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Ultrasonic Techniques for the Defect Monitoring of CFRP Composites for Lightweight Mobility Applications

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ABSTRACT

Nondestructive ultrasonic technology has attracted attention as an inspection tool in various fields, including agriculture, medical engineering, and airport security. In this study, ultrasonic technology was utilized for the reliability assessment of aerospace and automotive components, specifically applied to the defect monitoring of carbon-fiber-reinforced plastic (CFRP) composites. This study focused on using ultrasonic technology to assess defects in unidirectional CFRP laminate plates for lightweight applications. Ultrasonic reflection signals were monitored along the fiber orientation, revealing variations in amplitude profiles owing to defects. The most sensitive response was observed with the transducer distances of 4 to 15 mm, indicating that the amplitude range with a high signal-to-noise ratio is crucial for nondestructive evaluation.

1. Introduction

Recently, there has been a significant interest in advanced composite materials that possess excellent mechanical properties, lightweight characteristics, and heat resistance as part of energy conservation and new material development. In particular, carbon fiber reinforced plastics (CFRP) for lightweight mobility, as part of renewable energy initiatives, are being produced using composite materials that exhibit superior specific stiffness (elastic modulus/strength) and specific strength (tensile strength/density)[1,2]. Various processes are carried out during the manufacturing of CFRP composites for lightweight mobility. To ensure the stability and reliability of CFRP composites, functionalities that comply with aging, oxidation, waterproofing, anti-fouling, fire resistance, and electromagnetic shielding must be incorporated. CFRP composites are utilized across various industries, including automotive, aerospace, shipbuilding, and machinery, where coating processes are required[3-5].

Unidirectional CFRP composites are composed of prepreg sheets made of fibers and resin, which are stacked to the desired ply count and molded under high temperature and pressure. During this process, phenomena such as fiber movement, resin rich regions, unformed areas, and void

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creation may occur internally. By introducing artificial defects into unidirectional CFRP composites, ultrasonic techniques are employed to evaluate the characteristics and defects of the unidirectional carbon composite materials[6-12]. Non-destructive ultrasonic inspection and evaluation of the fibers, resin properties, and hidden defects within the unidirectional CFRP specimens are crucial for obtaining fundamental design data. During ultrasonic testing, CFRP composites are manufactured, and ultrasonic probes are used in both the unidirectional and vertical directions according to fiber orientation, applying pitch-catch modes. In this case, Rayleigh ultrasonic probes are utilized, enabling unidirectional measurements for any specimen and allowing for the adjustment of measurement depth as desired[13,14].

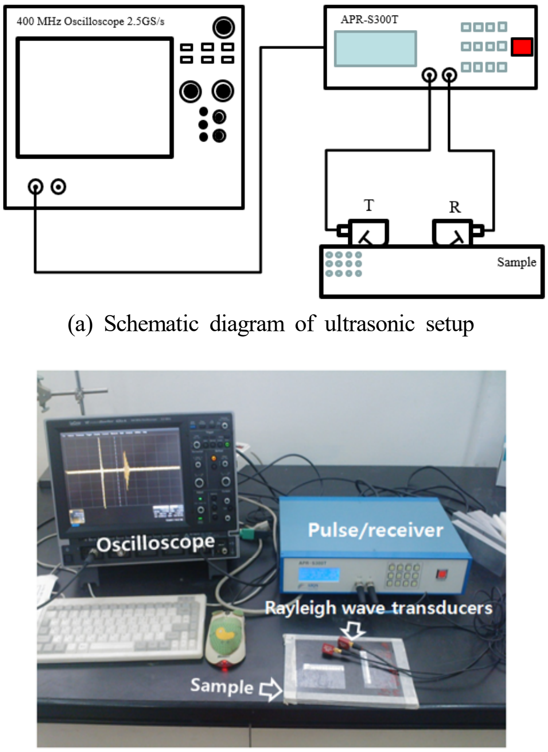
Therefore, this study utilizes a Rayleigh-type ultrasonic experimental device with a pitch-catch method to examine the fiber orientation of unidirectional CFRP composite laminated plates under unidirectional equilibrium and vertical fiber orientations. If the internal fiber orientation and defects of unidirectional CFRP composites can be quantitatively assessed, it is expected to lead to significant advancements in both safety design and the development of advanced materials. Furthermore, by implementing beam profiles of multiple ultrasonic reflection signals based on the presence of defects within the unidirectional CFRP composite, a more systematic and quantitative analysis of ultrasonic behavior will be conducted, and techniques for evaluating ultrasonic characteristics will be developed. Additionally, ultrasonic simulations were performed to assess defects in unidirectional CFRP composites. The aim is to identify effective areas by evaluating the differences between scenarios with and without defects.

In terms of experimental methodology, the pitch-catch ultrasonic testing method involved analyzing vertical and horizontal fiber orientations based on the presence of defects in the unidirectional setup. The beam profile behavior of pitch-catch ultrasounds was observed, and by adjusting the distance of the ultrasonic transducer, it became possible to calibrate the desired measurement depth of the specimen. To evaluate defects in unidirectional CFRP composites, comparisons were made between 3 to 6 main ultrasonic reflection signals at angles of 0°, 45°, 75°, and 90° relative to the unidirectional equilibrium fiber orientation. It was found that when defects are present in lightweight mobility unidirectional CFRP composites, the propagation of ultrasound is significantly affected by mode conversion, attenuation, and scattering.

In particular, selected range with high S/N ratios could be considered as effective parameters for NDE evaluation in the ultrasonic reflection signals under pitch-catch mode within unidirectional CFRP composites.

Table 1 Fiber stacking sequences of specimens

Types	Fiber stacking sequences	No. of prepreg sheets [ply]	Thickness [mm]	Materials	UT testing
A	[O96]	96	9.8	CF/EPOXY	



(a) Schematic diagram of ultrasonic setup

(b) Ultrasonic setup system

Fig. 1 Ultrasonic schematic diagram of ultrasonic testing setup

2. Ultrasonic system

2.1 Unidirectional CFRP specimen

The test specimen used in this study is a unidirectional CFRP composite laminate, fabricated by layering unidirectional carbon fiber prepreg combined with carbon fiber/epoxy resin (CF/EPOXY) through a hydraulic press method. The carbon fiber has a diameter of 7 μm, and the types of test specimens based on their orientation are presented in Table 1.

