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Influence of Ultrasonic Waves on the Stacking Orientation in Carbon Fiber/Epoxy Composite Laminates

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ABSTRACT: *In this study, an investigation of shear wave ultrasonic technique was carried out to detect stacking orientation error for CF/Epoxy quasi-isotropy composite laminates. The ultrasonic shear wave is particularly sensitive to ply orientation and layup sequence in the CF/Epoxy composite laminates. In the manufacturing of composite laminates, it is important that layup errors be detected in samples. In this work, an effortwas made to develop shear wave techniques that can be applied to composite laminates. During testing, the most significant problem is that the couplant conditions do not remain the same because of its changing viscosity. The design and use of a shear wave transducer would greatly alleviate the couplant problem. A pyramid of aluminum, with isosceles triangle (two 45o angles) sides, was made to generate shear waves, using two longitudinal transducers based on an ultrasonic-polarized mechanism. A signal splitter was connected to the pulser jack on apulser/receiver and to the longitudinal transducers. The longitudinal transducers were mounted with mineral oil, and the shear transducer was mounted with burnt honey on the bottom as a receiver. The shear wave was generated at a maximum and a minimum based on the ultrasonic-polarized mechanism. Results show it is feasible to measure layup error using shear wave transducers on a stacking of prepregs in composites.*

1. Introduction

Owing to the advantage of very large strength-to-weight and stiffness-to-weight ratios, composite materials (Im et al., 1999) are attractive for a wide range of applications. Increasingly more high performance engineering structures are being built with critical structural components made from composite materials. Especially, the importance of carbon-fiber reinforced plastics (CFRP) in both space and civil aircraft have been generally recognized, and CF/Epoxy(carbon/epoxy) composite laminates are widely used. Composite laminates often possess strong in-plane elastic anisotropy attributable to the specific fiber orientation and layup sequence (Tippler, 1982). However one of important factors is the layup sequence which can influence the CFRP composite performance. This greatly affects its properties in the composite laminate. If one ply is misaligned in the layup sequence, it can drastically alter the mechanical performance of composite laminates.

Some manufacturers cut a small sample from the waste edgeand use a microscope to optically verify the ply orientations on critical parts, but the practice adds more cost and is labor intensive. (Hale et al., 1996; Hsu and Margetan, 1993) Recently, Urabe and Yomoda (Urabe and Yomoda,1987; 1982) have utilized a nondestructive method using a 4 GHz microwave to determine the fiber orientation in the CFRP composites. This method is based on the electrical anisotropy in the orthotropic directions of a unidirectional laminate, with the principal direction aligned with the direction of the fibers. For this method, an incident standing wave is projected into the sample at a given orientation. The differences between the received signals, one with the receiving unit polarized horizontally and one with the receiving unit polarized vertically with respect to the apparatus, were used to determine the fiber orientation in samples constructed from two to eight plies of prepreg tape. Also, Urabe (Urabe, 1987) conducted a research using a 35 GHz microwave to determine fiber orientation in carbon fiber reinforced plastics. Studies were performed on thick composite laminates by Komsky et al. (1994). So, they have developed a method and successfully used it to predict the layer orientation for a 70-ply layer laminate through a neural network. And Komsky et al.(1992) have researched

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the interaction of ultrasonic shear waves with thick composite laminates. This research studied the transmission of shear waves through laminates with both the transmitter and receiver aligned and fixed with respect to the fiber directions in the outer layers of the sample. Results of the experiments showed that changing the layer orientations in the laminate caused a direct effect on the received signal shape and amplitude. A layer-by-layer vector decomposition model was presented to theoretically explain the interaction of shear waves as they propagated through the laminate, but no simulated results were given for the samples tested. Also, in practical area Koo and Kim (2007) had explored simulation of nonlinear numerical wave tank using a long wave induced by a Gaussian-shape submarine landside; also Woo et al. (2007) shows nondestructively FEM simulation of elastic wave propagation in a plate for the detection of damage. Lee et al. (2007) had made a experimentation in order to investigate initial layup error in composite laminates.

This paper aims at investigating the inspection of ply misorientation and layup sequence in CF/Epoxy laminates when normal incident ultrasound waves transmitted in the thickness direction of composite laminates. Therefore, a new technique is presented for determining ply orientation errors and sequencing errors in a composite laminate using through transmission of shear waves based on the theoretical ply-by-ply vector decomposition. Especially, a jig was made of aluminum for alleviating the couplant problems when properties of viscous couplant will easily be changed on time going during the testing. The design and use of a shear wave transducer will be presented for alleviating the couplant problem and the fiber orientation of composite laminates was characterized. Therefore, a technique is proposed for evaluating layup of CF/epoxy composite laminates using through transmission of shear waves based on the theoretical ply-by-ply vector decomposition. Finally, nondestructive characterization was made for fiber orientation of quasi-isotropic composites using a developed shear wave transducer.

