

Characterization of CFRP Laminates' Layups Using Through-Transmitting Ultrasound Waves

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Ultrasound waves interact strongly with the orientation and sequence of the plies in a layup when propagating in the thickness direction of composite laminates. Also the layup orientation greatly influences its properties in a composite laminate. If the layup orientation of a ply is misaligned, it could result in the part being rejected and discarded. Now, most researchers cut a small coupon from the waste edge and use a microscope to optically verify the ply sequences on important parts. This may add a substantial cost to the production since the test is both labor intensive and performed after the part is cured. A nondestructive technique would be very beneficial, which could be used to test the part after curing and requires less time than the optical test. Therefore we have developed, reduced, and implemented a novel ply-by-ply vector decomposition model for composite laminates fabricated from unidirectional plies. This model decomposes the transmission of a linearly polarized ultrasound wave into orthogonal components through each ply of a laminate. High probability is found, by comparisons between the model and tests, in characterizing cured layups of the laminates by using the proposed method.

Key Words : Ultrasound Waves, Composite Laminates, Vector Decomposition

Nomenclatures

N	: The total number of plies in the plate.	$e^{-\alpha_i(h_i)}$: The attenuation for the waves polarized parallel to the fibers in the i^{th} ply.
$\alpha_T, \alpha_i, \alpha_R$: The orientations of the transmitter, the i^{th} ply, and the receiver.	$e^{-\beta_i(h_i)}$: The attenuation for the waves polarized perpendicular to the fibers in the i^{th} ply.
$\Delta\theta_i$'s	: The orientation changes at each interface, eg., $\Delta\theta_2 = \alpha_2 - \alpha_1$	$e^{-\rho(tt)}$: The signal attenuations in the couplant layers.
S_T	: The shear wave at the transmitter	$e^{-\rho(tr)}$: The signal attenuations in the couplant layers.
S_R	: The received signal.	$f_{\bar{v}}(\delta)$: A signal reduction factor which includes all losses other than attenuation.
		Δt	: The total time shift of each component of the signal.

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ν_a, ν_B, ν_p : The wave velocities when the component is polarized parallel to the fibers, perpendicular to the fibers, and propagating through the couplant.

1. Introduction

Owing to the advantage of very high 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 aircrafts have been generally recognized, and CFRP composite laminates are widely used. So, CFRPs are a material class for which nondestructive material property characterization is as important as flaw detection (Hsu and Margetan, 1993; Hsu, 1994; Hale et al., 1996). Fiber reinforced 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 the composite laminate. So most manufacturers cut a small sample from the waste edge and use a microscope to optically verify the ply orientations on critical parts, which adds more cost to the composite fabrication due to intensive labor and corrective action after curing.

Recently, Urabe and Yomoda (Urabe and Yomoda, 1987; Yomoda, 1982) have utilized a nondestructive method using a 4 GHz microwave to determine the fiber orientation in the CFRP composite. 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 research using a 35 GHz microwave to determine the 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 laminate through a neural network. And Komsky et al. (1992) have researched 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 propagate through the laminate, but no simulated results were given for the samples tested.

This paper aims at investigating the inspection of ply misorientation and layup sequence in CFRP laminates when normal incident ultrasound waves transmit in the thickness direction of composite laminates. Therefore, a new technique is presented for determining the 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. The test is performed by rotating the transducers and plotting the peak-to-peak amplitude as a function of the transmitter orientation with the transducers in a crossed arrangement, and the received signal. Simulated and experimental results are presented for laminates fabricated from 32 plies, which confirm the high sensitivity to detect a single ply orientation error.

