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Evaluation of NDE Characteristics for Measuring the Painting Thickness in Wind Energy Turbine Power Blades Based on Ultrasonic Wave Simulation

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ABSTRACT

In recent years, wind energy turbine blades have been manufactured using composite materials. Post manufacturing, these blades are painted with special coatings to protect the surface. Subsequently, they are generally tested by breaking a specimen and checking the uniform coating state using an optical microscope. A non-destructive technique is considered as an inspection tool; therefore, ultrasonic techniques are widely selected to measure thin painting thicknesses. In this study, the NDE (Nondestructive evaluation) CIVA package (CIVA 2020 software, NDE CIVA) was adopted for ultrasound simulation. The package was used to propose parameters, which brings the measurement of painting thickness based on the non-destructive ultrasonic waves. An optimal technique was also proposed with a use of the time and amplitude reflected from the surface and the back in the samples according to the blade painting thicknesses.

1. Introduction

In recent years, increasing attention has been brought to advanced composite materials with excellent mechanical, lightweight, and heat resistance properties to save energy and develop new materials. In particular, wind energy turbine blades have been manufactured with a use of composite materials with superior specific stiffness (modulus of elasticity/strength) and specific strength (tensile strength/density) as part of new and renewable energy. The most common blades are made using glass fiber reinforced plastics (GFRP), balsa, and epoxy. After the blades are manufactured, they are painted with special paints and coatings to protect the surface [1-2]. These painting such as a surface coating film were made in order to extend the lifespan by preventing blade aging and oxidation, which provide features for specific purposes such as waterproofing, antifouling, fireproofing, electromagnetic shielding, and insulation, and bring a harmonious color with the surroundings. Thus, paints became core materials used in various industries that require painting work, such as automobiles, aircraft, ships, and machinery [3-5].

Painting work is significant to ensure the stability and protect the surface of wind turbine blades. It requires a specific thickness because too much paint may prevent the blades from performing their original functions. Paint thickness is usually measured by the conventional contact method by breaking a specimen and using an optical microscope to inspect the coating

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state. However, this method damages wind turbine blades, so it is difficult to apply destructive test methods to operating structures [6-11].

Testing and inspection techniques that are applicable to structures in use without damaging their parts are required to address the issues of traditional thickness measurement techniques. Many studies have been conducted on non-destructive testing methods using ultrasonic waves to measure paint thickness [12-13].

Therefore, ultrasonic tests were performed by preparing specimens with different paint thicknesses to find an appropriate ultrasonic testing method to measure blade paint thickness, but ultrasonic test parameters are needed to measure the optimal paint thickness. For these reasons, ultrasonic simulations were performed under various conditions to establish parameters for ultrasonic tests.

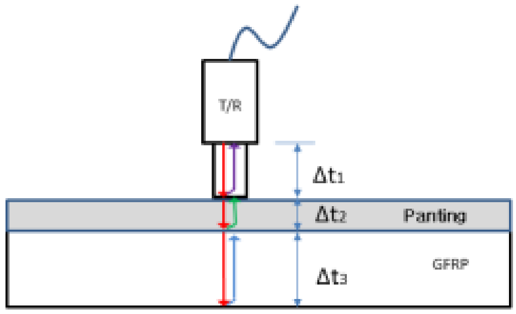
The NDE CIVA package (CIVA 2020 software, NDE CIVA) was used to perform ultrasound simulations. It implements the behavior of ultrasonic waves propagating inside materials and performs simulations in a short time [12]. This study used the NDE CIVA package to propose parameters that can non-destructively measure paint thickness using ultrasonic waves and an optimal technique using the time and amplitude reflected from the surface and back according to blade painting thickness. In particular, wind energy blades have a very thin paint thickness (~500 μm), which allows us to use nondestructive ultrasonic measuring techniques. There are factors to consider when measuring the paint thickness of the wind power blades using ultrasonic transducers. They include selecting the optimal conditions such as the size of the ultrasonic transducer, the frequency range, ultrasonic test conditions, and signal resolution.

Therefore, wind energy turbine blade specimens were prepared, and the painting thickness was calculated by measuring the time it takes for the ultrasonic wave to travel through the paint and reflect back from the inside surface. In particular, this study presented the optimal conditions for measuring a painting thickness of several tens of μm through ultrasonic simulation, and tracked and analyzed the factors influencing the frequency and delayline (wedge) according to the painting thickness.

