ORAL REFERENCE: ICF1001012

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

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ABSTRACT

Structures of Carbon Fiber Reinforced Plastics (CFRPs) tend to suffer serious internal damage when they are impacted by flying objects. The damage significantly reduces the residual strength of CFRP plates and an advanced nondestructive inspection system is needed for maintenance. The aim of this study is to develop such a system for damaged CFRPs by using laser surface acoustic waves (SAWs). SAWs are generated by a Q-switched pulse YAG laser and detected by a heterodyne-type laser interferometer without contact. Both lasers scanned on the surface of damaged CFRPs. Distance between the incident and probe laser was 10 to 100 mm. Delamination shapes were revealed by comparing the similarity of SAWs and wavelet coefficients calculated from detected waves over sound and damaged zone. Internal damage was clearly detected by taking a cross-correlation factor of a wavelet images for a small specimen. Amplitudes of 250kHz wavelet coefficients are used for inspecting a large specimen.

KEYWORDS

CFRP, impact, internal damage, non-contact inspection, laser ultrasonic, surface acoustic wave, cross-correlation, wavelet analysis

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. The thorough inspection of damage shape is important for aviation equipment.

In this study, we develop a non-contact damage inspection system by utilizing a laser ultrasonic system. Usefulness of laser-based ultrasonics for monitoring internal damage in thick composite members was demonstrated by Anastasi et al. [1]. In their report, ultrasonic waves generated by Q-switched YAG laser were detected by a Fabry-Perot laser interferometer, and used for evaluating impact damage and skin/stiffener interlaminar failure by using the time-of-flight scheme of bulk wave. This is basically a pulse-echo method, and requires a long inspection time. In our inspection system, SAWs can cover over a large distance. We utilized directional SAWs generated by a line-focused pulse YAG laser. Delamination in impacted cross-ply CFRP plates was detected using the similarity coefficients of monitored waveforms over damaged and non-damaged areas.

SPECIMENS AND EXPERIMENTAL SETUP

Two types of $[0^o{}_6/90^o{}_6]_{sym.}$ cross-ply CFRP plates were prepared, i.e., 90 mm square (called as a small specimen) and 185 mm square (a large specimen) plates. Small specimens were firmly held by steel flanges of 61-mm diameters, and impacted by a 30-m/s steel ball (7mm) at the front center . The large specimen was firmly clamped between flanges of 160-mm diameter and the center was quasi-statically loaded via steel ball (7mm). Load of 440 N was applied (with the deflection of 1.62 mm).

We first examined local damages by using a ultrasonic C-scan flaw-detection system (Hitachi AT-5000) from the back (layer 3) of the specimens. It was operated in the pulse-echo mode at 25 MHz using a focusing transducer of 8-mm diameter with a 10-mm focal distance. Ultrasonic C-scan method revealed double-tree-shaped delamination (50-mm-long for the small and 19-mm-long for the large specimen) between layers 2 and 3.

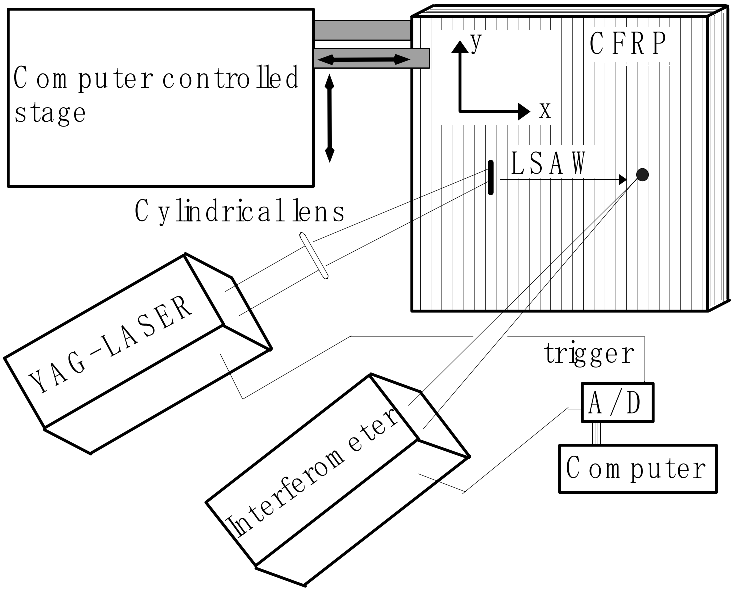

Figure 1: Non-contact impact damage inspection system by using LSAWs.

