Thin-Walled Structures 119 (2017) 33–46

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Vibration analysis of magneto-electro-elastic heterogeneous porous material plates resting on elastic foundations

Farzad Ebrahimi*, Ali Jafari, Mohammad Reza Barati

Department of Mechanical Engineering, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran

ARTICLE INFO

Keywords:
Magneto-electro-elastic FG plate
Porous materials
Free vibration
Refined plate theory
Elastic foundation

ABSTRACT

This paper proposes a four-variable shear deformation refined plate theory for free vibration analysis of embedded smart plates made of porous magneto-electro-elastic functionally graded (MEE-FG) materials. Magneto-electro-elastic properties of FG plate are supposed to vary through the thickness direction and are estimated through the modified power-law rule in which the porosities with even and uneven type are approximated. The governing differential equations and boundary conditions of embedded porous FG plate under magneto-electrical field are derived through Hamilton's principle based on a four-variable tangential-exponential refined theory which avoids the use of shear correction factors. An analytical solution procedure is used to achieve the natural frequencies of embedded porous FG plate supposed to magneto-electrical field with various boundary condition. Influences of several important parameters such as material graduation exponent, porosity volume fraction, magnetic potential, electric voltage, various boundary conditions, elastic foundation parameters and plate side-to-thickness ratio on natural frequencies of embedded porous MEE-FG plate are investigated and discussed in detail. It is concluded that these parameters play significant roles on the dynamic behavior of porous MEE-FG plates resting on elastic foundation. Presented numerical results can serve as benchmarks for future analyses of MEE-FG plates with porosity phases.

1. Introduction

Technology development in field of making materials with functional properties introduce Functionally graded materials (FGMs) as a new class of smart composite structures which have led many researchers to analyze the mechanical specifications of these materials with engineering structure like beam, plate and shell. Due to high strength and high temperature resistance of FGMs, they are increasingly utilized in the mechanical, civil, nuclear reactors, aerospace engineering and etc. as structural components [1–6]. The mentioned positive points are interesting enough for the authors to employ FGMs in researches dealing with the mechanical behavior of structures [7–15]. Thermo-electro-mechanical static and dynamic responses of circular FG plates are discussed and presented by Ebrahimi [16]. Due to immense applications of smart materials in contemporary technology, intelligent structures made of magneto electro elastic materials (MEEMs) are nowadays widely utilized in engineering fields. In 1990s, in two-phase composites of piezoelectric and piezo-magnetic materials, a strong magneto-electrical coupling effect was discovered which has potential practical application in many fields [17] and reported that this coupling effect cannot be found in a single-phase material. Furthermore, MEEMs shows some fascinating properties such as the piezo-electric, piezo-magnetic and magneto-electric influences in which the elastic deformations may be produced directly by mechanical loading or indirectly by an application of electric or magnetic field. Due to their superior properties, these materials may exhibit particular Specifications that make them acting as mechanical sensors, controller and actuators for converting energy [18]. Owing to these advantages, MEE have received wide applications in modern industries such as aircraft structures, vibration control of civil infrastructure, stress monitoring and non-destructive testing. Hitherto, many researchers attracted to discover mechanical response of structures made of MEEMs. Among them, Pan [19] provided three dimensional exact solutions for simply-supported anisotropic MEE multilayered rectangular plate subjected to surface and internal loads. By analytical solution method, Most recently, based on three-dimensional elasticity theory and employing the state space approach, Xin and Hu [20] presented semi-analytical evaluation of free vibration of arbitrary layered magneto-electro-elastic beams.

For more efficient and expand applications of magneto electro elastic structures, they were recently synthesized by using FGMs. Actually, functionally graded model enables the MEEMs to have the best properties. Recent investigations about MEEMs discuss mechanical

* Corresponding author.
E-mail address: febrahimy@eng.ikiu.ac.ir (F. Ebrahimi).

http://dx.doi.org/10.1016/j.tws.2017.04.002
Received 30 July 2016; Received in revised form 7 March 2017; Accepted 3 April 2017
0263-8231/

response of structural elements made of functional graded MEEMs. Pan and Han [21] provided exact solution for analysis of the rectangular plates composed of functionally graded, anisotropic, and linear magne-to-electro-elastic materials. Also Ebrahimi and Barati [22–34] investigated mechanical behavior of piezoelectric functionally graded beams and plates via nonlocal elasticity theory.