The CFRP composite laminate specimens were produced by stacking unidirectional carbon fiber prepreg sheets combined

Fig. 2 Ultrasonic wave transducers for generating Rayleigh wave

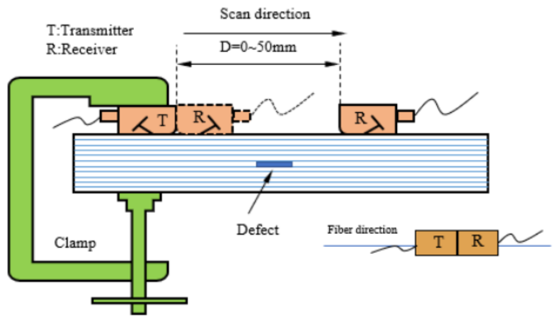


Fig. 3 One-sided measurement method along fiber of samples with one aluminum foil defect (6.35×6.35×0.05 mm)

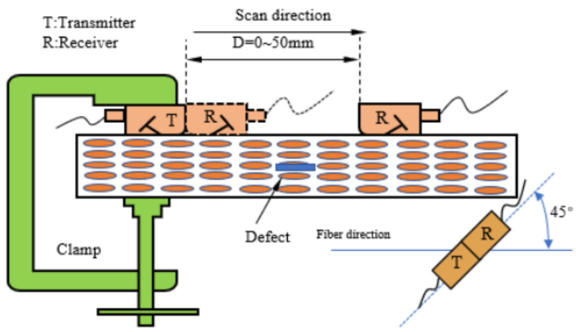


Fig. 4 One-sided measurement method with angle of 45 of samples with one aluminum foil defect (6.35×6.35×0.05 mm)

with CF/EPOXY using a hydraulic press device.

2.2 Experimental setup

Fig. 1 illustrates the ultrasonic testing system, with Fig. 1(a) showing a schematic diagram of the experimental setup, and Fig. 2(a) depicting a photograph of the ultrasonic test. The experimental method employed direct Rayleigh ultrasonic transducers, and ultrasonic waves were generated using the APR-S300T PR spike voltage pulser/receiver from AIQS. The RF waveform from the specimen was obtained on an oscilloscope (Wave Surfer 42Xs-A) and stored on a computer. The oscilloscope allows several echo waves to be independently manipulated, making it very convenient to store and compare echo waves on the screen for measurement.

In this experiment, CFRP composite plates with varying thicknesses were used. Due to the larger attenuation and scattering effects in the case of thicker backplates, two Rayleigh ultrasonic transducers were employed to maximize the ultrasonic signals. Therefore, a low frequency of 2.25 MHz, suitable for composite materials, was utilized in this experiment. Fig. 2 shows the two transducers used in the experiment, which are 2.25 MHz Rayleigh ultrasonic transducers (90° ST) from Harisonic.

2.3 Experimental method

The experimental setup for ultrasonic testing consists of a Digital Storage Oscilloscope (DOS: Lecory, Wave Surfer) that digitizes the ultrasonic signals and interfaces with a PC, a mid-range alarm gauge, and a pulser-receiver (AIQS, APR-S300T) capable of transmitting and receiving data at a rate of 250,000 bits per second over a distance of 1000 meters. Rayleigh ultrasonic transducers were utilized for the probes.

As shown in Figs. 3-6, when using two ultrasonic transducers in a pitch-catch mode on the unidirectional test specimen, the probe separation distance D between the transmitting transducer (T) and the receiving transducer (R) can be adjusted. Specifically, in Figs. 3-6, D was set to 50 mm.

Fig. 3 illustrates the signal measurement along the fiber direction of the unidirectional CFRP composite during the ultrasonic test. The transmitting transducer (T) was fixed while the receiving transducer (R) was moved to acquire the signals. The distance D between the two transducers can be measured from 0 mm to 50 mm. Defects (Aluminum foil: 6.35×6.35×0.05) were fabricated at the center of the CFRP test specimen, as well as a case without defects, and ultrasonic tests were conducted at 2 mm intervals for D.

Figs. 4-5 show the ultrasonic signal measurement at angles of 45° and 75° relative to the fiber direction of the unidirectional CFRP composite during the testing process. The transmitting transducer (T) was fixed while the receiving transducer (R) was moved to acquire the signals. Again, the distance D between the two transducers can be measured from 0 mm to 50 mm. Defects (Aluminum foil: 6.35×6.35×0.05) were fabricated at the center of the CFRP test specimen, as

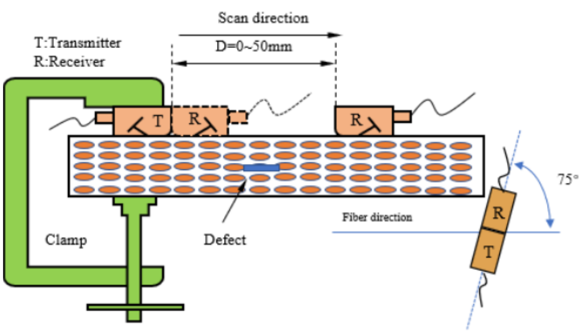


Fig. 5 One-sided measurement method with angle of 75 of samples with one aluminum foil defect (6.35×6.35×0.05 mm)

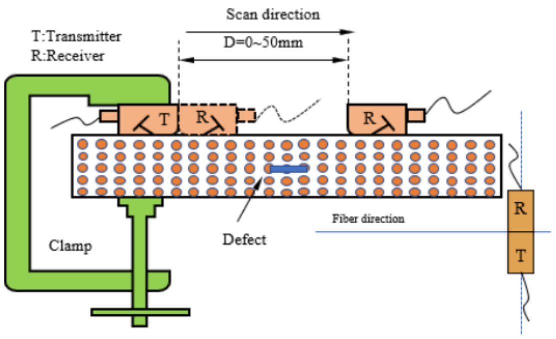


Fig. 6 One-sided measurement method normal to fiber of samples with one aluminum foil defect (6.35×6.35×0.05 mm)

well as a case without defects, and ultrasonic tests were conducted at 2 mm intervals for D.

Fig. 6 shows the signal measurement of CFRP composite material during ultrasonic testing with the fiber direction perpendicular to the measurement (Normal to fiber ⊥). The transmitter (T) transducer was fixed while the receiver (R) transducer was moved to acquire the signals. The distance (D) between the two ultrasonic transducers can be measured from 0mm to 50mm. The CFRP test specimens were prepared with a defect (Aluminum foil: 6.35×6.35×0.05) and without a defect, and ultrasonic tests were performed with D varying in 2 mm increments.

Through testing, the signals from the ultrasonic reflection position, referred to as the "sampling volume," can be identified. By adjusting the distance D between the ultrasonic transducers, it is possible to observe signals from deeper ultrasonic reflection positions in the "sampling volume." This indicates that the test specimen possesses the characteristic to control the ultrasonic reflection position, or "sampling volume." Therefore, if the fiber orientation or defect is embedded at any arbitrary depth in the ultrasonic reflection position, defect evaluation becomes feasible by aligning the "sampling volume" with the defect.

3. Ultrasonic simulation

In Section 2, a 2.25 MHz frequency ultrasonic transducer was used to measure defects in unidirectional CFRP composites for lightweight mobility applications. To evaluate the directional characteristics of the CFRP composites, pitch-catch ultrasonic beam characteristics were implemented at angles of 45° and 90° relative to the carbon fiber orientation reference (0°). It is essential to identify the effective parameters for ultrasonic testing under these various directional conditions. Therefore, to establish optimal ultrasonic simulations, the NDE CIVA package (CIVA 2023 software, NDE CIVA) was adopted.

