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Longitudinal and Shear Velocity Measurements in a Woven Fiber Reinforced Laminated Composite

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ABSTRACT
Carbon fiber reinforced laminated composites offer a strong, lightweight alternative to metals, such as steel and aluminum. Companies incorporating this high strength to weight ratio material often apply non-destructive testing methods while inspecting their product for quality assurance, but there is also a desire to extend the application space of non-destructive testing to include methods that provide information about the final part's processed properties. Studies performed by Markham [1], Reynolds and Wilkinson [2] and Rokhlin and Wang [3] have developed ultrasound methods for determining the elastic constants associated with a part manufactured using unidirectional fiber material. The current study discusses a through transmission technique, and both the longitudinal and the shear waves are observed in a single C-scan. The technique provides insight as to how the ultrasonic wave scatters as it travels through the laminated composite. This research focuses on the experimental setup, and the criteria used for determining the proper scan parameters. In particular, results are discussed for varying water paths and transducer orientations with respect to the part surface.

INTRODUCTION
Carbon fiber reinforced laminated composites are comprised of individual layers of carbon fiber material bound together within a resin, often of the thermoset variety. There are several methods for manufacturing these parts including: wet layup, vacuum assisted resin transfer method (commonly referred to as VARTM) and the use of prepreg materials. In the later technique the fibers are pre-impregnated with the resin prior to layup. While each of these methods has a unique set of advantages and disadvantages, they all require a cure cycle to transform the resin matrix from a liquid to a solid material. The transformation of the resin from a liquid to a solid material often requires some form of a thermal cycle where the part is exposed to increased temperatures before the crosslinking of the thermoset is complete. Both prior and during the thermal cycle, the part may also be exposed to pressure in an effort to remove air pockets within the part and assist in providing a smooth part surface. While the part may be designed to achieve a desired stiffness, manufacturing variations can impact the properties of the final part [4].

There are a variety of ASTM approved methods available to determine the properties of the as-manufactured part, but the majority of these methods are destructive in nature. If the part is to be used for its intended purpose, a nondestructive method of evaluating the part properties must be implemented. Researchers have been developing ultrasound methods for determining a part's elastic constants for over forty years. Markham [1] performed one of the earliest studies in this subject. He developed an immersion, through-transmission ultrasound technique which could measure the longitudinal and shear waves within a unidirectional composite part. The experimental setup included an ultrasonic transducer located on either side of the part. While the part is normal to the transducers, the slow quasi-shear wave is polarized and cannot be measured. In order to obtain the velocity measurements of both quasi-shear waves, the composite part was rotated relative to the transducers such that the incident wave entered the part at an angle. Measurements of the longitudinal and shear velocities are repeated for multiple angles of incidence, and the resulting data is used while calculating the elastic constants associated with the part.

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In 1989, Rokhlin and Wang [5] developed another ultrasound method of determining the elastic constants associated with a unidirectional composite plate. The authors began by proving that the measured velocities obtained using Markham's technique were actually the group velocities and not the phase velocities, the latter of which are necessary for proper calculation of the elastic constants. The one exception to this observation is when the incident plane is a plane of symmetry for the composite part, in which case the group velocities are equal to the phase velocities. In an effort to improve the accuracy of the calculated elastic constants, Rokhlin and Wang developed an ultrasound technique involving double through-transmission. The composite sample is placed in the center of a cylinder reflector. A reflective plate is located behind the part, and the ultrasonic transducer is placed a given distance away on the opposite side of the composite sample. A single transducer is used in pulse-echo mode, and the ultrasound wave travels through the part, reflects off of the reflective plate and travels back to the transducer using the same path it took traveling through the part the first time. While performing their experiment, the authors rotate the composite sample such that the incident wave enters the part at an oblique angle. This experimental setup eliminates the need to reposition the receiving transducer and consequently removes some of the uncertainty that was associated with Markham's method. After performing velocity measurements at various angles of incidence, Rokhlin and Wang relate the velocities to the elastic constants via Cardan's solution to the Christoffel equation and use a least-square optimization to calculate the elastic constants associated with the part. In 1992, Rokhlin and Wang [3] studied the stability of their least-square optimization technique by performing simulations with velocity data with up to 5% noise. Their results indicated no significant change in the elastic constants calculated with these velocities.

