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NDE Techniques of Fiber Characterization in Spar Caps of Wind Turbine Blades using Ultrasonic Waves

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ABSTRACT

Recently, ultrasonic waves (UT) have attracted attention as a tool for nondestructive evaluation (NDE) in various fields, including agriculture, medical engineering, and airport security. In this study, carbon fiber reinforced plastic (CFRP) materials are inspected during the fabrication process. Ultrasonic techniques are commonly used to evaluate composites in spar caps of wind turbine blades. Therefore, the fiber orientation and defects of composites are investigated using one-sided ultrasonic measurements to evaluate the soundness of CFRP composites in spar caps of wind turbine blades. Compared with the ultrasonic pulse-echo method, the ultrasonic pitch-catch method is effective in the receiving ultrasonic signals on the composites. Ultrasonic signals must be controlled at arbitrary depths of CFRP composite laminates; this is called a "sampling volume." Therefore, ultrasonic signals can be obtained at arbitrary depths of composites in any sampling volume.

1. Introduction

Recently, there has been a surge in interest towards advanced composite materials consisting of excellent properties such as mechanical characteristics, lightness, and heat resistance, as part of energy saving and new material development efforts. In particular, as a part of renewable energy, wind turbine blades are manufactured using composite materials that have excellent non-stiffness (elastic modulus/strength) and non-strength (tensile strength/density), especially using carbon fiber reinforced plastics (CFRP) for lightweighting of large wind turbine blades [1-2]. When blade production, the CFRP composites are strong to various environmental conditions in use, such as aging, oxidation, waterproofing, weather resistance, electromagnetic wave shielding, and insulation, and the CFRP composites are utilized in various industries such as automobiles, aircraft, ships, and machinery, here for a long use, painting work is required in final finish [3-5].

The carbon fiber direction and defect characterization will be evaluated using ultrasonic techniques for a use of spar caps, which are the core components of wind turbine blades. In particular, the nondestructive testing and evaluation of fiber

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and resin characteristics, as well as the detection of hidden defects inside CFRP composite test pieces, is crucial for obtaining fundamental design data. In this regard, the pitch-catch mode using Rayleigh ultrasonic transducers was employed during ultrasonic testing of a laminated CFRP composite plate, with measurements conducted in accordance with the fiber orientation [6-12]. It was found that one-directional pitch-catch mode measurements could be achievable in all testings, and the desired measurement depth of the test piece could be adjustable [13].

Therefore, if the fiber orientation of the unidirectional CFRP composite laminates is quantitatively evaluated using the Rayleigh ultrasonic testing device, significant progress is expected from the perspective of safety design or advanced material development. Furthermore, a more systematic and quantitative beam profile evaluation technique can be developed through ultrasonic behavior analysis, depending on the presence of defects inside the CFRP composite material. It is confirmed that pitch-catch mode measurement is particularly useful when measuring ultrasonic beam profiles. It is possible to measure the direction and amplitude of the generated waves when there is no gap (skip) between the transmitter and receiver probes on one side of the unidirectional CFRP laminated plate.

2. Ultrasonic system

2.1 CFRP samples

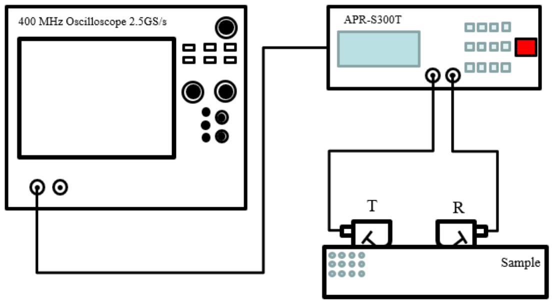
The test specimens used in this study were unidirectional carbon fiber reinforced polymer (CFRP) composite laminates, which were made by stacking unidirectional carbon fiber prepregs combined with epoxy resin (CF/EPOXY) and fabricated using a hydraulic press method. The carbon fibers had a diameter of 7 µm, and the types of test specimens according to the orientation of the test specimen are shown in Table 1. The CFRP composite laminates were produced by stacking unidirectional carbon fiber prepreg sheets combined with CF/EPOXY and using a hydraulic press device.

