EXPERIMENTAL EVALUATION OF DELAMINATION IN CFRP USING LASER-BASED ULTRASOUND

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Abstract. Composite material such as carbon fiber reinforced plastics (CFRP) should be inspected in fabrication process in order to enhance quality by preventing defects such as delamination and void. For the non-destructive evaluation of near-surface delamination in CFRP, generation technique of laser-based ultrasound and reception technique using air-coupled transducer are applied to this study. Technique using air-coupled transducer can make non-contact ultrasonic technique available in evaluation of CFRP. The pitch-catch arrangement using laser-based ultrasound and air-coupled transducer is very attractive for non-destructive testing and evaluation of materials, because it allows one-sided access to the object and is alternative for the immersion testing technique. Wave propagating through delamination region was received with air-coupled transducer and received signal is evaluated by using frequency spectrum analysis and wavelet transform technique.

Introduction

There are many advantages of fiber reinforced plastic (FRP) such as high strength, high stiffness, long fatigue life, low density, and adaptability. FRP is being used in a higher value-added business as space shuttle and leisure industry, etc. So substitution as automation technique satisfied needs of mass production, high precision, reproducibility was researched because of limitations of product design and stacking pattern in existing fabrication process. The fabrication process using recently developed 3-dimensional fiber placement system is stacking the prepreg of a tape shape on the mold automatically according to the designed sequence and thickness. It is possible to reduce production cost and have high precision, reproducibility and productivity by using this process. [1] However there is a possibility to be made defects such as delamination and porosity in this composites fabrication. Therefore, an on-line non-destructive evaluation is required greatly and it is needed to make up for the real-time when the defects occur.

The defect image by ultrasonic C-scan technique among non-destructive evaluation techniques is applied to useful detection technique for the defects of FRP. However, the conventional ultrasonic C-scan technique cannot be applied to inspection in the fabrication process because the test piece is immersed into the water. Therefore, non-contact ultrasonic technique should be applied during the fabrication process without applying the immersion method. For the development of these non-contact ultrasonic techniques, recent the hybrid laser generation and air-coupled detection ultrasonic system that transmit and receive ultrasounds in the air are studied as a non-contact ultrasonic technique available in evaluation of FRP. [2,3]

Therefore, in this study, generation and reception techniques of laser-generated ultrasound and characteristics of received signals upon the internal defects of composite were studied for the non-contact non-destructive inspection of carbon fiber reinforced plastic(CFRP). Research target is top most layer of the composite materials due to generated internal defects in process. In addition, there was an attempt to get the image of the defect by applying scanning laser ultrasonic technique using two types as shown in Fig. 1. [4]

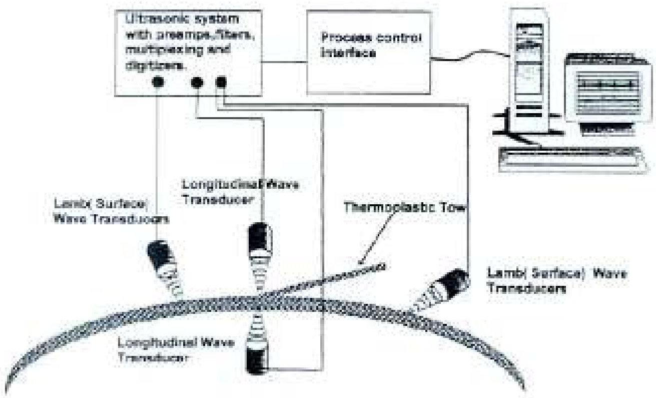
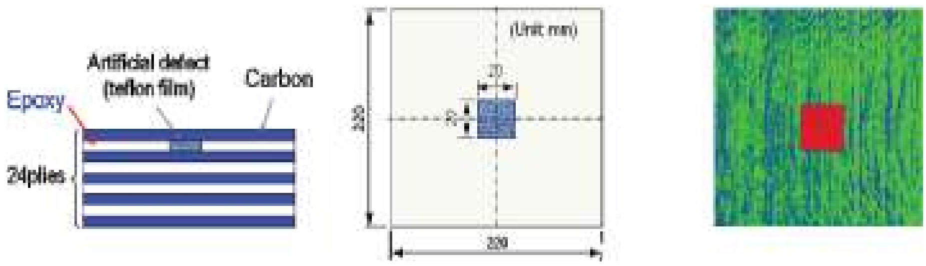


