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A PLAUSIBILITY ARGUMENT FOR ANGULAR ULTRASONIC SCATTERING IN FIBER-REINFORCED COMPOSITES

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ABSTRACT

NASA is currently pursuing an ultrasonic array-based approach to measure fiber waviness (via local fiber alignment) in fiber-reinforced composites, which is based upon the assertion that ultrasound scatters in many directions from the fibers and that the angular distribution of that scattering can be used to infer the direction of the originating fibers. This paper presents a non-rigorous physical argument for the plausibility of this hypothesis.

Keywords: composites, ultrasonics, angular scattering

1. INTRODUCTION

In-plane fiber waviness in composites is difficult to measure and quantify. In the 1980s, oblique-incidence ultrasonic backscattering, often called polar backscattering [1], was investigated for the measurement of local fiber orientation. While successful, this approach impractically required mechanical rotation of a transducer around each measurement point.

It is proposed that ultrasound scattered from the fibers in a composite would cover an angular distribution broader than that subtended by a conventional pulse-echo transducer, and that the angular distribution of that scattered sound would contain potentially useful information about the fiber orientations within the interrogated volume. Furthermore, a wide-aperture 2-D array could provide an efficient measurement of this angular scattering. The current NASA Advanced Composites Project has enabled us to investigate this hypothesis, in an effort to measure waviness.

This paper presents a physical argument, admittedly non-rigorous, to approximately describe the expected ultrasonic scattering behavior and compare it with some initial measured results.

2. ULTRASONIC SCATTERING FROM FIBERS

Consider the composite material pictured in Figure 1. This photomicrograph shows a single ply in a composite laminate, cut in a plane perpendicular to the fiber direction. The ends of the carbon fibers appear as light gray circles distributed among the medium gray matrix material, with a few darker areas, which are pores. This figure illustrates the dimension of the fiber diameter relative to the laminar thickness, and the fraction of the volume occupied by fibers and matrix.

Table I presents a number of numerical values pertinent to this discussion. For the sake of this discussion, a typical fiber diameter of 0.005 mm is used. Also, the laminates used in this study are comprised of eight lamina, with fiber orientations denoted $[45, 0, -45, 90]_S$, having a total thickness of 1 mm. Thus, each lamina represents a layer of thickness 0.125 mm of 0.005 mm diameter fibers running in one direction.

2.1 Approximation: Long Wavelength Ultrasonic Plane Waves

In the type of composite material under consideration, the ultrasonic speed of sound for longitudinal waves is typically measured to be 2.8-3.2 mm/μs for propagation perpendicular to

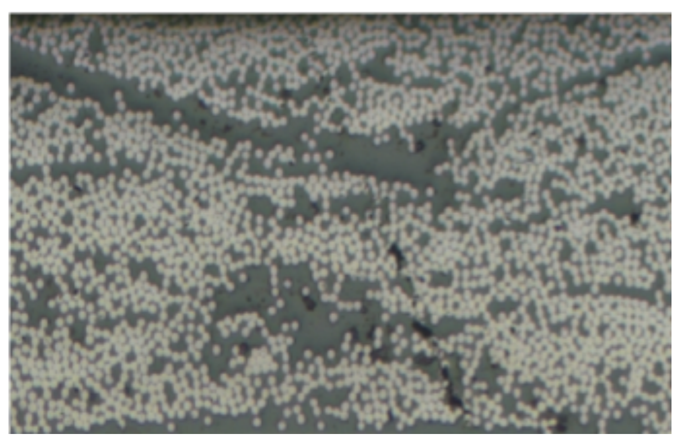

FIGURE 1: CROSS-SECTIONAL MICROGRAPH OF A LAMINA, SHOWING INDIVIDUAL CARBON FIBERS (LIGHT), POLYMER MATRIX (MEDIUM), AND PORES (DARK)

TABLE I: PERTINENT NUMERICAL QUANTITIES

Frequency	Quantity	Parallel	Perpendicular
	Wave Speed (Longitudinal)	8.40 mm/µs	2.80 mm/µs
	Wave Speed (Shear)	5.40 mm/µs	1.80 mm/µs
	Wave Speed (Water)	1.48 mm/µs	
2.25 MHz	Wavelength (Longitudinal)	3.73 mm	1.24 mm
	Wavelength (Shear)	2.00 mm	0.67 mm
	Wavelength (Water)	0.66 mm	
5 MHz	Wavelength (Longitudinal)	1.68 mm	0.56 mm
	Wavelength (Shear)	0.90 mm	0.30 mm
	Wavelength (Water)	0.296 mm	
10 MHz	Wavelength (Longitudinal)	0.84 mm	0.28 mm
	Wavelength (Shear)	0.45 mm	0.15 mm
	Wavelength (Water)	0.148 mm	
Thickness of Lamina		0.125 mm	
Diameter of Fiber		0.005 mm	

the fibers. The sound speed is anisotropic, with the other extreme being for propagation parallel to the fibers, ranging from 3 to 6 times the speed across the fibers. For this discussion, a longitudinal speed of 2.8 and anisotropy factor of 3 is used, as shown in Table I.

