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Wave propagation in magneto-electro-elastic multilayered plates with nonlocal effect

Jiangyi Chen [a], Junhong Guo [b], Ernian Pan [c,*]

[a] School of Mechanical Engineering, Zhengzhou University, Zhengzhou 450001, PR China
[b] Department of Mechanics, Inner Mongolia University of Technology, Hohhot 010051, PR China
[c] Department of Civil Engineering, University of Akron, OH 44325-3905, USA

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In this paper, analytical solutions for propagation of time-harmonic waves in three-dimensional, transversely isotropic, magnetoelectroelastic and multilayered plates with nonlocal effect are derived. We first convert the time-harmonic wave problem into a linear eigenvalue system, from which we obtain the general solutions of the extended displacements and stresses. The solutions are then employed to derive the propagator matrix which connects the field variables at the upper and lower interfaces of each layer. Making use of the continuity conditions of the physical quantities across the interface, the global propagator relation is assembled by propagating the solutions in each layer from the bottom to the top of the layered plate. From the global propagator matrix, the dispersion equation is obtained by imposing the traction-free boundary conditions on both the top and bottom surfaces of the layered plate. Dispersion curves and mode shapes in layered plates made of piezoelectric $BaTiO_3$ and magnetostrictive $CoFe_2O_4$ materials are presented to show the influence of the nonlocal parameter, stacking sequence, as well as the orientation of incident wave on the time-harmonic field response.

1. Introduction

Due to their excellent coupling behavior among mechanical, electric and magnetic fields, magneto-electro-elastic (MEE) nanostructures have attracted intensive attention in recent years [1,2]. To realize the magneto-electric coupling effect, $BaTiO_3$ is often used as piezoelectric phase and $CoFe_2O_4$ as magnetostrictive phase in the MEE nanocomposites with 2-2 (i.e., multilayered nanoplates) or 1–3 connectivity. Experimental results showed the size-dependent effect of the MEE material in small scale (i.e., micro- and nano-scale), which plays an important role in designing miniaturized smart devices [3,4]. Therefore it is necessary to understand the behaviors of the MEE nanostructure via an effective theoretical model. So far, the molecular dynamics simulations and continuum mechanics [5] are commonly used to describe the size-dependent effect in nanostructures. Since the molecular dynamics simulation is complicated and also time consuming, the continuum mechanic model is preferred in predicting the behaviors of small-scale structures. Among the latter models the nonlocal elasticity theory of Eringen is one of the commonly used [6–8] since only one size-dependent parameter is involved.

Based on the continuum nonlocal theory, some simplified nonlocal beam (one-dimensional or 1D) and plate (two-dimensional, or 2D) models were proposed. For example, Reddy [9] formulated various simplified beam theories, including

* Corresponding author.
E-mail address: pan2@uakron.edu (E. Pan).

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the Euler-Bernoulli, Timoshenko, Reddy and Levinson, by using the nonlocal differential constitutive relations of Eringen [6,7]. Nazemizadeh and Bakhtiari-Nejad [10] investigated analytically the size-dependent free vibration of nano/microbeams with piezo-layered actuators based on the nonlocal theory. Vaezi et al. [11] analyzed the free vibration of MEE microbeams subjected to magnetoelectric loads. As for the 2D plate case, Lu et al. [12] proposed a nonlocal plate model based on Eringen's theory of nonlocal continuum mechanics and derived the basic equations for nonlocal Kirchhoff and Mindlin plate theories. Liu et al. [13] studied the thermo-electro-elastic free vibration of piezoelectric nanoplates based on the nonlocal and Kirchhoff theories. Ke et al. [14] then investigated the free vibration of MEE nanoplates based on the nonlocal theory. Farajpour et al. [15] proposed a nonlocal nonlinear plate model for large amplitude vibration of MEE nanoplates. Nonlocal elastic theory was also used to analyze the nonlinear vibration of graphene/piezoelectric sandwich films [16]. So far, however, the truly three-dimensional (3D) deformation with nonlocal effect was seldom investigated, except for the recent work by Pan and Waksmanski [17] where the static deformation of a layered MEE simply-supported plate with nonlocal effect was solved analytically.