With the rapid development in technology of structural elements, structures with graded porosity can be introduced as one of the latest development in FGMs. The structures consider pores into microstructures by taking the local density into account. Researches focus on development in preparation methods of FGMs such as powder metallurgy, vapor deposition, self-propagation, centrifugal casting, and magnetic separation. These methods have their own ineffectiveness such as complexity of the technique and high costs. An efficient way to manufacture FGMs is sintering process in which due to difference in solidification of the material constituents, porosities or micro-voids through material can create. An investigation has been carried out on porosities existing in FGMs fabricated by a multi-step sequential infiltration technique. According to this information, for building more secure and accurate structures it is important to consider the porosity impact on designing FGM structures. Porous FG structures have many interesting combinations of mechanical properties, such as high stiffness in conjunction with very law specific weight. Since porous FG structures have reached remarkable attention by many engineers, recent paper in field of FG structures discuss mechanical response of structural ingredients made of porous functional graded materials. Wattanasakulpong and Ungbhakorn [35] examined the linear and non-linear vibration of porous FGM beams with elastically restrained ends. Ebrahimi and Mokhtari [36] provided differential transform method to examine vibration behavior of rotating Timoshenko FG beams with even porosities. They reported that porosity volume fraction has a key role on the vibrational response of the FG beams. In order to predict flexural vibration of porous FGM Timoshenko beams, Wattanasakulpong and Chaikittiratana [37] employed Chebyshev collocation method. Ebrahimi and Zia [38] applied the Galerkin and multiple scales methods to solve nonlinear vibration of porous FGM beams. Ebrahimi et al. [39] presented thermo-mechanical vibration response of temperature-dependent porous FG beams subjected to various temperature risings based on classic beam theory (CBT) which disregards the influence of shear deformation. In other words, CBT is unable to model thick beams and higher modes of vibration. Hereupon, first order shear deformation theory (FSDT) is suggested to overcome the defects of CPT with supposition a shear correction factor in the thickness direction of beam [40]. As respects FSDT isn't able to evaluate the zero-shear stress on the top and bottom surfaces of the beam, there appeared a need to develop new theory. In order to bypass these defects, higher order shear deformation theory (HSDT) was introduced. This theory predicts transverse shear stresses without need of any shear correction factors. Many papers are published which framework HSDT to investigate mechanical response of FG structures [41–46]. Moreover, Yahia et al. [47] study the porosity effect on the wave propagation of FG plates by using various higher-order shear deformation theories. Recently, Mechab et al. [48] developed nonlocal two-variable refined plate theory for free vibration of FG porous nanoplates resting on elastic foundations. FG structures resting on elastic foundations have wide applications in modern engineering. The interaction of a plate with its foundation can be explained by suggesting various basic models in the literature. One of the simplest model for the elastic foundation is Winkler model because it takes the foundation into account as a set of independent and separate springs. Pasternak improved this model later by introducing a new dependence parameter which takes the interactions between the separated springs in Winkler model into account. Many researchers use plates resting on foundations to model the interaction between elastic plates and media for many engineering problems [49–54].

Literature search in the area of vibration analyses of FG porous plate indicates that there is no published work considering magneto-electrical field and elastic parameters effects on vibration characteristics of FG plates with different porosity models with the concept of exact neutral axis position. This paper focuses on free vibration of magneto-electro-porous FG plates resting on elastic foundations with various boundary conditions based on a four-variable refined plate theory which provides a constant transverse displacement and higher-order variation of axial displacement through the depth of the plate so that there is no need for any shear correction factors. Two kinds of porosity distribution namely even and uneven through the thickness directions are considered. The modified power-law model is exploited to describe gradual variation of material properties of the porous MEE-FG plate. Applying Hamilton's principle, governing equations of higher order MEE-FG plate are obtained together with the exact position of neutral axis and they are solved applying an analytical solution method. Several numerical exercises indicate that various parameters such as magnetic potential, external electric voltage, porosity volume fraction, types of porosity distribution, elastic parameters, material graduation index and various boundary conditions have remarkable influence on fundamental frequencies of porous MEE-FG plate.

2. Theoretical formulations

2.1. The material properties of porous magneto-electro-elastic FG plates

Consider a magneto-electro-elastic functionally graded plate resting on elastic foundation with two different porosity distribution and rectangular cross-section of width b and thickness h according to Fig. 1. MEE-FG plate is composed of $BaTio_3$ and $CoFe_2O_4$ materials with the material properties presented in Table 1 and exposed to a magnetic potential $\gamma(x, z, t)$ and electric potential $\Phi(x, z, t)$. The effective material properties of MEE-FG plate change continuously in the thickness direction according to modified power-law distribution. The effective material properties (P_f) of porous FGM plate by using the modified rule of mixture can be expressed by [35]:

$$P_f = P_u(V_u - \frac{\alpha}{2}) + P_l(V_l - \frac{\alpha}{2}) \tag{1}$$

In which α denotes the volume fraction of porosities, for a perfect FGM α is set to zero, P_u and P_l are the material properties of top and bottom sides, V_u and V_l are the volume fraction of top and bottom surfaces, respectively and are related by:

$$V_u + V_l = 1 \tag{2}$$

Then the volume fraction of upper side (V_u) is defined as follows:

$$V_u = (\frac{z}{h} + \frac{1}{2})^{\,p} \tag{3}$$

where ($p \geq 0$) is a non-negative parameter (power-law exponent or the volume fraction index) which determine the material distribution across the plate thickness. According to Eqs. (1) and (2), the effective material properties of porous MEE-FG (I) plates with even porosities are variable across the thickness direction with the following form:

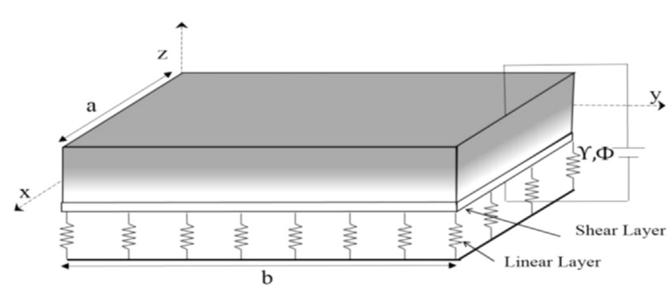

Fig. 1. Geometry of FGM plate under magneto-electrical field.