The goal of the present research is the development of an ultrasonic technique for determining the quasi-longitudinal and quasi-shear velocities as the ultrasound wave travels through the part. The results for determining the proper scan parameters presented in this paper are analyzed using qualitative criteria, but the authors are currently working on quantitative criteria to further optimize the scan parameters.

EXPERIMENTAL SETUP

For this study, a through-transmission ultrasound C-scan method was implemented as seen in Figure 1. The laminate and the pulser were held stationary while the receiver performed a user-defined C-scan across the top surface of the laminate capturing the ultrasound wave as it exits the part. The laminate of choice is a four ply carbon fiber reinforced plastic (CFRP), and each ply consists of an eight harness satin weave carbon fiber material preimpregnated with UF3352 TCR™ resin.

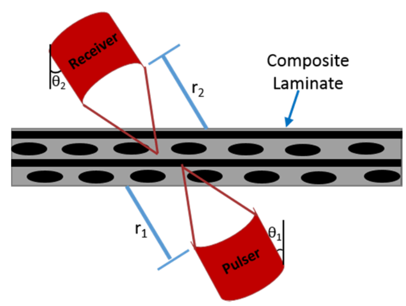

Figure 1: Experimental Setup

Several cases were considered for the orientations of the pulser and the receiver. For example, when the pulser is oriented at a given angle, such as θ_1= 5 degrees, C-scans were performed with the receiver oriented at θ_2= [2, 4, 6,…,20] degrees. The orientation of the pulser would then be changed, for example θ_1= 10 degrees, and the C-scans would be performed again for the same set of θ_2 angles. Another group of cases considered in this study is related to the water path values for the receiver. For example, C-scans were performed with the water path of the pulser, r_1, kept at a constant 2.0 inches while the water path of the receiver, r_2, was varied from 0.5 inches to 2.0 inches. A summary of the scans performed is provided in Table 1.

Table 1: Summary of Scans Performed

Pulser Orientation (deg)	Pulser Water Path (in.)	Receiver Orientation (deg)	Receiver Water Path (in.)
5	2.0	[2, 4, 6, 8, 10, 12, 14, 16, 18, and 20] 10 scans total	2.0
10	2.0	[2, 4, 6, 8, 10, 12, 14, 16, 18, and 20] 10 scans total	2.0
10	2.0	16	[0.5, 1.1, 1.5, 1.75 and 2.0] 5 scans total

RESULTS FROM IMMERSION ULTRASOUND TECHNIQUE

In the first set of ultrasound C-scan measurements, the pulser was held at a constant angle from the surface normal of θ_1= 5 degrees, while the receiver was varied from 2 to 20 degrees in increments of 2 degrees. Figure 2 shows the C-scans when the receiver was oriented at θ_2 = 4, 12 and 20 degrees with the arrows indicating the peak of the longitudinal and shear wave regions. Each C-scan traverses 1.5 inches along the horizontal axis and 1.0 inch along the vertical axis. Inspection of the A-scans for the case when the receiver is oriented at 4 degrees indicates the scan area is largely represented by a longitudinal wave with what appears to be a low amplitude quasi-shear wave located along the bottom edge of the figures. When the receiver is oriented at 12 degrees, the longitudinal and shear waves are clearly distinguished from one another as seen in Figure 3. Notice that the three points selected, A, B, and C, each indicate a different region of the C-scan. A shear wave, indicated by the near symmetric rise and fall of the intensity, is evident at both points A and C, whereas the longitudinal wave is evident by the rapid rise and slow decay of intensity at point B. When the receiver is oriented at 20 degrees, there is a noticeable decrease in the signal amplitude as compared to the 12 degrees case, but the longitudinal and shear waves are still separated from one another in the C-scan image.