2. The principle of ultrasonic testing

2.1 Application of ultrasonic waves

In this experiment, as shown in Fig. 1, a 20 MHz ultrasonic transducer was used in order to measure the painting thickness in wind energy turbine blades. The size of the ultrasonic transducer was 6.35 mm, and the delayline (wedge) was a distance of Δt1.



(a) Contact-typed ultrasonic measurement

(b) Measured A-scan with a delayline

Fig. 1 The pule-echo ultrasonic measurement of panting on the blade for a use of wind energy

Fig. 1(a) shows the pulse-echo ultrasonic technique, and T/R represents the ultrasonic transducer. Δt2 is the paint thickness, and Δt3 is the GFRP composite. Fig. 1(b) shows an ultrasound A-scan image of the ultrasound test in Fig. 1(a). This ultrasonic test shows the signal results of measuring the specimen's thickness and the paint thickness in pulse-echo mode. When the ultrasonic waves are incident on the specimen, they first reflect on the critical plane of the wedge and the painting layer (△t1), then reflect back on the critical plane of the painting layer and the GFRP (△t2), and finally reflect on the inside surface of the specimen (Δt3). The painting thickness can be obtained after calculating the time of flight (TOF) passing through the specimen's thickness and the reception time, respectively.

The interval between the peaks of the reflected signal is twice that between the front and rear surfaces of the specimen, and information about the painting layer thickness can be obtained by measuring the peak to peak time. In particular, using the delay line allows us to separate the ultrasonic signal reflected from the paint from the oscillating ultrasonic signal.

Eq. (1) shows how to calculate the thickness of a medium using the peak-to-peak time of ultrasonic waves.

$$D_{specimen} = C \times \triangle t/2 \quad (1)$$

where, $\triangle t$ is the peak-to-peak time of ultrasonic waves, C is the speed of ultrasonic waves in the medium, and $D_{specimen}$ is the thickness of the material.

3. Ultrasonic wave simulation

3.1 Set-up for ultrasonic wave simulation

In Section 2, a 20 MHz ultrasonic transducer was used to measure the paint thickness of wind turbine blades, but tests using ultrasonic transducers with different frequencies are required. Since the blade paint thickness is thin, delay lines (wedge) should also be used to prevent overlapping with oscillating signals. So, there is a need to find parameters that are conditions for various ultrasonic tests.

