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One-Sided Nondestructive Evaluation of CFRP Composites By Using Ultrasonic Sound

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초음파를 이용한 CFRP 복합재의 일방향 비파괴 평가

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Abstract

It is well known that stiffness of composites depends on layup sequence of CFRP(carbon fiber reinforced plastics) laminates because the layup of composite laminates influences their properties. Ultrasonic NDE of composite laminates is often based on the backwall echoes of the sample. A pair of such transducers was mounted in a holder in a nose-to-nose fashion to be used as a scanning probe on composites. Miniature potted angle beam transducers were used (Rayleigh waves in steel) on solid laminates of composites. Experiments were performed to understand the behavior of the transducers and the nature of the waves generated in the composite (mode, wave speed, angle of refraction). C-scan images of flaws and impact damage were then produced by combining the pitch-catch probe with a portable manual scanner known as the Generic Scanner ("GenScan"). The pitch-catch signal was found to be more sensitive than normal incidence backwall echo of longitudinal wave to fiber orientation of the CFRP composites, including low level porosity, ply waviness, and cracks. Therefore, it is found that the experimentally Rayleigh wave variation of pitch-catch ultrasonic signal was consistent with numerical results and one-side ultrasonic measurement might be very useful to detect the defects.

Key Words : Ultrasonic sound(초음파), Peak to peak amplitude(피크 대 피크 진폭), Composites(복합재료), Pitch-catch signal(피치캐치 신호), Backwall echo(배면 에코), Rayleigh wave(레일레이 파)

1. Introduction

The ply orientation and layup sequence are important manufacturing parameters of CF(Carbon fiber)/Epoxy composite laminates fabricated from unidirectional prepreg materials[1,2]. Especially the importance of carbon-fiber reinforced plastics (CFRP) has been generally recognized. For the composite evaluation of application, ultrasonic

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attenuation and velocity measurements have served material characterization purposes well for decades, however, such measurements are often performed on samples with flat and parallel faces using the "backwall" echoes. In industrial NDE of composite aircraft components, there are cases where the back surface echoes are absent due to part geometry. Due to their random nature, backscattered signals are usually processed with spatial averaging, or averaging by frequency agilation[3].

Ultrasonic attenuation deduced from backscattered signal has been used in the correlation with porosity content in solids[4]. Without the benefit of a backwall echo, one can resort to either the backscattered signals in a normal incidence pulse-echo setup or the obliquely scattered signals in a pitch-catch configuration. For this reason, an "A-scan" testing was made for a 5MHz contact transducer placed on a 7mm thick CFRP laminate. In metals, the backscattered signals (sometimes referred to as backscattered "noise") are attributed to grain boundaries and porosity.

In both metals and composites, the envelope of the backscattered signal amplitude is approximately an exponential decay curve. Extensive research had been reported in the literature on the use of scattered ultrasonic radiation for the purpose of material characterization.

In this work, the one-side measurement with pitch-catch technique is pursued for the purpose of nondestructively evaluate material properties. In a unidirectional CFRP laminates, the depth sampling scanning could be increased by increasing the separation distance between the two transducers[5~7]. Also, a pitch-catch ultrasonic technique will be characterized based on the numerical analysis and the technique is experimentally applied to analyze the ultrasonic beam path in CFRP composite laminates.

2. Experimental System

2.1 Configuration of system

First of all, Fig. 1 shows a photo of two Rayleigh wave transducers for using two plastic wedges together. The experimental configuration of the pitch-catch mode is shown in Fig. 2 A pair of miniature, potted angle beam or Rayleigh wave transducers is joined head-to-head as one unit. Probe separation represents the distance between two transducers