3.1 Ultrasonic simulation setup

In this simulation, ultrasonic behavior was modeled as shown in Figs. 2-3. The ultrasonic transducers were installed on the surface of the test specimen and modeled using the pitch-catch method. Fig. 2 illustrates the pitch-catch mode technique utilizing two ultrasonic transducers, with a distance of 10 mm between them, in the absence of defects in the CFRP composite. The ultrasonic receiving signal is represented as an A-scan on the left. Fig. 3 depicts the case where a defect is inherent within the unidirectional CFRP composite, again employing the pitch-catch mode technique with the same 10 mm distance between the two ultrasonic transducers. The receiving ultrasonic signal is also shown as an A-scan on the left. Analyzing the A-scan data reveals a significant number of reflected signals, which suggests that the defects and fiber orientations within the unidirectional CFRP composite have influenced the results. To specifically evaluate the directional characteristics of the CFRP

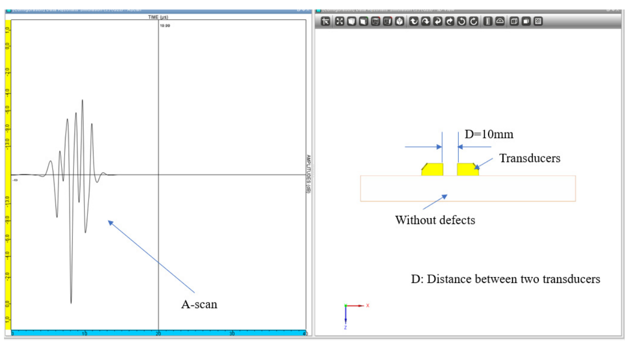


Fig. 7 Pitch-catch mode set up for two ultrasonic transducers at the distance of 10mm without defects

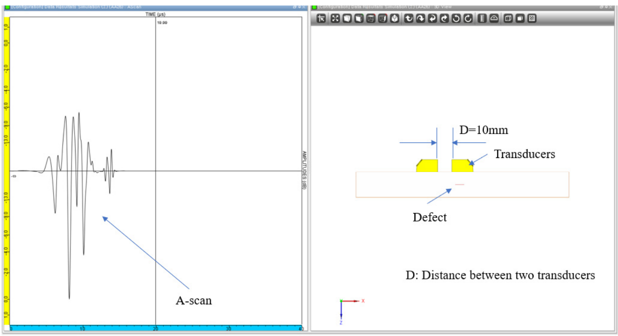
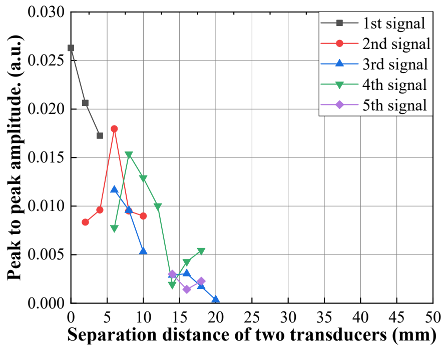
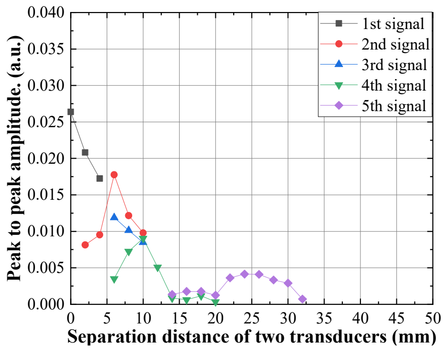


Fig. 8 Pitch-catch mode set up for two ultrasonic transducers at the distance of 24 mm with defects



(a) Peak-to-peak amplitude without defects



(b) Peak-to-peak amplitude with defects

Fig. 9 Simulation comparision between with defect and without defect in pitch-catch ultrasonic techniques

composites, the ultrasonic simulation modeled the pitch-catch ultrasonic beam profiles at 0°, 45°, and 90° relative to the fiber orientation.

4. Results and discussion

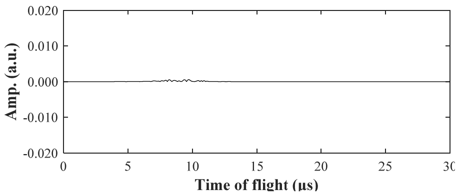
4.1 Ultrasonic simulation

Fig. 9 utilized unidirectional CFRP composites layered with 96 plies, depending on the presence of internal defects, and the measurement method involved simulating in the vertical fiber direction of the unidirectional material. Fig. 9(a) shows the results using unidirectional CFRP composites without internal defects, illustrating the distances of the ultrasonic transducers and the peak-to-peak amplitudes for five ultrasonic signals. Conversely, Fig. 9(b) presents the simulation implemented under the assumption of existing internal defects in the unidirectional CFRP composites. This figure indicates the relationship between the distance of the ultrasonic transducers and the amplitude.

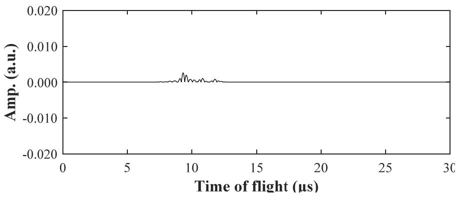
In Fig. 9, the X-axis represents the distances (D) between the two ultrasonic transducers, while the Y-axis denotes the peak-to-peak amplitudes. As shown in Fig. 9(a), these are the results of the ultrasonic simulation without defects. The symbols "■" represent the first ultrasonic amplitude, "●" the second, "▲" the third, "▼" the fourth, and "◆" the fifth ultrasonic amplitudes. It demonstrates the profiles of five ultrasonic beams, with the first, second, and fourth signals showing significant values within a distance of D = 15 mm. The third and fifth signals are relatively lower.

Fig. 9(b) shows the results of the ultrasonic simulation with inherent defects. Here, the profiles of the five ultrasonic beam simulations are presented, with significant amplitudes for the first through fourth signals within a distance of D = 12 mm. The fifth signal is relatively lower. Notably, in the absence of defects, the second and fourth signals were prominent, while in the presence of defects, there was a relative decrease; however, the fifth ultrasonic signal exhibited a different pattern. This suggests that the inherent defects in the unidirectional CFRP composites had a substantial impact. Additionally, at distances greater than D = 15 mm, the ultrasonic signals significantly decreased, which may indicate that the vertical fibers within the test specimen had some influence."

