Acoustic wave propagation in composite materials: an experimental study

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ABSTRACT

This paper demonstrates acoustic speed measurements in anisotropic composite materials using fiber -optic extrinsic Fabry-Perot interferometric sensor (EFPI). Acousto-ultrasound technique is used to generate unidirectional surface acoustic waves (SAW) in a multilayered composite specimen. The principle of operation and the fabrication of the EFPI sensor are explained. The composite specimen is interrogated by a piezoelectric transducer (PZT) driven by 1.2 MHz signal pulses from an RF generator. The acoustic speed is calculated by noting the difference in the arrival times of the acoustic signal detected by the sensor for different locations of the piezoelectric source separated by a known distance. The possible variation of the acoustic signal speed with respect to the direction of the fibers is studied. This study could be used in determining the dispersion curves of materials and impact location detection in composite materials.

2. INTRODUCTION

2.1 Acoustic emission and acousto-ultrasonic approach

The term acoustic emission (AE) implies ultrasonic sound signals emitted when a material is deformed or fractured. These signals are caused by sudden localized changes in stresses and when detected by a sensor can be used to study the material properties of the structure and hence improve the health and life time of the structure. Over the recent years acoustic emission has been accepted to play a major role in nondestructive testing (NDT) of materials. AE was used during the effects of heat treatment on the life cycle fatigue of D6ac steel specimen.[1] It was observed that the AE signals were different for materials with different toughness which was attributed to the failure modes of the material. Use of acoustic emission in cure monitoring, crack propagation, weld monitoring, leak detection and rock testing in mining have been cited in literature.

Composite materials are now widely being used in many structures mainly due to their light weight and increased strengths. Because of this there is a growing need for understanding of damage development in these anisotropic materials. Damages in composite materials can occur as a consequence of matrix cracks, delaminations, fiber breakage, fiber matrix disbond etc. The term acousto-ultrasonic denotes a nondestructive evaluation (NDE) technique that combines some aspects of acoustic emission methodology and ultrasonic simulation of stress waves. Acoustic ultrasonic approach has certain inherent advantages over conventional NDE methods[2] for material characterization of composites. In Acousto-ultrasonic approach, ultrasonic stress waves that resemble acoustic emission waves are periodically launched into the material without disrupting it.[3] These signals after being modulated by the material properties are then captured by a detector which reveal information about the specimen under test. Unlike acoustic emission location, the source and the nature of the wave is known apriori in the acousto-ultrasonic approach. To monitor damage

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development in composite materials simple tests need to be developed which can yield quantitative parameters descriptive of mechanical state of the material. Ultrasonic wave speed is directly related to material stiffness and hence is an important material property needed to be evaluated. It is also indirectly related to the information concerning strength and life.

2.2 Fiber optic sensors

Piezoelectric transducers have been the most common detectors in acousto-ultrasonic approach. Lately, fiber optic sensors are increasingly being used for detection of acoustic signals because of their inherent advantages over PZT's.[4] Fiber optic sensors have wide bandwidth (limited only by the detection electronics) and no resonant peaks. Fiber optic sensors can be broadly classified into intensity based and interferometric sensors. Even though interferometric sensors have non-linear outputs their sensitivities are much higher when compared to that of the intensity based sensors. Hence interferometric sensors are more viable for detection of sub-angstrom level acoustic waves. Surface acoustic waves propagate along the surface of the material and hence are useful for applications where the sensor cannot be embedded in the material. Fiber optic Michelson interferometer has been demonstrated for detection of surface acoustic waves.[5] The most effective optical fiber method developed to date for the quantitative analysis of ultrasonic wave fields is by the use of extrinsic Fabry-Perot interferometry (EFPI).[6] Surface acoustic wave have also been detected by EFPI sensors.[7]