2. Theoretical Model

This model decomposes the transmission of a linearly polarized ultrasound wave into orthogonal components through each ply of a laminate (Hsu et al., 1997). The input to the first ply is decomposed into one component which propagates through the first ply parallel to the fibers and one component which propagates through the first ply perpendicular to the fibers. These two components then become the input for the second ply, where each one is then decomposed into components parallel and perpendicular to the fibers in the second ply. This process continues for all remaining plies in the laminate. After all of the components have been decomposed and have propagated through the last ply in the laminate, the components are projected onto the axis of the receiver and are combined to predict a received signal. The model is general and applies to any layup produced from plies with orthogonal properties.

In the derivation of the model, α_i and β_i , are the attenuation coefficients of the orientations of the transmitter when the waves are polarized parallel and perpendicular to the fibers, ρ is the thickness the couplant layers, (h_i) is the thickness of the i^{th} ply, and (tt) and (tr) are the couplant thicknesses at the transmitter and receiver, respectively. Losses due to beam spreading and interface losses, which depend on the ply to ply orientations and thicknesses, are included in the $f_{ij}(\delta)$ signal reduction factor. The ply-by-ply vector decomposition model can now be derived.

A wave pulse, S_T , is generated by the transmitter at an angle α_T and propagates through the couplant to the face of the first ply. The wave now has the amplitude $S_T e^{-\rho(tt)}$ due to the signal attenuation of the couplant, and a time shift equal to the thickness of the couplant divided by the wave velocity through the couplant. This signal is then decomposed into two components through the angle $\Delta\theta_1 = \alpha_T - \alpha_1$ in directions parallel and perpendicular to the fibers in the first ply. These two components, shown in Fig. 1, then propagate through the first ply and are reduced by their

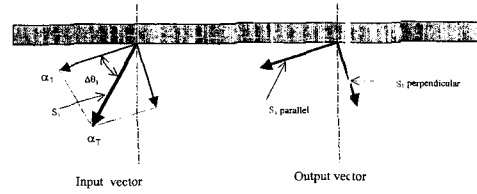


Fig. 1 Input and output vector projection in case of the first ply

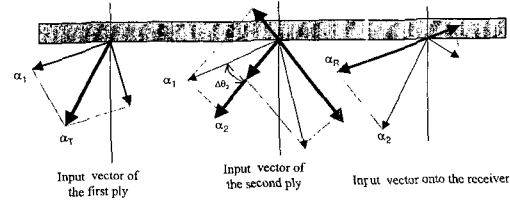


Fig. 2 Schematic of the ply to ply vector projections

respective attenuation, interface, and beam spreading losses. Time shifts of the two components, caused by the fact that ν_α and ν_β are not equal, are tabulated along with the magnitude changes due to losses in lieu of the typical phase term e^{-ikx} . New values and time shifts for each component are now given by Eq. (1).

$$\begin{aligned}
 & \text{Parallel Component in } 1^{st} \text{ ply at } \Delta t \\
 & = (tt) / \nu_\rho + (h1) / \nu_\alpha: \tag{1} \\
 & S_{1para.} = S_T e^{-\rho(tt)} e^{-\alpha_1(h1)} f_{11}(\delta) \cos(\Delta\theta_1) \\
 & \text{Perpendicular Component in } 1^{st} \text{ ply at} \\
 & \Delta t = (tt) / \nu_\rho + (h1) / \nu_\beta: \\
 & S_{1perp.} = S_T e^{-\rho(tt)} e^{-\beta_1(h1)} f_{12}(\delta) \sin(\Delta\theta_1)
 \end{aligned}$$

As these two components enter the second ply, with the fibers oriented at α_2 , each one will contribute two more components if angle α_2 does not equal angle α_1 . The components are projected onto the second ply, reduced by losses, and experience another time shift as they propagate into and through the second ply, given by Eq. (2). Note that each component must retain its corresponding time shift through the calculation as shown in Fig. 2. Parallel Components in 2nd ply at $\Delta t = (tt) / \nu_\rho + (h1) / \nu_\alpha + (h2) / \nu_\alpha$:

$$\begin{aligned}
 S_{2para.} = S_T e^{-\rho(tt)} \times \{ & e^{-\alpha_1(h1)} e^{-2(h2)} f_{11}(\delta) f_{21}(\delta) \\
 & \cos(\Delta\theta_1) \cos(\Delta\theta_2) + e^{-\beta_1(h1)} e^{-\alpha_2(h2)} \\
 & f_{12}(\delta) f_{24}(\delta) \sin(\Delta\theta_1) \sin(\Delta\theta_2) \}
 \end{aligned}$$