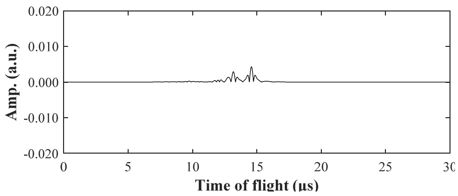
Figs. 10-12 compare and analyze how the amplitude varies according to the distance (D) between two ultrasonic transducers in unidirectional CFRP composites stacked with 96 plies, depending on the presence or absence of internal defects. Figure 10 shows the case where the ultrasonic simulation is performed in the horizontal fiber direction, while Figure 11 shows the simulation at a 45-degree angle, and Figure 12 depicts the simulation in the vertical fiber direction. In Figure 10(a), D = 0 mm; in Figure 10(b), D = 6 mm; and in Figure 10(c), D = 18 mm, indicating the amplitude difference based on the presence of defects. At D = 0 mm, there is no change in amplitude difference, but an amplitude difference



(a) At the probe separation of 0 mm

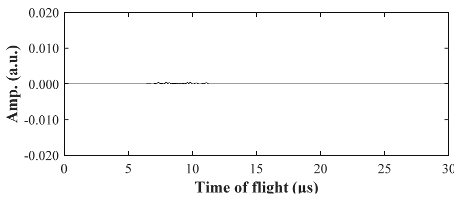


(b) At the probe separation of 6 mm

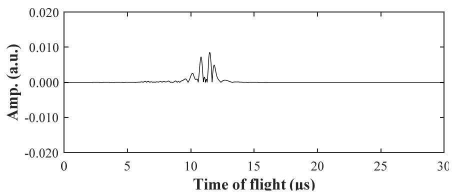


(c) At the probe separation of 18 mm

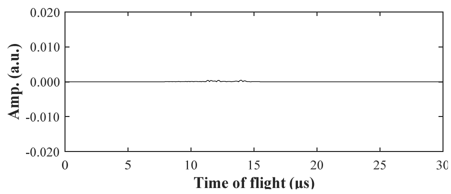
Fig. 10 Difference between without defects and with defects of pitch-catch ultrasonic amplitude along fiber



(a) At the probe separation of 0 mm



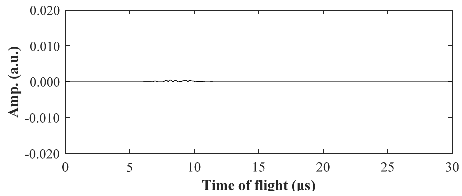
(b) At the probe separation of 2 mm



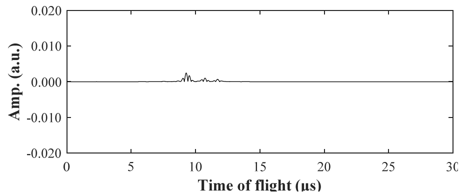
(c) At the probe separation of 14 mm

Fig. 11 Difference between without defects and with defects of pitch-catch ultrasonic amplitude with the angle of 45

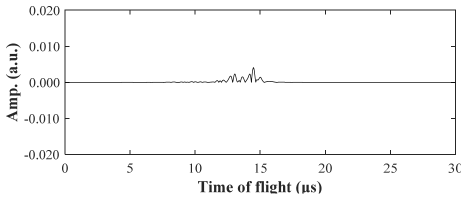
occurs at D = 6 mm, continuing to D = 18 mm, with an amplitude difference length of 12 mm. In Figure 11(a), D = 0 mm; in Figure 11(b), D = 2 mm; and in Figure 11(c), D = 12 mm, indicating the amplitude difference based on the presence of defects. Again, at D=0mm, there is no change in amplitude difference, but an amplitude difference occurs at D = 2 mm, continuing to D = 12 mm, with an amplitude difference length of 10 mm. Additionally, in Figure 12(a), D = 0 mm; in Figure 12(b), D = 6 mm; and in Figure 12(c), D = 18 mm, indicating the amplitude difference based on the presence of defects. At D = 0 mm, there is no change in amplitude difference, but an amplitude difference occurs at D = 6 mm, continuing to D = 18 mm, with an amplitude difference length of 14mm. This confirms the effective ultrasonic beam profile area where amplitude differences appear due to the presence or absence of defects in unidirectional CFRP composites through ultrasonic simulation.



(a) At the probe separation of 0 mm



(b) At the probe separation of 6 mm



(c) At the probe separation of 18 mm

Fig. 12 Difference between without defects and with defects of pitch-catch ultrasonic amplitude normal to fiber

4.2 Ultrasonic experimental behavior

Fig. 13 illustrates the ultrasound propagation direction generated by a Rayleigh transducer used in the pitch-catch mode. The pitch-catch mode measurement is very useful when measuring from one direction of the specimen. The propagation direction of the wave generated when there is no

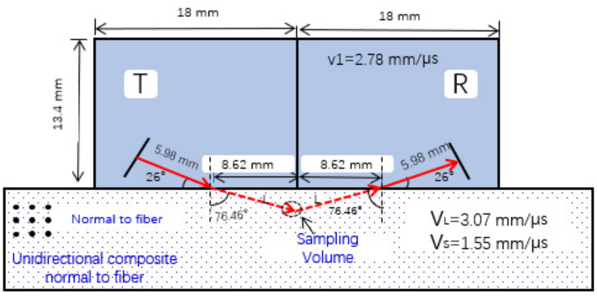
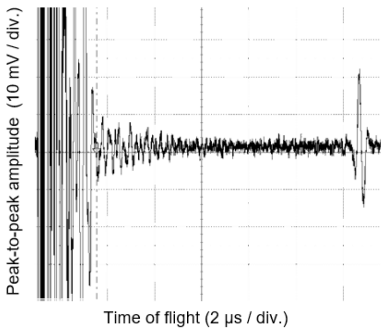
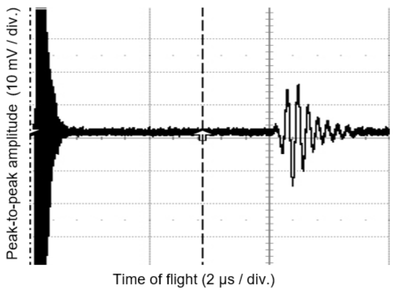


Fig. 13 Analysis of pitch-catch ultrasonic measurement



(a) In case of pulse-echo mode



(b) In case of pitch-catch mode

Fig. 14 Comparisons between pulse-echo mode and pitch-catch mode

gap between the transmitting transducer T and the receiving transducer R on one side of the CFRP laminate is shown in Fig. 13. A coupling medium is required to generate ultrasound in the specimen. The 'sampling volume' in Fig. 13 can be calculated through the time-of-flight for any arbitrary depth of the specimen. As the distance (skip) between the two transducers increases, the pitch-catch signals are captured. Two Rayleigh ultrasonic transducers were used, and by considering the angle of the vibrators and material properties from these two transducers, the ultrasound velocity and all conversions can be taken into account to easily predict the ultrasound propagation direction.