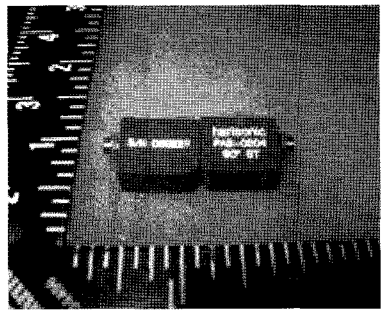


Fig. 1 Rayleigh wave transducers for generating Rayleigh waves

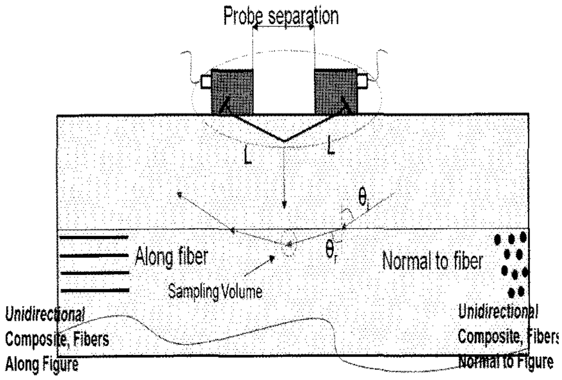


Fig. 2 Pitch-catch measurement

as shown in Fig. 2 The coupling to the sample is achieved with a small amount of oil. The transducers are originally intended for generating Rayleigh waves or refracted shear waves in steel (designated as 90°R, 60°ST, etc); they are chosen for making pitch-catch measurements on composites for their compactness and small size. Most of the tests in this work are carried out using a pair of 2.25 MHz Rayleigh wave probes[3].

To understand the mode of the waves, the angle of refraction, and the propagation speed of the pitch-catch signal, experiments are performed in unidirectional CFRP laminates. To map out the beam path, one-sided pitch-catch experiments are carried out, with a stationary transmitting transducer and a scanning receiving transducer. As shown in Fig. 1, the depth of this "sampling point"in the time-of-flight in the wedges is then subtracted from the total pitch-catch time-of-flight to obtain the propagation time in the composite.

In a unidirectional CFRP, the time offlight of the pitch catch signal normal to the composite, or the origin of the pitch-catch signal, can be increased by increasing the separation distance between the two transducers.

2.2 Samples

The CFRP composite laminates are made of 70 plies of these sheets stacked at the same angles. CFRPs made from uni-directional prepreg sheets of carbon fibers(CU125NS) by Korea HANKUK Fiber Co., have the material properties shown in Table 1, based on the manufacturer's specifications. They are cured by heating to the appropriate hardening temperature (130℃) by a heater in the vaccum bag of the autoclave. A type of specimens was used in this experimentation. Its lay-up, stacked with each ply, indicates that specimen are $[0_{70}]$. Test specimens were prepared with dimensions, about 100 mm × 100 mm × 7mm(width × length × thickness). And the fiber-direction of specimen surface is manufactured to correspond to 0° direction; thus, the fiber-direction is the same as the length direction.

3. Discussion And Results

3.1 Sensitivity of transducers

Fig. 3 shows backscattered signal acquired with a 5 MHz normal incidence contact transducer. Pitch-catch signal obtained using a pair of 5 MHz Rayleigh wave probes (for steel) held together head-to-head. The source was a spike pulser and the time scale is 2 ms per division.

A comparison of the backscattered signal was observed

Table 1 Material properties

Characteristics	Fiber	Resin	Prepreg
Density	1.75×10^3 [kg/m^3]	1.24×10^3 [kg/m^3]	CU125NS
Tensile strength	3.53 [GPa]	0.078 [GPa]	
Elastic modulus	230 [GPa]	3.96 [GPa]	
Elongation	1.5 [%]	2.0 [%]	
Resin content			37 [% Wt]

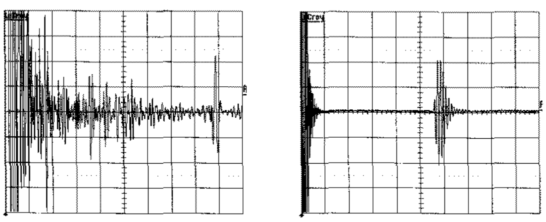


Fig. 3 A comparison of backscattered signal (left trace) and pitch-catch signal (right trace) for a unidirectional CFRP laminate

from a normal incidence contact transducer placed on a thick unidirectional CFRP laminate and the pitch-catch signal obtained using a pair of angle beam transducers, held together head-to-head as one unit. In contrast with the random, decaying backscattered signal, the pitch-catch signal is well defined, localized in time, and does not require extensive signal processing.

3.2 Charactering transducers

The miniature, potted angle beam transducers have external dimensions of 18 × 16 × 8.4 mm. The piezoelectric element, 6.3 mm × 6.3 mm, is located on the back surface of a plastic wedge. According to the transducer manufacturer[(3)], the angle of incidence in the plastic wedge is 64 degrees for the Rayleigh wave transducer (for steel) and the speed of sound in the wedge is 2.79 mm/μs. These data are verified in our laboratory. Using the x-ray image of the transducer, the incidence angle in the wedge is found to be 65 degrees. The speed of sound in the wedge is determined using the configuration of Fig. 4 Based on x-ray image of the transducers, the acoustic path in the wedge is 8.1 mm. The combined time-of-flight in the two wedges is measured to be 5.92 ms, hence the speed of sound is 2.74 mm/μs as shown in Fig. 4 The time-of-flight in the wedges is then subtracted from the total pitch-catch time-of-flight to obtain the propagation time in the composite. In a unidirectional CFRP, the time of flight of the pitch catch signal normal to the fibers is approximately 12 ms; based on this, the depth of the intersection of the transmitting beam and receiving beam is estimated to be about 4 mm below the top surface. The depth of this "sampling point" in the composite, or the origin of the pitch-catch signal, can be increased by increasing the separation distance between the two transducers.

