International Journal of Engineering Science 123 (2018) 214–235

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Shear excitation of a multilayered magneto-electro-elastic half-space considering a vast frequency content

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ARTICLE INFO

Article history:
Received 15 July 2017
Revised 21 September 2017
Accepted 15 November 2017

Keywords:
Smart material
Magneto-electro-elastic
Transversely isotropic
Multilayered
Dynamic shear loading

ABSTRACT

The objective of this paper is to present dynamic responses of a multilayered magneto-electro-elastic half-space due to an external/internal time-harmonic shear mechanical loading. To do so, a concrete mathematical tool is applied to solve a set of complicated high-order coupled equations of motion for a layered magneto-electro-elastic structure. The mathematical tool is constructed based on a new infinite dimensional vector space utilizing multiplication of exponential functions as a base for Fourier series in the tangential direction and Bessel function as a base in the radial direction. A cylindrical coordinate system is attached to the multi-layered half-space with the depth axis oriented perpendicular to the surface. In this way, with the use of this vector space, the coupled governing partial differential equations are changed to two sets of ordinary first-order differential equations, where their unknown functions are the coefficients of base functions in the Hankel-Fourier domain. It should be noted that these two sets of equations are completely decoupled based on the decoupling of SH-wave from P- and SV-waves. The effect of the layering is considered with the use of the dual-variable-position method. A mechanically uniform surface/internal shear time-harmonic loading is applied as a common excitation in nature to pursue the pattern of energy transformation in multifunctional magneto-electro-elastic structures with different material properties. Also, the effects of loading frequency and resonance phenomena are investigated in this paper numerically. The results show clearly how the arrangement and the designing process of different layers with different material properties can change responses in smart devices.

1. Introduction

Magneto-electro-elastic (MEE) materials, classified in smart material groups, couple the piezoelectric (PE) and piezomagnetic (PM) phases simultaneously in a way that an interaction among the magnetic, electric and elastic (E) fields is provided by the energy transformation with a predictable and controllable manner in different conditions (Van Den Boomgaard, Van Run, & Van Suchtelen, 1976). Owing to this prominent feature, MEE materials are increasingly applied in different sciences and industries such as medical, automotive, airplane, spacecraft, nuclear equipment, electronic devices and so forth. In many cases a multilayered structure containing this kind of material has been applied in industries. For example, lead zirconat titanate thin films have been used for capping copper electrodes or foils as multifunctional devices by Kingon and Srinivasan (2005). Electrically or magnetically tunable microwave resonators have been designated with multilayered MEE

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https://doi.org/10.1016/j.ijengsci.2017.11.012

composite materials by Blasi and Queffelec (2006), Semenov, Karmanenko, Demidov et al. (2006), Semenov, Karmanenko, Kalinikos et al. (2006). In addition, a voltage-controlled resistive switching has been reported for ferromagnetic multilayers and spin valves which are mechanically coupled to a ferroelectric substrate (Pertsev & Kohlstedt, 2010). Furthermore, ferroelectric-ferromagnetic multilayers have been applied to develop ultrasensitive magnetic-field sensors for technical and biomedical applications by Prokhorenko, Kohlstedt, and Pertsev (2014). Ferroelectric-ferromagnetic multilayers have also been utilized to control magnetization with magnon-assisted switching gate by Li, Chen, Berakdar, and Jia (2017). Consequently, research work on MEE materials has been increased intensively in recent years. Due to different demands, different aspects of MEE materials have been investigated either analytically or numerically, which can be generally categorized into evaluation of effective material properties, free vibration and wave propagation problems, static and dynamic analyses of fracture, large deflection, dislocation, inclusion, contact and thermal problems (Chen, Guo, & Pan, 2017; Chen, Heyliger, & Pan, 2014; Kuo & Wang, 2012; Li & Pan, 2016; Li, Zheng, Chen, Kang, Gao, & Müller, 2017; Li, Wang, & Han, 2010; Milazzo, 2014; Rodríguez-Tembleque, Buroni, Sáez, & Aliabadi, 2016; Sladek, Sladek, Repka, Kasala, & Bishay, 2017; Vinyas & Kattimani, 2017; Wang, Pan, Albrecht, & Feng, 2009). Experimentally, on the other hand, focus has been on the magnetoelectric coupling coefficients between the electric and magnetic fields (Nan, Bichurin, Dong, Viehland, & Srinivasan, 2008; Vopson, 2015).

