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Free vibration and biaxial buckling analysis of double magneto-electro-elastic nanoplate-systems coupled by a visco- Pasternak medium via nonlocal elasticity theory

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This paper deals with the analysis of free vibration and biaxial buckling of double-magneto-electro-elastic nanoplate-systems (DMEENPS) subjected to initial external electric and magnetic potentials, using nonlocal plate theory. It is supposed that the two nanoplates are bonded with each other using a visco-Pasternak medium, and are also limited to the external elastic substrate. Hamilton's variational principle is applied to acquire the partial differential equations of motion and corresponding boundary conditions for three modes (out-of-phase, in-phase and one nanoplate fixed) and solved analytically to determine clear closed-form phrase for complex natural frequencies natural frequencies and buckling loads. Numerical examples are performed to demonstrate the changes of the vibration frequency and buckling load ratio ($\frac{NL}{L}$) of DMEENP against to different values of the nonlocal parameters, initial external electric and magnetic potentials, aspect ratio, damping and transverse stiffness coefficients of the viscoelastic foundation, shear stiffness coefficient of Pasternak medium, length to thickness ratio, nanoplate thickness and higher modes. Also, the effect of biaxial compression ratio on the buckling load is investigated. Results of this study show that considering the interaction between two Magneto-electro-elastic nanoplates lead to achieving greater frequencies and biaxial buckling loads. Moreover, the influences of the nonlocal parameter become more pronounced when the half wave number, initial external electric potential and aspect ratio increase, while the effect of the length to thickness ratio and initial external magnetic potential has the opposite trend.

1. Introduction

In the recent years, studies on applications of a new group of composite materials called smart materials in engineering industries such as aerospace, automotive and biomedical engineering have been carried out. Smart materials can considerably change their mechanical and physical properties, in a predictable or controllable manner under various environmental conditions. Magneto-electro-elastic (MEE) composite materials are an important class of smart materials combining piezoelectric and piezomagnetic phases. Due to the capacity of converting energy among magnetism, electricity, or elasticity into another form, the MEE materials are suitable for smart applications.

So far, many buckling and vibration studies on MEE macrostructures such as beams and plates have been reported in several literature. The Euler beam model has been used to vibration analysis of beam with embedded piezoelectric actuator layer for various boundary conditions by Wang and Quek (2000). Applying finite element approach (Kumaravel et al., 2007), investigated critical buckling temperature and free vibration behavior of multiphase MEE beam and considered clamped-clamped boundary condition. Based on the Timoshenko beam theory, the exact solution for free and forced vibration of a magneto-electro-elastic bimorph beam under different boundary conditions are derived by Milazzo et al. (2009). For simply supported multilayered rectangular MEE plates including anisotropic materials (Pan, 2001; Pan and Heyliger, 2002), analytically derived a three-dimensional solution which can predict exactly static loads, natural frequencies and mode shapes. Bhangale and Ganesan (2006) used semi-analytical finite element method to

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study vibration behavior of anisotropic and linear MEE plates made of functionally graded materials. Based on a higher-order plate theory, (Simões Moita et al., 2009) numerically investigated static and free vibration of MEE plates via finite element models. Wang et al. (2011) presented three-dimensional exact solutions for axisymmetric bending of simply supported and clamped boundary FGM circular MEE plates. Zhang et al. (2013) derived Two-dimensional equations of piezoelectric nano-scale plate incorporating surface effect. Recently, on the basis of higher-order shear and normal deformable approach (Abdollahi et al., 2015), analytically investigated buckling behavior of a thick piezoelectric plate made of functionally graded material. Moreover, many researchers have studied the mechanical behavior of single or multilayered MEE plates at the macro scale (Chang, 2013; Kuang, 2014).

It should be noted that classical continuum theory was applied to study mechanical properties of MEE plates in all the papers mentioned above while to access material properties, the classical continuum theory cannot predict the small scale effect with high accuracy. However, the influences of atomic forces of small-scale structures cannot be ignored. Among all of the nonlocal theories that have been introduced to capture size effect in nanostructures, the Eringen's nonlocal elasticity theory (Eringen, 1983, 1972) has received considerable attention to show the size effect of nanostructures. Using nonlocal theory in conjunction with rod model (Demir and Civalek, 2013), studied the influence of small scale on the torsional and axial response of microtubules. In another work (Akgöz and Civalek, 2013), employed modified couple stress theory to investigate the static and dynamic behavior of microplates. Also, based on the Euler–Bernoulli beam assumption and finite element method, elastic instability of protein microtubules is analyzed by Civalek and Demir (2016). Applying the surface piezoelectricity model in conjunction with the nonlocal elasticity theory (Zhang et al., 2014), investigated the propagation characteristic of elastic waves in an infinite piezoelectric nanoplate. An investigation of the dynamic characteristics of the piezoelectric Mindlin nanoplate under various boundary conditions employing differential quadrature method (DQM) and nonlocal elasticity theory of Eringen is presented by Ke et al. (2015). Recently, According to Euler–Bernoulli beam theory, and Eringen's nonlocal elasticity theory and von Kármán's assumptions, a size-dependent model has been proposed to investigate nonlinear forced vibration of MEE nanobeam incorporating external electric voltage, external magnetic potential and uniform temperature rise by Ansari et al. (2015).