2.2 Experimental apparatus

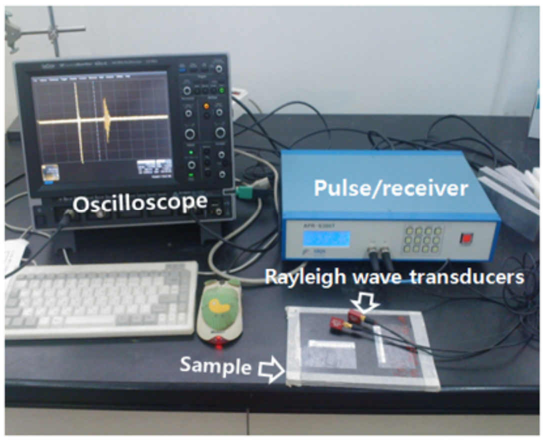
Fig. 1 illustrates the ultrasonic experimental setup system, where Fig. 1(a) shows a schematic diagram of the experimental setup and Fig. 1(b) shows a photograph of the ultrasonic test.

Table 1 Fiber stacking sequences of specimens

Types	Fiber stacking sequences	No. of prepreg sheets [ply]	Thickness [mm]	Materials	
A	[O24]	24	2.7	CF/EPOXY	UT testing
B	[O48]	48	4.9	CF/EPOXY	
C	[O96]	96	9.0	CF/EPOXY	



(a) Schematic diagram of ultrasonic setup



(b) Ultrasonic setup system

Fig. 1 Ultrasonic schematic diagram of ultrasonic testing setup

The experimental method used a direct rail lay ultrasonic probe and AIQS's APR-S300T PR spike voltage pulser/receiver to generate ultrasonic waves. The RF waveform due to the test specimen was acquired on an oscilloscope (Wave Surfer 42Xs-A) and stored on a computer.

Several echo waves can be independently moved on the screen and are convenient for measuring by saving and comparing signals.

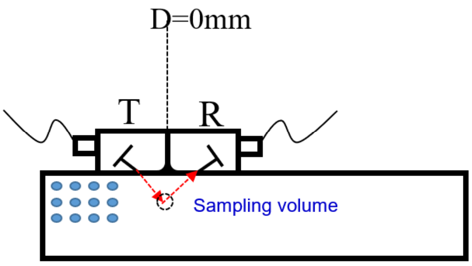
In this experiment, in cases where the thicknesses of CFRP composite laminates are different and thicker, attenuation and scattering were significant in measuring signals; so two Rayleigh ultrasound transducers were used to maximize the ultrasound signals. Therefore, a low frequency suitable for composite

Fig. 2 Ultrasonic wave transducers for generating Rayleigh wave

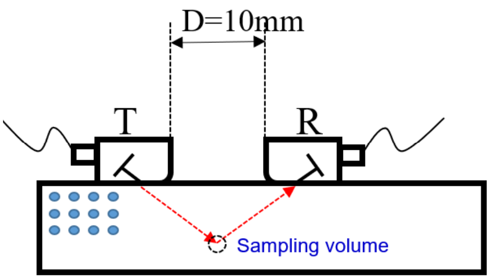
materials, 2.25 MHz, was used in this experiment. Fig. 2 shows the two probes used in the experiment, which are Harisonic's 2.25 MHz Rayleigh ultrasound transducers (90° ST).

2.3 Experimental method

The experimental setup for ultrasonic testing consisted of a Digital Storage Oscilloscope (DSO) (Lecory, Wave Surfer) that digitized ultrasonic signals and converted them to PC, a peak-to-peak amplitude gauge, and a pulsar receiver (AIQS, APR-S300T) capable of transmitting and receiving 250,000 bits of data per second up to a distance of 1000 m. Rayleigh ultrasonic probes were used as the transducers. In particular, as shown in Figs. 3-4, when two ultrasonic probes are used in pitch-catch mode on one side of the test piece, the probe separation distance

