0 mode.

The procedure discussed above for A_0 mode was repeated for the S_0 mode. For generation of S_0 mode, the tone burst pulse centered at 230 kHz was chosen as the response of S_0 mode is high at this frequency. The reconstructed narrowband signal is shown in Fig. 6b. The shape of the original pulse is not fully recovered because the various frequency components of the tone burst signals are differently scaled and superimposed during the time reversal process.

Furthermore, experiments were conducted on the composite specimen to study the similarity of the time reversed signal with the original input signal as a function of number of tone burst cycles. The similarity coefficient is evaluated using the equation,

$$S = 1 - \sqrt{\sum_N \left|A_i - A_j\right|^2 \Big/ \sum_N \left|A_j\right|^2}, \tag{4}$$

where N is the number of samples in the signal, A_i is the time reversed signal and A_i is the incident tone burst signal [14]. The similarity plot for unidirectional glass-epoxy composite is shown in Fig. 7. The similarity coefficient value for S_0 mode increases with the tone burst cycles. For A_0 mode, the similarity coefficient is high compared to S_0 mode and implies that the time reversed A_0 mode is closer in shape to the original tone burst signal.

Similar experiments were then conducted on glass-epoxy cross ply ($[0/90/0/90/09/0]_s$) and quasi-isotropic ($[0/90/45/-45/0/90]_s$)composite specimens to study the similarity coefficient value for the Lamb wave modes. The results are shown in Fig 8 and the study shows that similarity coefficient value for A_0 mode is high compared to S_0 mode. From these results we conclude that A_0 mode is more suitable for Lamb wave time reversal health monitoring applications.

4.2. Time reversal of A_0 + S_0 mode in Cross ply glass-epoxy composite

A broadband Gaussian pulse was used to actuate the PZT transmitter bonded to a cross ply glass/epoxy composite which generated both the A_0 and S_0 mode in the structure. The signal picked up by the PZT sensor is shown in Fig. 9a which clearly shows both the Lamb wave modes. After performing time reversal, three wave packets were obtained in the reconstructed signal as shown in Fig. 9b. The first and third wave packets were symmetrical about the second packet and the second packet resembles the incident Gaussian pulse.

Experiments were then performed under a narrowband excitation tone burst signal centered at 75 KHz. The results are shown in Fig. 10 and clearly indicate that the presence of both the modes introduces additional wave packets in the reconstructed signal. The above experiments show that the generation of both the Lamb wave modes in the structure results in additional wave packets in the reconstructed signal. These additional wave packets can cause problems in implementation of time reversal method as a damage detection technique [14, 18].

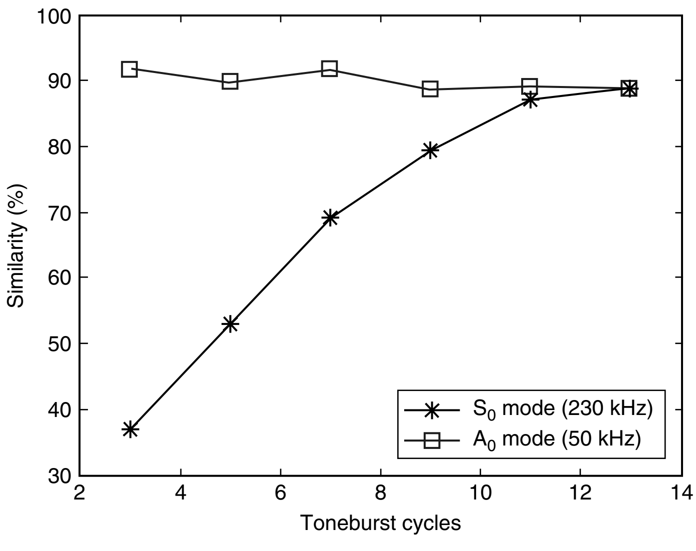

Figure 7. Unidirectional glass/epoxy composite: Similarity coefficient versus tone burst cycles.