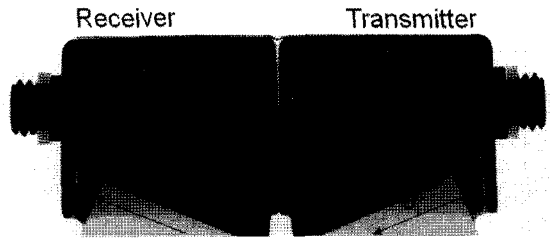
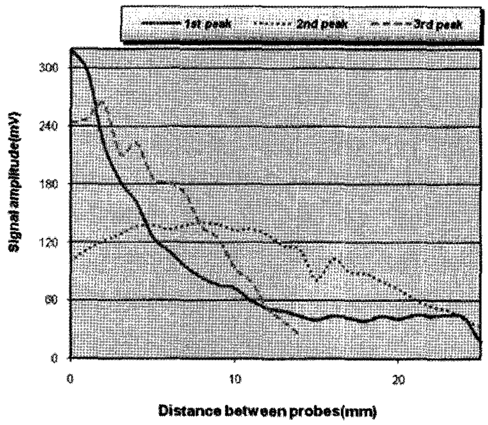


Fig. 4 Determination of combined time-of-flight in the two plastic wedges (X-ray images of the transducers are used here to illustrate the arrangement.)

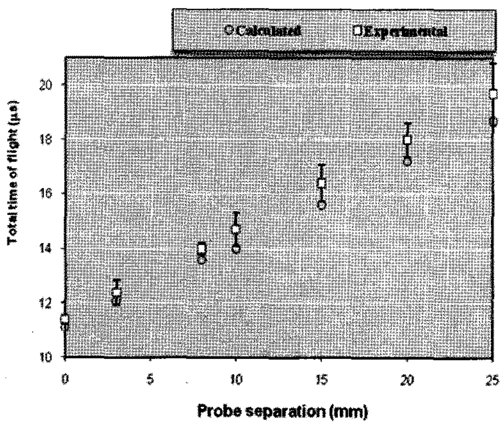
3.3 One-sided measurement

In this work, the pitch-catch method is used in the evaluation of fiber orientation in CFRP laminates so the pitch-catch method could be applied to the detection and imaging of foreign object inclusions and impact damage in CFRP laminates. To understand the mode of the waves, the angle of refraction, and the propagation speed of the pitchcatch signal, experiments are performed in unidirectional CFRP laminates. Fig. 5 shows signal amplitude of pitch-catch signal in one-sided beam profile experimentation using unidirectional CFRP laminates (7mm in thickness) normal to fiber. As described before, a pair of miniature with the Rayleigh wave ultrasonic transducer is joined head-to-head. At that time, three peak-to-peak amplitude are acquired when two Rayleigh wave transducers are touched with head-to-head position at the distance between probes. As shown in Fig. 5 (a), the graph was plotted between signal amplitude and distance of probes. At each peak, the peak UT signals were measured whenever the distance between probes were changed. Three peak values were observed as shown in Fig. 5 (a), which were related to sampling points.

The first peak decreased as probe distance increased and the second & third peaks go up and down as the probe distance increased. Also, Fig. 5(b) shows the relation between time-of-flight and probe separation. First of all, the 1st peak-to-peak values were measured by changing the probe separation between two transducers. A linear relationship was observed and experimental and calculated results were well agreed.



(a)



(b)

Fig. 5 Time-of-flight (a) and amplitude (b) of pitch-catch signal in one-sided beam profile experiment

3.4 Manual C-Scan using pitch-catch transducers on composites

In ultrasonic testing, a scan image of the inspected area can provide visual interpretation of the flaw size, shape, and severity. It is therefore desirable to use the pitch-catch probe in a scan mode. However, a portable manual scanner is preferred over a computer-controlled mechanized scanning frame. The pitch-catch probe was therefore combined with the Generic Scanner ("GenScan"), a system developed for NDI instruments a scanning capability[5]. The version of GenScan used here is based on the Mimio FlipChart, a device that keeps track of the position of a pen (here the pitch-catch probe) using acoustic triangulation.

