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Smart damping of geometrically nonlinear vibrations of magneto-electro-elastic plates

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A R T I C L E I N F O

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A B S T R A C T

This paper presents an analysis of the active constrained layer damping (**ACLD**) of large amplitude vibrations of smart magneto-electro-elastic (**MEE**) plates. The constraining layer of the **ACLD** treatment is composed of the vertically/obliquely reinforced 1–3 piezoelectric composite (**PZC**). The constrained viscoelastic layer of the **ACLD** treatment is modeled by using Golla–Hughes–McTavish (**GHM**) method in time domain. A three-dimensional finite element model of the overall smart **MEE** plates has been developed taking into account the electro-elastic and magneto-elastic coupling effects. The von Kármán type nonlinear strain displacement relations have been used for modeling such coupled **MEE** problems. Particular attention has been paid to investigate the performance of the **ACLD** treatment due to the variation of the piezoelectric fiber orientation angle.

1. Introduction

Emerging technologies in the production of advanced composites enhanced the application of smart structures particularly in aerospace, automotive, civil, marine, medical and high precision applications. Comprehensive research carried out over the last couple of decades reveals that the piezoelectric materials are the most widely used materials for the active stability, shape, vibration and noise control applications of high precision, high-functioning featherweight adaptive structures [1–6]. The superior electromechanical coupling property existing in piezoelectric materials empowered to become sensors as well as actuators of flexible structures. The structures integrated with such materials possess a self sensing and self diagnosing capabilities and are conventionally called as smart structures or intelligent structures. Monolithic piezoelectric materials used in distributed actuators and sensors have low electromechanical coupling coefficients, high acoustic impedance and high control voltage is required for satisfactory control of vibrations of host structures. However, if the monolithic piezoelectric materials used in the form of a fibers and reinforced within epoxy matrix particularly in 1–3 connectivity, the resulting 1–3 piezoelectric composite (**PZC**) possess effective material properties significantly superior to those of the monolithic piezoelectric materials [1]. Such composites are commonly known as active damping piezoelectric composites. Active damping requires relatively little control effort, further research on the masterly use of these low-control-authority monolithic piezoelectric materials led to the development of active constrained layer damping (**ACLD)** treatment [5,6]. In a typical **ACLD** treatment, the performance of the passive constrained layer damping (**PCLD**) treatment has been significantly enhanced by replacing the constraining layer by an active constraining layer made of smart materials such as piezoelectric materials/1–3 piezoelectric composites (**PZC**). The constrained layer made of viscoelastic material is sandwiched between the host structure and the 1–3 **PZC** active constraining layer. The low-stiff constrained viscoelastic layer in the **ACLD** treatment undergoes large transverse shear deformations causing more energy dissipation. The control effort required for causing high transverse shear deformations is conformable with the low-control authority of the existing monolithic piezoelectric materials. Thus, to accomplish the task of active damping of vibrations of smart structures, better performance of the piezoelectric materials of low control authority is achieved when they are employed as constraining layer of the **ACLD** treatment rather than when they are directly attached to the host structures. Also, if the constraining layer of the **ACLD** treatment is not activated with applied voltages, the **ACLD** treatment becomes the **PCLD** treatment. Thus, the **ACLD** treatment provides both passive and active damping simultaneously when under operation [7]. The successful experimental work on the **ACLD** treatment [5] has motivated the researchers to carry out further investigations on the use of the **ACLD** treatment for active damping of composite structures. Chantalakhana and Stanway [8] investigated the performance of the **ACLD**

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treatment for clamped–clamped plate. Lim et al. [9] implemented the closed loop finite element modeling of the **ACLD** in time domain analysis. Illaire and Kropp [10] studied the quantification of damping mechanisms of active constrained layer treatments. Ray and his coworkers have been performing the extensive research on the performance of the **ACLD** treatment for active damping of linear [11–13] and nonlinear [14–16] vibrations of smart structures (beams, plates and shells) and they demonstrated that the damping characteristics of these structures can be improved significantly using piezoelectric composites as the materials of the constraining layer of the **ACLD** treatment. Owing to the flexibility of composite structures and small material damping, vibrations induced in the structure may lead to large amplitudes. Thus, the effect of geometrically nonlinear deformations becomes prominent in the behavior of composite structures. Consequently, it is inevitable to investigate the induced geometrically nonlinear effects in the composite structures. Many researchers performed the active control of geometrically nonlinear analysis of composite structures using piezoelectric sensors and actuators for attenuating the undesired vibrations [17–20].