Figure 1 schematically illustrates the Laser SAW inspection system. The line-focused (0.04mm width and 4mm length) pulse YAG laser beam (half-value duration of 5ns) was irradiated on a surface of the impacted CFRPs. The SAWs are excited by an adiabatic thermal expansion of the surface at the focusing point. SAWs are monitored by a point-focused heterodyne laser interferometer at the distances of 10 mm (for the small specimen) and 100 mm (the large specimen).

The specimen was moved in both X- and Y-direction using a computer-controlled stage. Output of the interferometer was digitized by an A/D converter and fed to a computer for analysis.

RESULTS FOR THE SMALL SPECIMEN

Figure 2 shows the overlay of incident SAW positions (shown in vertical white line) and detection positions (black circle) on the C-scan image of the small specimen. The specimen was moved at 10 mm step in both X- and Y-direction. Typical SAWs detected are shown in the upper row of Fig. 3. SAWs propagate as dispersive Lamb waves. Detected SAWs on the damage area at (x, y) = (10, 20) and (20, 20) are quite different from the wave on the non-damage area at (0, 50). Waveforms themselves clearly indicate the presence of delamination. The middle row of Fig. 3 represents wavelet contour maps calculated from the detected SAWs (upper row). The images of wavelet contour maps show the characteristics of detected SAWs. High frequency components of SAWs are less-affected by the damage between layers 2 and 3. We next calculated low frequency components (250 kHz) of the wavelet coefficient (bottom row of Fig. 3).

Peak amplitudes and peak arrival times at damage areas ((10,20) and (20,20)) changed from those at non-damage area (0,50). We calculated cross-correlation of SAWs by taking the SAW at (x, y)=(0, 50) as the reference pattern. We defined a similarity coefficient (s.c.) as the maximum value of the cross correlation. The similarity coefficients show the waveform similarity from -1 to 1. The s.c. value of 1 represents the best matching. We next compared images of wavelet contour map by taking the image at (x, y) = (0, 50) as the reference pattern. Similarity coefficients for images are defined in our previous paper [2]. Calculated similarity coefficients are given in Fig. 3.