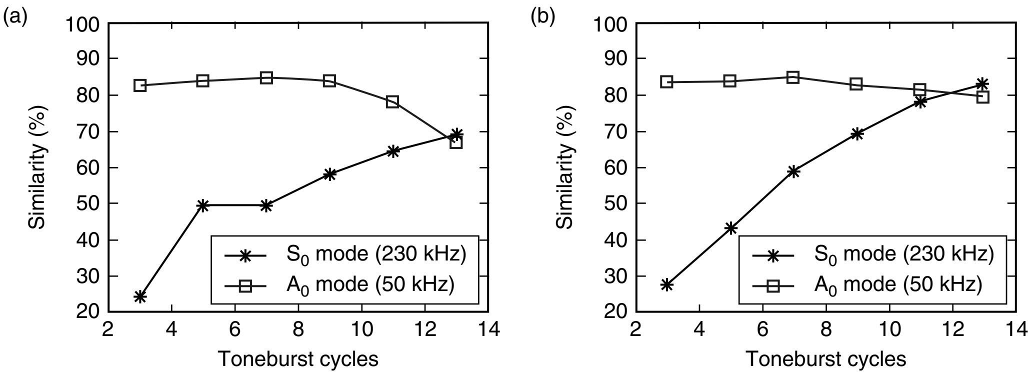

Figure 8. Similarity coefficient plot for glass-epoxy composite (a) Crossply (b) Quasi-isotropic.

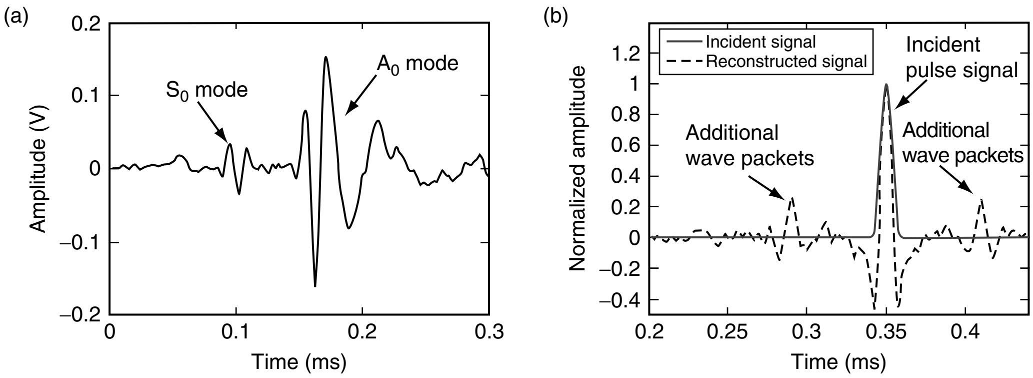

Figure 9. Cross ply glass-epoxy composite plate under Gaussian pulse excitation: (a) Forward propagating Lamb wave picked up by the sensor (b) Reconstructed time reversed Lamb wave picked up by sensor.

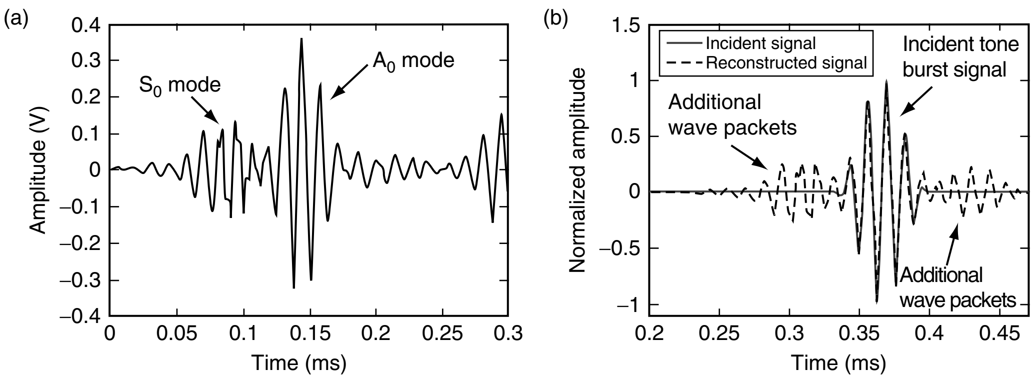

Figure 10. Cross ply glass-epoxy composite plate under narrow band excitation: (a) Forward propagating Lamb wave picked up by the sensor (b) Reconstructed time reversed Lamb wave picked up by sensor.