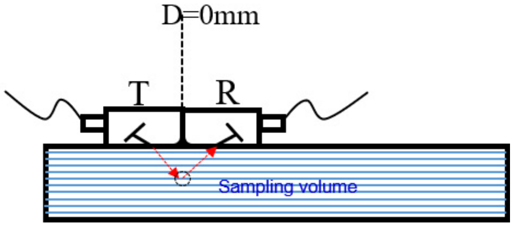


(a) In case of 0 mm of probe separation distance

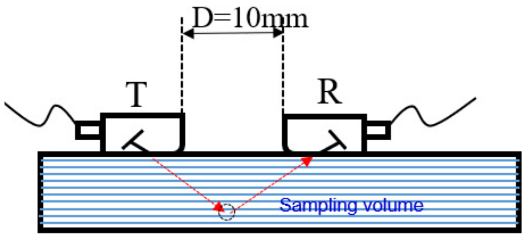


(b) In case of 10 mm of probe separation distance

Fig. 3 One-sided measurement method normal to fiber of samples



(a) In case of 0 mm of probe separation distance



(b) In case of 10 mm of probe separation distance

Fig. 4 One-sided measurement method along fiber of samples

(D) between the transmitting and receiving probes can be adjusted. Figs. 3(a) and 4(a) show the signal from the "sampling volume," which is the location of ultrasonic reflection when the probe separation distance is 0 mm. Figs. 3(b) and 4(b) show the signal from a deeper reflection location of the "sampling volume" when the probe separation distance is 10 mm. The test piece's "sampling volume" can be controlled to reflect defects or fiber orientation at any depth. Therefore, if the "sampling volume" is matched with a defect, the defect can be evaluated. In addition, Fig. 3 shows the ultrasonic measurement of the fiber perpendicular to the fiber orientation (normal to fiber⊥) at both ends of the CFRP composite material, while Fig. 4 shows the ultrasonic measurement of the fiber parallel to the fiber orientation (along fiber=) at both ends.

3. Experimental results and discussion

3.1 Pitch-catch mode analysis

Fig. 5 shows the direction of ultrasound generated from the Rayleigh transducers used in pitch-catch mode. Pitch-catch mode measurement is very useful when measuring in one direction of the test piece. Fig. 5 illustrates the shape of the transducers and the direction of the wave generated when there is no skip between the transmitting transducer T and the receiving probe R on one side of the CFRP laminate. Contact

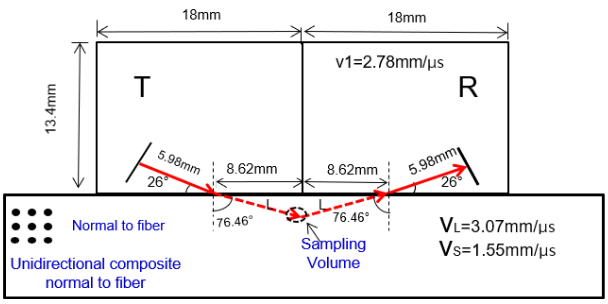
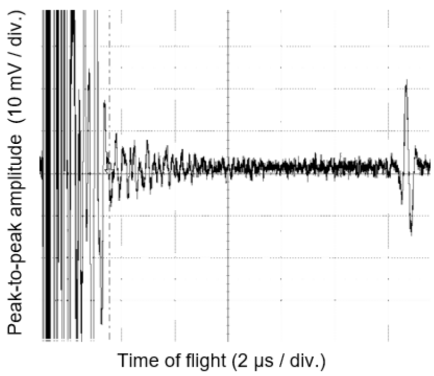


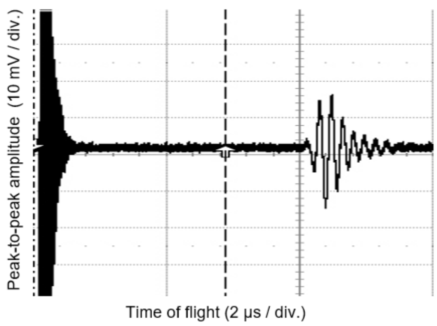
Fig. 5 Analysis of pitch-catch ultrasonic measurement

media is required to generate ultrasound on the test piece. The "sampling volume" in Fig. 5 can be calculated by the time-of-flight at any depth of the test piece. The pitch-catch signal is captured as the distance (skip) between the two probes increases.