Fig. 1. Possible ultrasonic test configurations for non-contact, on-line monitoring of fiber placement process. [4]

Experimental set-up

In order to assess the inspection capabilities of the non-contact ultrasonic system, tests were performed on a unidirectional Carbon/Epoxy thermoset composite material having the dimension of 220 mm long and 220 mm wide as described in Fig. 2(a). The laminates tested were fabricated with 24 layers and average thickness of the laminates was measured to be about 2.8 mm. Artificial delamination were made of a teflon film which inserted between the first and the second layer. The dimension of the delamination was a square 20 mm on a side. The delamination inside of the CFRP was verified from the ultrasonic C-scan image by the immersion technique as shown in Fig. 2(b).



(a) Dimension (b) C-scan image

Fig. 2. Dimension and location of artificial delamination in CFRP specimen and C-scan image

For generation and reception of ultrasound in the non-contact manner, two kinds of techniques are used. One is laser-generated ultrasonic technique using point source with broad band. In reception of trough-transmitted bulk waves generated by laser irradiation of point source without line array slit in thin plate, the PZT sensor and the air-coupled transducer were applied at the opposite surface. The other is laser-generated ultrasonic technique with line source which uses a line array slit to generate guided wave with narrow band. The guided wave was received on the same surface as the laser irradiation point. The method using a line array slit has several direct advantages as energy density, specific bandwidth, signal-to-noise enhancement opportunity relative to single point generation technique. The air-coupled transducer was used to receive these laser-generated guided waves for non-contact reception. The hybrid laser generation/air-coupled piezoelectric detection system used for composite inspection is shown in Fig. 3.

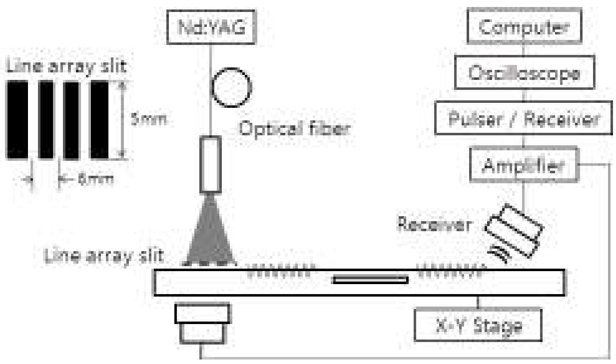
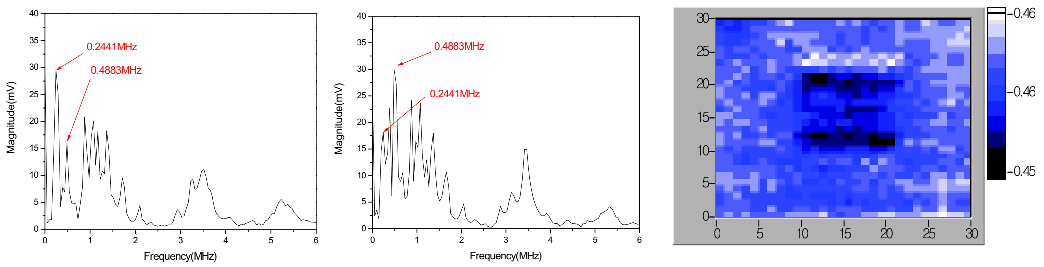


Fig. 3. Schematic diagram of experimental set-up

In this study, wavelength of fiberized Nd:YAG pulse laser system used to generate ultrasonic wave was 532nm. This pulse laser system emitted energy of 32mJ/pulse through the multi-mode optical fiber by fiber coupling. At terminal of optical fiber, the laser beam was outspreaded at an angle of 30 degrees. The distance between the terminal of optical fiber and linear slit array was kept a regular distance and irradiated laser could cover whole area of the linear slit array without additional lens.

