ARTICLE IN PRESS

Composites Part B xxx (2016) 1–7

Contents lists available at ScienceDirect

Composites Part B

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

Application of refined beam elements to the coupled-field analysis of magnetostrictive microbeams

S.A. Sheikholeslami [a], M.M. Aghdam [a], E. Zappino [b, *], E. Carrera [b]

[a] Department of Mechanical Engineering, Amirkabir University of Technology, Hafez Ave., Tehran, Iran
[b] Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Cso. Duca degli Abruzzi 24, 10129 Torino, Italy

ARTICLE INFO

Article history:
Received 17 October 2016
Accepted 19 October 2016
Available online xxx

Keywords:
Smart materials
Microstructures
Magnetic properties
Finite element analysis (FEA)
Carrera unified formulation

ABSTRACT

Bending of magnetostrictive unimorph microbeams is investigated using a one-dimensional refined finite element model based on the Carrera Unified Formulation. Since these type of smart devices are usually being used in low magnetic fields, the linear coupled magnetomechanical constitutive relations are used to characterize their coupling behavior. With the use of the principle of virtual displacement, components of the fundamental nucleus matrix are obtained and the governing equations are discretized. 2, 3 and 4-node beam elements are used for modelling the beam major axis while linear 4-node and quadratic 9-node Lagrange elements are used as expansion functions over the cross-section. Two examples of unimorph micro-devices are considered and the results of present work are compared with those of experimental and conventional finite element works existing in the literature. It is shown that the one-dimensional refined finite element model, which is capable of generating three-dimensional results, can accurately catch the experimental data with a lower computational cost than the classical models.

1. Introduction

Magnetostrictive-based sensors and actuators are widely used in high-tech MEMS recently. In such smart devices, thin films made of special magnetostrictive materials are bonded to a non-magnetic substrate to produce bending when subjected to magnetic fields. Since special magnetostrictive materials like Terfenol-D ($Tb_xDy_{1-x}Fe_2$) are able to produce high magnetic strains [1], they can be used in such sensitive devices. Some other materials like Terbium-iron (Tb-Fe) and Samarium-Iron (Sm-Fe) alloys are also reported to produce relatively high magnetostriction in low magnetic fields [2,3]. In the past years, some experimental and computational researches have been done to fabricate and develop magnetostrictive devices. Honda et al. [4] used a classical method to analyze the bending behavior of fabricated magnetostrictive bimorph cantilever actuators and traveling machines composed of TbFe and SmFe thin films on a polyimide substrate. Quandt et al. [5] studied the influence of the preparation conditions on the composition, microstructure, and in-plane magnetostrictive properties of amorphous thin Sm-Fe and Terfenol-D films. The authors [5] also used the finite element (FE) method to predict the maximum deflection of a silicon microbeam coated with Terfenol-D patches. A new magnetostrictive multilayer which combine giant magnetostrictive layers and layers with large magnetic polarization was reported by Quandt et al. [6]. The high magnetostriction at low magnetic fields and the possibility of engineering material properties through the layer thickness variation were reported to be the important features of this new multilayer. Some applications of multilayered magnetostrictive devices like membrane-type micropumps, linear ultrasonic motors and optical scanners are well-discussed in the literature [7–10].

Advances in fabrication and application of multilayered magnetostrictive structures led to a variety of theoretical modellings. Some analytical models were proposed to study the static behavior of magnetostrictive bilayers. Klokholm [11] proposed a formula to relate the magnetostriction of a thin magnetostrictive film deposited on a cantilever substrate to its deflection. This formula, however, was criticized by du Tremolet de Lacheisserie and Peuzin [12]. They observed that the proposed formula of Klokholm predicts the magnetostrictive strains about twice as large as the ones actually observed. This fact led them to derive a new formula based on a more realistic energy minimization method. This method was then extended to analysis of three different systems of magnetostrictive bilayers [13]. Some other analytical works can also be found in the open literature [14–17].

Based on the finite element (FE) method, some numerical modelings of magnetostrictive unimorphs are developed. With the use of ANSYS commercial finite element code, Watts et al. [18] analyzed the

* Corresponding author.
E-mail address: enrico.zappino@polito.it (E. Zappino).

http://dx.doi.org/10.1016/j.compositesb.2016.10.055
1359-8368/

Please cite this article in press as: Sheikholeslami SA, et al., Application of refined beam elements to the coupled-field analysis of magnetostrictive microbeams, Composites Part B (2016), http://dx.doi.org/10.1016/j.compositesb.2016.10.055