Two Rayleigh ultrasound transducers were used, and the direction of ultrasound propagation can be easily predicted by considering the angle of the vibrator and the physical properties, such as ultrasound velocity and all transformations, from these two transducers. Fig. 6 compares ultrasonic signals obtained using pulse-echo mode and pitch-catch mode with a 2.25 MHz frequency ultrasound transducer. In Fig. 6(a), many backscattering signals can be observed in the surface signal image, which may be caused by signals reflected from the fibers of the CFRP laminate in a unidirectional test specimen. However, in Fig. 6(b), only ultrasonic signals reflected from the "sampling volume" are shown, and the influence of other signals cannot be seen. This is because the ultrasonic transducer has the ability to obtain only the reflected signals from the "sampling volume" due to its characteristic of expecting any angle in undirectional CFRP composites.



(a) In case of pulse-echo mode



(b) In case of pitch-catch mode

Fig. 6 Comparisons between pulse-echo mode and pitch-catch mode

3.2 Analysis for normal to fiber

As shown in Fig. 3, the Rayleigh ultrasonic transducer was used to represent the unidirectional pitch-catch mode with the ultrasonic probe perpendicular to the fibers in the CFRP composite laminate. In particular, Fig. 7 shows the amplitude of the ultrasonic signal in the unidirectional pitch-catch mode for a 24-ply unidirectional CFRP composite laminate. In this case, three typical peak signals can be observed, and the flight time (TOF) and amplitude are measured while continuously measuring the flight time and amplitude while adjusting the "probe separation distance" of the two ultrasonic Rayleigh transducers.

First, Fig. 8 shows results for a 24-ply unidirectional CFRP composite. In particular, as shown in Fig. 8(a), the yellow shaded box indicates a significant range of variation in the ultrasound beam profile. Fig. 8(a) shows the peak-to-peak amplitude of five ultrasonic signals at different transducer distances, while Fig. 8(b) shows the relationship between transducer distance and time-of-flight (TOF). In Fig. 8(a), the

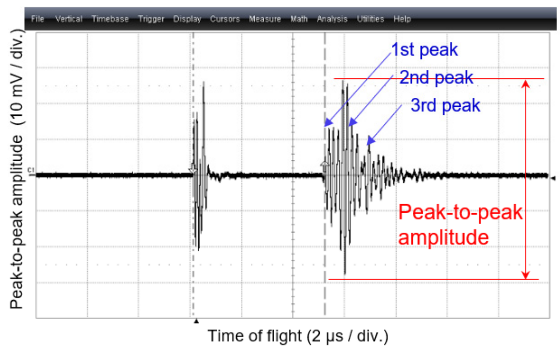
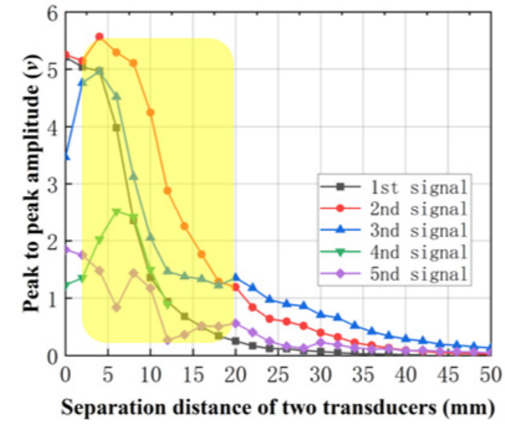
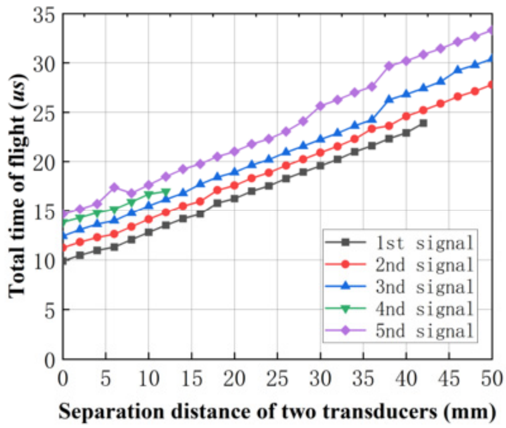


Fig. 7 Ultrasonic signal of Rayleigh wave transducers based on one-sided pitch-catch mode normal to fiber (24ply)

