Tensile Stress Acoustic Constants of Unidirectional Graphite/Epoxy Composites

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ABSTRACT

Previously, the stress acoustic constants (SAC's) of unidirectional graphite/epoxy composites were measured to determine the nonlinear moduli of this material. These measurements were made under compressive loading in order to obtain the sufficient number of values needed to calculate these moduli. However, because their strength in tension along fiber directions can be several times greater, most composites are used under tensile loading. Thus, it is important to characterize the nonlinear properties of these materials in tension as well.

The SAC's which are defined as the slope of the normalized change in ultrasonic "natural" velocity as a function of stress were measured in a unidirectional laminate of T300/5208 graphite/epoxy. Tensile load was applied along the fiber axis with the ultrasonic waves propagating perpendicular to the fiber direction. Changes in velocity were measured using a pulsed phase locked loop ultrasonic interferometer with the nominal frequency of the ultrasonic waves being 2.25 MHz.

INTRODUCTION

The stress acoustic constant (SAC) as defined by Heyman [1] and Cantrell [2] provides a measure of a mixture of second and third order elastic coefficients. This parameter thus provides information about the nonlinear elasticity of a material which is useful in understanding interatomic bonding forces in crystalline solids. The SAC also is needed in ultrasonic evaluation of applied and residual stresses in a material. Additionally, investigations have established a possible relationship between the SAC and ultimate strength in aluminum [3] and carbon steel [1].

Previous measurement of SAC's in composites were made under compressive stress [4]. Compression was used so that measurements could be made with the stress direction other than along the fiber direction without premature failure of the sample. These measurements were necessary to actually calculate the third order elastic moduli.

However, since composites are most often used under tensile loading because of their high tensile strength along fiber directions, it is important to evaluate their properties under this mode of loading. In this research, the SAC's for longitudinal and shear waves propagating perpendicular to the fiber direction were measured while tensile stress was applied in the direction of the fibers.

THEORY

The "natural" ultrasonic velocity (W) was defined by Thurston and Brugger [5] as the velocity referred to the unstressed or natural state. It is given by

$$W = \frac{L_0}{t} , \quad (1)$$

where L_0 is the specimen length in the unstressed state and t is the time of flight of the ultrasonic wave. Since L_0 is a constant, the normalized change in "natural" velocity with respect to stress is given by

$$\frac{\Delta W}{W} = - \frac{\Delta t}{t} . \quad (2)$$

The stress acoustic constant (H) is then given by

$$H = \frac{\frac{\Delta W}{W}}{\Delta \sigma} , \quad (3)$$

where σ is the applied stress.

Measurements of this quantity were made using a pulsed phase locked loop (P2L2) ultrasonic interferometer developed by Heyman [6]. The basis of this instrument, shown schematically in Figure 1, is a voltage controlled oscillator (VCO). A portion of the signal from the VCO is gated into a tone burst to excite the ultrasonic transducer. The received echo signal from the transducer is phase compared with the signal from the VCO at a preselected phase point using an electronic sample and hold device. The sampled voltage is then used to drive the VCO to a condition of quadrature. This causes the acoustic phase shift (θ), given by

$$\theta = 2\pi ft , \quad (4)$$

where f is the frequency, to be maintained as a constant. It can then be shown that

$$\frac{\Delta\theta}{\theta} = 0 = \frac{\Delta f}{f} + \frac{\Delta t}{t} \quad (5)$$

and thus,

$$\frac{\Delta f}{f} = -\frac{\Delta t}{t} = \frac{\Delta W}{W} . \quad (6)$$

Therefore, by monitoring the normalized change of frequency of the P2L2,the normalized change in "natural" velocity is determined which is used to calculated the SAC.

EXPERIMENT

A tensile specimen was cut from a 50 ply unidirectional laminate of graphite/epoxy with nominal dimensions of 28 cm. along the fiber direction (x_3), 0.66 cm. in the laminae stacking direction (x_1), and 2.5 cm. in the remaining orthogonal direction (x_2). The original laminate had been previously C-scanned for defects and none were found to be present. The cross sectional area used for stress calculations was that measured at the center of the specimen where the transducer was attached and had a value of 1.677 +/- 0.004 cm^2. Load was ramped in tension along the fiber direction to a maximum stress value of approximately 330 MPa at a rate of approximately 400 MPa/min.