2. Decomposition model

The final form for the theoretical ply-by-ply vector decomposition model, as well as similar decomposition models (Hsu et al., 1997), for a typical plate with numerous plies is a very lengthy and complex calculation. Based on decomposition models, the number of discrete components in the theoretical model grow at an exponential rate of 2N. Thus, a plate consisting of 32 plies will contribute 232, approximately 42.9 billion, discrete terms to the calculation of SR (the original time varying vector). An array of this size would be a highly time-consuming and inefficient computation even with the speed and power of today's computers. Another complication arises in determining the values and functions of a, b, r, and $f_{ij}(d)$ to be used in the computation of SR for many plies. Here In the derivation of the model, a, b and r are the attenuation coefficients of the orientations of the transmitter, the waves polarized parallel to the fibers and the couplant layers and $f_{ij}(d)$ is signal reduction factor. In order to utilize the ply-by-ply vector decomposition technique, some assumptions and simplifications are made to simplify the theoretical model.

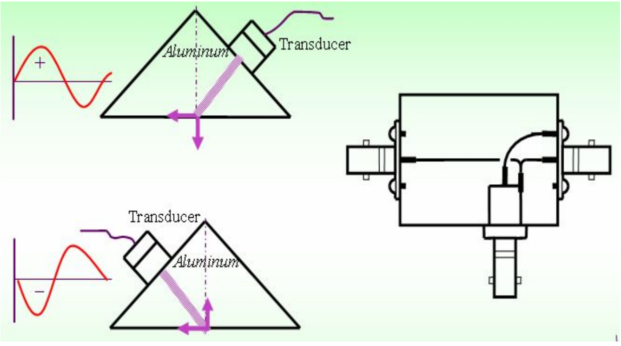
A plate consisting of two plies will be used to illustrate the transformation of the theoretical model to the reduced ply-by-ply vector decomposition model. The first assumption used is that the interface and beam spreading losses are negligible, that is, all $f_{ij}(d)$ terms equal one. This may seem to be a drastic assumption since these losses are sensitive to the order and orientation of the plies, but preliminary tests have shown this assumption to have little effect on the qualitative results and it is essential for further simplification. Next, by constraining all plies in the plate to be comprised of the same material, (hi), ai, and bi are assumed to be identical for every ply. Here (hi), ai, and bi are the thickness of the ithply, the couplant thicknesses at the transmitter and receiver, respectively. Finally, the couplant is a thin layer of highly viscous material and when the transducers are pressed onto the plate, it is assumed that the couplant spreads into a uniform and equal thickness for both transducers; therefore, $r(tt) = r(tr) = r'$. The result of incorporating these assumptions and grouping like terms is given by Eq. (1) at the first term of $Dt = (2tt)/nr + (2h)(sa)$. Here Dt, nr and sa are the time, the wave velocities when the component is polarized parallel to the fibers, perpendicular to the fibers, and propagating through the couplant respectively.

$$\begin{aligned} &SR = STe - 2r'e - 2a'\cos(Dq1)\cos(Dq2) \\ &\cos(DqR) + STe - 2r'e - a'\sin(Dq1)\sin \\ &(Dq2)\cos(DqR) - STe - 2r'e - a'e - b' \\ &\cos(Dq1)\sin(Dq2)\sin(DqR) + STe2r' - b' \\ &son(Dq1)cons(Dq2)\mathrm{sine}(SqR) \end{aligned} \tag{1}$$

where $h=h1$, ..., hN, $a'=a1(h1)$, ..., $aN(hN)$, $b'=b1(h1)$, ..., $bN(hN)$, $sa=1/na$, and $sb=1/nb$.

3. Experimental method

3.1 Specimen configurations



(a) Schematic for shear waves (b) Signal splitter

Fig.1 Schematic mechanism and signal splitter for generating shear waves

Table 1 Layups of CF/Epoxy composites

Name of specimens	Layup	Others
A	$[(0/45/90/-45)_8]_T$	-
B	$[(0/45/90/-45)_4]_S$	-
C	$[(0/45/90/-45)_4]_S$	16th ply at $+45^0$ instead of -45^0

The laminates of the specimens manufactured from uni-directional prepreg sheets of carbon fibers (CU125NS) by Korea HANKUK Fiber Co., had the material properties based on the manufacturer's specifications. The CFRP composite laminates are made of 32 plies of these sheets stacked at different angles. They are cured by heating to the appropriate hardening temperature (130 ℃) by a heater in the vaccum bag of the autoclave.