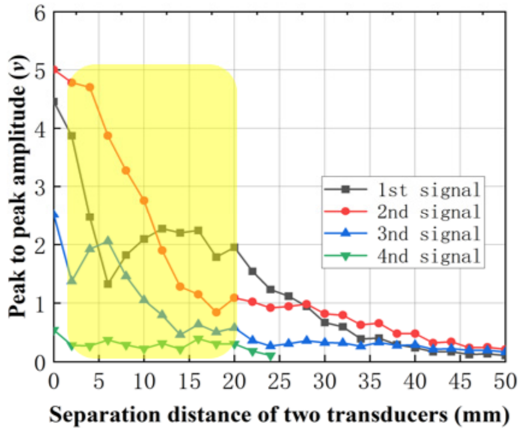


(a) Peak-to-peak amplitude

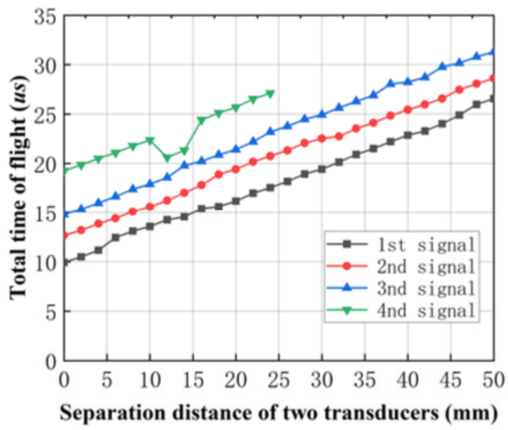


(b) Time-of-flight

Fig. 8 Peak to peak amplitude (a) and time-of-flight (b) of pitch-catch signal in one-sided beam profile experiment on 24ply CFRP laminate



(a) Peak-to-peak amplitude



(b) Time-of-flight

Fig. 9 Peak to peak amplitude (a) and time-of-flight (b) of pitch-catch signal in one-sided beam profile experiment on 48ply CFRP laminate

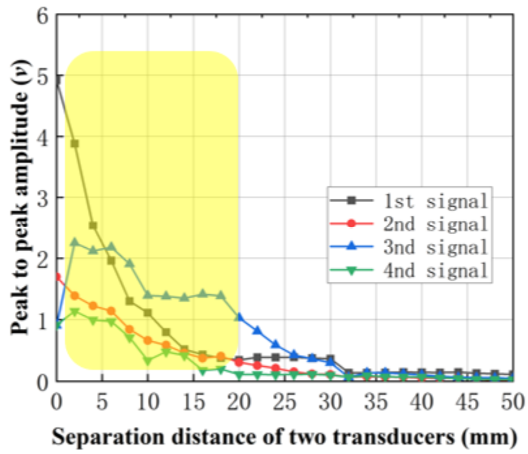
peak-to-peak amplitude signals of the first two ultrasonic signals are very strong, but those of the fourth and fifth are weak. As the probe distance increases, the peak-to-peak amplitude values decrease slightly, but the second ultrasonic signal appears somewhat larger. It is considered that the ultrasonic signals are received with very high sensitivity while adjusting the probe distance, and the beam profile characteristics of each ultrasonic signal can also be identified. Fig. 8(b) shows the relationship between probe distance and TOF, where TOF increases as the probe distance and each ultrasonic signal increases. This is a phenomenon that occurs as the ultrasonic propagation distance increases.

First, Fig. 9 shows results for a unidirectional CFRP composite material stacked with 48 plies. Fig. 9(a) shows the peak-to-peak amplitude and distance of 4 ultrasonic signals, and Fig. 9(b) shows the relationship between the ultrasonic transducer distance and the time of flight (TOF).

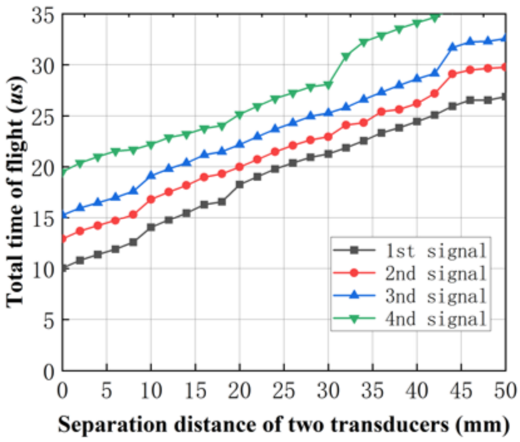
In Fig. 9(a), the beam profile was received with 4 ultrasonic signals and the peak-to-peak amplitude and distance relationship was shown. Especially, the first ultrasonic beam profile had a low amplitude at first, but a large beam profile was observed when the ultrasonic transducer distance was around 10 mm. It was confirmed that the receiving ultrasonic probe was operating optimally at the optimal position.