It is known that many crucial physical properties such as electrical conductance, magnetic-electric coupling, optical transition and dynamical behaviors are quite sensitive to wave induced by dynamic deformation. As such, wave propagation in MEE materials is of great interest for researchers, particularly when propagating in layered structures. Based on the classical elasticity, Liu et al. [18] investigated the propagation of Love waves in layered piezoelectric/piezomagnetic structures. Wu et al. [19] presented a dynamic solution for the propagation of harmonic waves in inhomogeneous functionally graded MEE plates. He et al. [20] derived the equations of coupled Lamb waves in multilayered anisotropic laminates based on the linear 3D elasticity theory. Xiao et al. [21] analyzed the characteristics of elastic guided waves in an infinite functionally graded MEE plate by the Chebyshev spectral element method. By using the state-space method, Chen et al. [22] discussed the 3D dispersion problem in MEE layered plate.

Dispersion relations and mode shapes of wave are important for understanding dynamic behaviors of structures made of discrete particles [23], lattices [24], as well as continuum smart materials [19]. Besides the traditional nondestructive inspection, wave propagation features in piezoelectric or MEE plates could be also useful in the design of high-accuracy microsensors and transducers [25]. Moreover, these devices in small scales can operate in the ultrahigh and even terahertz frequency range, showing the size-dependent effect [26] which needs to be considered.

Based on the nonlocal differential constitutive relations of Eringen, Pradhan and Phadikar [27] derived the motion equations of the nonlocal theory and then the analytical solutions for vibration of the 2D nanoplates such as graphene sheets. Yang et al. [28] concerned with the wave propagation in double-walled carbon nanotubes based on the nonlocal continuum elasticity. Tong et al. [29] developed a new technique to treat wave propagation in fluid saturated porous materials by combining Biot theory and nonlocal elasticity. Li et al. [30] investigated the buckling and free vibration of MEE nanoplate resting on Pasternak foundation based on the nonlocal Mindlin theory. Ansari et al. [31] developed a nonlocal geometrically nonlinear beam model for thermo-MEE nanobeams subjected to external electric, magnetic and thermal loadings. Narendar [32] studied the dispersion of elastic waves in a functionally graded MEE rod based on the nonlocal continuum mechanics. As it is reviewed above, so far, studies on the wave propagation are either limited to 3D structures without nonlocal effect or to 1D/2D simplified structure models with nonlocal effect. To the authors' best knowledge, no work on wave propagation in truly 3D MEE multilayered plates with nonlocal effect has been reported, which motivates the present study.

This paper focuses on the propagation of time-harmonic waves in 3D multilayered MEE plates by taking the nonlocal effect into account. The dispersion equations and mode shapes of 3D MEE layered plates with nonlocal effect are derived analytically by means of the propagator matrix method, which can serve as benchmarks to wave propagation of various thin MEE plates with nonlocal effect. Numerical examples are carried out to show the effect of the nonlocal parameter as well as the stacking sequence on the dispersion curves and mode shapes.

2. Basic equations

We consider a transversely isotropic and multilayered 3D MEE plate which is horizontally infinite but vertically finite in the thickness direction with a total thickness *H*, as shown in Fig. 1. A Cartesian coordinate system is placed on the horizontal *xoy*-plane of the bottom surface and the plate is in the positive *z*-region. The symmetry axis of the material is along the

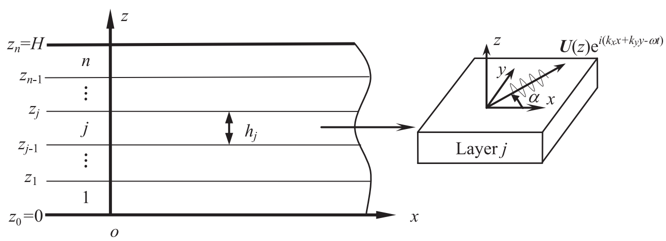

Fig. 1. Wave propagation in a magneto-electro-elastic multilayered plate.