magnetostriction of a bilayer cantilever through an analogous anisotropic thermal expansion simulation. Based on a weak formulation, Benbouzid et al. [19] studied the magnetomechanical coupling of magnetostrictive thin films with a two-dimensional finite element model. Body and Reyne [20] presented strong formulations and modeled magnetomechanical coupling in giant magnetostrictive thin films. Si and Cho [21] stated that the previous FE models are not applicable to a general variety of magnetostrictive actuators, including different geometries and multilayer configurations. In order to overcome these problems, they presented an FE model including beam and plate elements and applied it to the magnetomechanical coupling of magnetostrictive multilayers. In this model, six-degrees of freedom (6-DOF) beam and twelve-degrees of freedom (12-DOF) plate elements are used to model the bending of magnetostrictive multilayers. Some refined FE formulations have recently been developed to deal with elements with more DOFs. It has been shown that these higher-order elements can accurately model the deformations of complex structures with less computational cost than the conventional full three-dimensional FE models. One of these refined finite element formulations which is the basis of present work is the well-known Carrera Unified Formulation (CUF). According to the CUF, higher-order kinematics can be hierarchically developed in an automatic manner [22]. The principal characteristic of CUF models is that the order of the theory is a free parameter of the analysis. Hence, in a FEM framework, classical and arbitrarily refined elements can be formally developed by using the same formulation. This makes CUF a valuable tool to evaluate the accuracy of any structural model in a unified manner and gives the capability of generating three-dimensional results with one-dimensional formulations [23–25]. CUF has been successfully applied to thin-walled structures [26,27], buckling problems [28], free vibration and dynamic response analyses [29,30], composite structures [31,32] and component-wise analysis of aerospace and civil structures [23,33]. This formulation has also been successfully applied to coupled multifield analyses, like thermo-mechanical [34–36], electro-mechanical [37,38], and mixed thermo-electro-mechanical [39,40] problems. The main aim of the present work is to apply the one-dimensional CUF to magneto-mechanical coupling analysis of magnetostrictive micro-devices.

2. One-dimensional refined FE model based on Carrera Unified Formulation

There are 4 generalized displacement parameters when dealing with magnetomechanical coupling analysis of structures. These parameters are

$$\mathbf{u} = \{ u_1 \quad u_2 \quad u_3 \quad \varphi \}^T \tag{1}$$

where u_1, u_2 and u_3 are components of the displacement field and φ denotes the magnetic potential. The generalized strain and stress vectors can be defined as

$$\mathbf{X} = \{ \varepsilon_{11} \quad \varepsilon_{22} \quad \varepsilon_{33} \quad \varepsilon_{23} \quad \varepsilon_{13} \quad \varepsilon_{12} \quad H_1 \quad H_2 \quad H_3 \}^T \tag{2}$$

$$\mathbf{Y} = \{ \sigma_{11} \quad \sigma_{22} \quad \sigma_{33} \quad \sigma_{23} \quad \sigma_{13} \quad \sigma_{12} \quad B_1 \quad B_2 \quad B_3 \}^T \tag{3}$$

where σ, ε, B and H stand for stress, strain, magnetic flux density and magnetic field intensity, respectively. It should be noted that the magnetic field intensity is related to the magnetic potential as

$$\mathbf{H} = \nabla\varphi \tag{4}$$

where ∇ is the gradient operator. The generalized strain components are related to the generalized displacement components of Eq. (1) through the following relation

$$\mathbf{X} = \mathbf{D}\mathbf{u} \tag{5}$$

where the 9×4 matrix $\mathbf{D}$ is

$$\mathbf{D} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & 0 \\ 0 & \frac{\partial}{\partial y} & 0 & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 \\ 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} & 0 \\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} & 0 \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 & 0 \\ 0 & 0 & 0 & -\frac{\partial}{\partial x} \\ 0 & 0 & 0 & -\frac{\partial}{\partial y} \\ 0 & 0 & 0 & -\frac{\partial}{\partial z} \end{bmatrix} \tag{6}$$

The linear coupled constitutive relations for piezomagnetic materials can be written in index notation as

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} - e_{kij}H_k \tag{7}$$

$$B_i = e_{ikl}\varepsilon_{kl} + \chi_{ik}H_k \tag{8}$$

where e_{kij} and χ_{ik} are the magnetostrictive coupling constants and magnetic permeability, respectively, and the repeated indices i,j and k count for summation. With the definition of generalized stress and strain vectors (Eqs. (2) and (3)), the constitutive relations can be written in compact form as

$$\mathbf{Y} = \mathbf{R}\mathbf{X} \tag{9}$$

where the 9×9 matrix $\mathbf{R}$ is

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_{11} & \mathbf{R}_{12} \\ \mathbf{R}_{21} & \mathbf{R}_{22} \end{bmatrix} \tag{10}$$

with the submatrices defined as

$$\mathbf{R}_{11} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \tag{11}$$

$$\mathbf{R}_{21} = \mathbf{R}_{12}^T = \begin{bmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & 0 & 0 & e_{15} \\ e_{13} & e_{13} & e_{33} & 0 & 0 & 0 \end{bmatrix} \tag{12}$$

$$\mathbf{R}_{22} = \begin{bmatrix} \chi_{11} & 0 & 0 \\ 0 & \chi_{11} & 0 \\ 0 & 0 & \chi_{33} \end{bmatrix} \tag{13}$$

For homogeneous and orthotropic piezomagnetic materials. The principle of virtual displacement in the absence of inertial works

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