Three types of specimens were used in this experimentation as shown in Table1. Their lay-up, stacked with 32 plies, indicates that specimen A is $[(0/45/90/-45)_8]_T$, specimen B is $[(0/45/90/-45)_4]_S$ and specimen C is $[(0/45/90/-45)_4]_S$ with the 16th ply at +45° instead of -45°. Test specimens were prepared with dimensions, 70 mm × 70 mm × 4.23 mm (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.

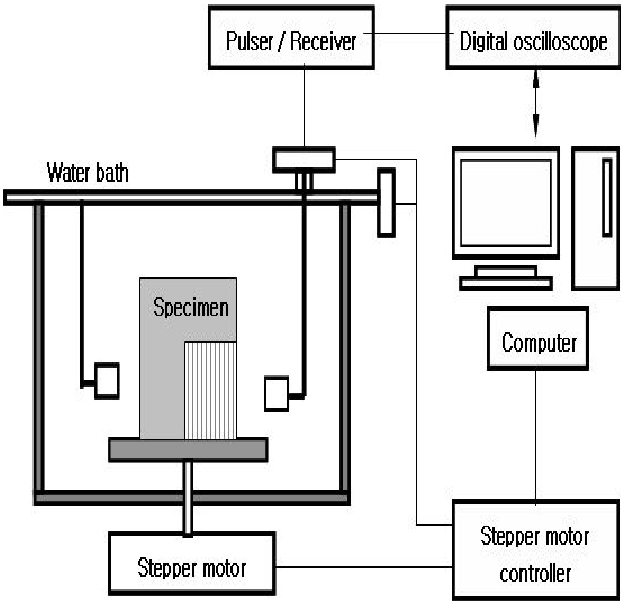


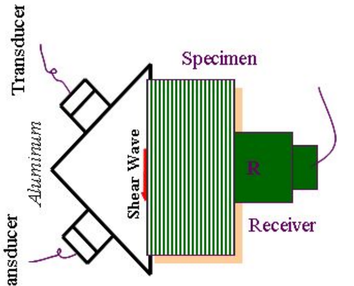
Fig. 2 Schematic for ultrasound testing

3.2 Experimental setup

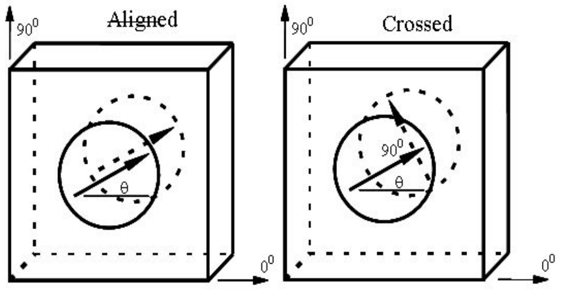
Fig.1 shows schematic mechanism and signal splitter for generating shear waves. The jig is to use two longitudinal wave transducers driven at 180° out of phase to generate a pure shear wave at the bottom base. Here two 1 MHz transducers (Panametrics Co.) were used to generate the longitudinal waves. The polarity of the driving voltage was reversed on one in order to produce a wave 180oout of phase with respect to the other by means of the signal splitter. A wedge was fabricated from aluminum such that the cross section consists of an isosceles triangle with two 45o. It was necessary to keep the cases insulated from each other because the transducer cases are normally grounded and changing the polarity of one transducer changed this condition. A schematic diagram of the motorized contact mode scanner is shown in Fig. 2. Two longitudinal wave transducers with 1 MHz resonance frequency and 12.7 mm in diameter were used in contact transmission mode with on shear wave transducer with 1 MHz. The two transducers are supported by a holder which can be manually rotated with a resolution of 10 degree. The signal splitter was connected to the pulser jack on the pulser/receiver and to the longitudinal transducers. Schematic for ultrasound testing was used to perform the experiments shown in Fig. 2.

This instrumentation included a Panametrics #5052PR pulser/receiver and a LeCroy 9400 digital oscilloscope. The waves were generated and received using two longitudinal wave transducers and a shear wave transducers (Panametrics V153, 12.7 mm diameter, 1 MHz) which were coupled to the composite laminates using a burnt honey couplant supplied by Panametrics. Also, for performing an initials experimentation. a simple fixture was fabricated from two 196 x 196 x 6 (mm) aluminum plates to hold the composite laminate being tested. Each plate has a 18 mm hole at the

Fig. 3 Splitter for making shear wave on pyramid



(a) Setup for ultrasonic testing



(b) Aligned transducers (c) Crossed transducers

Fig. 4 Experimental method using two shear wave transducers

center, to keep the transducers aligned during testing, and one 6 mm hole at each corner for aligning the plates.