Fig. 9(b) shows the relationship between the ultrasonic transducer distance and the time of flight (TOF), showing that the TOF increases as the ultrasonic probe distance increases. Here, the fourth ultrasonic TOF showed some significant changes around the ultrasonic probe distance of 12 mm. This is thought to be due to the anisotropy of the composite material and some effects of the test conditions.

First of all, Fig. 10 shows results for a unidirectional CFRP



(a) Peak-to-peak amplitude



(b) Time-of-flight

Fig. 10 Peak to peak amplitude (a) and time-of-flight (b) of pitch-catch signal in one-sided beam profile experiment on 96 ply CFRP laminate

composite material stacked with 96 plies. Fig. 10(a) shows four ultrasonic signals, each representing the peak-to-peak amplitude and ultrasonic transducer distance, and Fig. 10(b) shows the relationship between ultrasonic transducer distance and flight time (TOF).

Fig. 10(a) represents the relationship between ultrasonic transducer distance and peak-to-peak amplitude, where four ultrasonic signals were generated and beam profiles were received. In particular, the first ultrasonic signal was the largest, and attenuation could be observed with respect to ultrasonic distance. The third ultrasonic signal showed the largest amplitude when the ultrasonic distance exceeded 7 mm.

For 24, 48, and 96 plies, five or four peak-to-peak ultrasonic amplitudes were measured, but by acquiring more effective amplitude data, it was possible to mainly specify three ultrasonic amplitude signals. Such things could be an

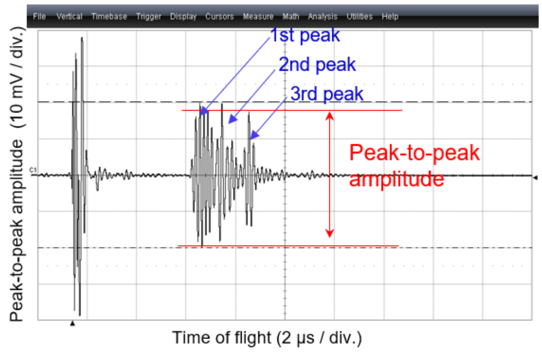


Fig. 11 Ultrasonic signal of Rayleigh wave transducers based on one-sided pitch-catch mode along fiber (48 ply)

evaluation parameter for NDE evaluation through the effective ultrasonic amplitude range. Additionally, in Figs. 8-10, the yellow box area in the ultrasonic amplitude results could be considered as the effective ultrasonic measurement range.

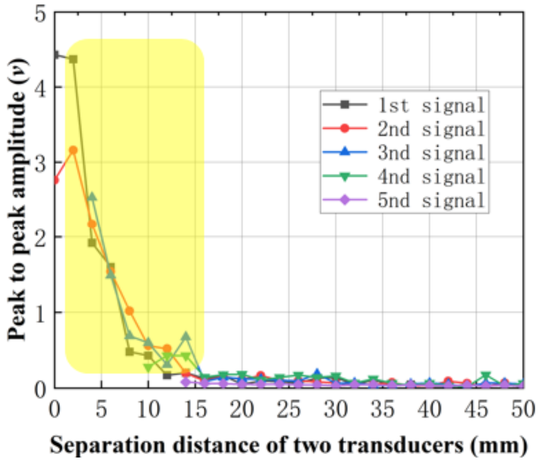
Generally, the first ultrasonic amplitude value occurs prominently, but in 24 and 48 plies, the test specimens were somewhat thin, and various reflection wave effects were considered. However, in the relatively thick 96-ply, the influence of reflection waves was relatively reduced.

Fig. 10(b) shows that, as ultrasonic transducer distance increases, flight time (TOF) also increases, as shown in the waveforms displayed for both 24 and 48 plies.