By considering the Eringen's nonlocal theory and Kirchhoff plate theory, the size-dependent vibration behavior of simply supported rectangular MEE nanoplate is investigated by Ke et al. (2014). In this work, the governing equations of motion and boundary conditions are derived from Hamilton's principle and Navier approach is used to solve the equilibrium equations of the system. An analytical investigation on buckling and free vibration behavior of Mindlin rectangular MEE nanoplates resting on Pasternak medium via nonlocal elasticity theory has been carried out by Li et al. (2014). They showed that the normalized frequency of system decreases by increasing the value of electric potential. However, the normalized frequency of system increases by increasing the value of magnetic potential. Recently, according to the nonlinear von Kármán's strain-displacement and nonlocal elasticity theory (Liu et al., 2015), analytically obtained nonlinear frequencies of Kirchhoff Piezoelectric nanoplates resting on the Winkler foundation. Furthermore (Ansari and Gholami, 2016a), examined the buckling and post-buckling of MEE nanoplates under thermal loading via nonlocal form of Mindlin plate theory. Ghorbanpour Arani et al. (2016) applied a nonlocal model of sinusoidal shear deformation plate theory to analysis of wave propagation of viscoelastic sandwich nanoplates by taking into account the surface effects.

Sometimes, for a good optimization design such as the design of continuous dynamic vibration absorber and isolation, we need complex systems of plates and beams. Double plate systems are composed of two plates embedded in elastic medium or visco-elastic medium. For the first time (Seelig, 1964; Seelig and Hoppmann, 1964), presented a complex model for vibration analysis of beams which was composed of two parallel beams embedded in an elastic medium with different boundary conditions. After that, many research works have been carried out focusing on the vibration and buckling investigation of complex shapes of plates, beams and rods at the macro (Oniszczuk, 2000), micro (Ghorbanpour Arani et al., 2015; Jamalpoor and Hosseini, 2015) and nano scales (Hosseini and Jamalpoor, 2015; Karličić et al., 2015). Based upon the nonlocal elasticity theory, an explicit closed-form for natural frequencies of double-piezoelectric-nanoplate-systems connected by a homogeneous Winkler elastic layer subject to external electric voltage for two cases (synchronous and asynchronous vibration) is presented by Asemi and Farajpour (2014a). In another work of Asemi and Farajpour (2014b), dynamic characteristics of a coupled piezoelectric nanoplates-system embedded in a polymer matrix subjected to temperature change and non-uniform voltage distribution is studied. The authors used differential quadrature method (DQM) to obtain natural frequencies for different boundary conditions.

However, by review of papers presented about free vibration and buckling analysis of magneto-electro-elastic (MEE) nanoplates according to Eringen's nonlocal elasticity theory, it is found that no study has been presented in the literature on the free vibration and biaxial buckling analysis of double-MEE nanoplate systems. In this study, a visco-Pasternak medium is used to model the interaction between two simply supported rectangular MEE nanoplates. Partial differential equations of motion are derived by applying the Hamilton's principle and using the analytical method, natural frequencies and buckling load of the system are proposed in explicit closed-form for three different cases (out-of-phase, in-phase and one nanoplate being stationary).

2. Modeling of the problem and formulation

2.1. Geometrical configuration

As seen in Fig. 1, two rectangular nanoplates with uniform thickness (h) consist of MEE materials coupled by a visco-Pasternak substrate and are limited to the elastic foundation. The length and width of each nanoplate are considered, respectively, by L_x and L_y. Furthermore, the transverse displacements of the two nanoplates are assumed to be $w_1(x,y,t)$, $w_2(x,y,t)$, and physical and geometrical properties of the two MEE nanoplate are supposed to be identical.

2.2. Constitutive relations for nonlocal Kirchhoff MEE nanoplate

By applying Kirchhoff plate hypothesis, the displacement fields (u_1, u_2, u_3) of the plate at an arbitrary point along x, y and z directions at time t can be illustrated as

$$u_1(x,y,z,t) = -z\frac{\partial w(x,y,t)}{\partial x}$$
$$u_2(x,y,z,t) = -z\frac{\partial w(x,y,t)}{\partial y} \quad (1)$$
$$u_3(x,y,z,t) = w(x,y,t)$$

where w indicates the middle-plane lateral displacement of the nanoplate across to the z direction.