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Interface/interphase effects on scattering of elastic P- and SV-waves from a circular nanoinclusion embedded in a solid viscoelastic matrix

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A B S T R A C T

This study aims to present an analytical investigation of the dynamic effects of the interfacial region on scattering of elastic P- and SV-waves by a circular nanoinclusion. The nanoinclusion is assumed to be surrounded by an interphase region and embedded in a polymer viscoelastic matrix. Wave function expansion method is utilized to solve the Navier wave equation in all three phases (fiber-interphase-matrix) and for the viscoelastic regions, the features of Havriliak-Negami model are used to account for the frequency-dependent material properties. Dynamic Stress Concentration Factor (DSCF) and Scattering Cross Section (SCS) results are obtained for both cases of incident waves. To focus on the interfaces, Gurtin-Murdoch model of surface elasticity is applied in modeling the interfaces. Additionally, effects of interphase inhomogeneity and viscoelasticity on the results are studied. The results indicate that considering the simultaneous effects of nanoscale interface parameter and inhomogeneity and viscoelasticity of the interphase has a considerable impact on the dynamic behavior of the nanoinclusion.

1. Introduction

As the science of nanotechnology develops, nanocomposites tend to gain more and more attention from industry and material science researchers. Among them, polymer nanocomposites have been shown to possess superior mechanical and physical properties (such as increased strength modulus, increased dimensional stability, stiffness, fracture toughness, etc.) to their host polymer system (Ramanathan et al. (2005, 2007), Sandler et al. (2003)). These enhanced properties mainly emanate from the superior characteristics of the nanoinclusions which are capable of providing multifunctionality for the material and more importantly, create a large amount of interfacial region (interfaces or interphases) with distinct material properties (Baur and Silverman (2007)). It is also interesting to note that such improved properties emerge at even very low concentrations of nanoinclusions and just like the conventional composites, polymer nanocomposites can also be tailored through a smart control of morphology (Coleman et al. (1998)). Despite all the improvements observed so far in nanocomposites, one aspect yet needs to be investigated with more care and that is the ability of this class of materials in vibration damping. Studies regarding the problem of vibration damping in mechanical systems may generally fall into two general categories: Active damping, which deals with outside mechanisms to damp the unwanted vibrations, and passive damping which focuses on the materials' intrinsic capability to attenuate the vibration. Following the second approach (which is the main focus of the present study), it is known that vibration induces elastic waves to propagate in the material (Guz and Rushchitsky (2007)). Therefore, a careful investigation of the propagation and attenuation of such waves in the structure is an efficient way to find out about damping process in the material. A major source of wave attenuation in composites is the process of wave scattering by the inclusions in the structure. Scattering of waves by embedded inclusions in composites has been the subject of various studies. Early major studies of this topic go back to the works of White (1958), Pao and Mow (1973) and Bose and Mal (1974). Carcione et al. (1988) developed a new approach for viscoacoustic wave propagation by implementing the Boltzmann's superposition principle based on the general standard linear solid rheology in the equation of motion by the introduction of memory variables. Biwa et al. (2003) analyzed wave attenuation characteristics of unidirectional fiber-reinforced polymer composites theoretically by a micromechanical differential (incremental) scheme for their macroscopic acoustic properties. Kim et al. (1994) studied the dispersion and attenuation characteristics of elastic waves propagating in viscoelastic fiber-reinforced composites, based on the multiple scattering formulation for randomly distributed scatterers in an absorbing medium. Wei (2005) studied the frequency-dependent dynamic effective properties of the particle-reinforced composites with the viscoelastic matrix and discussed several equations to predict the effective wavenumber of the

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coherent plane waves. Kim and Lee (2009) gave a rigorous derivation of the extinction cross-section for elastic wave scattering by an object in an absorbing medium. Kim (2003) derived forward scattering theorem for elastic longitudinal and shear wave scatterings by an arbitrary-shaped three-dimensional object embedded in a viscoelastic medium. He showed that the formulae for extinction cross sections of an object in an energy-absorbing medium are formally the same with those of the object in the lossless elastic medium. Lonné et al. (2003) developed a model coupling viscoelastic and multiple-scattering losses is to predict ultrasonic attenuation in unidirectional fiber reinforced composite of high fiber volume fraction. Waves of various polarities (SH, SV, L) relatively to the fiber direction are considered. Liu et al. (2000) investigated the scattering of elastic waves by an elastic or viscoelastic cylinder numerically. They derived analytical solutions of the scattered and internal fields excited by a normally incident plane P wave or SV wave. Solutions for cylindrical P-wave incidence and for some special cases of the cylinder medium and the matrix medium are also evaluated explicitly. Numerical results for scattering cross-sections are given for both nonabsorbing and absorbing cylinders in their work. Gaunaurd and Oberall (1978), using an approach familiar in nuclear scattering theory but novel to acoustics and elastodynamics, expressed the scattering amplitudes for the scattered P-and S-waves. Hasheminejad and Miri (2008) studied the interaction of time harmonic monochromatic longitudinal and shear ultrasonic waves with a single fiber coated by homogeneous dissipative (polymeric) materials and embedded in an unbounded elastic matrix using the classical method of eigenfunction expansion.