The acoustic measurements were made using commercial damped 2.25 MHz transducers. A frequency counter monitored the frequency of the P2L2 which was recorded by a computer which also read voltage values from the load cell. The frequency and load voltage were measured at one second intervals during the load ramp. Following the ramp to maximum stress and return to zero, the stress and normalized frequency shifts were plotted and stored. Since the curves exhibited nonlinear (quadratic) behavior, they were fitted using a quadratic least squares routine. A block diagram of the apparatus used is shown in Figure 2.

Since variations in natural velocity are sensitive to temperature changes as well as stress, the sample was insulated during the test in an attempt to maintain a constant temperature. Following any disturbance of the sample and transducer, approximately thirty minutes was allowed to settle the temperature to equilibrium. Also, to determine the effects of bond thickness variations which sometimes can be significant in these measurements, each SAC measurement was repeated at least nine times with the transducer removed and rebonded every third measurement.

The shear wave SAC measurements were completed with transverse mode acoustic waves propagating along the x_1 direction. The direction of polarization was either along the fiber direction in which case the measurement was designated H_{313} or along the x_2 direction and designated H_{312}. The data from the measurement of H_{313} is displayed in Figure 3. The measured points for all nine measurements are shown with the quadratic least squares fit displayed as the solid line. The quadratic fit parameters are shown in Table 1 along with the value measured under compressive loading. The values for the compressive SAC's for comparison are the negative of those presented in [4]. This is to account for the fact that in both tests the stress was taken to be positive. The data from this measurement was the most reproducible which is to be expected as it is the one in which the largest frequency change occurs.

Measurements of H_{312} are shown in Figure 4 with the fitted parameters again displayed in Table 1. The data for this measurement were not as reproducible as shown by the scatter in the graph. The majority of the measurements were within good agreement. However, three of the measurements which were taken in sequence following rebonding of the transducer did not exactly follow the trend. This may indicate that there was a bond irregularity such as dust contamination in these three measurements.

Longitudinal SAC measurements were made with the waves propagating along the laminate stacking direction (x_1) with the polarization in the same direction. These measurements were designated H_{311} and the data is presented in Figure 5. The fit parameters are shown in Table 1. These measurements showed the worst reproducibility due to the small frequency shifts exhibited. Again bonding variations contributed to the scatter in the data.

DISCUSSION

Although the tensile SAC values of unidirectional graphite/epoxy do not agree with those made under compression to within experimental uncertainty, in each case the values were of the correct sign and agree to within an order of magnitude. There are a number of possible causes to explain the discrepancy between the tensile and compressive SAC values. It may be due to sample to sample variation in material properties as the specimen for each test were cut from different laminates. The difference in specimen geometry needed in an attempt to obtain pure tensile or compressive loading and the difference in the method of applying the load may also account for some of the discrepancy. It may also be due to differences in the material behavior under compressive and tensile loading. Further experimentation with a large number of specimen cut from the same and different laminates is needed to separate out these effects.

Another difference in the tensile measurements is the much higher stress levels applied during the test. Because of the greater tensile strength, these tests were carried out to higher loads without damaging the specimen. Higher order elastic nonlinearities were manifested at these higher stresses by the nonlinearity of the measured curves. This caused the need for using a quadratic fit to determine the SAC values but should not contribute to the discrepancy between compressive and tensile values.

CONCLUSIONS

This study provides the first measurements of tensile SAC's in unidirectional graphite/epoxy composite materials thus yielding further information on the mechanical behavior of fiber reinforced composite materials. These measurements may be useful in developing nondestructive techniques to monitor applied and residual stresses in composites. They may also be helpful in nondestructively determining other important engineering properties such as ultimate strength and fiber-matrix interfacial properties.