A new class of smart composites made of combined piezoelectric and magnetostrictive materials generally referred as magneto-electro-elastic (**MEE**) or multiferroic composites. These composites have attracted significant attention of the researchers over the past several years on account of encouraging properties for the applications of sensors, actuators, transducers, space structures, sonar applications, ultrasonic imaging devices etc. The unique property of the **MEE** materials is that they have the ability to covert energy from one form into the other (among magnetic, electric and mechanical energies) [21]. The effects of **MEE** couplings have been observed in both single-phase materials as well as in composites made of piezoelectric and magnetostrictive phases. However, composites made of piezoelectric and magnetostrictive phases can exhibit significantly high magnetoelectric coupling coefficient than the individual piezoelectric or magnetostrictive materials. The **MEE** composites in layered forms are preferred to the bulk/fiber form because of the higher electromechanical coupling effect, the absence of leakage current and the ease of poling to align the electric dipole [22]. On account of multi behavior properties, **MEE** composites gained significant importance and needs an extra care and effort in the design and analyses of smart composite structures. Research concerned with the coupled magneto-electric effect in elastic media has received growing attention of the researchers [23–25]. Pan [21] demonstrated the exact solution of simply supported multilayered magneto-electro-elastic plates under surface and internal loads by using modified Stroh formalism and propagator matrix method. The same approach was extended to free vibration analysis by Pan and Heyliger [26] and for exact solutions of functionally graded **MEE** plates by Pan and Han [27]. Lage et al. [28] presented the layerwise partial finite element model for static analysis of **MEE** plates. Buchanan [29] computed the natural frequencies of vibration for **MEE** layered infinite plate. Several methods have been implemented to investigate the free vibration analysis of functionally graded **MEE** plates/shells namely, independent state equations by Chen et al. [30], finite element method by Bhangale and Ganesan [31,32] and discrete layer method by Ramirez et al. [33]. Haitao et al. [34] studied the static/dynamic analysis of functionally graded and layered **MEE** plate/pipe under Hamiltonian system. Tsai et al. [35] presented the static analysis of three-dimensional doubly curved functionally graded **MEE** shells by an asymptotic approach. The finite element model based on a higher order shear deformation theory for static and free vibration analysis of **MEE** plates has been developed by Moita et al. [36]. Liu and Chang [37] derived the closed form expression for the transverse vibration of the **MEE** thin plates. Extensive research is also devoted to the prediction of the effective properties [38–40] and crack related problems [41–43]. It is evident from the open literature that the most of the proposed work refers to the linear problems, whereas to the authors' best knowledge little work has been reported on the large deflection analysis of the **MEE** plates. Xue et al. [44] proposed the analytical solutions for large-deflections of rectangular **MEE** thin plate under the action of a transverse static mechanical load. They observed that coupling effect on the deflection is negligible for the **MEE** plate made of different volume fractions of piezoelectric and piezomagnetic phases. Sladek et al. [45] presented the meshless local Petrov–Galerkin method for the analysis of large deformation of **MEE** thick plates under static and time-harmonic mechanical load and stationary electromagnetic load. Most recently, Alaimo et al. [46] proposed an equivalent single-layer model for the large deflection analysis of multilayered **MEE** laminates by the finite element method. It should be noted that the 1–3 **PZC**s are commercially available and implemented for active control of conventional composite structures. However, the active damping of geometrically nonlinear vibrations of the **MEE** composite plates using such **PZC**s has not yet been studied and provides an ample scope for further research. It is noteworthy to mention that to the authors' best knowledge, the research concerning the active control of geometrically nonlinear vibrations of the **MEE** plates is not yet reported. Hence, in this study, the effectiveness of the vertically/obliquely reinforced 1–3 **PZC**s as the materials of the constraining layer of the **ACLD** treatment for active damping of geometrically nonlinear vibrations of the **MEE** plates has been investigated. For such investigation, three dimensional analysis of the **ACLD** of **MEE** plates integrated with the patches of the **ACLD** treatment has been carried out by the finite element method. The effects of various parameters such as the effect of coupling coefficients, boundary conditions and the variation of the piezoelectric fiber orientation angle in the 1–3 **PZC** constraining layer on the suppression of geometrically nonlinear vibrations of the **MEE** plates have been thoroughly investigated.

2. Problem description and governing equations

A schematic diagram of a magneto-electro-elastic (**MEE**) smart composite plate integrated with a patch of the **ACLD** treatment on its top surface is illustrated in Fig. 1. Although one patch is shown in Fig. 1, the model will be derived for multiple number of patches. The length, the width and the total thickness of the **MEE** plate are a, b and H, respectively. The thickness of the constraining **PZC** layer and the constrained viscoelastic layer of the **ACLD** treatment are h_p and h_v, respectively. The substrate of this plate consists of three layers. The top layer and the bottom layer of the plate are made of the piezoelectric material called $\mathbf{BaTiO_3}$ (Barium Titanate) while the middle layer is composed of the magnetostrictive material called $\mathbf{CoFe_2O_4}$ (Cobalt Ferrite). However, different stacking sequence can be used such as **B/F/B** and **F/B/F** in which **B** stands for $\mathbf{BaTiO_3}$ and **F** stands for $\mathbf{CoFe_2O_4}$. The constrained viscoelastic layer is sandwiched between the host **MEE** substrate and the constraining layer of the **ACLD** treatment. A layer of the obliquely reinforced 1–3 **PZC** material in which the piezoelectric fibers are coplanar with the *xz* plane with their orientation angle being λ with the *z*-axis is also illustrated in Fig. 1. Although not shown here, the piezoelectric fibers can be coplanar with the yz-plane while the orientation angle with the *z*-axis is λ. In case of the obliquely reinforced 1–3 **PZC**, the orientation angle (λ) is nonzero while it is zero for the vertically reinforced 1–3 **PZC**. Since, the structure is made of layers of dissimilar materials, the kinematics of deformations of the overall structure cannot be described by an equivalent single layer displacement theory because of the fact that the elastic properties of the adjacent continua of the overall