Experimental result

Defect signal characteristic of transmitted wave. The characteristic of ultrasonic wave transmitted in bulk wave mode was investigated to evaluate delamination of CFRP. The feature for detecting delamination is represented in frequency spectrum of transmitted wave received by contacting PZT sensor on the surface opposite to laser irradiation point, as shown in Fig. 4. The characteristic variation due to delamination is shown from the variation of magnitude ratio between 244 kHz and 488 kHz components. When there was no defect, the magnitude of low frequency (244 kHz) component was higher than the magnitude of high frequency (488 kHz) components as shown in Fig. 4(a). However, the magnitude ratio was reversed when there was delamination inside CFRP. If there was delamination in wave propagation region, the magnitude of high frequency components became higher and the magnitude of low frequency components became lower as shown in Fig. 4(b). A defect image can be constructed by using this feature as shown in Fig. 4(c). The point source of laser beam for generation and the air-coupled transducer for reception of ultrasonic wave were scanned over CFRP specimen containing delamination. Frequency feature was extracted and represented with color according to magnitude ratio of frequencies. And then delamination region was described with dark in the middle of bright region where there is no defect.



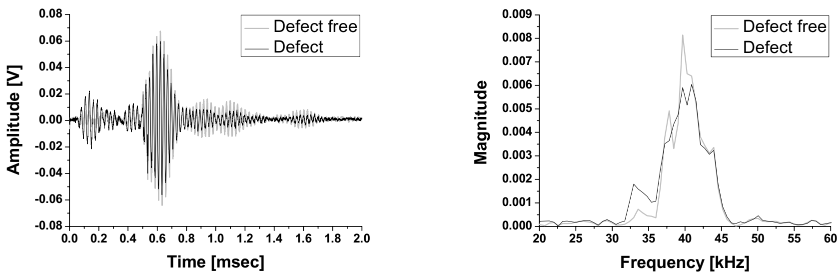
(a) No defect (b) With delamination (c) Laser ultrasonic scanning image

Fig. 4. Frequency spectrums of laser-generated transmitted wave received with 1 MHz PZT sensor and laser ultrasonic scanning image using fully non-contact transmission method

Defect signal characteristic of guided wave. Single-sided access is, in many cases, more realistic. The measurements were based on a test configuration using array laser sources and an air coupled ultrasonic detector optimized for non-contact/remote sensing of surface waves in CFRP. The method to receive leaky wave from defects is to adjust reception angle. It is possible to receive waves reflected from defects as well as leaked through defects. [5]

Fig. 5 shows characteristics of signal received as 6.6 degrees. Fig. 5(a) is a waveform received along the fiber and Fig. 5(b) is a frequency spectrum respectively. Comparing with non-defect region signal, the amplitude of leaky signal which pass by defect region is bigger in time interval between 0.05 msec and 0.3 msec and smaller in time interval between 1 msec and 1.2 msec. These characteristics are confirmed by using wavelet transform as shown in Fig. 6. The magnitude of frequency 40 kHz is bigger at “A” time domain but smaller at “B” time domain.

Distinction of defect region is possible by using peak amplitude at each time domain. Fig. 7 shows peak value which receives at each time domain by line scanning on specimen.