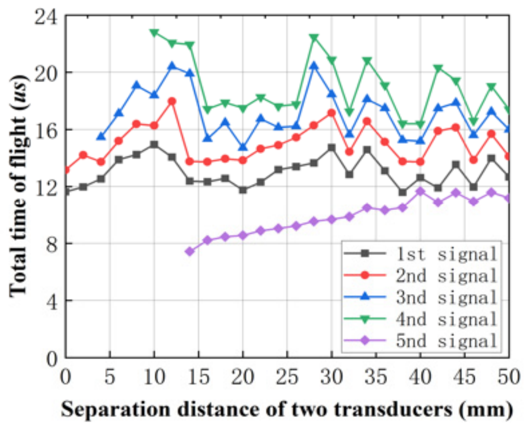
3.3 Analysis for along fiber

Firstly, using a Rayleigh ultrasonic transducer with a 48-ply unidirectional composite material, experiments were conducted on a unidirectional CFRP composite laminate with the ultrasonic transducer parallel to the fibers and using the unidirectional pitch-catch mode. In particular, Fig. 11 shows the amplitude of the ultrasonic signal in the unidirectional pitch-catch mode for the 48-ply CFRP composite laminate. In this case, three typical peak signals could be shown and the time of flight (TOF) and amplitude were measured for each peak signal while continuously controlling the probe separation distance of two ultrasonic transducers.

Firstly, Fig. 12 shows reault for a 24-ply unidirectional CFRP composite laminated material. In particular, as shown in Fig. 8(a), the yellow shaded box indicates a significant range of variation in the ultrasound beam profile. Fig. 12(a) shows the peak-to-peak amplitude and ultrasonic transducer distance for each of the five ultrasonic signals, while Fig. 12(b) shows the

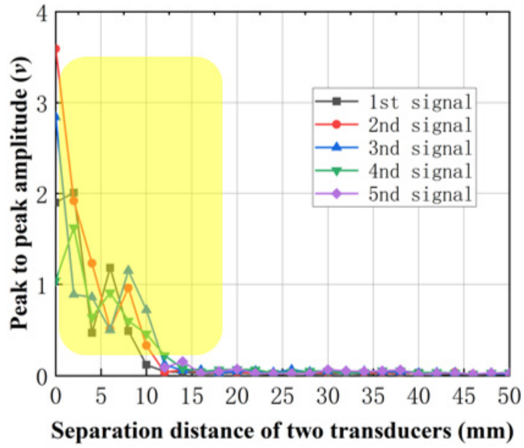


(a) Peak-to-peak amplitude

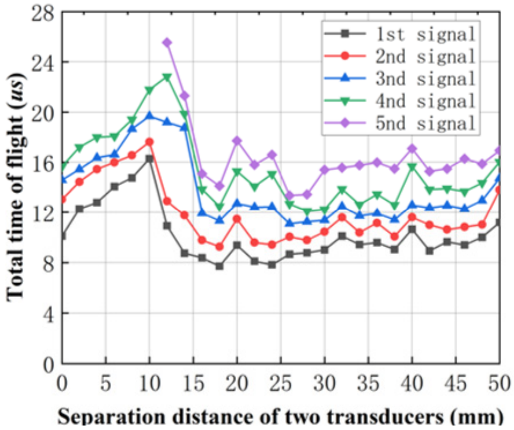


(b) Time-of-flight

Fig. 12 Peak to peak amplitude (a) and time-of-flight (b) of pitch-catch signal in one-sided beam profile experiment on 24ply CFRP laminate



(a) Peak-to-peak amplitude



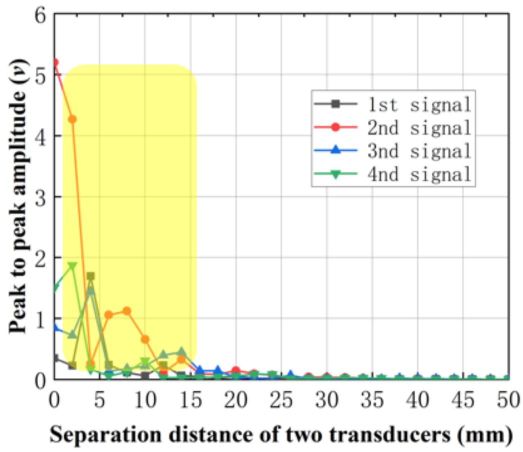
(b) Time-of-flight

Fig. 13 Peak to peak amplitude (a) and time-of-flight (b) of pitch-catch signal in one-sided beam profile experiment on 48ply CFRP laminate

