Non-contact Detection of Delamination in Impacted Cross-ply CFRP Using Laser Generated Lamb Waves

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ABSTRACT

Carbon fiber reinforced plastic (CFRP) plate tends to suffer large and complicate internal damages at being impacted. The damage significantly reduces the residual compressive strength, and is needed to be detected by an advanced nondestructive method. Both the real-time source location and non-contact damage inspection systems are important for transportation equipment. We first develop a new source location method of impact position by using the arrival time difference of zero-th order anti-symmetric Lamb waves (A0-Lamb waves) at selected frequency. AE monitoring system was utilized for this study. The arrival times were automatically determined from the peak arrivals of time-transient wavelet coefficients of four AE transducer signals. This system enables us to determine the impact location within two times of plate thickness within 1 second. Next, we propose a non-contact laser ultrasonic system for detecting the damage location and shape in cross-ply CFRP plate impacted by flying steel balls. Delamination shapes were revealed by comparing the cross-correlation and/or amplitude difference of laser Lamb waves over sound and damaged zone. Here, A0-Lamb waves were monitored by scanning both a line focused pulse YAG laser and a probe laser of heterodyne-type laser interferometer at 5 to 10 mm step. Distance between the incident and probe laser was changed from 10 to 100 mm. Double-tree shaped delamination with 25 mm long was revealed in ball hit CFRP plate.

Keywords: CFRP, impact, internal damage, non-contact inspection, laser ultrasonic, AE, lamb-wave, source location

1. INTRODUCTION

Carbon-fiber reinforced plastics (CFRPs) are widely used in transportation equipment due to their high specific strength and stiffness. Upon impact of even moderate energy, CFRPs are likely to suffer internal damages, and the damages significantly reduce the residual compressive strength. Both the real-time monitoring of impact location and the detail inspection of damage shape are important for aviation equipment. Ultimate goal of our research project is to develop a hybrid damage inspection system which involves both the AE (Acoustic Emission) monitoring and the laser ultrasonic inspection techniques as shown in Fig. 1. Here, A0-Lamb waves were monitored by scanning both a line focused pulse YAG laser and a probe laser of heterodyne-type laser interferometer at 5 to 10 mm step. Distance between the incident and probe laser was changed from 10 to 100 mm. Double-tree shaped delamination with 25 mm long was revealed in ball hit CFRP plate.
detection of ultrasonics by laser have been discussed in detail by Monchalin and Heon, Scruby, Wagner and Hutchins. Ultrasonic is generally generated by laser pulses by either adiabatic thermal expansion (rapid heating) or ablation modes. Break down of painted liquid also produces strong ultrasonic. Usefulness of laser-based ultrasonic for monitoring internal damage in thick composite members were demonstrated by R. F. Anastasi et al. In their report, ultrasonic generated by Q-switched YAG laser was detected by a Fabry-Perot laser interferometer, and used for evaluating impact damage and skin/stiffener interlaminar failure by using the time-of-flight change of bulk wave. This is basically a pulse-echo method, and takes a long inspection time. In this study, we have developed a damage inspection system over long distance. We utilized one-directional Lamb waves generated by line focused pulse YAG laser. Delamination in impacted cross-ply CFRP plate was revealed by taking the cross-correlation of monitored waveforms over damaged and non-damaged area.

![Delamination zone and shape](image)

**Fig. 1** Hybrid damage-inspection system for large CFRP structure. AE system for source location in service, and Laser ultrasonic system for damage inspection in a factory.