A polar grid for orienting the transducers is mounted on the outside face of each plate and the transmitter face plate has a second polar grid mounted on its inside face. This grid is used for orienting the composite laminate. Other components of the fixture include miscellaneous hardware shown in Fig. 2 as well.

3.3 Measurement techniques

The fixture is assembled for experimental data acquisition by first placing the test specimen face down on the transmitter face plate and aligning its 0o, 90o axis between two transducers as shown in Fig. 4. Two bolts are then inserted up on the aluminum pyramid block for keeping transducers in position, the receiver face plate is lowered carefully onto the laminate, and two wing nuts are then installed on the bolts.

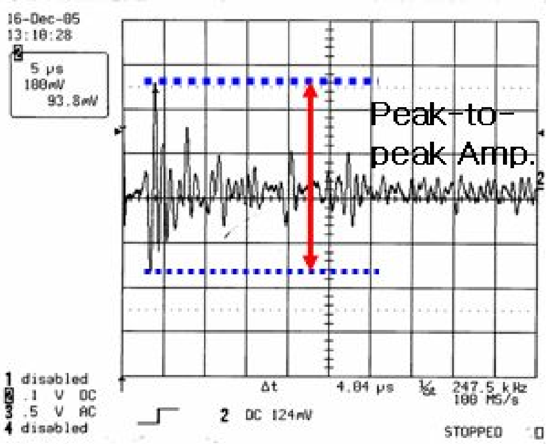


Fig. 5 Typical peak-to-peak amplitude in through-transmission method

Fig. 3 shows a splitter for making shear wave using two transducers. The fixture is then flipped over and the other two bolts are installed and secured with wing nuts. Next, a thin layer of burnt honey couplant is applied to the faces of the transducers, which are then inserted into the 18 mm holes in the fixture. The transducers are held against the laminate under a slight pressure during the test by means of the rubber stoppers, steel washers, and steel clamping bars. Fig. 5 shows a typical peak-to-peak amplitude display from a LeCroy 9400 digital oscilloscope measurement in a through-transmission.

4. Results and Discussions

4.1 Experimental verification of the suggested model

All tests utilized a through-transmitted ultrasonic pulse which was generated and received by a pair of 1 MHz wave transducers. An impulse signal was generated by a pulser/receiver, and the received signal was displayed on a digital oscilloscope. To verify that the reduced model worked at various transducer angles, the first set of experiments were performed using one specimen of 32 aligned plies. This simplifies the reduced ply-by-ply vector decomposition model to Eq. (2) below, where $Dq1 = aT-a1$, $DqR = aR-a32$, here a_T and a_R are the attenuation coefficients of the orientations of the transmitter and receiver and *R*[032/900] and *R*[00/9032] are the experimentally acquired signals. At that time, the other 31 reference signals are not required since all of the fibers in the pack are assumed to be perfectly aligned. These terms sin(*Dqi*)=0, for *i*=2 to 32, produce coefficients equal to zero for those reference signals.

$$Sr = R[0_{32}/9_{00}]\cos(Dq1)\cos(DqR) + R[0_{0}/90_{32}]\sin(Dq1)\ \sin(DqR) \quad (2)$$

The above signals were acquired and stored in the personal computer by aligning the transducers parallel to the fibers for *R*[032/900] and perpendicular to the fiber for *R*[00/9032]. The transmitter and receiver were then oriented at specified angles, a_T and a_R, to the fibers and the received signal for each orientation was acquired and stored in the computer. A spreadsheet was utilized to synthesize the received signal from the stored reference signals and the transducer orientations using Eq. (2). Fig. 6 shows a comparison of the received signal and the modeled signal. The slight differences in amplitudes can be attributed to a change of couplant conditions and ply orientation errors due to small random layup errors. This good agreement between the experimental and modeled wave forms verifies the reduced model.

4.2 Experimental and theoretical solutions

Experimentation consists of performing a polar scan using a through transmission with the transducers in a crossed arrangement, that is, the receiver polarization is oriented at 90o to the polarization of the transmitter. For an isotropic material, this test will produce a null, or zero received signal at any transmitter orientation. However, for a laminate consisting of orthotropic plies, this test is very sensitive to fiber orientation and ply sequence as shown by both the computer modeled and experimental results. The specimens used for this test are based on a realistic layup sequence used in manufacturing composite components and possible errors which can occur during fabrication. When the fixture is assembled for experimental data acquisition by first placing the test specimen face down on the transmitter face plate and aligning its 0o, 90o axis between two transducers, it is found that the results was very sensitive receiver in the through-transmission method.