3. THEORY

3.1 Wave propagation in composites

As mentioned composites are anisotropic in nature due to their multilayered structure. If a plane wave is incident upon an interface between two semi infinite media, the plane wave will be reflected and refracted in such a manner as to satisfy the boundary condition at the interface. Because of the direction dependence of the elastic properties of the anisotropic materials, their reflection coefficients vary in a more complicated manner than those of the isotropic material. Surface waves are characterized as decaying exponentially with depth from free surface and have elliptically polarized displacements. In isotropic materials the surface waves travel in all directions and in anisotropic materials there are certain regions where the bulk waves dominate the surface waves. Surface waves are also known as Raleigh waves after the name of its originator. When the wavelength of the plane waves is larger than the thickness of the plate then the waves manifest itself as extensional, shear, or flexural waves. However, if the wavelength is smaller compared to the thickness of the plate, Lamb waves propagate in the medium causing standing waves in the transverse direction and traveling waves in the plane of the plate. The complete analysis of wave propagation involves three dimensional elasticity and fundamental plate wave equations which will be omitted here for the sake of simplicity. However, it will be mentioned that Raleigh waves, Lamb waves and flexural waves will be propagate in a composite plate when the composite panel is interrogated with a simulated ultrasonic stress wave. Attenuation is an important material property that can be used in NDE of materials. Attenuation of acoustic waves in composites is much higher when compared to aluminum because of the scattering of the waves due to the fibers in a composite.

3.2 Sensor fabrication and operation

The extrinsic Fabry-Perot interferometric sensor consists of a singlemode (830 nm) fiber that acts as both as a input and output signal carrier and a multimode fiber that serves the purpose of a reflector. Figure 1 shows the schematic of EFPI sensor. As shown the endfaces of the singlemode and multimode fibers are housed in a hollow tube and the ends of the hollow tube are glued to the fibers using epoxy. The gap between the endfaces of the singlemode and multimode form a low-finesse Fabry-Perot cavity. In order to avoid reflections from the far end of the multimode fiber, it is either shattered or covered with index matching gel. Laser light (830 nm) from a pigtailed laser diode is launched into the singlemode fiber. The first reflection R1 caused by the glass/air interface serves as the reference signal. The transmitted signal through the first interface is again reflected by the multimode endface giving rise to the sensing signal R2. The interference between these two signals produces an output intensity signal that depends on the separation of the endfaces of the singlemode and multimode fiber. The coherent plane wave detected at the output of the sensor can be approximately represented in terms of its complex amplitude U_i (x, z, t), by

$$U_i = A_i exp(j\phi_i), \quad i = 1, 2, \tag{1}$$

where the variable A_i can be a function of the transverse coordinate x and the distance traveled z and the subscripts i = 1, 2 stand for the reference and sensing reflections respectively.[6] Assuming the reflection coefficient $A_1 = A$, the sensing reflection can be approximated by the relation[8]

$$A_2 = A\left[\frac{ta}{a + 2s\tan\left(\sin^{-1}(\mathrm{NA})\right)}\right], \tag{2}$$

where a is the fiber core radius, t is the transmission coefficient of the air/glass interface (0.98), s is the air-gap separation, and NA is the numerical aperture of the singlemode fiber. The observed intensity at the detector is superposition of the two amplitudes and is given by

$$\mathrm{I_{det}} = \left|\mathrm{U_1} + \mathrm{U_2}\right|^2 = \mathrm{A_1}^2 + \mathrm{A_2}^2 + 2\mathrm{A_1A_2}\cos(\phi_1 - \phi_2), \tag{3a}$$

which can be rewritten as

$$\mathrm{I_{det}} = \mathrm{A}^2\left[1 + \frac{2ta}{a + 2s\tan\left(\sin^{-1}(NA)\right)}\cos\left(\frac{4\pi\mathrm{s}}{\lambda}\right) + \left(\frac{\mathrm{ta}}{\mathrm{a} + 2s\tan\left(\sin^{-1}(NA)\right)}\right)^2\right], \tag{3b}$$

where we have assumed that $\phi_1 = 0$ and $\phi_2 = 4\pi s/\lambda$ and λ is the wavelength of operation on free space. The gauge length of the sensor (the distance between the two epoxied ends of the hollow tube) was set to about 8 mm and the gap separation to about 15 μm.