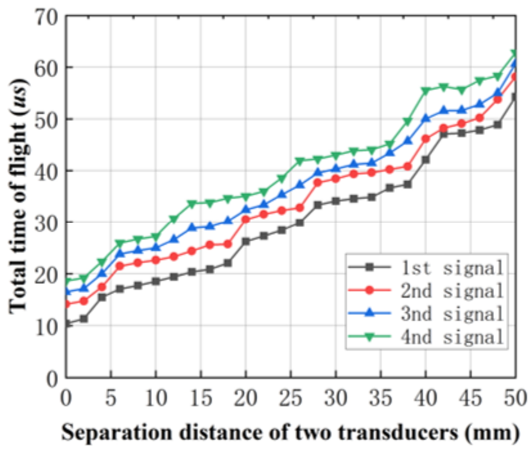
relationship between the ultrasonic transducer distance and time-of-flight (TOF). Within a distance of 10 mm from the ultrasonic transducer, three ultrasonic signals were observed, but at distances greater than 12 mm, the 4th and 5th ultrasonic signals were detected, which were attributed to reflections inside the test specimen. The 2nd ultrasonic signal appeared to be relatively large, which indicated that it was located at the optimal sensitivity position. Firstly, Fig. 13 shows the resulta for a unidirectional CFRP composite plate with 48 plies, and Fig. 13(a) shows the peak-to-peak amplitudes of five ultrasonic signals as a function of transducer distance, while Fig. 13(b) shows the relationship between transducer distance and time-of-flight (TOF). In Fig. 13(a), four ultrasonic signals were detected within a transducer distance of 10 mm, and another signal was detected after passing 12 mm, indicating the strong influence of internal reflection in the test specimen.

First of all, Fig. 14 uses a unidirectional CFRP composite material stacked with 96 plies. Fig. 14(a) shows four ultrasonic signals representing the distance and peak-to-peak amplitude, while Fig. 14(b) depicts the relationship between the ultrasonic transducer distance and time-of-flight (TOF) during flight. In Fig. 14(a), the ultrasonic signals were barely measurable within 15 mm of distance, but all four signals were detectable. Notably, the second signal appeared relatively strong.

Furthermore, within 5 mm of ultrasonic probe distance, all four ultrasonic signals had a effective amplitude range. In Fig. 14(b), the relationship between the ultrasonic transducer distance and TOF is shown, and it is possible to observe that the travel time increases as the distance increases. Four TOF values were found to increase relatively stably as the ultrasonic



(a) Peak-to-peak amplitude



(b) Time-of-flight

Fig. 14 Peak to peak amplitude (a) and time-of-flight (b) of pitch-catch signal in one-sided beam profile experiment on 96ply CFRP laminate

transducer distance increased.

4. Conclusions

In this study, the fiber orientation of unidirectional CFRP composite laminates were quantitatively evaluated for a use of wind turbine blade sparcaps by using a Rayleigh ultrasonic testing device with a unidirectional pitch-catch mode. To evaluate the fiber orientation within the unidirectional CFRP composite, beam profiles of 24 ply, 48 ply, and 96 ply composites were constructed for ultrasonic wave analysis.

1) The pitch-catch mode of Rayleigh ultrasonic transducers was successfully utilized to perform one-sided measurements on unidirectional CFRP composite, allowing for adjustment of the desired measurement depth of the specimen.

2) In order to assess the fiber orientation of unidirectional CFRP composite utilized in wind turbine blade spar caps, measurements were carried out based on the unidirectional fiber orientation perpendicular to the fibers and the unidirectional fiber orientation parallel to the fibers. It was confirmed that the effective range of the ultrasonic beam profile was approximately 20 mm for the unidirectional fiber orientation normal to fibers, and approximately 15mm for the unidirectional fiber orientation along fibers.

3) For the wind turbine blade sparcap components of 24 ply, 48 ply, and 96 ply, although we measured 5 or 4 peak-to-peak amplitudes of ultrasonic signals, 3 effective peak amplitudes could be considered as effective signals only when securing more valid amplitude data. It was found that the effective range of ultrasonic peak amplitude can be considered as a key parameter for NDE evaluation.

Acknowledgments

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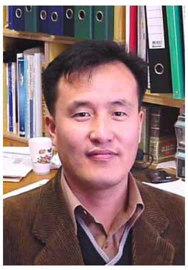

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