Fig. 6 shows the combined pitch-catch and GenScan system. The pitch-catch transducers were driven by a portable flaw detector, an Epoch-4, and the Mimio position tracking transmitter, mounted on top of the pitch-catch probe, and the acoustic triangulation receiver are both shown in the photo. The software in the note book computer communicates via serial port with the Mimio position tracker and the flaw

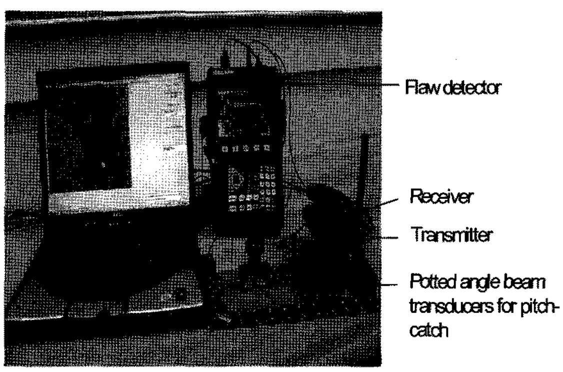


Fig. 6 Producing pitch-catch C-scans using the Mimio-based GenScan system

detector to merge the pitch-catch signal amplitude with the probe position in the generation of the C-scan image.

The pitch-catch and GenScan combination was used to map out embedded flaws and impact damages in a variety of glass fiber reinforced composite laminates and carbon composites. Fig. 6 shows the pitch-catch C-scan image of an impact damage in a 24-ply woven glass composite laminate caused by a drop weight kinetic energy of 16.6J. The damage was detectable by the pitch-catch probe placed. The outer dimension of the circular impact damage was approximately 30mm diameter. Using the pair of potted angle beam Rayleigh transducers and the GenScan setup, a

C-scan image was generated, as shown in Fig. 6 The footprint of the pair of Rayleigh wave transducers was about 38.1 × 6.35 mm. Fig. 6 shows two pixel sizes: the scan was first made with 6.35 mm pixels and then refined around the flaw to obtain a finer definition of the flaw shape.

Higher number (right side of Fig. 6) represents high signal amplitude, lower number represents low signal amplitude, and the boundary area was not scanned. The image of the circular 30 mm diameter impact damage in the GFRP laminate appears flattened and slightly oversized in the horizontal direction. This little distortion was caused by the fact that the footprint of the pitch-catch transducers was a rectangle and its negative left-side long dimension was slightly greater than the flaw size. Images like the one shown in Fig. 6 can be generated manually very quickly using the pitch-catch and GenScan combination. Even though the wave mode(s) produced by the pitch-catch probe in the relatively thin glass composite laminate cannot be easily determined, the lower number region (low signal amplitude) was a reasonably good representation of the impact damage in the laminate in terms of size and shape.

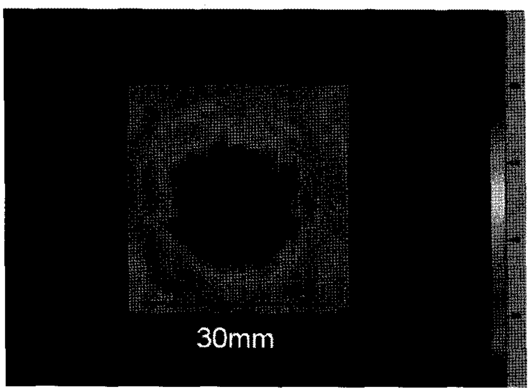


Fig. 7 Pitch-catch scan image of an impact site on a 24-ply woven glass composite laminate

4. Conclusions

In our aim to develop ultrasonic inspection techniques for thick composite solid laminates on the primary structures of the new generation of airplanes, the pitch-catch configuration was investigated for cases where the backwall echo is not available as follows;

(1) Initial results were made in the investigation of one-sided, pitch-catch ultrasonic testing of composite laminates. The approach is believed to hold potential for inspecting composite components when no usable back surface echoes are present.

(2) Both material property anomalies and defects and damage in composites may be inspected with this method. Compared to normal incidence backscattering approach, the pitch-catch method affords a well defined robust signal as compared to the random backscattered noise that requires extensive signal processing.

(3) The pitch-catch technique is preferred in the NDE of material property anomalies, whereas normal incidence backscattering works well for discrete, planar flaws like delaminations.

(4) A pitch-catch probe made of two miniature potted angle beam transducers has basically a fixed angle of incidence and specific angles of refraction for each wave mode.

(5) It is clearly less capable than a phase array of ultrasonic transducers where the beam can be steered. However, the pitch-catch approach is a much simpler and less costly alternative for the inspection of composites.

Knowledgments

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