4. EXPERIMENT

To study the possible variation of acoustic wave speed with respect to the direction of the fibers of the composites, an experiment was conducted. Figure 2 shows the schematic of the experimental setup used to determine the speed of the acoustic signal. A 10 ply graphite epoxy composite specimen of dimensions 31 cm X 9.5 cm X 0.62 cm was cut out of a larger composite panel. An extrinsic Fabry-Perot interferometric sensor was fabricated and maintained at Q-point. The sensor was attached to the surface of the composite panel using glycerin to couple the acoustic energy. Three arcs with the same center each separated by half an inch were then drawn on the surface of the composite. These arcs were then divided into ten angles spanning from 0^0 to 90^0 in steps of 10^0. A piezoelectric transducer mounted on a wedge inclined at an angle of 30^0 to the flat surface of the specimen was used generate surface acoustic waves on the specimen. The PZT exhibited resonance at 1.2 MHz and hence was driven by an 1.2 MHz exponentially decaying periodic pulses from the RF generator. As shown a pigtailed laser diode is connected to the EFPI sensor through a coupler. The interference signal from the sensor is then captured by the photodetector connected to the other arm of the coupler. The signal from the photodetector is amplified by a preamplifier having a 3 dB bandwidth of 1.3 MHz. One of the three arcs was used to place the sensor and the other two arcs were used for displacing the sensor. The time difference in the arrival times of the two signals due to the displacement of the PZT is noted and the speed is calculated by dividing the displacement with the time difference. The speed or the phase velocity V_p is thus given by

$$V_p = \Delta d / \Delta t, \tag{4}$$

where Δd is the distance the source was translated and Δt is the time difference in the arrival time of the two signals. The same experimental set is also used to compare the attenuation coefficients in aluminum and the graphite epoxy composite specimen. The attenuation is obtained by noting the peak amplitudes detected by the sensor as the PZT is displaced away from the sensor.

5. CONCLUSION AND SUMMARY

Figure 3. Shows the input pulse to the PZT and the time delay between the arrival time of the signals detected by the EFPI sensor for two locations of the ultrasonic source. Table I summarizes the results obtained when the surface acoustic waves are launched at ten different angles to a reference axis x along the length of the fibers of the composite. It can be concluded from the data in the table that even though the composites are considered to be anisotropic in nature, there is no variation in the speed with respect to the direction of the fibers within an experimental accuracy of 3μs. The phase velocity can be used to calculate the wave number and if the thickness of the composite material is known the dispersion curves for the material could be plotted. Figure 4a and 4b show the attenuation curves and their curve fits for aluminum and composite respectively. The attenuation coefficients were then calculated to be 0.06 cm^{-1} and 0.49 cm^{-1} for aluminum and the graphite epoxy composite specimen respectively showing an order of magnitude difference.

6. REFERENCES

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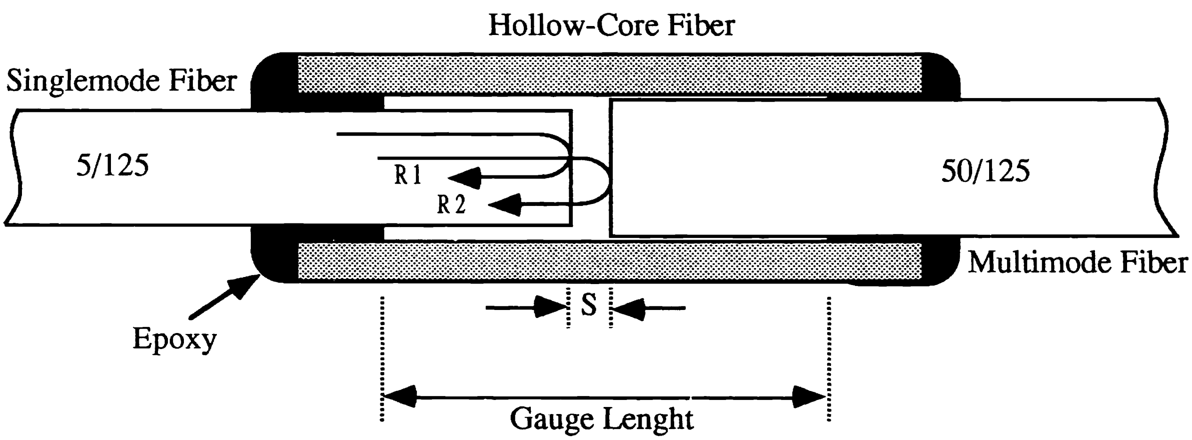

Figure 1. Construction of an EFPI sensor.