### 2. SOURCE LOCATION BY LAMB WAVE ANALYSIS

#### 2.1 Materials and Velocity Profile

A plate of [0°/90°]s symmetric cross-ply CFRP plate with 160mm-long × 185mm-wide × 2.4mm-height was prepared by laminating 24 plies of CFRP pre-preg sheets. Carbon fibers were XN-50 from Nippon Graphite Fiber, which were pitch-based with the nominal modulus of 490 GPa. The stiffness coefficients of a unidirectional laminate of the same material were determined by using the laser surface acoustic waves as: C_{11} = 168 GPa, C_{12} = 1.5 GPa, C_{22} = 8.3 GPa, C_{44} = 2.1 GPa and C_{55} = 5.5 GPa. Orientation dependence of phase velocity dispersion in the cross-ply CFRP plate were computed using the Adler's matrix transfer method and shown in Figs. 2 and 3. Here, the velocity dispersions were represented along the X-(outer fiber direction) and Y-direction (90 degree fiber direction) in Figs. 2 and 3, respectively. Layer numbers near the dispersion curves mean that “layer 1” represents only the front 0° lamina, and that “layers 1 and 2” the two layers of 0° and 90° laminas. These curves are for examining the velocity differences of Lamb waves through the delaminated layer. It is concluded that the S_0-wave at lower frequency shows less dispersions but large velocity difference depending on the layer number and orientation, indicating non-welcome mode wave for delaminated plate. Contrary to this, the velocities of A_0-mode Lamb wave at around 0.2 MHz is almost 0.8 to 1 mm/μs, independent on the frequency, layer number and orientation, indicating an appropriate mode for the source location. The S_0-mode waves by impact is generally too weak to be detected, but the A_0-mode shows large amplitude.
Fig. 2  Phase velocity dispersion curves for cross-ply CFRP plate in the outer fiber or x-direction, obtained by the matrix transfer method.

Fig. 3  Phase velocity dispersion in the y-direction of cross-ply CFRP plate.

We measured the orientation dependence of $A_0$-Lamb group velocities. As shown in Fig. 4, the Lamb waves were generated by compression-type ultrasonic transducer with pin and detected by two small transducers (PAC, Type PICO, 4 mm diameter, nominal resonant frequency 0.45 MHz) mounted on circles of 50 and 100 mm radius at angle $\theta$ (measured from the 0° fiber). Examples of detected waveforms and their wavelet coefficients at 260 kHz, in the direction of $\theta = 0°$ (fiber direction), 30° and 90° are shown in Fig. 5. In this study, we used the Gabor function as a mother wavelet function.

Fig. 4  Method for monitoring the Lamb waves propagating in the direction $\theta$. 

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Wavelet transform is useful for determining the arrival-times with a high S/N ratio and sharp peak definition. Arrival time of 260kHz \( A_0 \)-mode at two transducers can be determined by strong peaks. Thus the orientation dependence of the group velocity were determined by dividing the inter-transducer distance (50 mm) by the first-peak arrival time differences \( \Delta t \) of wavelet coefficients at selected frequency. Orientation dependence of \( A_0 \)-Lamb group velocities at 110 and 260 kHz for a cross-ply CFRP are shown in Fig. 6. It is noted that the velocity orientation at 110kHz and 260 kHz is less and approximated by a circle of 1320 and 1380 m/s in the radius, respectively. We should select the frequency by examining the source type or the frequency component of the source. We used group velocities at 260 kHz for pencil lead break source and those at 110 kHz for steel ball drop.
2.2 Source location of impact

2.2.1 Arrival time measurement

Figure 7 shows the schematic illustration of source location method. Source location experiment used four AE transducers. These were mounted on the corners of a 100 mm square on CFRP specimen. The origin of the coordinate is set at the channel 1 transducer. Lamb waves were produced by simulated impacts (pencil-lead break and steel-ball drops) at #1 to #9 positions. Outputs of the transducers were amplified 40 dB and digitized at an interval of 200 ns with 1024 points at 10 bit amplitude resolution, and fed to a PC for analysis. Shown in the top row of Fig. 8 are examples of Lamb AEIs produced by a pencil-lead break (the left) and steel-ball drop (the right) at #2 position, corresponding to the coordinate (50, 75). These waves were monitored by channel 1-4 transducer. The waves produced by the pencil-lead break contains both the S<sub>0</sub>-mode (arriving before 50 μs with high-frequency but low-amplitude) and the late-arriving large amplitude A<sub>0</sub>-mode. The wave due to steel-ball impact contains only the A<sub>0</sub>-mode, having lower frequency and large amplitude. This is because the pencil lead break is the force release at about 1 μs or high frequency source, but the ball drop is the mountain-shaped impact force history with duration of 50 μs. The bottom two figures represent the time transient of 260 kHz wavelet coefficient (the left) and that of 110 kHz. The S<sub>0</sub>-components can not be seen in wavelet figures because of their low amplitude. The arrival times of A<sub>0</sub>-mode can be determined at high accuracy by the proposed method.