Fig. 14 compares the ultrasonic signals obtained using a pulsed-echo mode and a pitch-catch mode with an ultrasonic

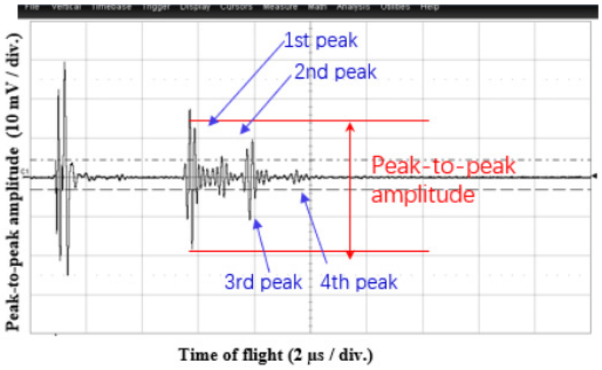


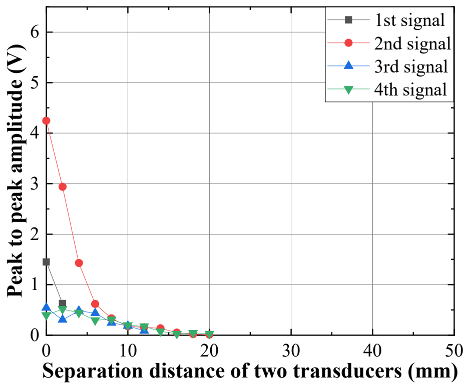
Fig. 15 Ultrasonic signal of Rayleigh wave transducers based on one-sided pitch-catch mode normal to fiber (96ply)

transducer operating at a frequency of 2.25 MHz[14]. Fig. 14(a) shows the back signal image, which exhibits a significant amount of backscattering signals, likely due to the influence of signals reflected from the fibers of the CFRP laminate in the unidirectional specimen. In contrast, Fig. 14(b) only displays the ultrasonic signals reflected from the 'sampling volume' mentioned earlier, without any interference from other signals. This is due to the characteristic of the ultrasonic transducer, which is positioned at an arbitrary angle, allowing it to capture only the signals reflected from the 'sampling volume'.

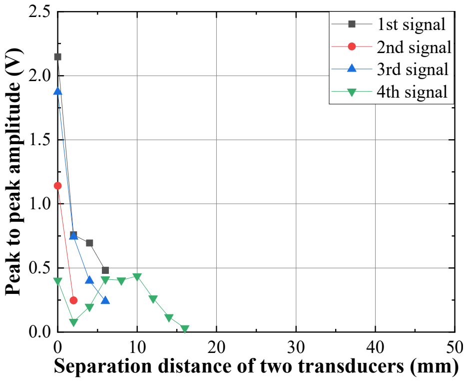
4.2.1 Unidirectional fiber direction analysis

Initially, ultrasonic testing was conducted on a unidirectional CFRP composite laminate using a Rayleigh ultrasonic transducer, with the transducer positioned perpendicular to the fibers in a unidirectional pitch-catch mode. In particular, Fig. 15 presents the amplitude of the ultrasonic signals for the unidirectional pitch-catch mode of the 96-ply CFRP composite laminate. In this instance, typical peak signals of 3 to 4 can be observed, each of which has been measured for both time of flight (TOF) and amplitude. Additionally, the 'D (Probe separation distance)' between the two ultrasonic transducers was continuously controlled during the measurements.

Initially, Fig. 16 illustrates the use of unidirectional CFRP composite laminated with 96 plies, conducted according to the presence or absence of internal defects, with measurements taken in the parallel fiber direction. Fig. 16(a) depicts the results for a defect-free unidirectional CFRP composite, showcasing the distances of the ultrasonic transducers and the peak-to-peak amplitudes represented by four distinct



(a) Peak-to-peak amplitude without defects



(b) Peak-to-peak amplitude with defects

Fig. 16 Peak to peak amplitude of pitch-catch signal in one-sided beam profile experiment on 96ply CFRP laminate

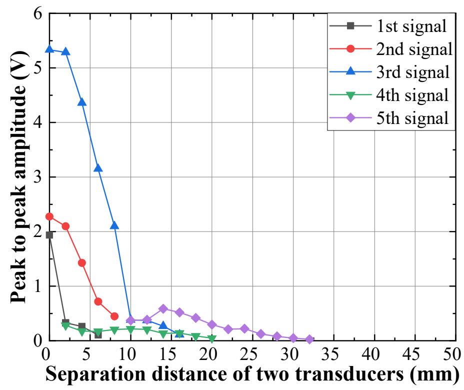
ultrasonic signals. Conversely, Fig. 16(b) presents the results for a unidirectional CFRP composite with internal defects, from which peak-to-peak ultrasonic signals were obtained. It is noteworthy that the relationship between the distance of the ultrasonic transducers and the time of flight (TOF) exhibited a linear trend.

In this context, the X-axis of Fig. 16 represents the distance (D) between the two ultrasonic transducers, while the Y-axis denotes the peak-to-peak amplitude. As shown in Fig. 16(a), the results of the ultrasonic testing for the defect-free specimen are illustrated. The symbol "■" corresponds to the first ultrasonic amplitude, "●" to the second, "▲" to the third, and "▼" to the fourth ultrasonic amplitude. The four ultrasonic beam profiles are represented here, where the first and second signals are prominently displayed within the distance of D = 6 mm. The third and fourth signals are comparatively lower.

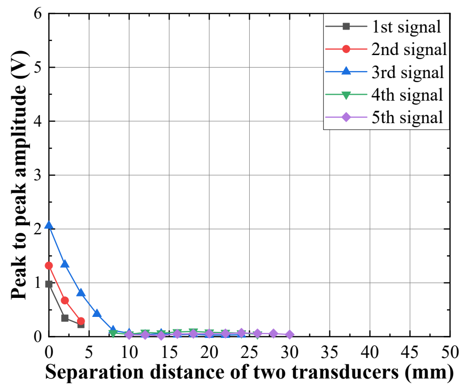
As indicated in Fig. 16(b), the results of the ultrasonic testing for the specimen with internal defects are shown. The four ultrasonic beam profiles are similarly represented, with the first, second, and third signals being pronounced within the distance of D = 6 mm, whereas the fourth signal appears relatively lower. Notably, in the absence of defects, the second signal is prominently displayed; however, in the presence of internal defects, it experiences a significant decline, while the second and third signals remain substantial. This suggests that the internal defects inherent in the unidirectional CFRP composite have a considerable impact. Furthermore, beyond a distance of D = 6 mm, there is a marked reduction in the ultrasonic signals, which may indicate a certain influence of the parallel fibers within the test specimen.

4.2.2 Unidirectional 45° fiber direction analysis

First, Fig. 17 utilizes unidirectional CFRP composites layered with 96 plies, depending on the presence or absence of internal defects, and the measurement method was conducted at a 45° fiber direction in the unidirectional configuration. Fig. 17(a) depicts the results from unidirectional CFRP composites without internal defects,



(a) Peak-to-peak amplitude without defects



(b) Peak-to-peak amplitude with defects

Fig. 17 Peak to peak amplitude of pitch-catch signal in one-sided beam profile experiment on 96ply CFRP laminate

showing five distinct ultrasonic amplitude signals represented by the distance of the ultrasonic transducer and peak-to-peak amplitude. Conversely, Fig. 17(b) illustrates the results obtained from unidirectional CFRP composites with inherent internal defects, capturing the ultrasonic peak-to-peak signals. The relationship between the ultrasonic transducer distance and the time of flight (TOF) exhibited a linear trend.