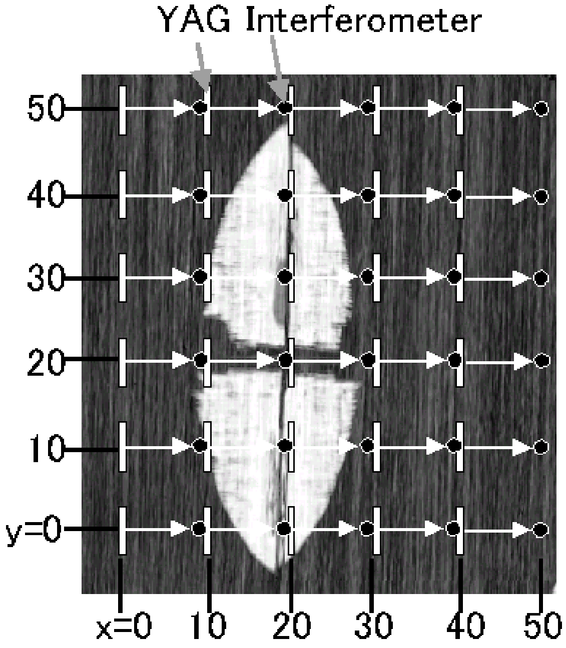

FIGURE 2: Over lapping of C-scan image and laser generated and detected points

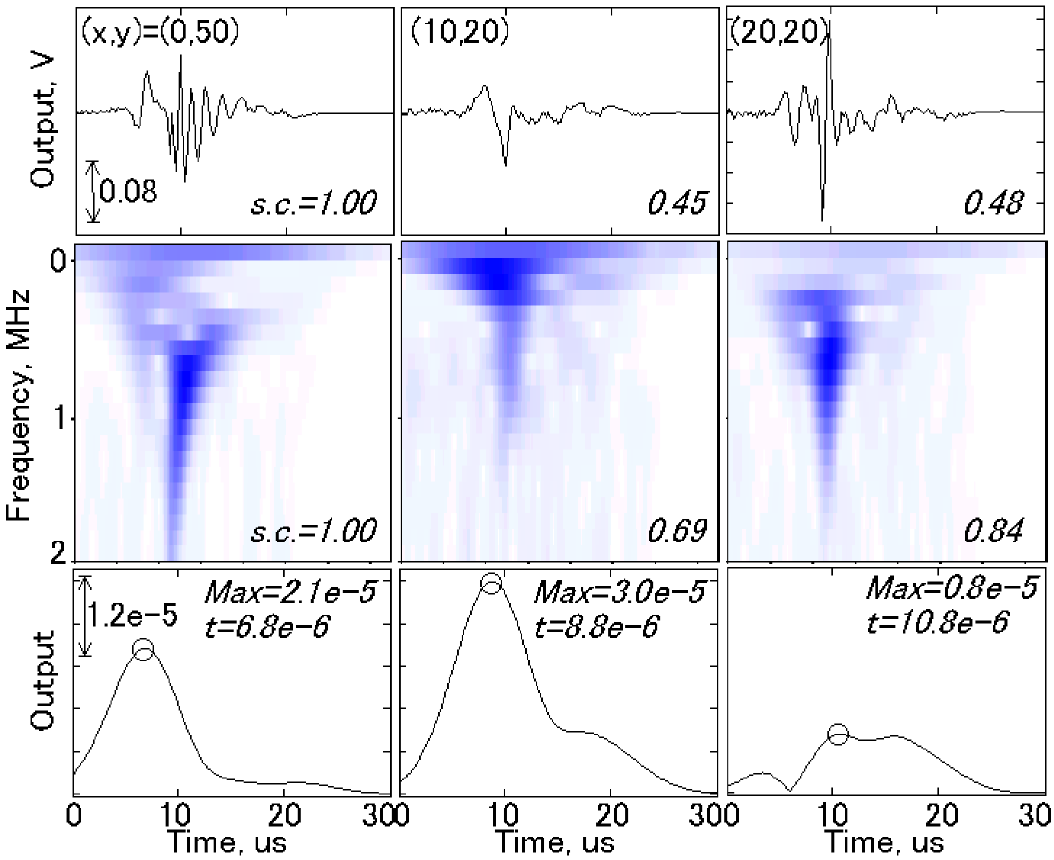

FIGURE 3: Detected waves (upper), wavelet contour map (middle) and 250-kHz wavelet coefficients over non-damaged and damaged area.

Contour maps of correlation factors of waveforms Fig. 4(a) and wavelet contour map Fig. 4(b) are shown. Here the black part corresponds with the correlation factor of 1.0. We next calculated peak-amplitude Fig. 4(d) and peak- time difference Fig. 4(c) of 250kHz wavelet coefficients by taking the coefficient at (0,50) as the reference data. White part indicates a large difference of peak amplitude or peak arrival time. The difference between damage and non-damage areas was small in both Fig. 4(c) and (d). This unsatisfactory result is primarily due to the short propagation length of SAWs (10mm) compared to the wave length of the frequency (250kHz). On the other hand, Fig. 4(a) and (b) clearly revealed the delamination zone. Difference of similarity coefficients is much smaller in (b) method than (a), but (b) method better detected the delamination zone.