(a) Time of flight (b) Frequency spectrum

Fig. 5. Signal characteristics at defect/defect free region(received angle: 6.6°)

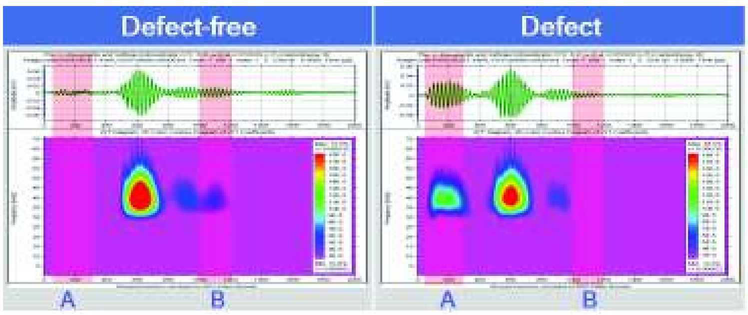
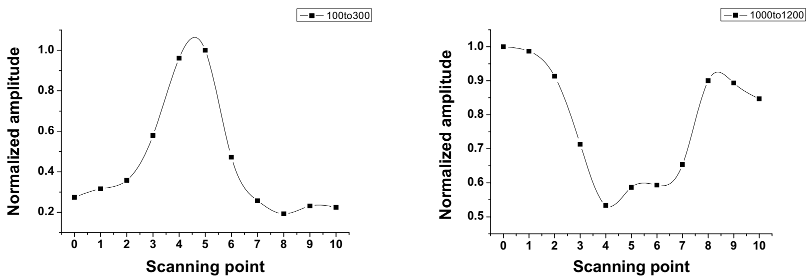


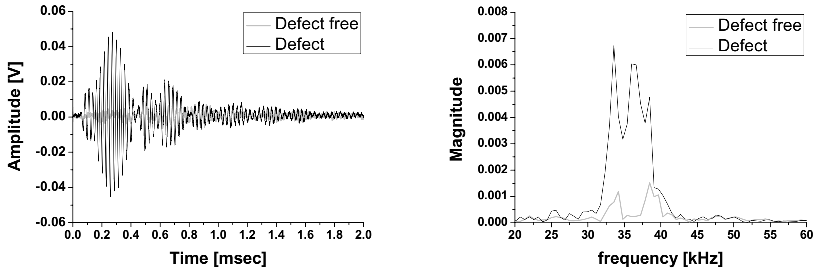
Fig. 6. Wavelet transform analysis of defect/defect free signal(received angle: 6.6°)



(a) A time domain (b) B time domain

Fig. 7. Results of linear scanning passing by defect region(received angle: 6.6°)

Fig. 8 shows characteristics of signal received as -6.6 degrees. We can see certain difference of frequency and waveform at defect region. Leaky wave which is reflected by defect region is not received from defect free region. This result shows that specific signal characteristics appear only at defect region. Fig. 9 is wavelet transformed results of signal at defect and defect free region. The amplitude of waveform and the peak magnitude of frequency 35-40 kHz in “C” time domain are bigger by passing defect region. Results of linear scanning is shown in Fig. 10. It is proved that the amplitude of waveform and the peak magnitude of frequency are parameter of dilamination.



(a) Time of flight (b) Frequency spectrum

Fig. 8. Signal characteristics at defect/defect free region(received angle: -6.6°)

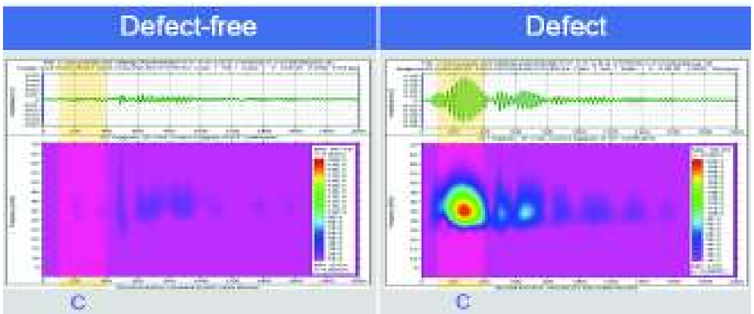
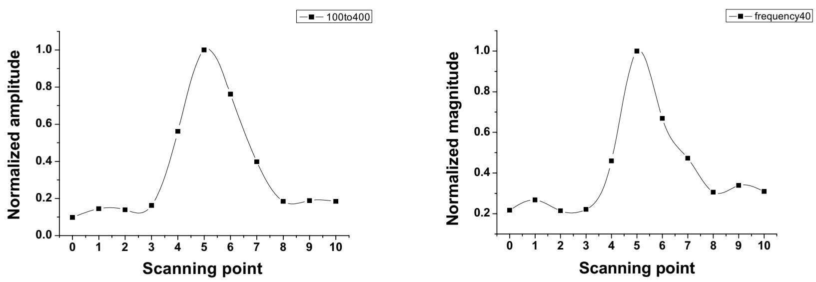