In this study, the NDE CIVA package (CIVA 2020 software,

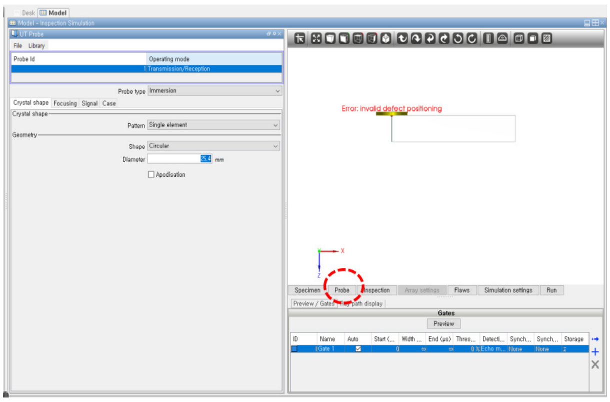


Fig. 2 Mode set up for ultrasonic transducers

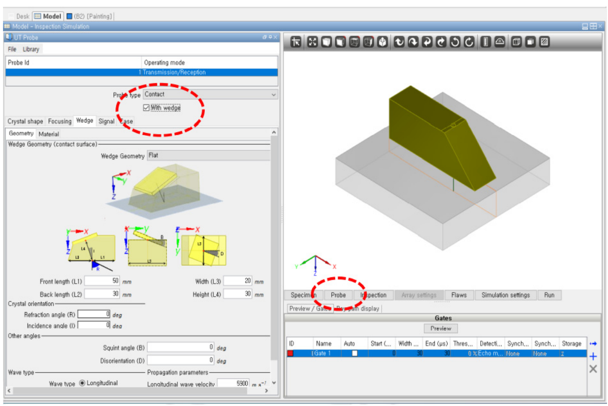


Fig. 3 Ultrasonic transducers with wedge set up

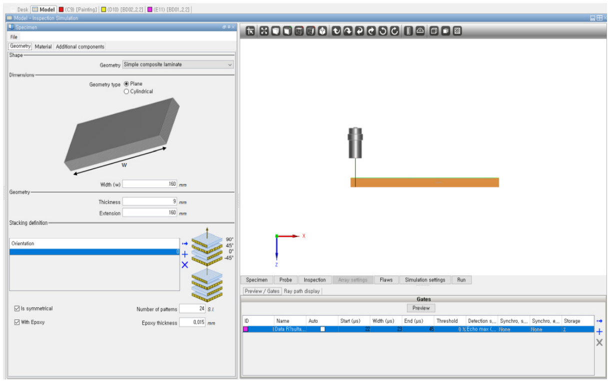


Fig. 4 Mode set up for painting layer on the GFRP composite

NDE CIVA) was adopted in order to build optimal ultrasound simulations.

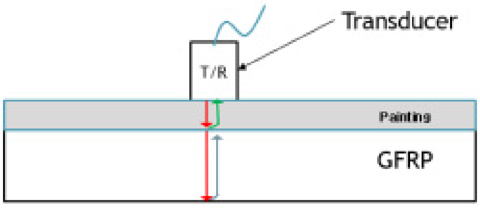
Fig. 2 shows the ultrasonic simulation model design to realize the ultrasonic behavior. The ultrasonic transducer was modeled by the pulse-echo method and installed on the upper surface of the specimen. As shown in Fig. 3, the ultrasonic transducer was installed at a certain distance from the specimen to apply a delay line. Fig. 4 presents a simulation model design to apply a painting layer on the wind turbine composite. The specimen's thickness was 9 mm, and the upper surface was painted. Ultrasonic waves were generated on the upper surface of the specimen to obtain reflected signals between the upper surface of the specimen, the paint, and the specimen.

The simulation used the UT transmission/reception mode and a 25.4 mm diameter circular ultrasonic transducer. There were five transducer modes, including frequencies using the delay line (5 MHz-with delay line, 10 MHz-with delay line, and 20 MHz-with delay line) and those without using the delay line (10 MHz-without delay line, 20 MHz-without delay line). Fig. 4 shows the set-up for the painting layer on the GFRP composite, where the fiber orientation in the composite was unidirectional, and the thickness was 9 mm. The thicknesses of the wind energy turbine blade painting layers were 50 μm, 100 μm, 150 μm, 200 μm, 300 μm, 400 μm, 500 μm, 600 μm, 700 μm, 800 μm, 900 μm, and 1000 μm, respectively (12 specimens in total).

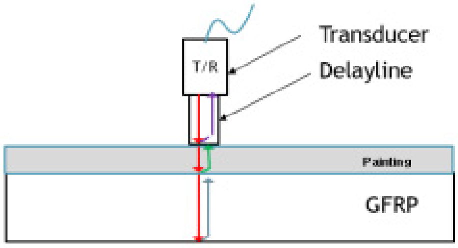
4. Results and discussion of the ultrasonic wave simulation

4.1 A-scan ultrasonic wave behavior

First, Fig. 5 shows the ultrasonic simulation test model with and without a delay line. Fig. 5(a) is the model without a delay line, and Fig. 5(b) is the model using a delay line.