Perpendicular Components in 2nd ply at $\Delta t = (tt) / \nu_\rho + (h1) / \nu_\beta + (h2) / \nu_\beta$:

$$S_{2perp.} = S_T e^{-\rho(tt)} \times \{ e^{-\beta_1(h_1)} e^{-\beta_2(h_2)} f_{12}(\delta) f_{22}(\delta) \sin(\Delta\theta_1) \cos(\Delta\theta_2) - e^{-\alpha_1(h_1)} e^{-\beta_2(h_2)} f_{11}(\delta) f_{23}(\delta) \cos(\Delta\theta_1) \sin(\Delta\theta_2) \}$$

This process continues in the same manner for subsequent plies in the plate at an exponential rate of 2^i components decomposed for the i^{th} ply, and a plate with N plies will have a total of 2^N discrete, decomposed components. To demonstrate the projection of the signals onto the receiver, a plate with only two plies will be used. The signal components exiting in the second ply are given in Eq. (2) and all four components will be reduced by $e^{-\rho(tr)}$ as they propagate through the couplant to the face of the receiver. The parallel component is then projected onto the receiver axis by multiplying it by $\cos(\Delta\theta_R)$; likewise, the perpendicular component is projected onto the receiver axis by multiplying it by $\sin(\Delta\theta_R)$, where $\Delta\theta_R = \alpha_R - \alpha_2$. The received signal is given by Eq. (3). This equation demonstrates that the received signal is the combination of four new time varying vectors for a plate with two plies. Each new vector is constructed by multiplying the original time varying vector, S_T , by a scalar term, and shifting the new vector by its corresponding Δt .

Component parallel to receiver axis at

$$\Delta t = (tt) / \nu_\rho + (h_1) / \nu_\alpha + (h_2) / \nu_\alpha + (tr) / \nu_\rho \quad (3)$$

$$S_R = S_T e^{-\rho(tt)} e^{-\rho(tr)} \times \{ e^{-\alpha_1(h_1)} e^{-\alpha_2(h_2)} f_{11}(\delta) f_{21}(\delta) \cos(\Delta\theta_1) \cos(\Delta\theta_2) \cos(\Delta\theta_R) + e^{-\beta_1(h_1)} e^{-\beta_2(h_2)} f_{12}(\delta) f_{24}(\delta) \sin(\Delta\theta_1) \sin(\Delta\theta_2) \cos(\Delta\theta_R) - e^{-\alpha_1(h_1)} e^{-\beta_2(h_2)} f_{11}(\delta) f_{23}(\delta) \cos(\Delta\theta_1) \sin(\Delta\theta_2) \sin(\Delta\theta_R) + e^{-\beta_1(h_1)} e^{-\beta_2(h_2)} f_{12}(\delta) f_{22}(\delta) \sin(\Delta\theta_1) \cos(\Delta\theta_2) \sin(\Delta\theta_R) \}$$

The ply-by-ply vector decomposition model is a very powerful tool for the ultrasonic testing of composite plates consisting of unidirectional plies. As with most theoretical methods, the ply-by-ply vector decomposition model has many complications involved in its implementation and requires that some assumptions be made to reduce it to a practical level for nondestructive testing.