5. UNIDIRECTIONAL GLASS/EPOXY COMPOSITE WITH DELAMINATION

The experiments were carried out on healthy and delaminated unidirectional glass-epoxy composite plates ($[0_{12}]$) of dimensions 360 mm × 360 mm × 2.4 mm. The delamination was simulated by inserting a release film between sixth and seventh layer in the plate. The delamination dimensions were chosen to be 20 mm in length and 40 mm in width. The schematic diagram of the specimen with PWAS and delamination is shown in Fig. 11. The center of delamination is kept at a distance of 210 mm from the PWAS actuator. A broad band Gaussian pulse was used to actuate the PWAS and the Lamb

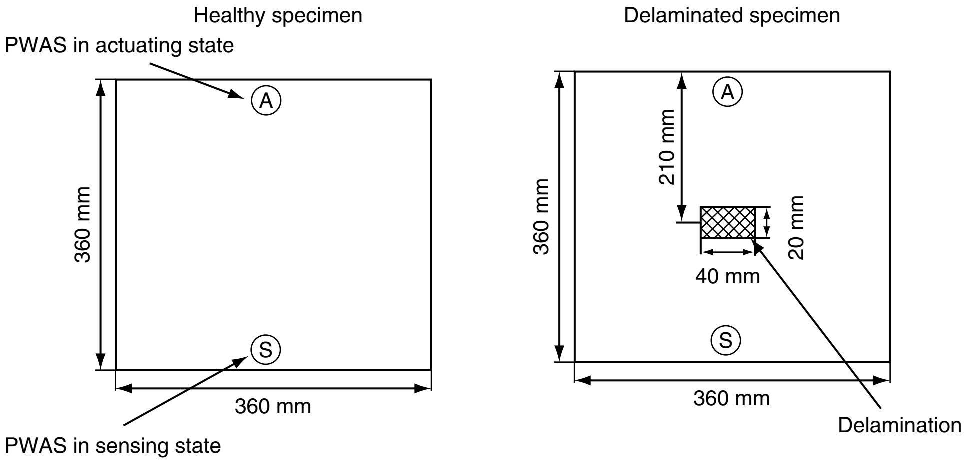

Figure 11. Schematic diagram of the healthy and delaminated unidirectional glass-epoxy composite plate with PWAS sensors.

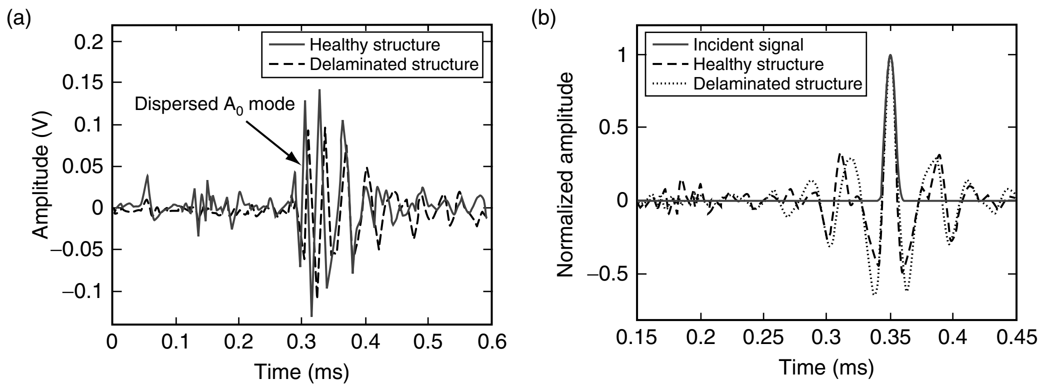

Figure 12. Unidirectional glass-epoxy composite with delamination under Gaussian pulse excitation: (a) Forward propagating Lamb wave picked up by the sensor (b) Reconstructed time reversed Lamb wave picked up by sensor.

wave modes picked up by the sensor for healthy and delaminated plates are shown in Fig. 12(a). Due to delamination there is a reduction in amplitude and time spread of the wave picked up by the sensor (Fig. 12(a)). The time reversed results under Gaussian pulse excitation is shown in Fig. 12(b) which clearly shows the change in the shape of the pulse with delamination. The similarity coefficient computed both for the healthy and delaminated structure is given by 30.15% and 24.51% respectively. The decrease in the value of similarity coefficient indicates the presence of delamination in the structure. Thus Gaussian pulse excitation along with time reversal was used successfully for damage detection in composite plate.