Distinctively, to narrow the current literature review of MEE structures, only some analytical studies for the problems under static or dynamic sources will be briefly mentioned. Liu, Liu, and Zhao (2001) obtained static Green's functions of two-dimensional anisotropic MEE based on the extended Stroh formalism combined with the technique of conformal mapping and Laurent series expansion. The exact solution of functionally graded and multilayered, anisotropic, linear MEE rectangular plates was presented via the pseudo Stroh formalism for the static case by Pan and Han (2005). The similar problem was studied further by Bhangale and Ganesan (2006) using a semi-analytical finite elements method. Wu and Tsai (2007) studied the three-dimensional static behavior of functionally graded MEE shells under the effects of mechanical load, electric displacement and magnetic flux using the asymptotic approach. Static analysis of anisotropic functionally graded MEE beams was reported by Huang, Ding, and Chen (2010) who defined three in-plane stresses, electric displacement and magnetic induction in terms of potential functions to obtain unknown fields. Chen, Pan, and Heyliger (2015) studied the static deformation of a spherically anisotropic and multilayered MEE hollow sphere using the spherical system of vector functions and domain transformation. Guo, Chen, and Pan (2016) analyzed the static deformation of anisotropic MEE layered plates based on the modified couple-stress theory for surface loading. Also, Chen and Guo (2017) have presented static response of MEE half-space structure under circular surface loading utilizing the cylindrical system of vector functions and applying stiffness matrix method.

In contrast, there exist only very few analytical studies related to MEE structures under dynamic sources. Chen, Shen, and Tian (2006) derived the dynamic potentials of a quasi-plane MEE medium of transversely isotropic space with an inclusion and obtained explicit expressions for the dynamic Green's functions for this medium. Rojas-Díaz, Sáez, García-Sánchez, and Zhang (2008) derived dynamic Green's functions in both two-dimensional and three-dimensional linear MEE solids by means of Radon-transform due to a time-harmonic point force, point charge and magnetic mono-pole. Milazzo (2013) presented a one-dimensional model employing first-order shear theory for dynamic analysis of layered MEE beams due to applied electric/magnetic potential or in free vibration case. Moshtagh, Pan, and Eskandari-Ghadi (2017) have analytically studied the mechanically vertical dynamic loading of a multilayered MEE structure, utilizing a system of orthogonal vector functions to investigate the responses of different layers for some limited frequencies.

To the best of our knowledge, there is no analytical solution for layered MEE structures excited by dynamic shear sources. Therefore, the main goals of the current paper are to present an analytical solution for the boundary value problem of a layered MEE half-space under a shear excitation with a vast frequency domain and to investigate the frequency effects on responses considering different material properties and layering.

The governing equations of motion for a multilayered MEE half-space under a dynamic source are a set of complicated high-order coupled partial differential equations. To come up with the solution of this complicated problem, a complete orthogonal infinite dimensional vector space is defined as a new system of functions consisting of exponential functions as a base for Fourier series, and Bessel functions as a base in Hankel integral transforms. To start, all equations are expressed using the cylindrical coordinates r, θ and z. Then, equations of motion and boundary values are transformed from physical domain to this new space of vector functions (called transformed domain), which forms new governing equations for two groups of decoupled first-order ordinary differential equations with ten unknown quantities called expansion coefficients. Group I denotes P- and SV-waves while Group II presents SH-waves. These two sets of first-order ordinary differential equations are solved separately based on the transformed continuum boundary values. It should be noted that to correlate unknown fields and boundary conditions in different levels of the structure in the transformed domain, instead of the common propagator matrix and stiffness matrix, the dual-variable-position (DVP) method will be applied, which is more stable and efficient computationally (Liu, Pan, & Cai, 2017). Finally, all unknown fields in the physical-domain are obtained by carrying out the inverse integration numerically.

This paper is an extension of our recent work in Moshtagh et al. (2017) (hereafter is called Paper I) to the shear excitation. Different numerical results are presented to investigate the effects of layers arrangement and frequency content of excitation on the responses including resonance phenomena. To validate the formulations and numerical calculations, the solution of this paper is degenerated to the pure elastic layered half-space and compared with the existing solution where a very good agreement is observed.