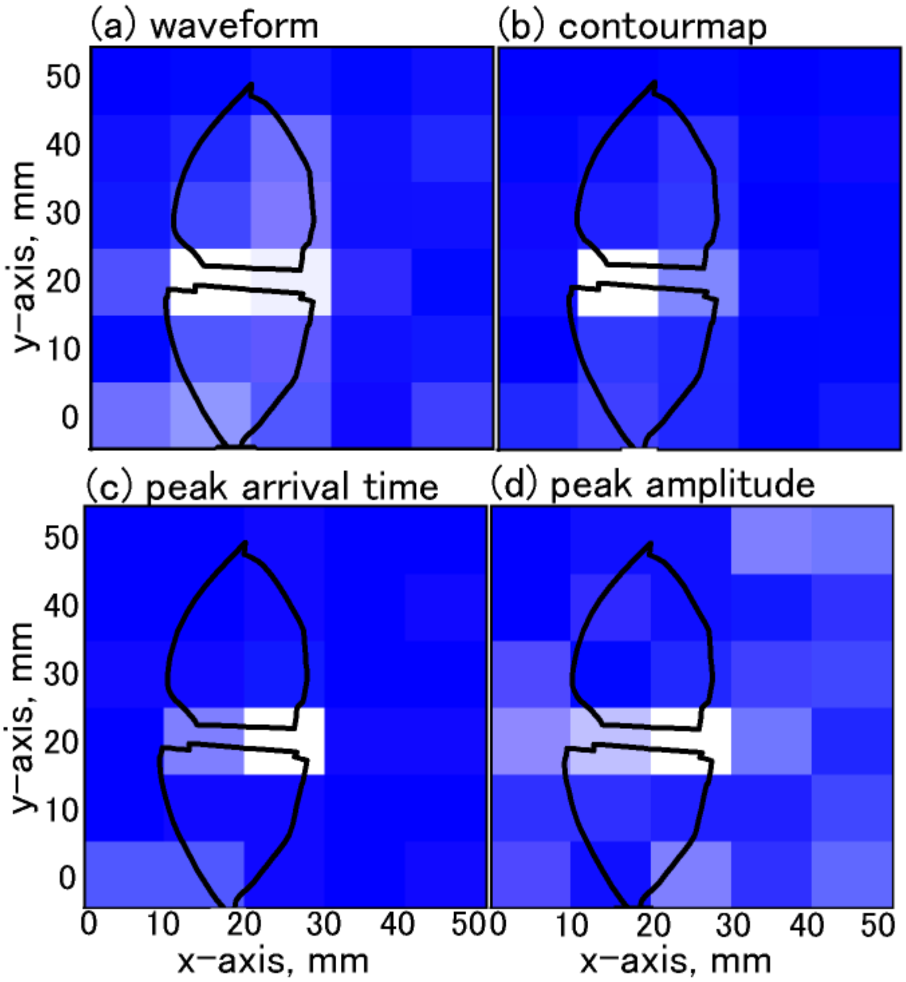

FIGURE 4: Contour map of similarity coefficients (waveform (a) and contour map (b)) and peak arrival time (c) and peak amplitude (d) of wavelet coefficients at 250kHz over an impacted CFRP with internal damage.

RESULTS FOR LARGE SPECIMEN

For efficient inspection of damage areas in large structural members, a laser SAW method is appropriate, but we have to scan the laser SAW at a large step over a long distance. We evaluated this method for a large specimen with delamination. Laser SAW scanning method and waveforms detected are shown in Fig. 5. SAWs were scanned in Y-direction at 10 mm step and monitored by an interferometer at 100 mm from the incident laser. Ultrasonic C-scan revealed delamination at the center as shown. Waveforms of SAWs resemble each other, but the arrival times of the second negative peaks at around 85 μs changed slightly, i.e, later arrival over the delamination area or at y=20 and 30 mm. Values in the figure represent similarity coefficients of these waves using SAW at 60 mm as the reference. Observed changes were too small to be useful. The contour map of similarity coefficients of waveforms is shown in Fig. 7(a). Damage was detected at y=20mm and 30mm axis; however, damage at y=40mm was not clearly detected.