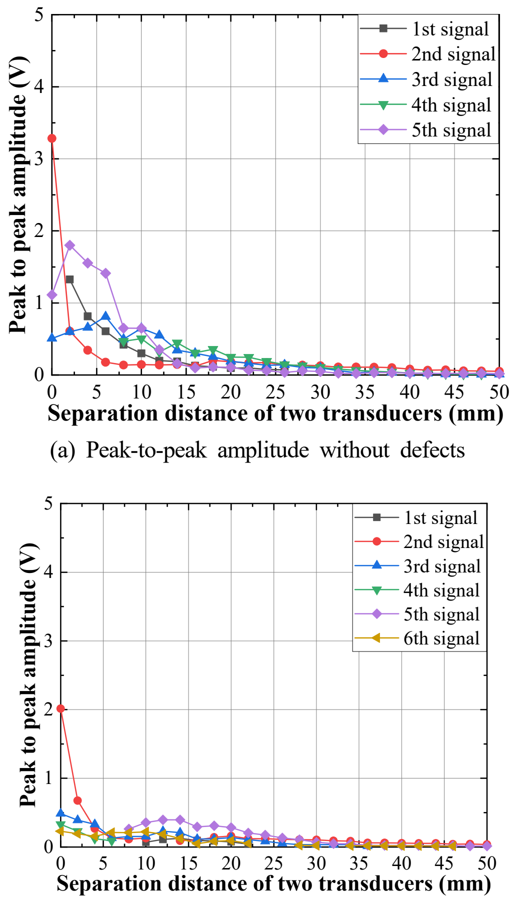
In Fig. 17, the X-axis represents the distance (D) between the two ultrasonic transducers, while the Y-axis indicates the peak-to-peak amplitude. As shown in Fig. 17(a), the ultrasonic testing results indicate no defects. The symbols "■" denote the first ultrasonic amplitude, "●" the second, "▲" the third, "▼" the fourth, and "◆" the fifth amplitude. Four ultrasonic beam profiles are presented, with the second and third signals exhibiting significant amplitudes within D = 10 mm. The first signal displayed a somewhat effective amplitude up to D = 5 mm, while the fourth and fifth signals appeared relatively low.

Fig. 17(b) presents the ultrasonic testing results for samples with inherent defects. In this case, five ultrasonic beam profiles are shown, where the first, second, and third signals demonstrated significant amplitudes within D=5mm. The fourth and fifth signals were relatively low. Notably, while the third signal was prominent in the defect-free scenario, it showed a marked decrease in the presence of defects, along with a similar reduction in the first and second signals. It is believed that the defects inherent in the unidirectional CFRP composites and the 45° fiber orientation within the specimen significantly influenced these results.

4.2.3 Unidirectional 45° fiber direction analysis

First, Fig. 18 illustrates the use of unidirectional CFRP composites layered with 96 plies, depending on the presence of internal defects. The measurement was conducted at a fiber direction of 75 degrees in the unidirectional setup. Fig. 18(a) depicts the results for the unidirectional CFRP composite without internal defects, showing the distance of the ultrasonic transducer and the peak-to-peak amplitude represented by six distinct ultrasonic amplitude signals. In contrast, Fig. 18(b) presents the results for the unidirectional CFRP composite with inherent internal defects, where the peak-to-peak ultrasonic signals were obtained. The relationship between the ultrasonic transducer distance and the time of flight (TOF) exhibited a linear correlation.

In Fig. 18, the X-axis represents the distance (D) between the two ultrasonic transducers, while the Y-axis displays the peak-to-peak amplitude. As shown in Fig. 18(a), these are the results of the ultrasonic test without defects. The symbol "■" denotes the first ultrasonic amplitude, "●" represents the second, "▲" indicates the third, "▼" corresponds to the fourth, "◆" signifies the fifth, and "◀" illustrates the sixth ultrasonic amplitude. This indicates five profiles of ultrasonic beams, where the first, second, and third signals exhibited relatively large amplitudes within D = 7 mm, while the fifth signal showed a somewhat effective amplitude up to D = 5 mm, but the fourth signal was relatively low.

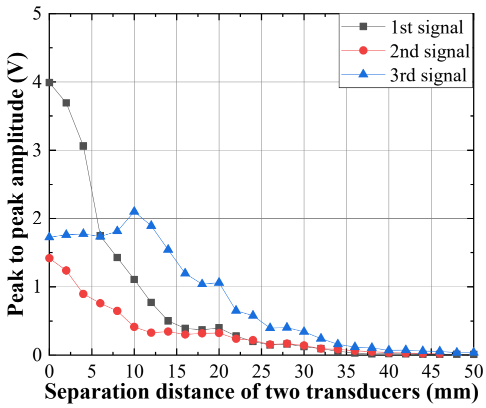


(a) Peak-to-peak amplitude without defects

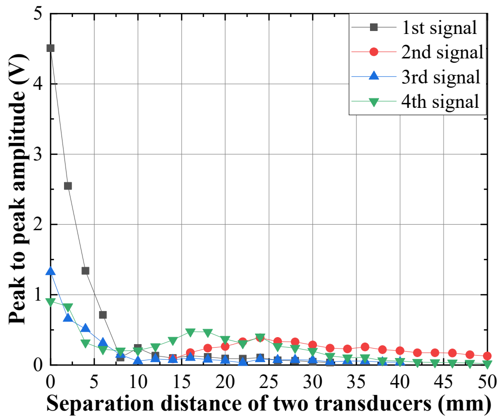
(b) Peak-to-peak amplitude with defects

Fig. 18 Peak to peak amplitude of pitch-catch signal in one-sided beam profile experiment on 96ply CFRP laminate

In Fig. 18(b), the results of the ultrasonic test with inherent defects are presented. Here, six ultrasonic beam profiles are shown, where the second, third, and fourth signals appeared relatively large within D = 5 mm. The first, fourth, fifth, and sixth signals were relatively low. Notably, in the absence of defects, the second signal was prominent, whereas in the presence of defects, there was a significant reduction,



(a) Peak-to-peak amplitude without defects



(b) Peak-to-peak amplitude with defects

Fig. 19 Peak to peak amplitude of pitch-catch signal in one-sided beam profile experiment on 96ply CFRP laminate

particularly for the first and second signals. This suggests that the inherent defects in the unidirectional CFRP composite and the 75-degree fiber orientation within the specimen significantly influenced the results.

4.2.4 Unidirectional vertical fiber direction analysis

"First, Fig. 19 utilizes unidirectional CFRP composites, laminated with 96 plies, depending on the presence or absence of internal defects. The measurement method was conducted in the vertical fiber direction of the unidirectional material. Fig. 19(a) represents the ultrasonic amplitude signals for the unidirectional CFRP composite without internal defects, showing three ultrasonic amplitude signals corresponding to the distance of the ultrasonic transducer and peak-to-peak amplitude. Fig. 19(b) illustrates the ultrasonic peak-to-peak signals obtained using the unidirectional CFRP composite with inherent internal defects, showing four ultrasonic signals. The relationship between the distance of the ultrasonic transducer and the time of flight (TOF) exhibited a linear trend.

