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On the influence of the magnetic field on the eigenmodes of thin laminated cylindrical shells containing magnetorheological elastomer

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ABSTRACT

Laminated cylindrical sandwich shells composed by embedding magnetorheological elastomers (MREs) between elastic layers is the subject of this investigation. Physical properties of the magnetorheological (MR) layers are assumed to be functions of the magnetic field induction and curvilinear coordinates. A system of differential equations with complex variable coefficients depending upon the magnetic field and based on both the assumptions of the generalized kinematic hypothesis for the whole sandwich and experimental data for MREs is used as the governing one. To analyze damping capabilities of adaptive materials, free vibrations of a three-layered circular cylinder containing MRE core layer are studied at different levels of the magnetic field. Using the asymptotic approach, eigenmodes of free vibrations of a laminated cylindrical shell with variable physical characteristics of MRE are constructed in the form of functions decaying far from the weakest plot on the shell structure. It has been shown that applying constant magnetic field may result in localization of eigenmodes corresponding to low-frequency spectrum of three-layered circular thin cylinder with embedded nonuniform MRE layer. Dependencies of natural frequencies, damping decrement and parameter characterizing the power of the eigenmode localization on the intensity of applied magnetic field are analyzed.

1. Introduction

Thin multi-layered shells have a wide range of applications in many engineering structures, such as airborne/spaceborne vehicles, underwater objects, and cars [1,2]. Applying new materials with different physical properties one can design sandwich structures fulfilling up-to-date requirements such as high-specific stiffness, good buckling resistance, safety and noiselessness. The vibroprotection of thin-walled structures experiencing external vibrational loads is of great practical interest for mechanical engineers which develop and model similar structures. The appearance of new multi-functional composite materials with active and adaptive properties (so-called smart materials) opens new possibilities [3–5]. Some of them are electrorheological (ER) and magnetorheological (MR) composites and, particularly, magnetorheological elastomers (MREs).

MRE are magnetizable particles molded in either rubbery polymers or deformed inorganic polymer matrices [6]. The optimum weight/density ratio of magnetic particles, carrier viscous liquid and polymer determines shear modulus, viscosity and response time of smart materials [7]. They belong to the group of active materials which physical properties such as viscosity and shear modulus can vary when subjected to different magnetic field levels [6,7]. It is expected that MREs embedded between elastic layers will provide for a sandwich a wide range of rheological properties which may be controlled rapidly and reversibly by the application of an external magnetic field.

There is a significant number of studies dedicated to the exploration of the mechanical and rheological properties of magnetorheological media and elastomers (see, e.g., [6–11]). It is obvious that the properties of MREs depend on its components. The basic ones, revealed in above and many other papers, are the following: increasing the magnetic field intensity leads to the ordering of magnetic particles in the matrix and finally results in increasing both the storage and the loss moduli (the real and imaginary parts of the complex shear modulus, respectively). The saturation moment for a wide range of MREs is achieved in magnetic field of about 300–400 mT. As shown in [12–14], the properties of MREs depend strongly on the manufacturing technology. For instance, if the polymerization reaction is carried out in an external homogeneous

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magnetic field, then MRE becomes highly polarized [13] and has anisotropic properties [12]. Furthermore, experimental works [14] demonstrate that the maximum increase in the storage modulus of the polarized MRE under homogeneous magnetic field action strongly depends on the particles arrangement within the matrix with respect to the magnetic field. All these properties should be taken into account when designing or studying tunable composite structures containing MREs as adaptive elements.

Referring to studies on the dynamic calculation of thin sandwich structures containing MRE, the majority of available papers deals with three-layered beams with MR core [15–23]. Considerable contribution to fundamental investigations of MRE-based sandwich beams was done by Zhou and Wang [17–19]. They studied the field-controllable dynamic properties of a sandwich beam composed of the MRE core and non-conductive [17] or conductive thin outer skins [18,19]. It was observed that the change of the dynamic properties of the sandwich beam is mainly caused by the change of shear modulus of MRE. The parametric instability of a soft-cored sandwich beam with MRE subjected to periodic axial load is studied in [20,21]. Free and forced vibrations of a three-layered beam with MRE core and outer aluminum layers at different levels of magnetic field is analyzed in paper [23]. As shown in [23], for the considered parameters of the MRE-based sandwich the optimal intensity of magnetic field (about 350 mT) provides the best suppression of vibrations. In addition, the pulsed signal of an external magnetic field may results in excitation of non-stationary high-frequency vibrations of the adaptive beam containing MR core.

Very few literature is available on the dynamic simulation of sandwich shells with magnetosensitive embedded core or layers. In [24] an analytical model is developed and adopted to the discrete finite element method to investigate the vibration and damping characteristics of a three layered orthotropic cylindrical shell with electrorheological core and outer constraining layers. In [25] a rectangular plate combined with an MRE core layer and constraining layers is assumed to improve the vibration behavior of the sandwich system. Free vibrations of a circular three-layered thin cylinder with homogeneous MR core under different level of the magnetic field are investigated in [23]. It is shown that the MRE has a significant effect on the vibration characteristics of the sandwich rectangular plate [25] and circular thin cylinders [26].