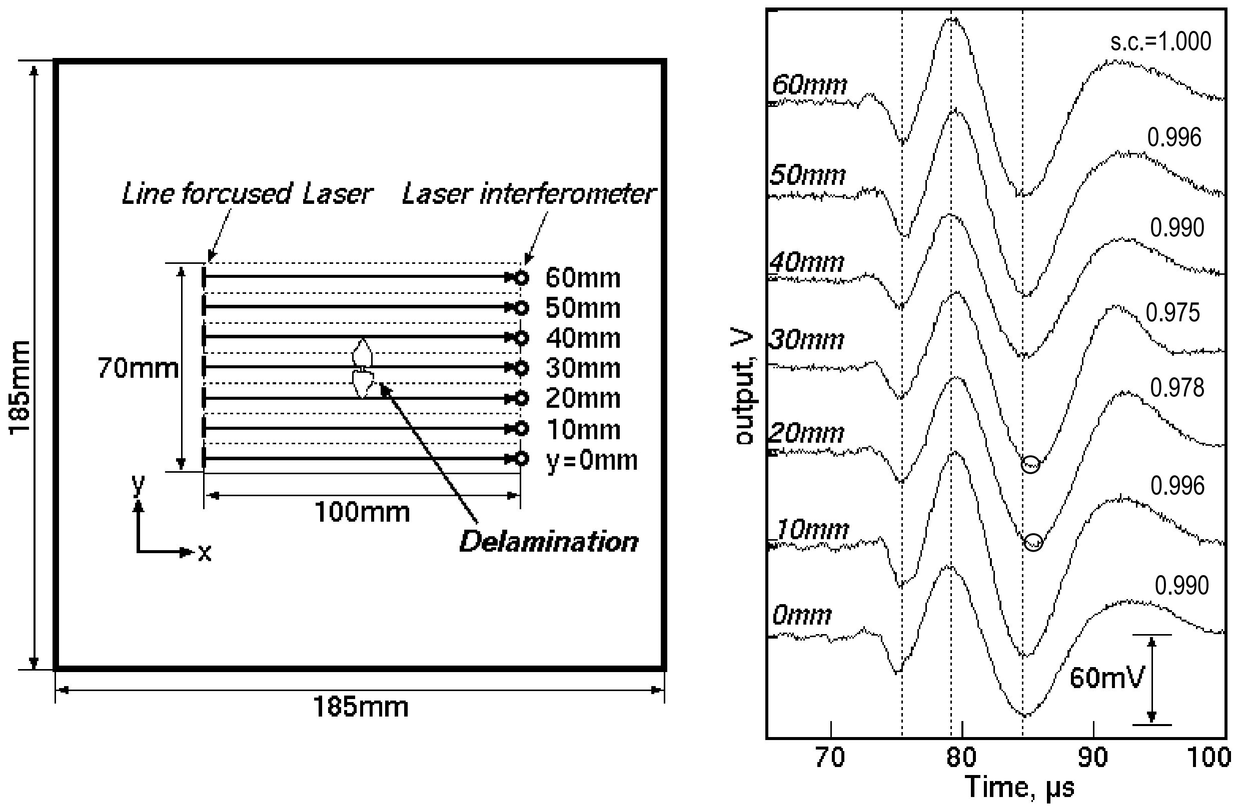

FIGURE 5: Laser SAW inspection method (the left) and Lamb waveforms detected for CFRP plate (right).

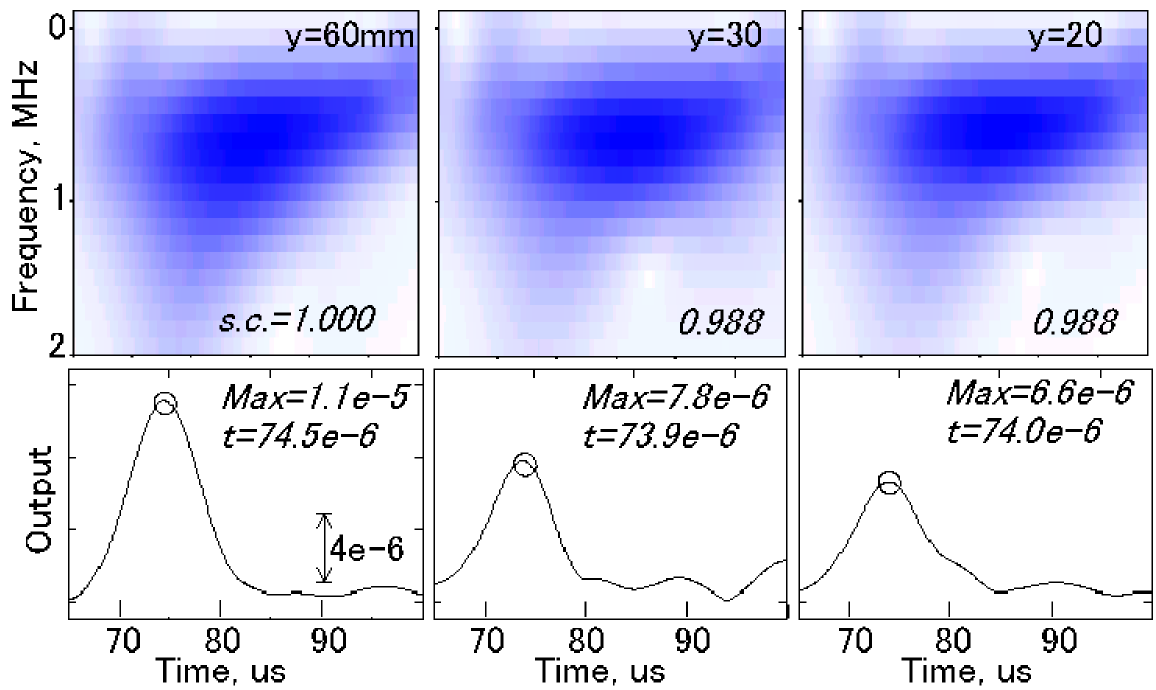

FIGURE 6: Wavelet contour map (top) and 250-kHz wavelet coefficients of detected waves over non-damaged and damaged areas.