(a) In case of no delayline



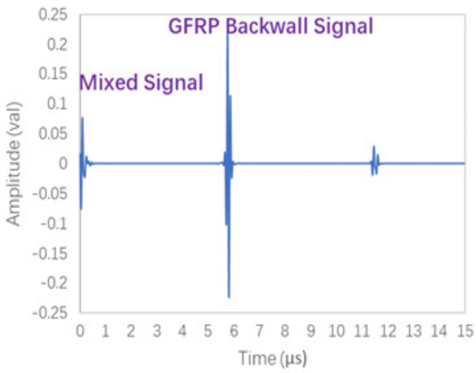
(b) In case with a delayline

Fig. 5 Ultrasonic simulation configuration for measuring the painting thickness

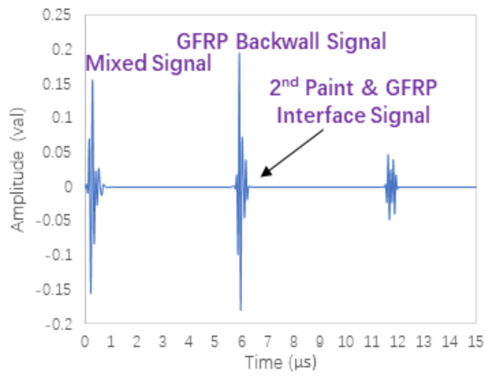
Fig. 6 shows the ultrasonic simulation results at 10 MHz. Fig. 6(a) shows the signal of the 50 μm painting layer, where the layer signal overlapped at 0 μs. Fig. 6(b) is a 200 μm layer, where overlap occurs at 0 μs, as in Fig. 6(a). The second reflected signal also overlaps with the GFRP backwall signal, and the overlap is observed up to a thickness of about 400 μm painting layer. Fig. 6(c) shows the signal of the 500 μm painting layer. The GFRP backwall signal and the second reflected signal are separated from the interface signal. Fig. 6(d) shows the signal of the 1000 μm painting layer, where it is completely decomposed. At 10 MHz, it was possible to evaluate the paint thickness when the painting layer thickness was 500 μm or more.

Fig. 7 shows the ultrasonic simulation results at 20 MHz. Fig. 7(a) shows the signal of the 50 μm painting layer. Fig. 7(b) and Fig. 7(c) show the GFRP backwall signal, the second painting signal, and the GFRP interface signal, but it is difficult to distinguish them. Fig. 7(d) shows the signal when the painting layer is 400 μm thick, and the thickness can be analyzed through the GFRP backwall signal and the painting and GFRP interface signals.

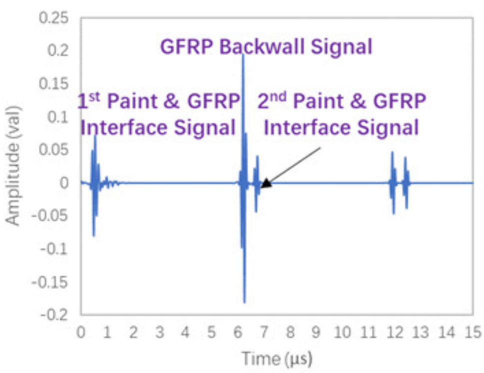
At 20 MHz, it was possible to measure the thickness when the painting layer thickness was 400 μm or more. These results were attributed to the ringing of the ultrasonic signal rather than the resolution according to the frequency. Ultrasonic delay



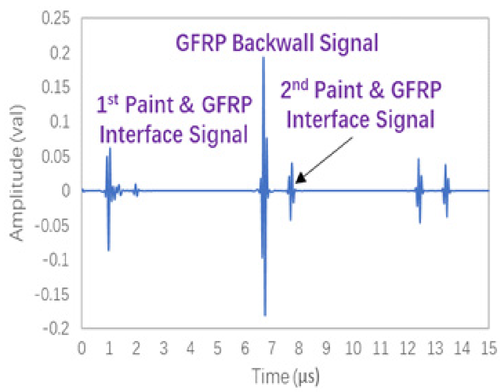
(a) Thickness is 50 μm with frequency of 10 MHz