3. The Reduced Vector 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. As shown previously, the number of discrete components in the theoretical model grow at an exponential rate of 2^N . Thus, a plate consisting of 32 plies will contribute 2^{32} , approximately 42.9 billion, discrete terms to the calculation of S_R . An array of this size would require 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 α , β , ρ , and $f_{ij}(\delta)$ to be used in the computation of S_R for many plies. 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 $f_{ij}(\delta)$ 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, (h_i) , α_i , and β_i are assumed to be identical for all plies. 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 film for both transducers; therefore, $\rho(tt) = \rho(tr) \rho'$. The result of incorporating these assumptions into Eq. (3) and grouping like terms is given by Eq. (4) at $\Delta t = (2tt) / \nu_\rho + (2h) (s_\alpha)$.

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]

$$S_R = S_T e^{-2\rho'} e^{-2\alpha'} \cos(\Delta\theta_1) \cos(\Delta\theta_2) \cos(\Delta\theta_R) + S_T e^{-2\rho'} e^{-\beta'} e^{-\alpha'} \sin(\Delta\theta_1) \sin(\Delta\theta_2) \cos(\Delta\theta_R) - S_T e^{-2\rho'} e^{-\alpha'} e^{-\beta'} \cos(\Delta\theta_1) \sin(\Delta\theta_2) \sin(\Delta\theta_R) + S_T e^{-2\rho'} e^{-\beta'} \sin(\Delta\theta_1) \cos(\Delta\theta_2) \sin(\Delta\theta_R) \tag{4}$$

where $h = h_1, \dots, h_N$, $\alpha' = \alpha_1(h_1), \dots, \alpha_N(h_N)$, $\beta' = \beta_1(h_1), \dots, \beta_N(h_N)$, $s_\alpha = 1/\nu_\alpha$, and $s_\beta = 1/\nu_\beta$.

4. Experimental Method

4.1 Specimen configurations

The laminates of the specimens were made from uni-directional prepreg sheets of carbon fibers (CU125NS) produced by Korea HANKUK Fiber Co., and had the material properties shown in Table 1, 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°C) by a heater in the vacuum bag of the autoclave shown in Figs. 3 and 4.

Three types of specimens were used in this experimentation. Their layout, 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, 70mm×70mm×4.23mm (width×length×thickness). And the fiber-direction of specimen surface is made correspond to 0° direction; thus, the fiber-direction is the same as the length direction.

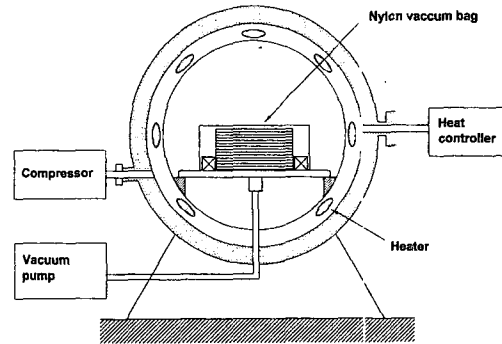


Fig. 3 Schematic diagram of autoclave

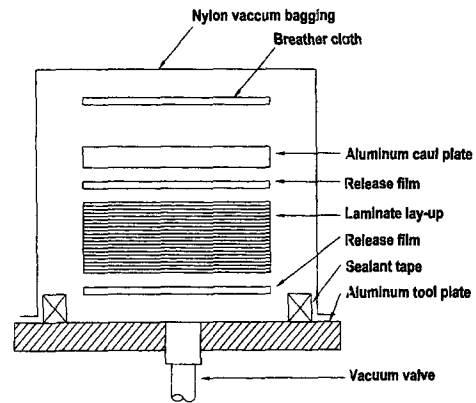


Fig. 4 Autoclave laminate stack layout

4.2 Experimental setup

Schematic for ultrasound testing used to perform the experiments is shown in Fig. 5. This instrumentation included a Panametrics #5052PR pulser/receiver and a LeCroy 9400 digital oscilloscope. The waves were generated and received using a pair of Panametrics V153, 12.7 mm diameter, 1 MHz, shear wave transducers which were coupled to the composite laminates using a burnt honey couplant supplied by Panametrics. A simple fixture was fabricated from two 196×196×6 (mm) aluminum plates to hold the composite laminate being tested. Each plate has a 18 mm hole at the 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