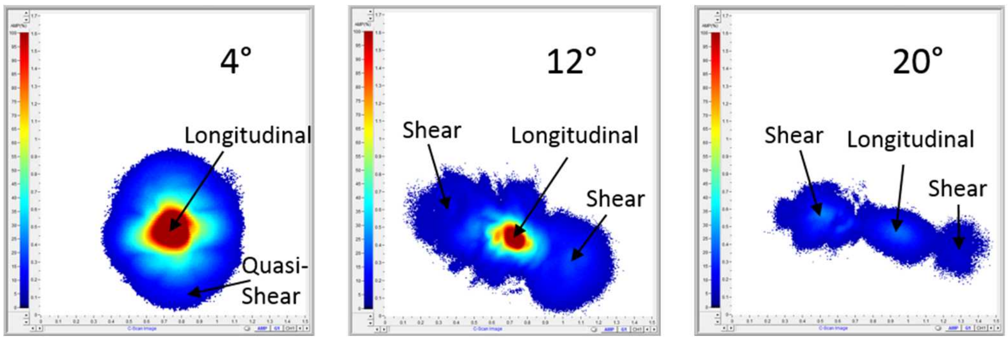

Figure 2: Comparison of C-scan results when the pulser is oriented at 5 degrees from the vertical and the angle of the receiver is varied (4, 12, and 20 degrees). The colorbar is identical across these three plots, ranging from 0% (blue) to 100% (red) of the highest recorded amplitude. The axes on each plot range from 0 to 1.5 inches in both the horizontal and vertical directions.

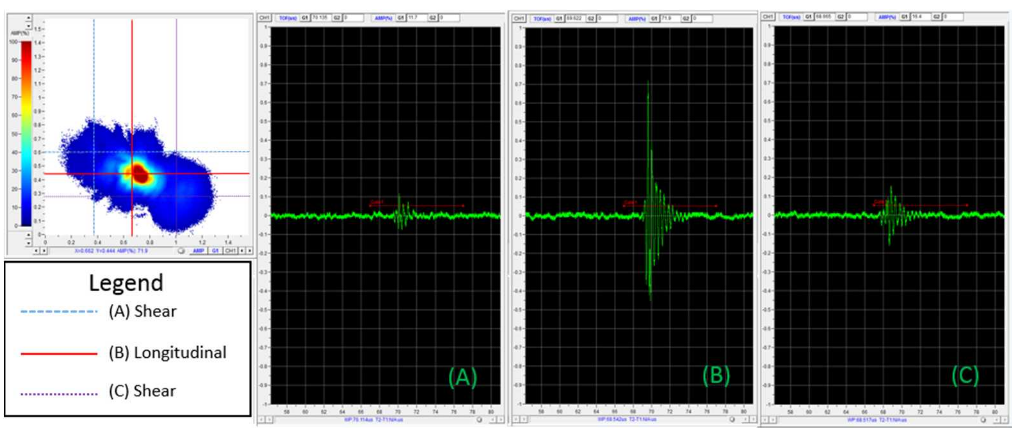

Figure 3: Analysis of the A-scan associated with three different points on the C-scan where the pulser is oriented at 5 degrees and the receiver is oriented at 12 degrees

Next, the water path of the pulser and the orientation of both the pulser and the receiver were kept constant at an angle of 10 degrees and 16 degrees, respectively, while the water path of the receiver was varied from 0.5 inches to 2.0 inches. These results are summarized in Figure 4. The focal length of each of the transducers used in this study was 2.0 inches. Based on a visual interpretation of the C-scans in Figure 4, the results obtained when the receiver's water path was between 1.5 inches - 2.0 inches are almost indistinguishable. These C-scans were performed across the same surface area with the water path of the receiver being the only variable changed between scans. With this in mind, the A-scan at a single point in the scan area could be compared with the A-scan obtained at the same point across each of the five cases depicted in Figure 4 with the comparison point indicated by the crosshairs at (x_1,x_2) =

(0.70 in., 0.55 in.). The comparisons of the A-scans at this location are presented in Figure 5. Notice the amplitudes of the A-scans vary from case to case. The peak amplitudes in cases (A) – (E) in Figure 5 are, respectively, 33.5%, 50.0%, 31.3%, 16.4%, and 24.2%.

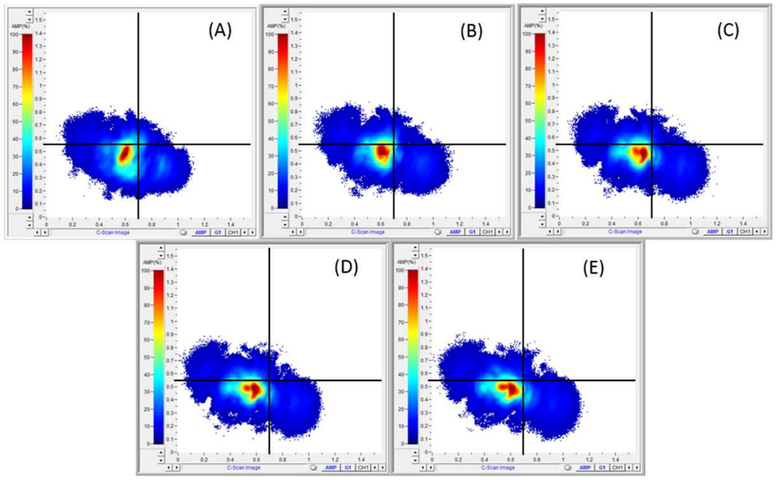

Figure 4: C-scan results for varying the water path of the receiver while keeping the water path of the pulser constant at 2.0 in. The water path of the receiver is: (A) 0.5 in., (B) 1.1 in., (C) 1.5 in., (D) 1.75 in., and (E) 2.0 in.