We next constructed wavelet contour map (the top of Fig. 6) and calculated 250kHz wavelet coefficients (the bottom of Fig. 6). Wavelet contour maps over damaged (y=20, 30mm) and non-damaged (y=60mm) areas resemble each other, but the peak amplitude and peak arrival times of 250kHz wavelet coefficients show large differences. Similarity coefficients and peak value and peak arrival time are written in the figure.

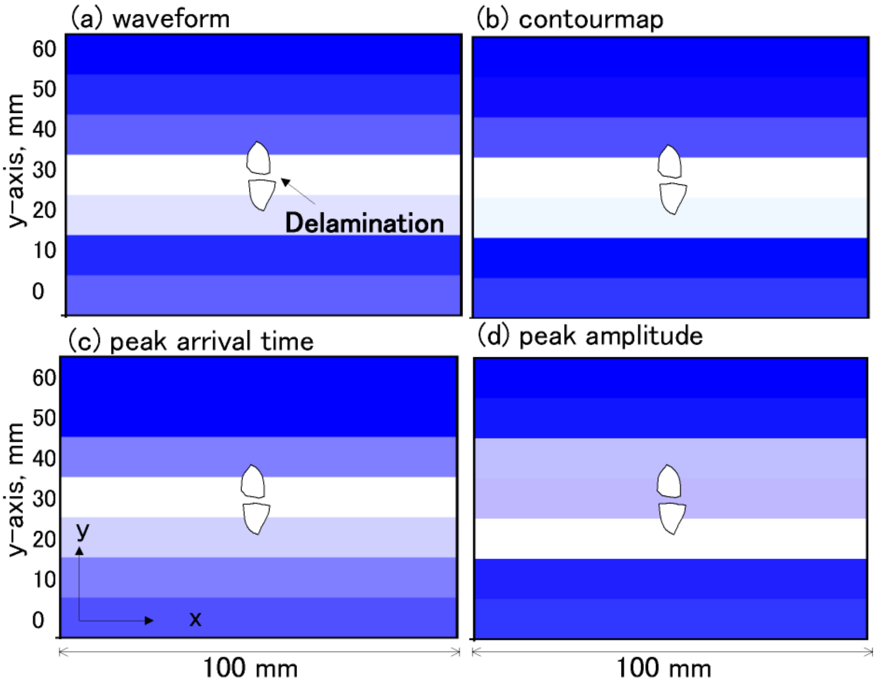

FIGURE 7: Contour map of similarity coefficients (waveform (a) and contour map (b)) and peak arrival time (c) and peak amplitude (d) of wavelet coefficients at 250kHz over an impacted CFRP with internal damage.

Contour maps are constructed by using similarity coefficients and peak value and peak arrival time of 250 kHz wavelet coefficients. The color definition is the same as in the previous section. The damages at y=20mm and 30mm are clearly detected by all the methods; however, only the method (c) detected damage at y=40 mm. This indicates that 100-mm propagation length can be used for 250 kHz SAW inspection. Extracted low frequency components is found to be effective in detecting impact damage.

CONCLUSION

A non-destructive and no-contact impact damage inspection system using laser-induced SAW is developed. SAWs were generated by a line-focus pulse YAG laser and monitored by a heterodyne type laser interferometer. Interlayer delaminations were revealed by similarity coefficients of wavelet contour map of detected waves for a small specimen. 250kHz-wavelet coefficients did not clearly represented the damage due to a short propagation length (10mm). The laser SAW inspection system is also used for a large specimen with the propagation length of 100 mm. For an impacted CFRP with the delamination area of 19-mm-long double-tree-shape, four different methods were utilized to detect the damage. The method using 250 kHz-wavelet coefficients was the most effective.

ACKNOWLEDGEMENT

A part of this research was supported by the fellowship to Y. Mizutani from the Japan Soc. for Promotion of Science and the Circle for the Promotion of Science and Engineering.

Reference

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