(b) Thickness is 200 μm with frequency of 10 MHz

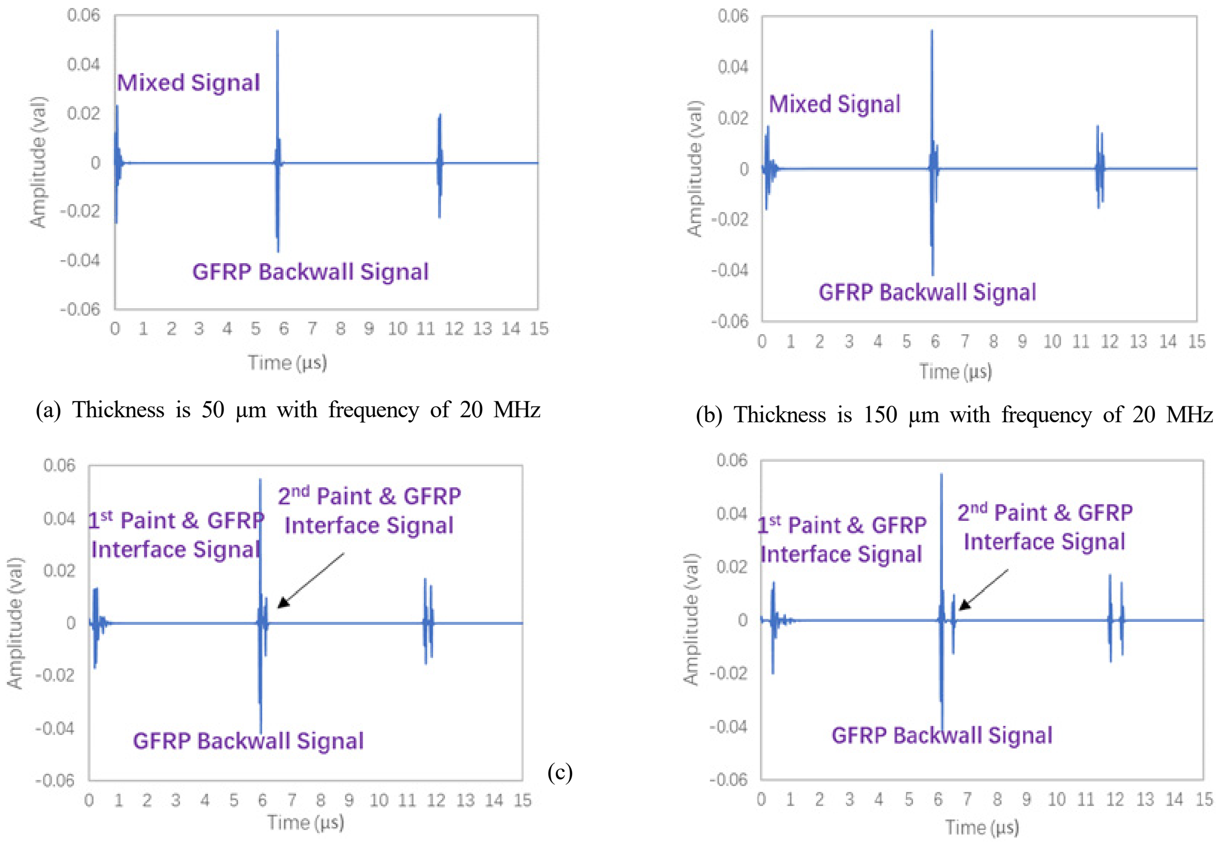


(c) Thickness is 500 μm with frequency of 10 MHz



(d) Thickness is 1000 μm with frequency of 10 MHz

Fig. 6 Ultrasonic simulation results without a delayline for measuring the painting thickness



(a) Thickness is 50 µm with frequency of 20 MHz

(b) Thickness is 150 µm with frequency of 20 MHz

(c) Thickness is 200 µm with frequency of 20 MHz

(d) Thickness is 400 µm with frequency of 20 MHz

Fig. 7 Ultrasonic simulation results without a delayline for measuring the painting thickness

lines were used to increase the signal resolution.

The ultrasonic wedge was set to 5.5 mm, considering the resolution of the ultrasonic signal. In terms of material, Rexolite was applied because it has less signal attenuation at high frequencies.

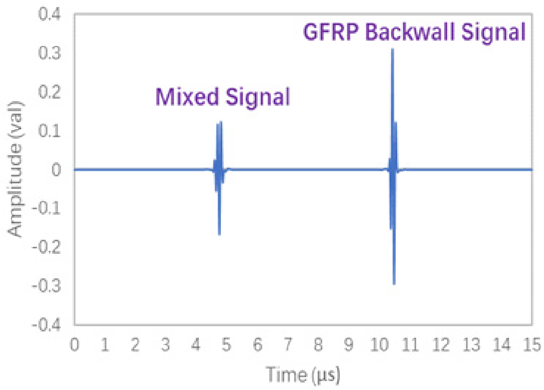
Fig. 8 shows the ultrasonic simulation results applying ultrasonic delay lines at 10 MHz and 20 MHz.

Fig. 8(a) shows the ultrasonic simulation result using an ultrasonic wedge (thickness: 100 µm, frequency: 10 MHz), where it is impossible to distinguish the delay line and the painting interface signal. In Fig. 8(b), the wedge and painting interface signal and the painting and GFRP interface signal are separated. Fig. 8(c) shows the result when the thickness is 100 µm with a frequency of 20 MHz, where the wedge and painting interface signal and the painting and GFRP interface signal are overlapped. Fig. 8(d) shows the result when the thickness is 150 µm, where the signals are separated.