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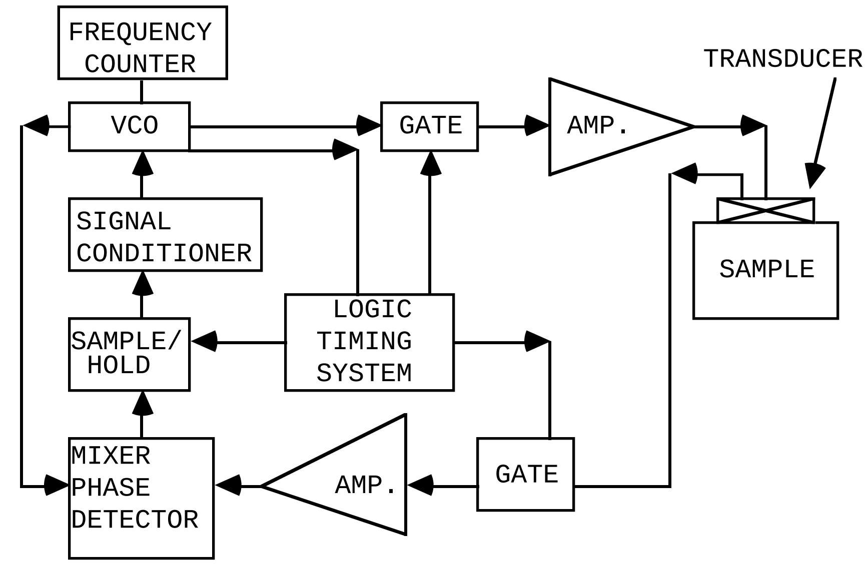

Fig. 1. Block diagram of the pulsed phase locked loop ultrasonic interferometer.

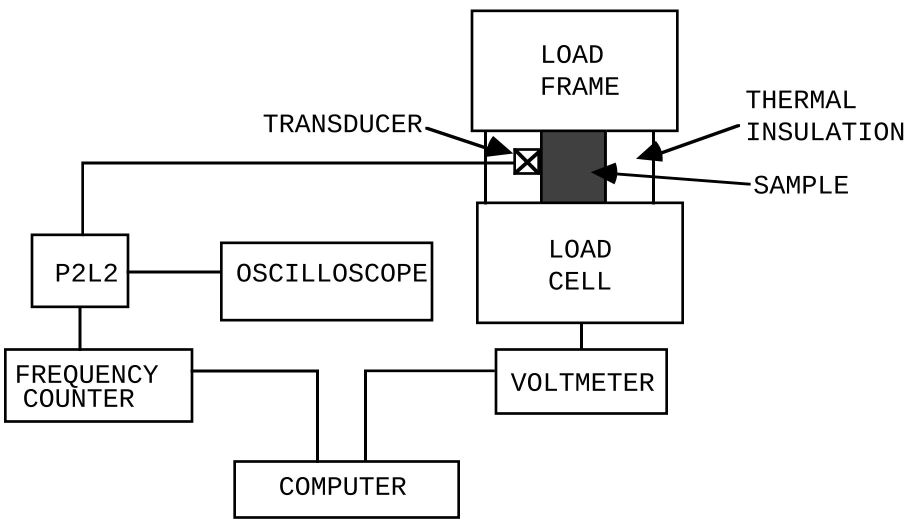

Fig. 2. Block diagram of stress acoustic constant measurement apparatus.