Fig. 7 Schematic illustration of source location method of Lamb waves produced by impacts at #1 to #9 positions on CFRP plate.

Fig. 8 Examples of Lamb waveforms (the top) and their time transient of wavelet coefficients at 260 and 110 kHz produced by pencil-lead break (the left) and steel ball drop (the right) on cross-ply CFRP plate.
2.2.2 Source Location Method

We constructed an optimized source location method as shown in Fig. 9. It consists of the following steps: 1) Perform wavelet transform of detected AEs, extracting the A₀-mode component at a selected frequency. This frequency is chosen to be the major component of the observed signals and to best differentiate the desired wave mode from others. 2) Determine the arrival times of the detected waveforms. The arrival time is defined by the first wavelet peak which is larger than 50 % of the maximum peak. 3) Select a zone. Utilizing the sequence of the arrival times, the source location is confined to a zone; e.g., one of the four quadrants for a square four-transducer arrangement (step 1 in Fig.9). 4) Determine the source location by sequentially minimizing the differences of the measured arrival times and the arrival time differences computed by moving a virtual source position in the quadrant determined in the previous step. The position is moved by a preset amount (typically 10 to 20 mm) in the X-and Y-directions. When a minimum is found, the preset amount is halved and a minimum is searched again in the immediate neighborhood (step 2 and 3). This is repeated several times until a certain level of accuracy is achieved. Orientation dependence of the A₀-mode group velocities (Fig. 6) at selected frequency is incorporated.

Source location results are shown in Fig. 10 by symbol X. The estimated source locations agree with the given locations (□) quit well. The source locations were determined within 0.9 mm average error for pencil-lead break, and 1.3mm average error for steel ball drop. Computation time for one source location is less than one second.

![Fig. 9 Algorithm for source location](image)

![Fig. 10 Estimated source location on cross-ply CFRP plate.](image)
3. LASER ULTRASONIC INSPECTION OF INTERNAL DAMAGE

3.1 Specimen and experimental method

We prepared two specimens, i.e., 90mm-long × 90mm-wide (call as a small specimen) and 185mm square (large specimen) cross-ply CFRP plates. Small specimens were firmly fixed by a steel flanges of 61 mm diameters, and impacted by 30 m/s steel ball (ϕ 7mm) at the center on a front surface (layer 1). Force history of impact is shown in Fig. 11. It was estimated by simplex assisted waveform synthesis method5.6,7. We first observed local damages by using the ultrasonic C-scan flaw-detection system (Hitachi AT-5000) from back side (layer 3) of the specimen. It was operated in the pulse-echo mode at 25 MHz using an focusing transducer of 8 mm diameter with a 10 mm focal distance. The right of Fig. 11 shows C-scan result. The center of the images corresponds to the impact point. Ultrasonic C-scan method revealed 50-mm-long double-tree-shaped delamination between layers 2 and 3. Dotted area in right figure indicates search area by our laser ultrasonic system.

The large specimen was firmly clamped by a flange of 160 mm diameter and the center was quasi-statically loaded via steel ball (ϕ 7mm) on a front surface. Load was applied to 440N (deflection of 1.62 mm). For this specimen, we observed 19-mm-long double-tree-shaped delamination between layers 2 and 3.