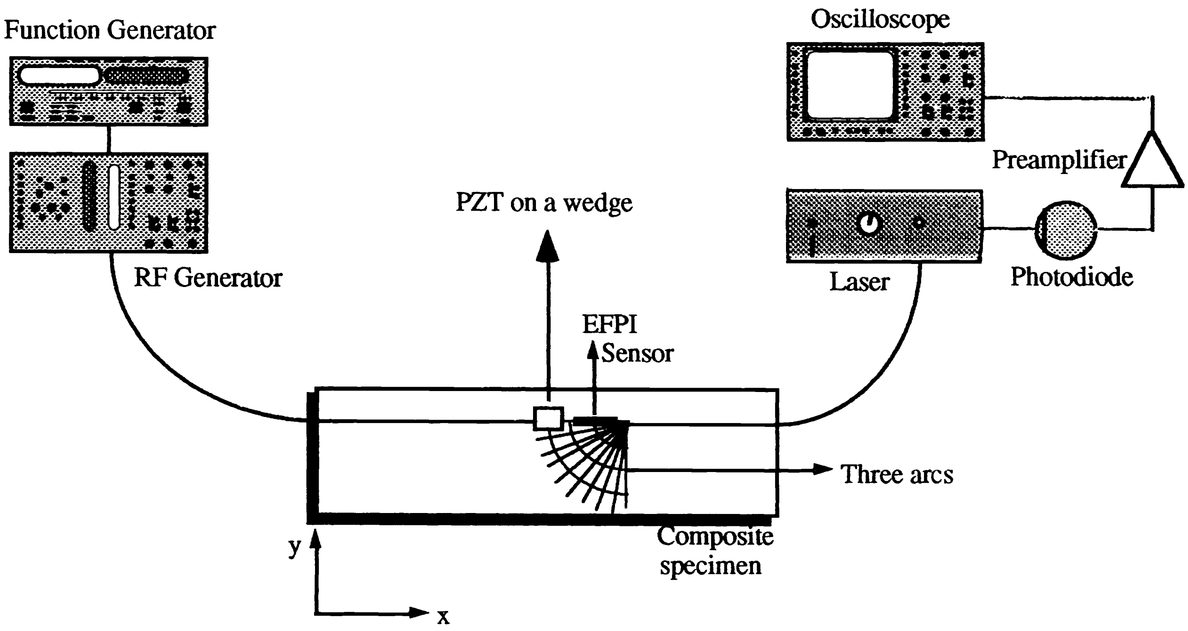

Figure 2. Experimetal setup used for the determination of acoustic wave speeds.