The material supports shear waves, as well, which have speeds a bit more than half that of the corresponding longitudinal waves. For this discussion, values of 1.8 and 5.4 mm/µs are used.

From Table I, even the shortest wavelength shown, for 10 MHz shear waves across the fibers, is 30 times the diameter of a fiber. Experimentally, even focused ultrasonic beams are 0.5 mm (100 fiber diameters) or larger in lateral dimension. Because of anisotropy of the medium, the wave modes at the fiber will not be purely longitudinal or shear, but they can still be accurately described as plane waves.

2.2 Approximation: Fiber in Continuous Medium

The composite lamina behaves as an anisotropic continuous medium for wave propagation. The many tiny perturbations made by the fibers contribute to dispersion and attenuation, but their primary effect is due to the oriented stiffness caused by the fibers.

In the backward directions, each fiber contributes a scattered wave. Because the fiber diameter is so small, the scattered magnitude will be very small. Thus, the magnitude of any multiple scattering would be extremely small, so as to be negligible, for this discussion.

Under these assumptions, the ultrasound backscattering is considered to be the sum of single scattering events from individual fibers surrounded by continuous medium.

2.3 Break Plane Wave into Components

The incident plane wave is considered to be the sum of two plane waves: one incident parallel to the fiber direction and one perpendicular to the fiber. The parallel plane wave moves along, practically unperturbed by the fiber. The perpendicular wave excites a scattering event. The scattered waves are then summed with the unperturbed parallel wave to obtain the net scattered waves.

2.4 Scattering from Fiber

Scattering of normally-incident sound by cylinders has been considered by many, including Faran [2]. Under the conditions of long wavelength plane wave incidence, the scattered field produced is radial in nature with little variation around the azimuthal direction.

Variation in scattering with the polar angle is to be expected. Measurements in our lab of a bundle of Kevlar thread in plain resin showed measurable backscattering from approximately 80° to 100° incidence [3]. This variation is assumed to apply here.

3. RESULTS AND DISCUSSION

A representation of the predicted behavior is presented in Figures 2 and 3. In Figure 2, the vertical line represents an isolated fiber, and a plane wave is incident normal (perpendicular) to the fiber. There is no parallel component to the incident wave. The magnitude of angular scattering from a point on the fiber is depicted as a surface, uniform radially, and having a narrow (10°-20°) width symmetrically around the radial direction.

A case of non-normal incidence is depicted in Figure 3. Similarly to the normal-incidence case, the fiber scatters over a narrow range of angles, but each scattered wave is combined

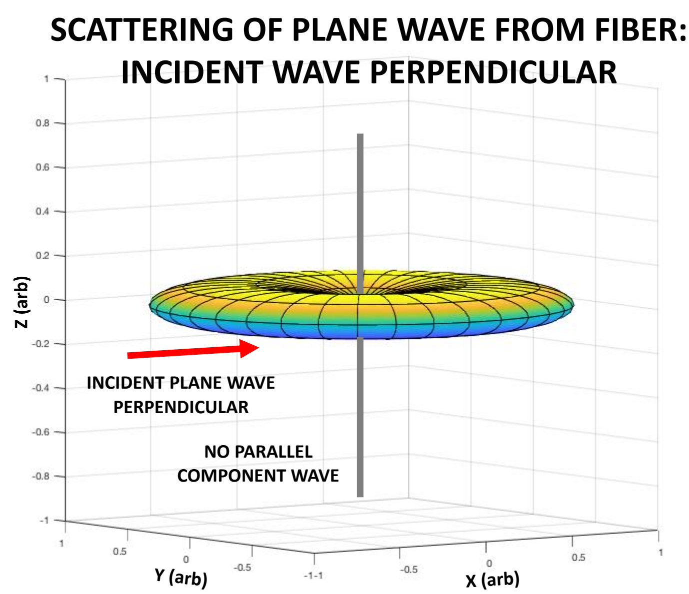

FIGURE 2: REPRESENTATION OF ANGULAR SCATTERING OF NORMALLY-INCIDENT PLANE WAVE BY A FIBER

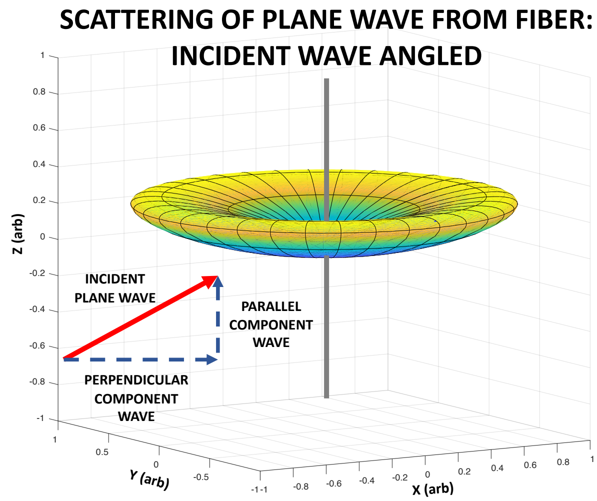

FIGURE 3: REPRESENTATION OF THE ANGULAR SCATTER OF A NON-NORMALLY INCIDENT PLANE WAVE BY A FIBER

with the component of the incident wave parallel to the fiber, producing a distortion of the scattering parallel to the fiber.

