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Nonlinear elastic effects in graphite/epoxy: An analytical and numerical prediction of energy flux deviation

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HIGHLIGHTS

- Applying external load to graphite/epoxy changes its anisotropy.
- Using acoustoelastic theory we predict the energy flux shift for QL, QT and PT waves.
- We predict the energy flux shift for QT wave is higher for shear compared to normal load.
- Finite element simulations validate acoustoelastic theory predictions.

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ABSTRACT

Manipulating acoustic wave propagation through a material have several interdisciplinary applications. Here we predict shift in energy flux deviation for acoustic waves propagating in unidirectional graphite/epoxy due to applied normal and shear stresses using both an analytical model, using acoustoelastic continuum theory, and a finite element discrete numerical model. The acoustoelastic theory predicts that the quasi-transverse (QT) wave exhibits larger shifts in energy flux deviation compared to quasi-longitudinal (QL) or the pure transverse (PT) due to an applied shear stress for fiber orientation angle ranging from 0° to 60°. Due to an applied shear stress the QT wave exhibits a shift in energy flux deviation at 0° fiber orientation angle as compared to normal stress case where the flux deviation and its load induced shift are both zero. A finite element model (FEM) is developed where equations of motion include the effect of nonlinear elastic coefficients. Element equations were integrated in time using Newmark's method to determine the shift in energy flux deviations in graphite/epoxy for different loading cases. The energy flux shift of QT waves predicted by FEM for fiber orientation angles from 0° to 60° for applied shear stress case is in excellent agreement with acoustoelastic theory. Because energy shift magnitudes are not small, it is possible to experimentally measure these shifts and calibrate shifts with respect to load type (normal/shear) and magnitude.

1. Introduction

Recent developments in guiding and magnifying acoustic wave propagation through a medium and their application to engineering have invoked tremendous interest among the scientific community. Developments of acoustic metamaterials

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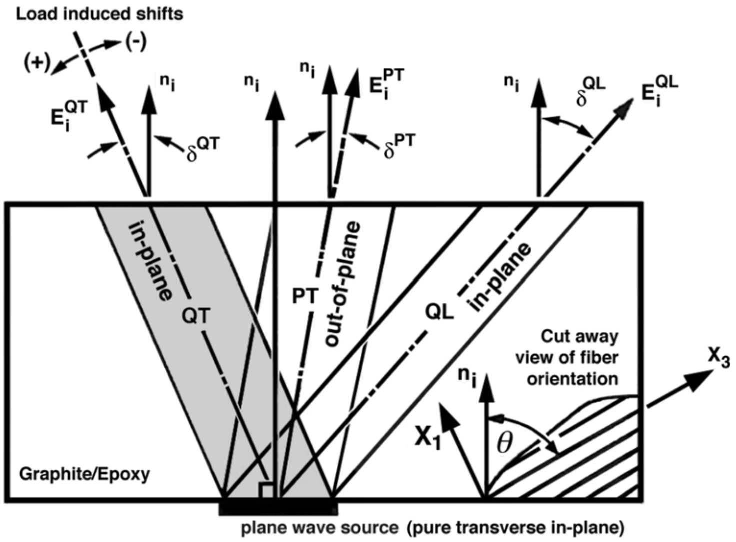

Fig. 1. Wave types (QT, QL, PT), energy flux propagation directions, E_i, and in-plane co-ordinate axes, x_1–x_3, defined with respect to fiber orientation for a unidirectional graphite/epoxy composite.

have proven to act as hyperlenses for several applications in non-destructive material testing and medical ultra-sound imaging [1–3]. In these studies, the anisotropy of the material is the governing factor in guiding the wave propagation. Several studies [4–7] have shown that acoustic cloaking can be achieved by controlling the microstructure of the material. These studies indicate that by changing the anisotropy of the material, the acoustic waves can be guided through a material. Acoustic wave propagation has interdisciplinary applications and is a widely used technique in engineering and medical sciences [8–10]. In this paper, we show how the anisotropy changes due to an externally applied load to a fiber reinforced composite material, which in turn can be used to control the acoustic wave propagation direction.

In an anisotropic material, the direction of energy flux (energy per unit time per unit area) of an ultrasonic plane wave deviates from the intended direction of propagation as compared to an isotropic material, where the energy flux propagates in a direction parallel to the wave front normal vector, n_i, see Fig. 1. This phenomenon, exhibited by linear elastic anisotropic materials, is known as the energy flux deviation. The elastic coefficients of the material influence the energy flux deviation [11,12]. Energy flux deviation was experimentally observed in quartz crystals [11,13] and unidirectional graphite fiber reinforced epoxy [14,15].

Nonlinear elastic behavior is generally neglected in ultrasonic wave propagation due to small strains (or small amplitude) imposed on the sample; however this effect can be predominant in three cases of wave propagation as pointed out by Green [13]. First, the amplitude of the wave may be large enough to cause finite strains in the material. In the second case nonlinear behavior occurs when a small amplitude wave is superimposed on a large external static stress, and finally nonlinear effects caused by defects in the material. In this paper the second case of nonlinear effects is studied for measurable shifts in energy flux deviations of waves propagating in graphite/epoxy. Tokuoka and Iwashimizu [16] derived the Christoffel equation for an anisotropic material under stress assuming hyperelasticity using plane wave solution. Man and Lu [17] later extended the applicability of Christoffel equation to general types of loading history and plastic deformations. Prosser et al. [18] studied graphite/epoxy for applied stress along fiber axis and laminate stacking direction using acoustoelastic theory and measured the flux deviation angle. Using Man and Lu's theory [17] Degtyar and Rokhlin [19] derived in detail the equation of motion due to wave propagation superimposed on a prestressed solid and also studied the elastic wave propagation between two generally anisotropic stressed solids as well as stressed solid and fluid for different materials [20]. Zhuk and Guz [21] studied nanocomposite material with prestress, where the nonlinearity was described by the Murnaghan potential. Similarly, Parnell [22] used asymptotic homogenization theory in the deformed configuration to find the effective response of a prestressed nonlinear elastic composite bar. The flux shift is also observed in graphite/epoxy due to the moisture absorption by the matrix or fiber degradation [23]. A recent study involving experiments and simulations show that stress wave trajectory can be controlled [24] by the anisotropy of the material. Even though Prosser et al. [18] studied shifts in energy flux deviations due to normal stress effects on graphite/epoxy, the flux deviation due to shear stress was left unexplored.

In this paper, we study the effect of nonlinear elasticity on shifts in energy flux deviation in unidirectional graphite/epoxy due to applied normal and shear stresses. Due to elastic nonlinearity the angle of flux deviation can be measured as a function of applied stresses. We model the energy flux deviation using acoustoelastic theory [17] and the flux shift, which is the difference between flux deviation angle due to applied stress and the flux deviation due to zero stress state, is compared for different stresses. Finite element equations are derived for equation of motion containing nonlinear elastic coefficients, C_{ijklmn}, and integrated in time using Newmark's method. We predict the energy flux shift for quasi-transverse (QT) wave using finite element method (FEM) for fiber angle orientations ranging from 0° to 60° and then compare with acoustoelastic