Next, we detected the impact induced delamination by using the laser ultrasonic or laser surface acoustic wave (SAW) system. The left of Fig. 12 shows a schematic illustration of the system. We excited the guided Lamb waves by an adiabatic thermal expansion of a line-focused Q-switched YAG laser (half-value duration time of 5 ns) with 0.04 mm width and 4 mm length. Lamb waves were excited in the direction normal to the laser line and monitored by a point-focused heterodyne laser interferometer with YAG probe laser at distances of 10 mm (short distance) and 100 mm. The specimen was moved at 10 mm step in the X-direction and 5 mm step in the Y-direction using a computer-controlled X-Y stage. Output of the interferometer was digitized by an A/D converter at sampling intervals of 200 ns. The right of Fig. 12 shows overlapping of SAW incident positions (shown in vertical white line) and detection positions (open circle) on the C-scan image of small specimen.
3.2 Results for Short Propagation Distance or Small Specimen

Figure 13 shows the typical Lamb waves monitored in the x=10mm axis. Waveforms detected over damage area, i.e., (10,20) and (10,30), are much different from those at non-damage area. Our previous study on GFRP with artificial delamination showed that the amplitude of low frequency Lamb waves increased when the subsurface delamination existed\textsuperscript{17}. Peak amplitude of Lamb wave at (10,20) is larger than those of others due to large delamination. The amplitude of lamb wave at (10,30) was very small because the incident line laser is just in the matrix crack. Waveforms themselves clearly indicate the position of delamination. Figure 14 shows wavelet coefficients at 0.9MHz of the waves detected at (10,0), (10,20) and (10,30). The maximum amplitude and peak arrival time of waves at (10,20) and (10,30) are much different from that at (10,10), and can be used for detecting the internal damage.
Two-dimensional distribution of wavelet amplitudes at 0.9MHz over an inspection area is shown in Fig. 15 by gray scale of 15 steps. White part indicates small amplitude and the black the large amplitude. The difference between damage or non-damage area is not so clearly represented. Therefore, we next examined cross-correlation of detected waves. The cross-correlation factor shows the waveform similarity from -1 to 1. Factor 1 represents the best matching. Contour map of correlation factors is shown in Fig. 16. Here the black part corresponds with the factor 1.0. Delamination area is clearly represented by this method.
3.3 Results for Long Propagation Distance or Large Specimen

For the first and fast inspection of damage area in large member, we have to scan the laser SAW at large step for long distance. This method was studied for large specimen with delamination. Laser SAW method and waveform detected are shown in Fig. 17. SAWs were scanned in Y-direction at 10 mm step over 70 x 100 mm area, and monitored by interferometer at 100 mm from the incident line laser. Ultrasonic C-scan revealed delamination at the center. Waveform of $A_0$-Lamb modes resembles each others, but the arrival times of second negative peaks at around 85 $\mu$s change slightly, i.e., later arrival over the delamination area or at Y=20, 30 and 40 mm. Cross correlation or similarity factors of these waves are shown in the left of Fig. 18. Here, the waveform at Y=0 and 60 mm was used as reference patterns. Small coefficients at around 0.98 were found over delamination area. Contour map of correlation factors (waves at Y=60 mm as a reference pattern) is shown in the right of Fig. 18. Small delamination in the large area were clearly detected by contour map of correlation factors.

Fig. 17 Laser SAW inspection method (the left) and Lamb waveforms detected for CFRP plate (right).

Fig. 18 Distribution of cross-correlation factors as a function of SAW propagation position y.
4. CONCLUSION

We developed a new source location method applicable to anisotropic plates, and demonstrated its utility for cross-ply CFRP plates. The orientation dependence of $A_0$-Lamb velocities at selected frequencies, presented by a wavelet transform, was incorporated for the source location analysis. Sophisticated computer system provides 1) wavelet transform, 2) determining the arrival time of $A_0$-lamb waves at selected frequency and 3) computing the source coordinates. The source was first estimated to one of four quadrants within 4 transducers, and then accurately determined by sequential iteration. This processing was performed within 1 second. The source locations of pencil-lead breaks and steel ball drop over $300 \times 300$ mm square enclosed by four transducers on cross-ply CFRP plates were determined with the average error of 13mm.

Laser generated SAW was successfully utilized for detection of internal damage in cross-ply CFRP plate. Guided $A_0$-Lamb waves were generated by a line-focus pulse YAG laser and monitored by a hetero-dyne type laser interferometer. Interlayer delaminations were revealed by taking the cross-correlation of monitored waveforms.

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