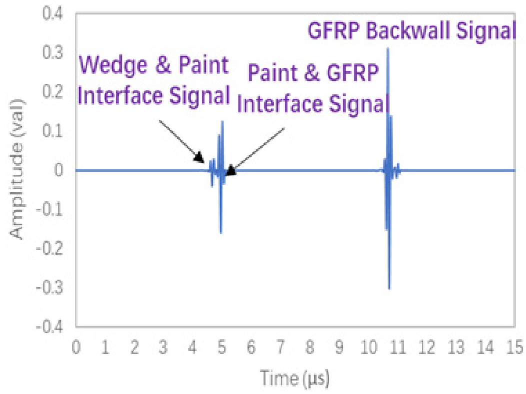
The ultrasonic simulation results in Fig. 8 show that the optimal condition for evaluating paint thickness is using a 20 MHz frequency with an ultrasonic delay line.

Table 1 shows the peak-to-peak time measurement results of the ultrasonic signals of each paint specimen using CIVA simulation. When using a 5 MHz transducer, measurement is possible when paint thickness is 600 µm or more. When using 10 MHz and 20 MHz transducers, measurements can be made when the paint thicknesses are more than 300 µm and 150 µm, respectively.

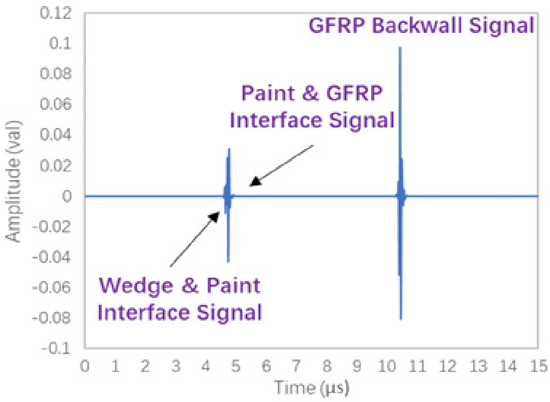
Fig. 9 shows the results of measuring paint thickness using a delay line to prevent overlap with the oscillating ultrasonic signals. The paint thickness and the TOF were compared according to the ultrasonic transducer frequency using a delay line. When the frequency was 20 MHz, paint thickness could be measured from 150 µs to 1,000 µs, showing a linear relationship. Even when the frequencies were 5 MHz and 10 MHz, measurements could be made from 600 µs to 1,000 µs and from 300 µs to 1,000 µs, respectively. At high frequencies, the measurement range was wide because the wavelength (λ) was short, but at low frequencies, the measurement range was short because the wavelength (λ) was relatively long.



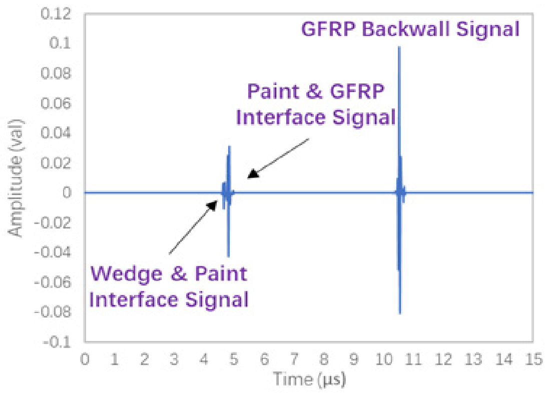
(a) Thickness is 100 μm with frequency of 10 MHz



(b) Thickness is 300 μm with frequency of 10 MHz



(c) Thickness is 100 μm with frequency of 20 MHz



(d) Thickness is 150 μm with frequency of 20 MHz

Fig. 8 Ultrasonic simulation results with a delayline for measuring the painting thickness

4.2 Ultrasonic wave simulations

Fig. 10 shows the results when using a 20 MHz ultrasonic transducer with a 6.35 mm diameter. The behavior of ultrasonic waves was simulated using a delayline (wedge), assuming that painting is on the upper surface of the composite. The figure shows simulation images after 0.5 μs and 2.8 μs when ultrasonic waves were propagated and then the effect of the delayline was confirmed. Fig. 10(a) shows ultrasonic waves oscillating