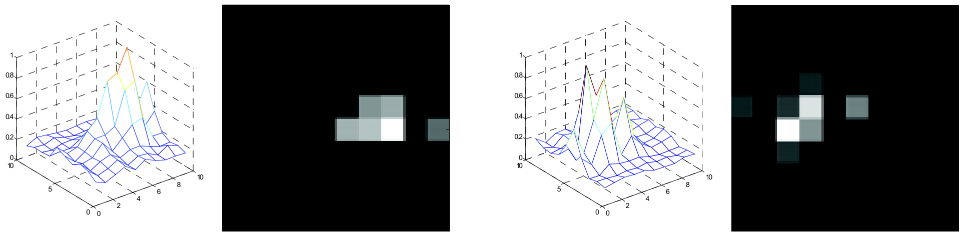
Fig. 9. Wavelet transform analysis of defect/defect free signal(received angle: -6.6°)



(a) C time domain (b) Peak magnitude of 35-40 kHz

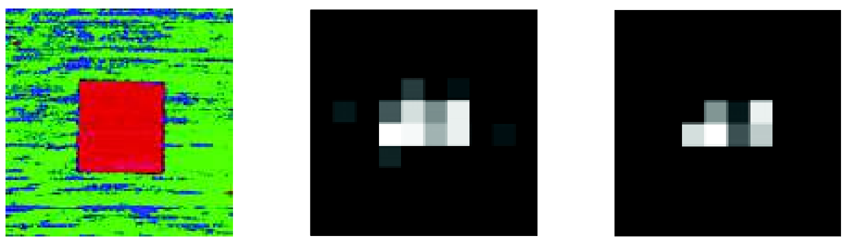
Fig. 10. Results of linear scanning passing by defect region(received angle: -6.6°)

Through signal characteristic received from angle of 6.6 and -6.6 degrees, we get defect images by using laser ultrasonic C-scan technique. Signal is bigger on the edge of defect region. The defect images are not in the center of scanning area because there is interval between leaky and receiving point as shown in Fig. 11. It is possible to move defect location to the center position by using interpolation of receiving distance or time gap. Fig. 12(b) is the result which averages signal data received at each direction for getting reiterated defect characteristic. Fig. 12(c) is the result to multiply signal data which is received at each direction for getting signal property of defect edge. These figures are results of scanning by every 5mm step. Compared with conventional contact C-scan image, result of using laser ultrasonic C-scan is similar to it.



(a) Received angle: 6.6°　　　(b) Received angle: -6.6°

Fig. 11. Laser ultrasonic defect images



(a)　　　(b)　　　(c)

Fig. 12. Comparison with ultrasonic C-scan images of (a) conventional contact type, (b) non-contact laser type using mean value process and (c) using multiply process

Summary

The hybrid ultrasonic system is suitable for non-contact evaluation of subsurface defect in thermoset composite materials. In the thin plate of composite material, it is possible to receive a transmitted wave in bulk mode of laser-generated ultrasound. And the magnitude changing ratio for low frequency components versus high frequency components was represented for sensitive feature to detect delamination. The delamination in CFRP can be detected and scanning image can be obtained to show defect shape by using this frequency feature in non-contact ultrasonic inspection using pulse laser for generating ultrasound and air-coupled transducer for receiving ultrasound. And in case of reception of guided wave using single sided access, it is possible to detect internal defect rapidly by using linear scanning method and obtain 2-dimension defect image by using the amplitude change. The results present these characteristics show possibility for the use of the proposed configuration in on-line control of the fiber placement system with in situ consolidation.

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