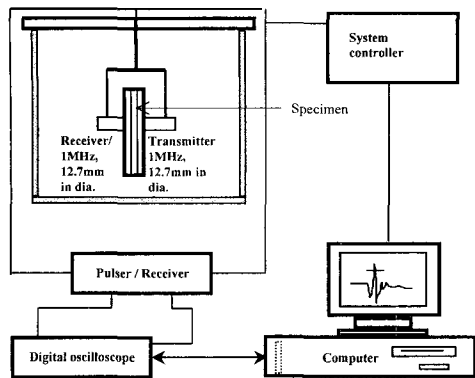


Fig. 5 Schematic for ultrasound testing

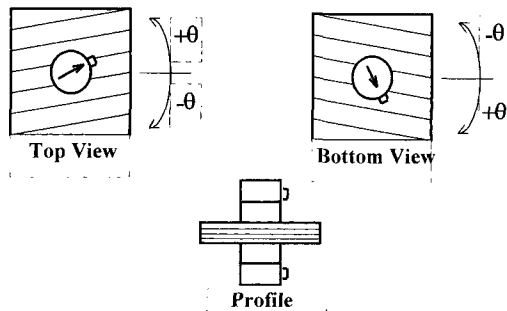


Fig. 6 Schematic of through-transmission method for ultrasound pulses

composite laminate. Other components of the fixture include miscellaneous hardware shown in Fig. 5 as well.

4.3 Measurement techniques

The fixture is assembled for experimental data acquisition (see Fig. 6) by first placing the test specimen face down on the transmitter face plate and aligning its 0° , 45° , 90° axis between two transducers as shown in Fig. 7. Two bolts are then inserted up through the opposite corners of the plate, the receiver face plate is lowered carefully onto the laminate, and two wing nuts are then installed on the bolts. 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

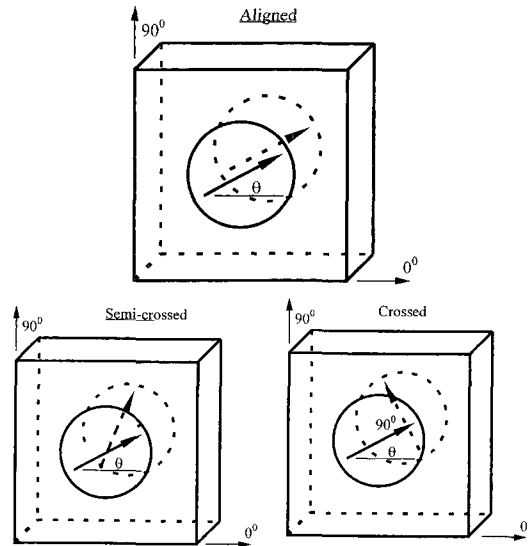


Fig. 7 Experimental method using two shear wave transducers

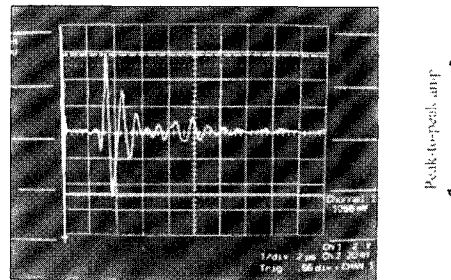


Fig. 8 Typical peak-to-peak amplitude in through-transmission method

during the test by means of the rubber stoppers, steel washers, and steel clamping bars. Fig. 8 shows a typical peak-to-peak amplitude display from a LeCroy 9400 digital oscilloscope in a through-transmission experiment.