The small number of papers on vibrations of MRE-based sandwich shells may be explained by extreme difficulty and complexity of accurate laminated shell theories. The 3D models of elasticity for laminated shells are rather complicated when presented in curvilinear shell coordinates. New advanced theories (for example [28]) based on 3D stress analysis and rigid-body motions as well as available high accurate layer-wise theories ([29–33] and reviews [2,34]) are rather sophisticated in the theoretical formulations and numerical computations, thus preventing their general use in modeling practical shell vibration problems. In our opinion, the equivalent single layer (ESL) models are more perspective for dynamic simulation of thin multi-layered shells and, particularly, for tunable laminated thin-walled structures containing MR layers. Survey articles and monographs devoted to ESL theories are, e.g., [2,31,35–39].

The attempt to apply one of ESL models for the dynamic analysis of thin MRE-based laminated shells has been done in [26]. Based on the assumptions of the generalized kinematic hypothesis of Timoshenko for the whole sandwich, the governing equations derived earlier in [35] are adapted to the description of dynamics of MR adaptive cylindrical shells. The reduced constitutive equations for the sandwich are taken in the complex form. The complex shear modulus for MRE is determined experimentally at different levels of the induced magnetic field. It should be noted that in all available papers on vibrations of MRE-based sandwich structures, the MR core is considered as isotropic and homogeneous and the applied magnetic field is assumed to be uniform. To simplify the problem, the dependence of physical properties in polarized MRE on the direction of the magnetic field force lines [14] is always ignored. To eliminate this gap, in [26] the case when physical characteristics of MR layers are functions of curvilinear co-ordinates is considered. Thus, the generalized differential equations derived [26] contain complex coefficients (elastic and damping parameters) which depend on elastic and rheological properties of MRE. They are functions of the magnetic field induction.

In this study, based on the ESL model adapted in [26] for thin MRE sandwiches, the influence of applied magnetic field on eigenmodes, natural frequencies and damping ratios of thin laminated cylindrical shell containing MRE is investigated. In the general case, the physical properties of MR layers embedded between elastic layers are functions of the curvilinear co-ordinates at the shell surface, and the applied magnetic field may be nonhomogeneous. As the first step, the principle complex parameters of the accepted model (complex coefficients appearing in the governing equations) vs. the homogeneous magnetic field is studied on the example of a three-layered adaptive MR cylinder. Variations in the reduced complex stiffness and shear parameters of the sandwich are achieved in response to different levels of applied magnetic field. Then the natural frequencies and damping ratio are calculated for different thicknesses of the MR core under action of the external magnetic field.

One basic goal of this study is to show that the applied magnetic field may result in distortion of eigenmodes of sandwich shells containing polarized MRE. The case when the reduced elastic and rheological properties of MRE-based laminated cylindrical shell become nonhomogeneous under action of magnetic field is considered. Using the asymptotic method proposed in [40] (see the later developments in [41,42]), free low-frequency vibrations localized in the neighborhood of some generator at the surface of the MRE-based cylinder under different levels of magnetic field are studied. As the first example, we consider the earlier examined case of thin isotropic shells [42] when the localization is caused by the complex geometry of the shell: applying different magnetic fields, we predict eigenmodes for a non-circular cylindrical MR shell localized near the asymptotic line at which the shell curvature is minimum. Then the new problem on free localized vibrations of a circular cylindrical sandwich shell containing MR layers is considered, the localization being the consequence of either strong inhomogeneity of applied magnetic field or initial polarization of the MR.

2. Governing equations for thin-walled laminated cylindrical shells

We consider a thin cylindrical sandwich shell (see Fig. 1) consisting of N transversely isotropic layers characterized by length L, thickness h_k, density ρ_k, Young's modulus E_k, and Poisson's ratio ν_k where $k = 1, 2, \dots, N$, and N is an odd number. Let the layers with the odd numbers (including load-bearing ones) be made of elastic material which is not affected by external magnetic field, and the layers having the even numbers be fabricated from a visco-elastic magneto-rheological (MR) material whose rheological properties depend on the intensity of a magnetic field. The middle surface of any fixed layer is taken as the original surface. The coordinate system α_1, α_2 is illustrated in Fig. 1, where α_1, α_2 are the axial and circumferential coordinates, respectively.

If every layer is made of elastic and homogeneous material, the parameters E_k as well as the shear moduli G_k are real constants for any k. When the sandwich is formed by embedding magneto-rheological materials between elastic layers, some of these parameters corresponding to the viscoelastic lamina with adaptive rheological properties are assumed to be complex functions

$$E_k = E'_k + \imath E''_k, \;\; G_k = G'_k + \imath G''_k, \quad \imath = \sqrt{-1}. \tag{1}$$