As was mentioned before, an important consequence of adding nanoinclusions to the structure of composites is the formation of interfacial regions. Modeling attempts to consider the mentioned interfacial effects can be divided into two main groups (Li and Sun (2013)). The first group considers interfacial regions as layers having certain thicknesses. These layers are called “interphases” and are assumed to have mechanical properties different from those of the matrix or the nanoinclusion (Hashin (2002)). The reason for this difference comes from the fact that the dimensions of nanoinclusions are considerably close to those of the radius of gyration of the polymer chains and this causes a difference of mechanical behavior in the neighboring “interphase” region compared with the bulk polymer matrix (Liu and Brinson (2006)). In conventional composites, interphases are mainly studied because of the important role they play in the stress transfer from the matrix to the inclusion. However, for the case of nanocompsites, another significant feature of the interphase becomes highlighted and that is the relatively higher order of surface area to volume/weight ratio compared with conventional fibers. This feature leads to formation of a more enormous amount of interphase and consequently the resulting interfacial effects become stronger (Liu and Brinson (2006)). In fact, it has been estimated that for only a 1% volume fraction of nanoparticles (with a size of 2 nm), the interphase region can take almost 63% of the whole volume (Winey and Vaia (2007)). Another interesting fact about interphases lies in the source of their formation. One group of reasons for the formation of these regions may be voids, mechanical imperfections, unreacted polymer components or the like, while on the other hand we have “engineered” interphases which are formed intentionally as a third phase with the aim of achieving a specific performance in nanocomposites. The fact that interphases give way to be “designed” makes it very important to investigate their effects on various aspects of nanocomposite behavior (Hasheminejad and Miri (2008)). A great body of work exists in the literature dealing with the effects of elastic and viscoelastic interphase effects on wave scattering. Achenbach and Zhu (1990) investigated the effect of interphase stiffness on microstresses and macromechanical behavior for transverse loading of a hexagonal-array unidirectional fiber composite. Fisher and Brinson (2001) investigate the mechanical property predictions for a three-phase viscoelastic composite by the use of two micromechanical models. Li and Weng (1996) examined the influence of a viscoelastic interphase on the overall creep compliances and stress/strain relationships of fiber-reinforced polymer-matrix composites under a constant stress and a constant strain-rate loading. They considered fibers as elastic and the matrix as viscoelastic in their work. Liu and Brinson (2006) presented a novel hybrid numerical-analytical modeling method that is capable of predicting viscoelastic behavior of multiphase polymer nanocomposites, in which the nanoscopic fillers can assume complex configurations. Wei and Huang (2004) studied the effects of viscoelastic behavior of the interphase on the dynamic effective properties of composite materials reinforced by the distributed coated spherical inclusions. Patel et al. (2008) devised a finite element (FE) based unit cell model with periodic boundary conditions to calculate the effective tanδ of a composite as a function of frequency. Sancaktar and Zhang (1990) presented a nonlinear viscoelastic analysis of the carbon fiber-thermoset (or thermoplastic) matrix interphase and showed that the thickness and material properties of the interphase have strong influence in reducing the shear stress magnitudes and distribution along the fiber. Yang and Pitchumani (2004) adopted a thermodynamic model for interphase formation to predict the interphase material properties in the finite element analysis of the overall composite. They directly linked two major composite properties, modulus and stress concentration factor, to the interphase formation parameters. Nozaki and Shindo (1998) considered the scattering of P and SV waves in SiC fiber-reinforced Al composite with interfacial inhomogeneous layers and presented numerical values of scattering cross-sections, phase velocities and attenuations of coherent plane waves. Li et al. (2002) made use of elastodynamics theory in the study of scattering of elastic waves and dynamic stress concentration in fiber-reinforced composite with interface layers. Diani and Gilormini (2014) applied the self-consistent model based on morphological representative patterns to the realistic case of the linear viscoelasticity of polymers reinforced by elastic nanoparticles coated with a viscoelastic interphase.

The second category of modeling attempts to consider the interfacial effects deals with interfaces. Interfaces are known as layers with negligible thicknesses which exist between two material phases. Generally speaking, the interfaces can be categorized into two groups: First, perfect interfaces, in which the displacements and stresses are continuous across the boundaries between phases. Mathematically speaking, they are boundaries in solids that can be modeled as mathematical smooth enough surfaces with additional physical properties (Özgür et al. (2005)). On the other hand, we have the imperfect interfacial regions where such continuity in tractions and displacements is not observed. These interfacial regions have an undeniable effect on the overall mechanical behavior of the nanocomposites (Li and Sun (2013)). In comparison with interphases, Hashin (1990) believed that interface models (which are simpler from a mathematical point of view) can be applied in the case that it is not possible to define or identify an interphase. Studies on mechanics of surface/interface phenomena have roots in the works of Laplace (1806), Young (1805) and de Poisson (1831). A very successful model of surface elasticity for elastic solids has been presented by Gurtin and Murdoch (1975a, b). They considered the interface as a membrane attached to its adjacent phase. They formulated this phenomenon and defined surface stresses as the stress resultant tensor acting in the membrane (Eremeyev (2016)). Ever since their introduction, interface effects have been the subject of numerous researches in this field (Wang et al. (2011)). Mal and Bose (1974) studied the imperfect bonding between the spheres and the matrix in a random distribution of identical spherical particles and calculated the velocity and attenuation of the average harmonic elastic waves propagating through such a medium. Datta et al. (1988) considered effective-plane-wave propagation, both longitudinal and shear, through a medium containing a random distribution of spherical inclusions, assuming a thin layer of elastic material with different properties to exist between the particles and matrix. The studies involving interface models are also reflected in the works by Benveniste (1985), (formulating a mathematical framework for interfaces) and Aboudi (1987)