5. Results and Discussion

5.1 Experimental verification of the reduced model

Experiments were performed on specimens fabricated from 32 plies of graphite/epoxy prepreg sheets, carbon fibers (CU125NS) by Korea HANKUK Fiber Co., with all fibers oriented parallel to each other to verify the reduced ply-by-ply vector decomposition model. All tests utilized

a through-transmitting ultrasonic pulse which was generated and received by a pair of 1 MHz shear 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 works 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. (5) below, where $\Delta\theta_l = \alpha_T - \alpha_l$, $\Delta\theta_R = \alpha_R - \alpha_{32}$, and $R[0_{32}/90_0]$ and $R[0_0/90_{32}]$ 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 $\sin(\Delta\theta_i) = 0$, for $i=2$ to 32, produce coefficients equal to zero for those reference signals.

$$S_R = R[0_{32}/90_0] \cos(\Delta\theta_l) \cos(\Delta\theta_R) + R[0_0/90_{32}] \sin(\Delta\theta_l) \sin(\Delta\theta_R), \quad (5)$$

The above signals were acquired and stored in the personal computer by aligning the transducers parallel to the fibers for $R[0_{32}/90_0]$ and perpendicular to the fiber for $R[0_0/90_{32}]$. The transmitter and receiver were then oriented at specified angles, α_T and α_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. (5). Fig. 9 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.

5.2 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 90° to the polarization of the transmitter. For an isotropic material, this test will produce a null, or zero received signal at any transmitter orientation.

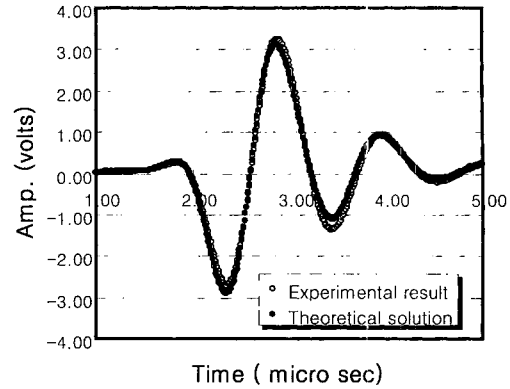


Fig. 9 Comparisons of experimental and theoretical solutions

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 0° , 45° , 90° axis between two transducers, it is found that the results was very sensitive with the aligned angle of 90° between the transmitter and receiver in the through-transmission method.

Specimens A, B and C 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 Figs. 10, 11 and 12. First of all, in the case of specimen A with unsymmetric layups, experimental and theoretical solutions were shown in Fig. 10. Figure 11 shows comparisons of experimental and theoretical results in the case of specimen B with symmetric layups. So it is found that there exists a good agreement in the amplitude and angle between experimental and theoretical results. Figure 12 shows comparisons of experimental and theoretical results in the case of specimen C with a single misoriented ply with symmetric layups.