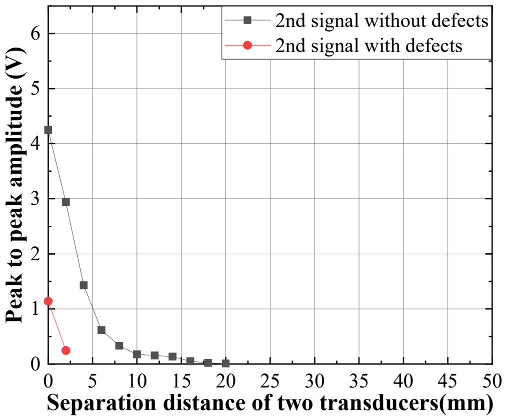
In this context, the X-axis of Fig. 19 represents the distance (D) of the two ultrasonic transducers, while the Y-axis indicates the peak-to-peak amplitude. As shown in Fig. 19(a), the results of the ultrasonic testing without defects are presented. The symbol "■" denotes the first ultrasonic amplitude, "●" represents the second ultrasonic amplitude, and "▲" indicates the third ultrasonic amplitude. Here, three ultrasonic beam profiles are shown, with all first, second, and third signals appearing significantly large within D=30mm, and very large within D = 10 mm.

In Fig. 19(b), the results of the ultrasonic testing with inherent defects are shown. Here, four ultrasonic beam profiles are presented, where the first, third, and fourth signals exhibit somewhat large amplitudes within D = 6 mm. The second ultrasonic signal appears around D = 12 mm, with a very low amplitude value. This is believed to be influenced by the reflection and refraction of ultrasonic waves due to the defects present in the unidirectional CFRP composite. Notably, the peak-to-peak amplitude values increased significantly according to the distance (D) of the two ultrasonic transducers in the vertical fiber direction, indicating an extended ultrasonic transducer distance (D). This allowed for a substantial increase in the effective area of the ultrasonic beam profile."

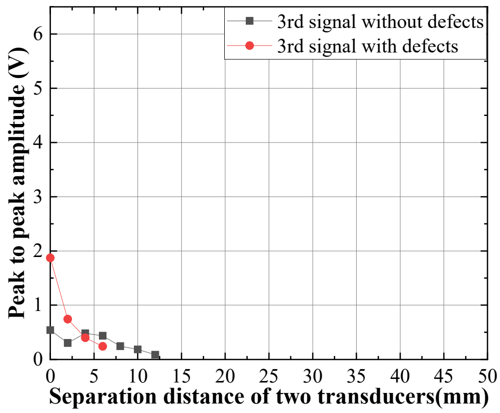
4.3 Presence of defects

4.3.1 Unidirectional fiber direction analysis

First, to identify the presence of defects in the unidirectional CFRP composite laminated with 96 plies, the ultrasonic peak signals were compared sequentially. Additionally, among the ultrasonic methods, the amplitude signals and travel time variations were analyzed, focusing on the ultrasonic transducer that exhibited the greatest change in relation to the distance. Under unidirectional test conditions, the ultrasonic amplitude sizes were compared at the second and third peaks, as shown in Fig. 20. In Fig. 20(a), the amplitude signals of the second peak were compared, illustrating the relationship between the distance of the ultrasonic transducer and the amplitude. The ultrasonic test data indicated by "■" represents the case without defects, while the data indicated by "●" corresponds to results with inherent defects. In the absence of defects, it was observed that the "D" value was

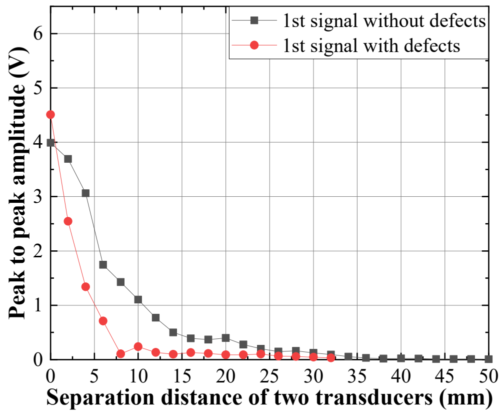


(a) 2nd signal of peak-to-peak amplitude

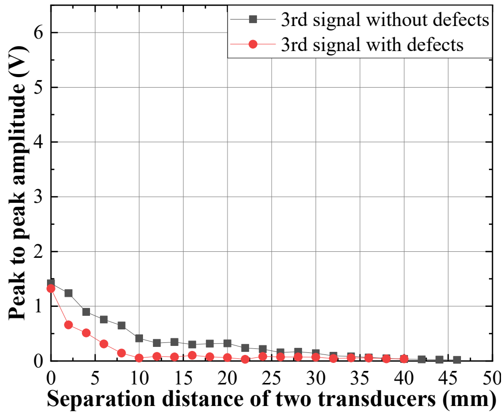


(b) 3rd signal of peak-to-peak amplitude

Fig. 20 Comparisons of peak to peak amplitude with and without defect in one-sided beam profile experiment on 48ply CFRP laminate



(a) 1st signal of peak-to-peak amplitude



(b) 3rd signal of peak-to-peak amplitude

Fig. 21 Comparisons of peak to peak amplitude with and without defect in two-sided beam profile experiment on 96ply CFRP laminate

valid up to an amplitude value of 20 mm; however, in the presence of defects, the "D" value only exhibited an amplitude up to approximately 4 mm. Furthermore, in Fig. 20(b), although the inherent defect case initially showed a high amplitude value, it dropped sharply around a transducer distance of approximately 4 mm. This is believed to be due to the inherent defect within the specimen interfering with the ultrasonic propagation direction, resulting in the observed differences.

4.3.2 Unidirectional vertical fiber direction analysis

Fig. 21 Comparisons of peak to peak amplitude with and without defect in two-sided beam profile experiment on 96ply CFRP laminate

In order to identify the presence of defects in unidirectional CFRP composites layered with 96 plies, the peak ultrasonic signals were compared sequentially. Additionally, the ultrasonic probe exhibiting the largest amplitude variation concerning the distance was selected to compare and analyze in the vertical fiber direction. Figure 19 illustrates the comparison of the first and third peak values of ultrasonic amplitude under unidirectional testing conditions, as shown in Figure 21. In Figure 21(a), the amplitude signals of the first peak are compared, depicting the relationship between the ultrasonic probe distance and amplitude. The ultrasonic test data indicated by "■" represents a defect-free case, while the data marked by "●" indicates the presence of defects. In Figure 21(a), although the trends of the two datasets are similar, a difference was observed when "D" is within 30 mm. Notably, when "D" is between 5-10 mm, a significant difference can be confirmed. This discrepancy is believed to be due to the inherent defects within the specimen interfering with the ultrasonic propagation direction. Similarly, in Figure 21(b), the trends of the two datasets are also comparable, but a difference was observed again when "D" is within 30 mm. Particularly, a considerable difference can be seen when "D" is between 4-10 mm. This phenomenon is attributed to mode conversion, attenuation, and scattering as the ultrasound travels within the unidirectional CFRP composite, resulting in the emergence of second, third, and fourth signals. Furthermore, the difference in ultrasonic signals due to the presence of defects is evident. It is considered that the presence of defects within the CFRP composite significantly affects the ultrasonic amplitude values, and areas with substantial amplitude differences could be effectively utilized as valid parameters for C-scan imaging, showing a high S/N ratio.