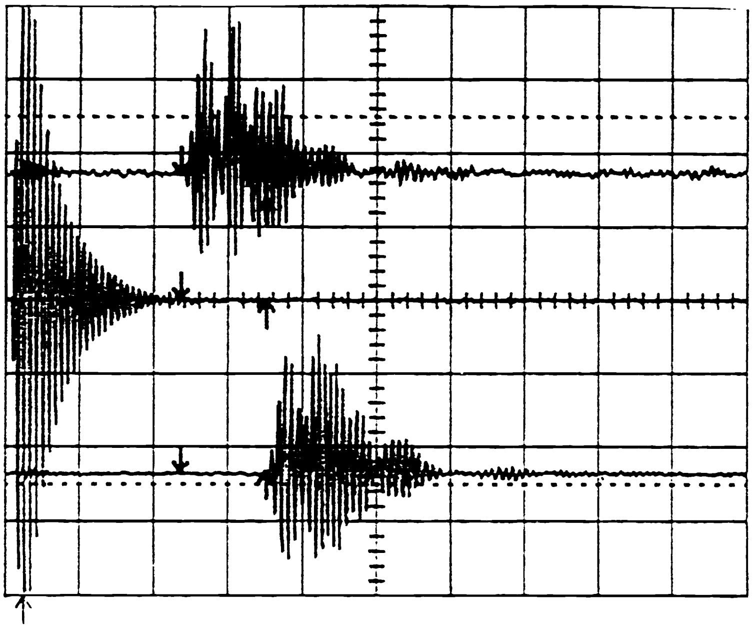

Figure 3. A plot of the input pulse and the signals detected by the EFPI sensor showing the time delay.

Table I. Variation of SAW speed with respect to the direction of the length of the composite specimen.

Angle (degrees)	Distance beween the two source location points (inches)	Time delay (μs)	Speed\ (m/s)
0	0.5	10.6	1198
10	0.5	11.8	1076
20	0.5	8.8	1443
30	0.5	11.6	1095
40	0.5	10.9	1165
50	0.5	10.9	1165
60	9.5	10.4	1221
70	0.5	11.2	1134
80	0.5	11	1154
90	0.5	8	1587

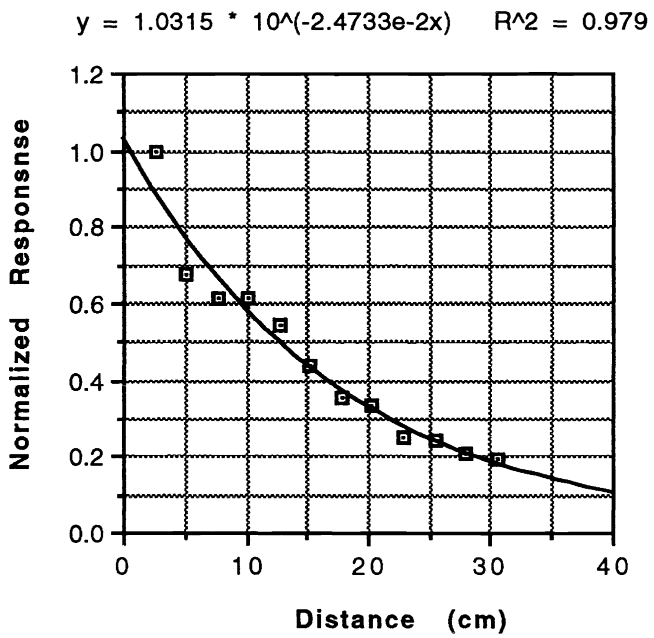

Figure 4a. Attenuation curve for an aluminum sample.

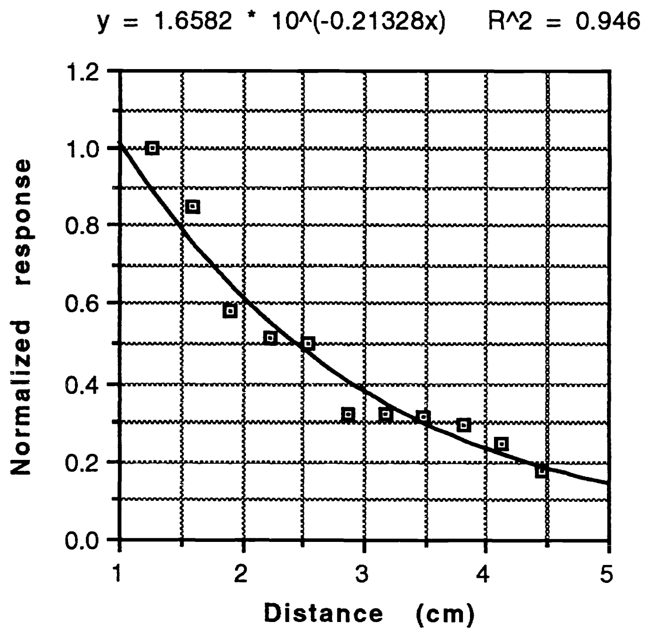

Figure 4b. Attenuation curve for graphite epoxy composite specimen.