Table 1 Results of the simulation measurement

Painting thickness (μm)	5 MHz with delayline	10 MHz with delayline	20 MHz with delayline	10 MHz without delayline	20 MHz without delayline
50	-	-	-	-	-
100	-	-	-	-	-
150	-	-	0.150	-	0.172
200	-	-	0.200	-	0.224
300	-	0.289	0.299	0.349	0.324
400	-	0.395	0.397	0.446	0.424
500	-	0.498	0.496	0.549	0.521
600	0.583	0.597	0.597	0.646	0.628
700	0.689	0.694	0.699	0.746	0.721
800	0.792	0.793	0.796	0.842	0.821
900	0.877	0.892	0.896	0.945	0.920
1000	0.988	0.989	0.993	1.055	1.021

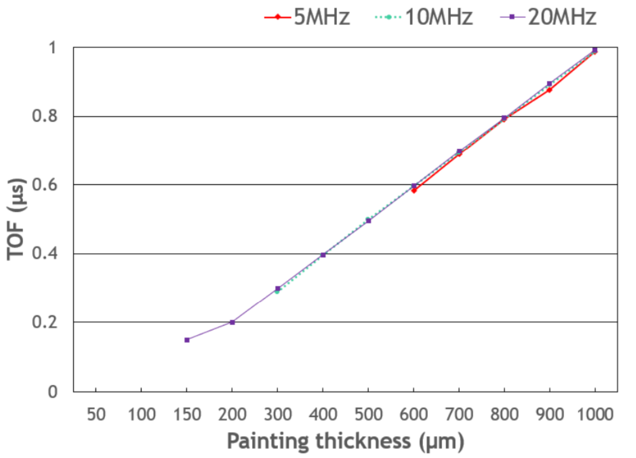
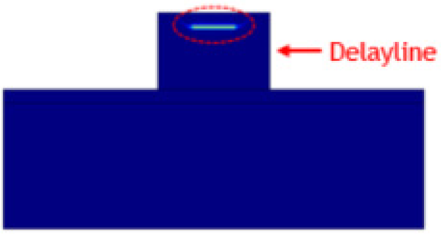
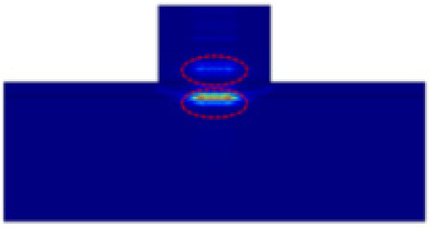


Fig. 9 Comparison of TOF measurement results with the painting thickness using 5 MHz, 10 MHz, and 20 MHz ultrasonic transducers with a delayline



(a) After 0.5 µs



(b) After 2.8 µs

Fig. 10 Ultrasonic simulation results with a delayline (wedge) (frequency of 20.0 MHz and 6.35 mm in dia. for a transducer)

from the upper surface of the delay line. Fig. 10(b) shows the behavior of ultrasonic waves reflected from the upper surface of the painting and passing through the bottom of the painting. It also allows us to understand the behavior of the ultrasonic waves passing through the painting and reflecting from the lower surface to the back of the composite. Therefore, it was possible to propose an optimal ultrasonic measurement technique through ultrasonic simulation to evaluate the painting thickness on the surface of wind energy turbine blades.

5. Conclusions

In this study, wind turbine blade specimens were prepared and painting thickness was measured by utilizing ultrasonic waves with a non-destructive technique. Also ultrasonic NDE simulations were performed under various test conditions to obtain the most optimal parameter for ultrasonic measurement. An optimal technique was also proposed using the time and amplitude reflected from the surface and the back according to the blade painting thickness.

(1) It was possible to measure the painting thickness using a delayline (wedge) to prevent overlapping between the ultrasonic signal propagated from the ultrasonic transducer and the reflected signal.

(2) Especially in very thin thickness, the measurement detectable range was wide because the wavelength (λ) was short at high frequencies, but at low frequencies, the measurement detectable range was short because the wavelength (λ) was relatively long.

(3) When measuring the painting thickness of wind energy turbine blades with the ultrasonic simulation range of this study, one of the optimal parameters was to be found a 20 MHz frequency with a delayline(wedge), which way allowed ultrasonic reflected signals to be measured up to 150 µm in painting thickness.

Acknowledgments

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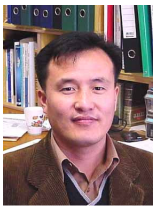

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