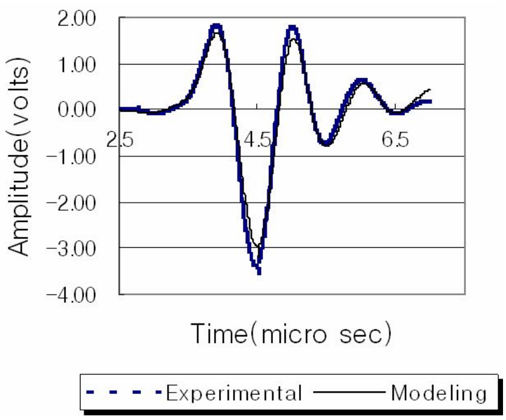
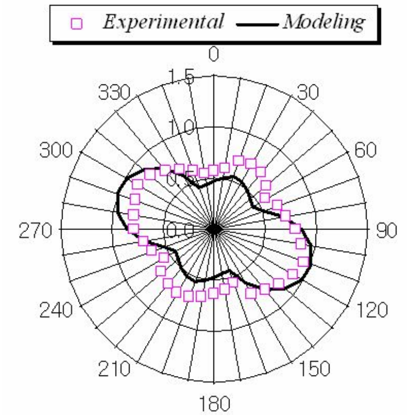
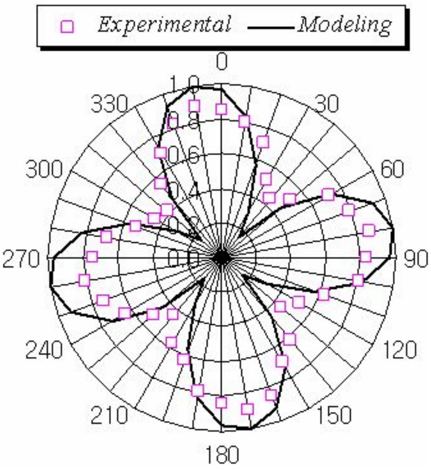


Fig 6 Comparisons of experimental and theoretical solutions with the aligned angle of 90o between the transmitter and receiver

Specimens were compared to demonstrate the test's capability and sensitivity in determining a misoriented ply or an unsymmetrical layup with the same base sequence as a symmetrical layup with the experimental and theoretical results shown in Fig. 7(a) and (b). First of all, in the case of $[(0/45/90/-45)_8]_T$ specimen with unsymmetric layups, experimental and theoretical solutions were obviously shown in Fig. 7. Figure 7(b) shows comparisons of experimental and theoretical results in the case of $[(0/45/90/-45)_4]_S$ specimen with symmetric layups. So it is found that there exists a good agreement in the amplitude and angle between experimental and theoretical results. Those results show a strong qualitative agreement between the experimental and computational solutions. The data in each plot was normalized by dividing it by the smallest peak-to-peak amplitude value contained in the data for each respective plot.



(a) $[(0/45/90/-45)_8]_T$ specimen



(b) $[(0/45/90/-45)_4]_S$ specimen

Fig. 7 Comparison of experimental and theoretical results for specimens $[(0/45/90/-45)_8]_T$ and $[(0/45/90/-45)_4]_S$

5. Conclusions

It was attempted that the special-designed mechanism was build up for generating shear wave because of alleviating the couplant problem. A pyramid with an isosceles triangle with two 45o was made of aluminum to generate shear waves using two longitudinal transducers based on ultrasonic-polarized mechanism. Also, the signal splitter was connected to the pulser jack on the pulser/receiver and to the longitudinal transducers. The results are obtained as follows;

1) The jig was utilized on unidirectional graphite epoxy laminate and a good agreement between the experiment and model was obtained. The developed technique can be applied to for generating shear waves.

2) Sequencing errors were nondestructively detected for symmetric and non-symmetric CF/Epoxy composite laminates about the mid plane. Also, to this end a through-transmission ultrasound test method has successfully been performed to evaluate the layup error of CF/Epoxy composite laminates.

3) After an ultrasonic scanner for contact mode in the newly-developed shear wave transmission method has been designed and tested for NDE of anisotropic composite plates. both theoretical and experimental results demonstrated high sensitivity of the method.

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