6. T-PULL CARBON-EPOXY COMPOSITE SPECIMEN

Experiments were performed on t-pull carbon-epoxy specimen (Fig. 13) and the change in shape of the time reversed Lamb wave in the presence of delamination was studied. The t-pull specimen was subjected to tensile loading in a universal testing machine. As a result of loading, delamination was induced in the specimen. To begin with the interaction of the time reversed A_0 mode with delamination was studied. A 7 cycle hanning window tone burst signal centered at 50 KHz was used to excite the PZT sensor. Time reversal experiments were performed on healthy and damaged specimens. The forward propagating A_0 mode is shown in Fig. 14a for both healthy and delaminated specimens. Fig. 14b clearly shows that for healthy specimen the time reversed signal closely resembles the original tone burst signal, but for delaminated specimen the shape of the time reversed signal is distorted. The similarity coefficient of the time reversed A_0 mode was computed for both healthy (48.42%) and

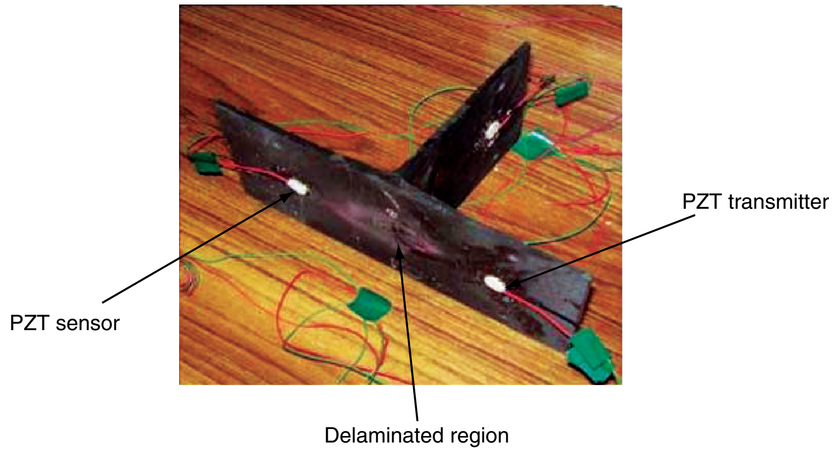

Figure 13. T-pull composite specimen with surface bonded PZT sensors.

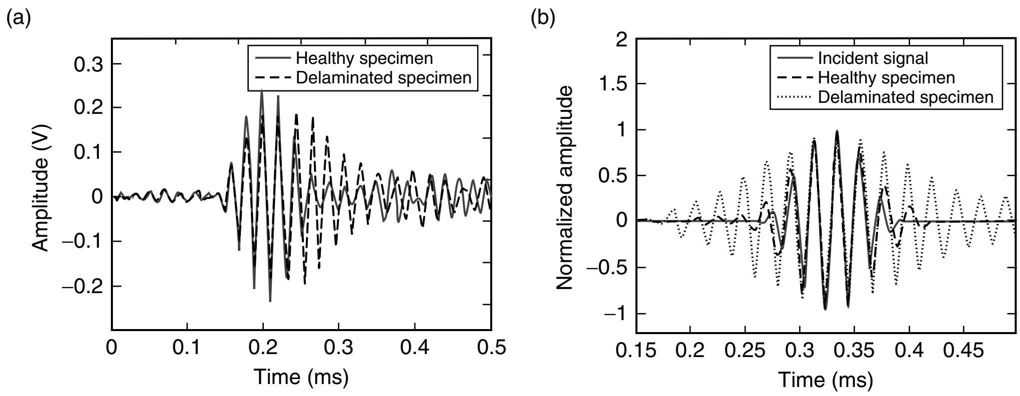

Figure 14. T-pull specimen (a) Forward propagating A_0 mode picked up by sensor (b) Time reversed A_0 mode picked up by sensor.

delaminated structure (14.22%). This result clearly indicates that the delamination breaks the time reversibility condition and the decrease in the similarity coefficient shows the effectiveness of time reversed A_0 mode for damage detection.