4. Conclusions

In this study, ultrasonic technology is employed as an inspection tool for the reliability assessment of aerospace and automotive components, specifically applied to defect monitoring of unidirectional CFRP (carbon fiber reinforced plastics) composites for lightweight mobility. Notably, utilizing the Rayleigh ultrasonic method, a pitch-catch technique, we quantitatively diagnosed defects within the unidirectional CFRP composites, leading to the following conclusions.

1) Ultrasonic simulations were performed to evaluate defects in unidirectional CFRP composites. To assess the impact of defect reflections within the CFRP composites, differences were observed between defect-free cases and those with inherent defects, indicating significant variations in the valid region. This is expected to be useful as an effective parameter for ultrasound.

2) Based on the pitch-catch mode, ultrasonic transducers were used to measure the ultrasonic reflection signals of the unidirectional CFRP composites. It was possible to obtain only backscattering signals without reflections from arbitrary fibers, capturing only the back surface signals.

3) In the defect-free case, the second signal was significantly pronounced in the direction of the unidirectional aligned fibers. However, in the presence of defects, there was a relative sharp decrease, although the second and third signals remained substantial. This suggests that the inherent defects in unidirectional CFRP composites had a significant impact.

4) Depending on the presence of internal defects, measurements were conducted in the direction of the unidirectional vertical fibers, where 3 to 4 peak-to-peak amplitude signals were recorded. The relatively high S/N ratio indicates potential utility of these signals as effective ultrasonic parameters.

5) The presence of internal defects resulted in significant differences in “D (Probe separation distance)” ranging from 4 to 10 mm in the direction of the unidirectional vertical fibers. This indicates that as ultrasound progresses through the unidirectional CFRP composites, mode conversion, attenuation, and scattering occur, leading to the generation of the second, third, and fourth signals. Additionally, differences in ultrasonic signals based on defect presence were observed.

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References

[1] Im, K. H., Zhang, G. L., Choi, S. R., Ye, C. H., Ryu, J. S., Lim, S. H., Han, M. G., Hsu, D. K., 2011, One-sided Nondestructive Evaluation of CFRP Composites By Using Ultrasonic Sound, J. Korean Soc. Manuf. Technol. Eng., 20:1 47-52.

[2] Zhang, G. L., Yeom, Y. T., Kim, S. K., Cho, Y. T., Woo, Y. D., Im, K. H., 2022, Evaluation of NDE Characteristics for Measuring the Painting Thickness in Wind Energy Turbine Power Blades Based on Ultrasonic Wave Simulation, J. Korean Soc. Manuf. Technol. Eng., 31:3 154-161, https://doi.org/10.7735/ksmte.2022.31.3.154.

[3] Liang, H., Shi, X. L., Zhang, P., Zhang, G. L., Yeom, Y. T., Cho, Y. T., Woo, Y. D., Im, K. H., 2023, Characterization on the Beam Profile for Defect Detection of Unidirectional CFRP Composites Using NDE Techniques, J. Korean Soc. Manuf. Technol. Eng., 32:6 326-339, https://doi.org/10.7735/ksmte.2023.32.6.326.

[4] Im, K. H., Lee, K. S., Yang, I. Y., Yang, Y. J., Seo, Y. H., Hsu, D. K., 2013, Advanced T-ray Nondestructive Evaluation of Defects in FRP Solid Composites, Int. J. Precis. Eng. Manuf., 14 1093-1098, https://doi.org/10.1007/s12541-013-0147-2.

[5] Im, K. H., Kim, S. K., Woo, Y. D., Cho, Y. T., Lee, G. S., Yu, B. M., Jung, J. A., Zhang, G. L., 2017, NDE Terahertz Techniques

for Measurement of Paint Thickness on Blades for Use in Wind Power, J. Korean Soc. Manuf. Technol. Eng., 26:6 610-616, https://doi.org/10.7735/ksmte.2017.26.6.610.

[6] Jeong, J. A., Hsu, D. K., Im, K. H., 2011, One-sided Nondestructive Evaluation of Back-Side Wedge By using Ultrasonic Sound, J. Korean Soc. Manuf. Technol. Eng., 20:6 773-777.

[7] Goebble, K., 1980, Structure Analysis by Scattered Ultrasonic Radiation in Research Techniques in Nondestructive Testing Vol. 4 (ed. Sharpe, R. S.), 30-38, Academic Press, London.

[8] Hsu, D. K., Thompson, D. O., Thompson, R. B., 1986, Evaluation of Porosity in Aluminum Alloy Castings by Single-Sided Access Ultrasonic Backscattering in Review of Progress in Quantitative Nondestructive Evaluation: Volume 5 (ed. Thompson, D. O., Chimenti, D. E.), 1633-1642, Plenum Press, NY.

[9] Park, H. B., Kim, Y. K., 2019, A Study on Coating Film Thickness Measurement in Vehicle using Eddy Current Coil Sensor, J. Korea Inst. Inf. Commu. Eng., 23:9 1131-1138, https://doi.org/10.6109/jkiice.2019.23.9.1131.

[10] Zhang, X., Augereau, F., Laux, D., Le Clezio, E., Ismaili, N. A., Kuntz, M., Despaux, G., 2014, Non-destructive Testing of Paint Coatings on Steel Plates by Ultrasonic Reflectometry, J. Nondestruct. Eval., 33 504-514, https://doi.org/10.1007/s10921-014-0246-8.

[11] Mezghani, S., Perrin, E., Vrabie, V., Bodnar, J. L., Marthe, J., Cauwe, B., 2016, Evaluation of Paint Coating Thickness Variations based on Pulsed Infrared Thermography Laser Technique, Infrared Phys. Technol., 76 393-401, https://doi.org/10.1016/j.infrared.2016.03.018.

[12] Kim, G. W., Seo. M. K., Choi, N. K., Kim, K. B., Kwon, S. K., Kim, Y. C., 2017, Development of Phased Array Ultrasonic Transducers for Detecting Defects of KR60 Rail Road (I) - Simulation by CIVA Software, J. Korean Soc. Nondestruc. Test., 37:6 411-417, https://doi.org/10.7779/JKSNT.2017.37.6.411.

[13] Jang, H. L., Han, D. H., Kang, L. H., 2020, Thickness Measurement Method of the Paint Coating Layer Using THz-TDS System, J. Korean Soc. Nondestruc. Test., 40:4 259-265, https://doi.org/10.7779/JKSNT.2020.40.4.259.

[14] Shia, X. L., Liang, H., Zhou, Z. H., Zhang, P., Zhang, G. L., Cho, Y. T., Woo, Y. D., Im, K. H., 2023, NDE Techniques of Fiber Characterization in Spar Caps of Wind Turbine Blades using Ultrasonic Waves, J. Korean Soc. Manuf. Technol. Eng., 32:3 119-128, https://doi.org/10.7735/ksmte.2023.32.3.119.

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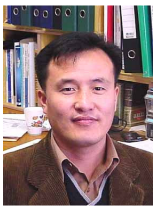

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