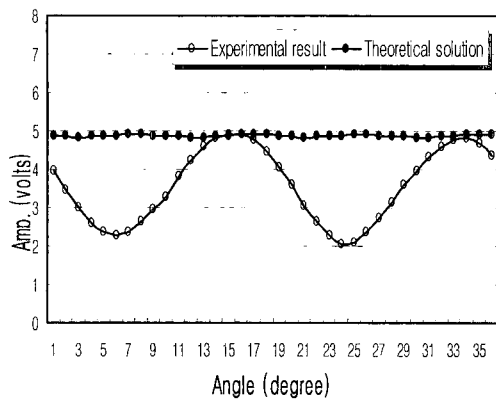


Fig. 10 Comparison of experimental and theoretical results for specimen A

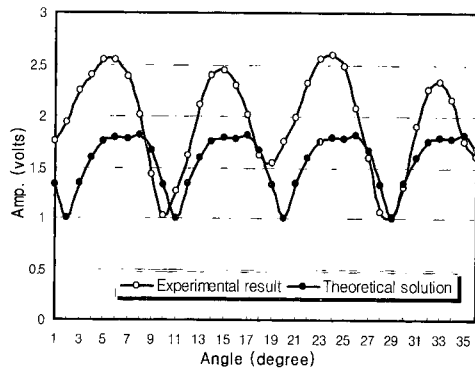


Fig. 11 Comparison of experimental and theoretical results for specimen B

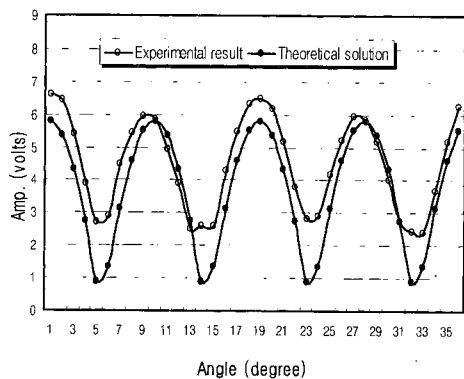


Fig. 12 Comparison of experimental and theoretical results for specimen C

Again, a strong correlation is observed in this figure.

Experimental data were obtained by placing the transducers on each sample with a viscous

couplant, orienting the transmitter, crossing the receiver's orientation such that a minimum peak-to-peak amplitude was displayed on the oscilloscope, and measuring the peak-to-peak amplitude of the minimized signal. This was done for transmitter orientations from 0° to 360° in 10° increments. The results for the experimental and modeling data are graphed in Figs 10, 11 and 12 for comparing the difference between test and model. Modeling results were obtained by implementing the reduced ply-by-ply vector decomposition model. A program was written to compute the reference signal coefficients for any transducer and ply orientations, multiply the coefficients by their respective reference signal, combine the resultant signals to synthesize a received signal, and compute the peak-to-peak amplitude of the synthesized signal. Since the dominant signal segments of $R[0_{32}/90_0]$ and $R[0_0/90_{32}]$ are approximately of the same shape and size, the required 33 reference signals were assembled by linearly interpolating the previously obtained $R[0_{32}/90_0]$ reference signals through 32 time shifts. Each sample's layup sequence was entered, and the program computed the peak-to-peak values for the synthesized signal for transmitter angles ranging from 0° to 360° in 10° increments with the receiver oriented at +90° with respect to the transmitter.

Those results show a strong qualitative agreement between the experimental and computational solutions. The data in each plot were normalized by dividing by the smallest peak-to-peak amplitude value contained in the data for each respective plot. This was done to minimize the effect of changing couplant conditions from test to test which has a significant effect on the amplitude of the received signal. This suggests that there is possibly an error contained in the specimen which has been detected by the test. However, we need to identify or confirm this error discussed in this paper.

6. Summary

It was attempted to detect sequencing errors for symmetric and non-symmetric laminates about

the mid plane, i. e. $[(0/45/90/-45)_4]_S$ versus $[(0/45/90/-45)_8]_T$. To this end, a through-transmitting ultrasound test method has been used to evaluate the layups of CFRP composite laminates. Both theoretical and experimental results demonstrated high sensitivity of the method. In the case of a specimen with unsymmetric layups, discrepancy was found between the experimental and theoretical results. However, there exists a good agreement between experimental and theoretical results in the case of a specimen with symmetric layups. Also, a more strong correlation has been observed between the experimental and theoretical results for a specimen with a single misoriented ply with symmetric layups. This high sensitivity is good for characterizing the layup sequence in a laminate and detecting real manufacturing errors. And the implementation of the reduced ply-by-ply vector decomposition model has been successfully utilized to qualitatively model the behavior of ultrasound waves transmitted through a composite laminate fabricated from unidirectional plies. This model has the capability to qualitatively predict the effects of a ply misorientation and layup symmetry, as demonstrated by comparing the theoretical and experimental results. Also, ultrasound shear waves require a highly viscous couplant between the transducer and the test piece. The usual shear wave couplant is burnt honey; unfortunately, it is very difficult to maintain its property. Experimental measurement results could not be duplicated with a high degree of quantitative reproducibility due to this couplant problem.

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