Further, time reversal experiments were repeated for S_0 mode on healthy and delaminated specimens. For S_0 mode the similarity coefficient increases with the tone burst cycles and a 13 cycle hanning window signal centered at 230 KHz was used for actuation. The experimental results are shown in Fig 15 and the similarity coefficient of the time reversed S_0 mode computed for both healthy

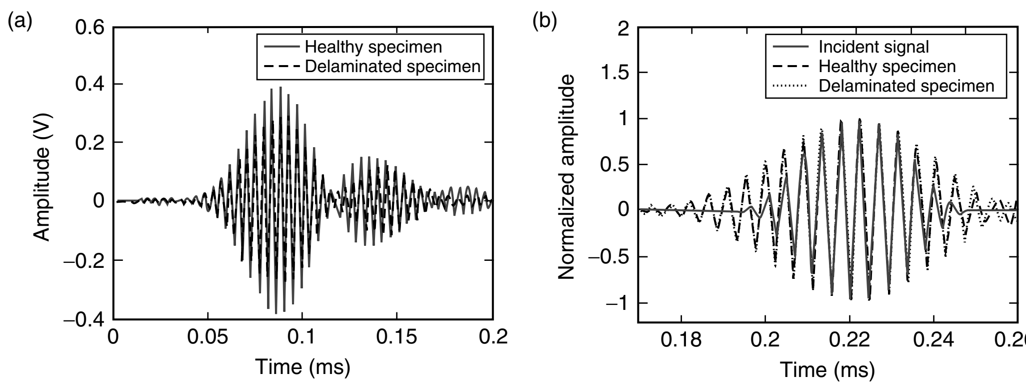

Figure 15. T-pull specimen (a) Forward propagating S_0 mode picked up by sensor (b) Time reversed S_0 mode picked up by sensor.

and delaminated structure is given by 43.80% and 41.80% respectively. The results show that the time reversed S_0 mode has under gone less change in shape due to delamination when compared to A_0 mode. Thus both the A_0 and S_0 Lamb wave modes under narrow band excitation were combined with time reversal for damage detection in t-pull composite specimen.

7. CONCLUSION

Time reversal technique using Lamb waves was investigated experimentally for health monitoring of a composite structure. Experiments were conducted on glass-epoxy composite plates to study the time reversal behavior of A_0 and S_0 Lamb wave modes under broadband and narrowband excitation. The experimental results confirm the spread of the time reversed wave under broadband excitation which is attributed to the frequency dependency of the time reversal operation. The experimental results also showed that the reconstructed time reversed wave closely resembles the narrowband tone burst signal for both the Lamb wave modes. The variation of similarity coefficient with tone burst cycles was obtained for unidirectional, cross ply and quasi-isotropic composite plates. For S_0 mode, the similarity coefficient increases with the number of tone burst cycles. In the case of A_0 mode, the similarity coefficient variation is less with the tone burst cycles. The similarity coefficient is high for A_0 mode compared to S_0 mode and therefore we can conclude that A_0 mode is more suitable for time reversal based SHM applications. Also, time reversal of two ($A_0 + S_0$) modes was studied under broad band and narrow band excitation on cross ply glass-epoxy composite plate and the results showed the presence of unwanted additional wave packets in the reconstructed signal.

Time reversibility of Lamb waves was then studied on a unidirectional glass-epoxy composite and t-pull carbon-epoxy composite specimens for detection of delamination. In the case of glass-epoxy composite plate, the broad band Gaussian pulse was used along with time reversal technique for delamination detection. In the case of t-pull specimen, both the A_0 and S_0 mode under narrow band excitation were combined with time reversal for delamination detection. The results showed that for healthy specimen the time reversed signal resembles the original input signal and for damaged specimen, the presence of nonlinearity due to delamination distorts the shape of the time reversed signal. Thus the above results establish Lamb wave time reversal method as a baseline free technique for damage detection in composite structure.

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