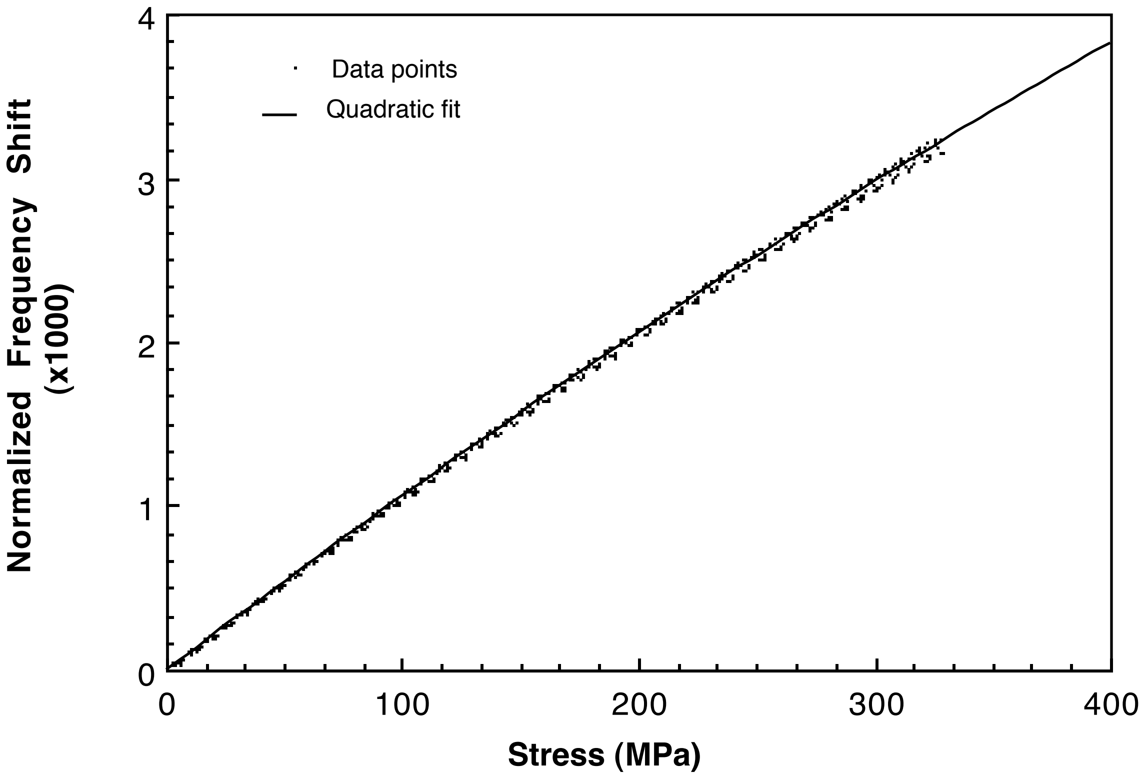

Fig. 3 H_{313} SAC measurement

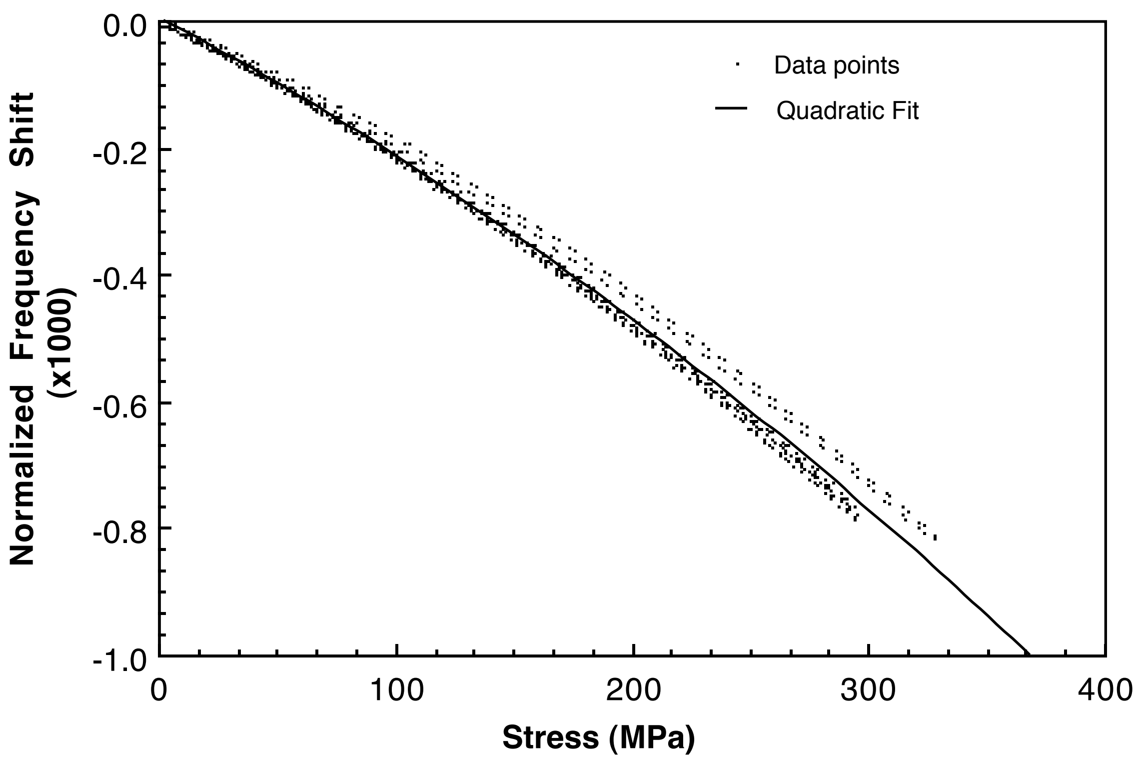

Fig. 4 H_{312} SAC measurements

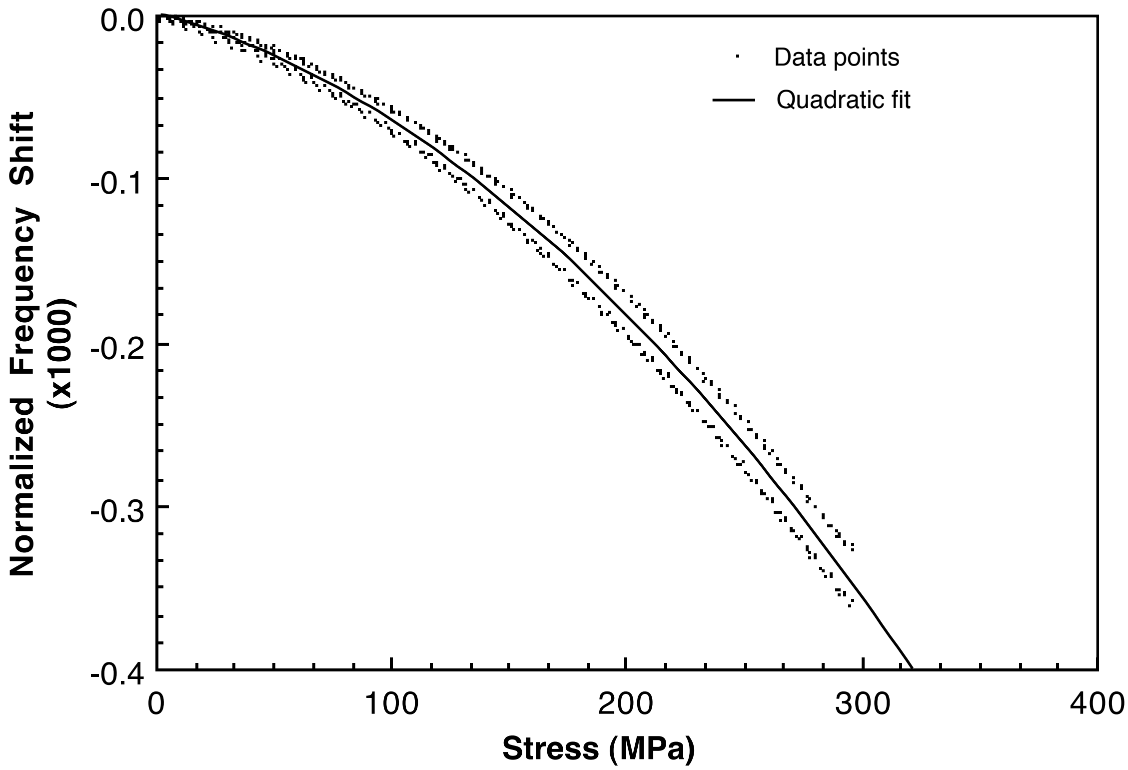

Fig. 5 H_{311} SAC measurements

Table 1

	Quadratic Coef. (Pa^{-2})	Y-intercept	Tensile SAC (Linear Coef.) ($\times 10^{-12} Pa^{-1}$)	Compressive SAC [4] ($\times 10^{-12} Pa^{-1}$)
H_{313}	-3.5×10^{-21}	-2.5×10^{-6}	10.99 +/- 0.01	9.2 +/- 0.3
H_{312}	-2.1×10^{-21}	4.6×10^{-6}	-2.0 +/- 0.1	-2.8 +/- 0.1
H_{311}	-2.7×10^{-21}	1.7×10^{-6}	-0.39 +/- 0.07	-1.23 +/- 0.01