Let's apply this model to explain some measured signals. Figure 4 depicts a wide-angle backscatter array interrogating a quasi-isotropic composite laminate. The array comprises 96 elements, 2.25 MHz, 0.25 inch diameter, unfocused, on a spherical surface of radius 7 inches. Elements are hexagonally arranged with 3.6° minimum spacing. The transmitting element, on the outer edge of the array, lies at 18.7° from the normal.

The received signal by the transmitting element is shown in Figure 5 as the circled element labeled A, and corresponds to polar backscatter. The elements on the opposite edge of the array are dominated by the large surface reflections, and are labeled B. The incident sound is perpendicular to the 0° fibers, and the scattering originating therefrom is received between the vertical dashed lines, labeled C. The scattering from the diagonal +45° and -45° fibers incur some shift due to the parallel component of the incident waves; the scattering from these fibers are in areas D and E, respectively. The array does not seem to receive any scattering from the 90° fibers, consistent with the shift along the fiber direction to area F, which is outside of the array.

4. CONCLUSION

A simple physical model for the angular scattering of ultrasonic waves from the fibers was described, which appears to fit with the early results of wide-angle backscatter measurements.

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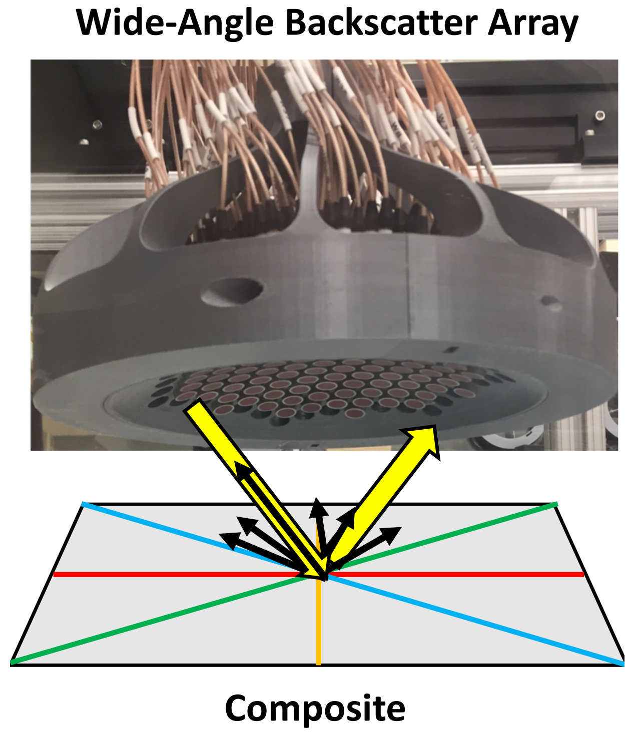

FIGURE 4: SCHEMATIC OF WIDE-ANGLE BACKSCATTER ARRAY MEASUREMENT: TRANSMIT WITH ONE ELEMENT ON THE EDGE, ELEMENTS ON OPPOSITE SIDE RECEIVE SURFACE REFLECTIONS, ALL OTHER ELEMENTS RECEIVE WIDE-ANGLE BACKSCATTER

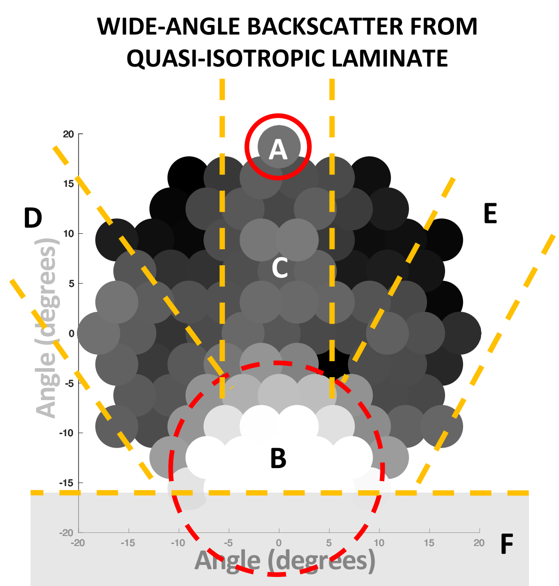

FIGURE 5: SIGNALS FROM WIDE-ANGLE BACKSCATTER ARRAY SEGMENTED ACCORDING TO SOURCE OF SCATTER