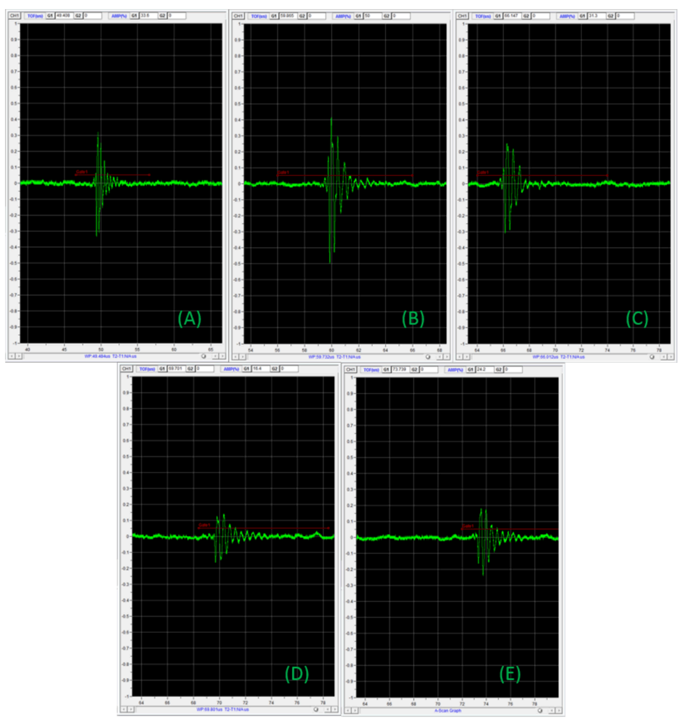

Figure 5: A-scan comparison at the point (0.70, 0.55), which is indicated by the crosshairs in Figure 4 (A)-(E), for each of the C-scans performed while varying the water path of the receiver relative to the top surface of the part.

As evident from Figures 2-5, the incident ultrasound wave scatters as it travels through the carbon fiber reinforced laminated composite. This method is able to capture a C-scan image of the ultrasound wave travelling through the part, and both the quasi-longitudinal and quasi-shear waves can be observed in the image. The qualitative criteria used while analyzing the cases presented in this paper were: (1) Can we observe both the longitudinal and the shear waves in the composite in a single C-scan? and (2) Do any of the scan parameters (i.e. transducer orientation or water path) significantly alter the C-scan results? If so, at what values do these changes occur? Based on these criteria and the discussion of the results, a receiver orientation of θ_2 = 10-14 degrees with a water path between 1.5 and 2.0 inches would be recommended when using a pulser oriented at θ_1 =5 degrees with a water path of 2.0 inches.

CONCLUSIONS

The purpose of this study was to develop a through-transmission ultrasound C-scan technique that could capture both the longitudinal and shear waves in a single scan. Earlier studies have successfully developed ultrasound techniques for determining the longitudinal and shear velocities in a composite laminate manufactured using unidirectional fabric. Measurements in this study were performed on a four ply carbon fiber reinforced laminated composite manufactured using an eight harness satin weave preimpregnated carbon fiber fabric. As evidenced by the results presented in Figures 2-5, the proposed ultrasound technique is capable of capturing both types of waves travelling through the carbon fiber reinforced laminated composite. Qualitative analysis of the results obtained using a pulser oriented at θ_1 =5 degrees suggests the orientation of the receiver should be θ_2 = 10-14 degrees while the receiver's water path should be between 1.5 - 2.0 inches.

FUTURE WORK

The authors are currently working on quantitative methods of comparing the C-scan measurements to further optimize the scan parameters used in this technique. Once the scan parameters are optimized, the measured longitudinal and shear velocities will be incorporated into calculations for determining the elastic constants associated with the scanned part.

ACKNOWLEDGEMENTS

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