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Finite element modeling of magnetoelectric laminate composites in considering nonlinear and load effects for energy harvesting

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ABSTRACT

This paper presents the finite element analysis of a magnetoelectric energy harvester using a laminate composite constituted of laminated piezoelectric and magnetostrictive layers. In this study, both the nonlinear characteristics of the material and the dependency on the load impedance are considered. The multiphysics problem involving different physics equations is solved through a strongly coupled model. The nonlinear magnetostrictive behavior is considered using the Newton–Raphson method for various magnetic biases. The electrical circuit equation is incorporated in the finite element equations for the analysis load effect. The obtained results show a good concordance with the measurements and with those obtained by other analytical methods.

1. Introduction

In the last decade, the multiple-phase magnetoelectric (ME) composite materials composed of laminated piezoelectric and magnetostrictive layers have received intense interests from many researchers in various scientific domains. Indeed, their property to exhibit, under a simultaneously applied external dc bias H_{dc} field and ac field H_{ac}, a high output voltage magnetic sensitivity is very practical for modern potential applications such as magnetic field sensors, gyrators, variable inductances or energy transducers [1–3]. Although early studies have started in the years 1970–1980 with notably the discovery of Terfenol-D (Tb1-xDyxFe2), it was not until the early 2000s to see their interest arise with the emergence of new magnetostrictive composite materials such as Metglas, FeGa (Galfenol), TbFeCo (Terfecohan), $NiZnFe_2O_4$ or FeCuNbSiB and piezoelectric materials such as PMN-PT (Pb(Mg, Nb)O_3–$PbTiO_3$), PZT-4/5/8 (Pb(Zr, Ti)O_3), BTO ($BaTiO_3$) or $NiFe_2O_4$ (NFO). The parameter of importance to predict the performance of a ME composite material is the magnetoelectric field or voltage coefficient defined as $\alpha_E = \delta E/\delta H$ or $\alpha_V = \delta V/\delta H$, where δE, δV are dynamic electric field and dynamic voltage, respectively, when an ac magnetic δH is applied. Employing a homogenous approach for bilayer composite, Harshe et al. [4] proposed a 2D longitudinal (L) α_E for low-frequency depending on field orientations, boundary conditions and material parameters (nature, number, and volume fraction of the layer thicknesses). These expressions have been confirmed in non-linear case by Srinivasan et al. [5] and were generalized in dynamic regime and enriched by Bichurin et al. [6,7] in including transverse modes (T) and a coefficient factor to take account the imperfect interface coupling. Dong et al have proposed 1D expressions [8–10] of the α_V for trilayer laminate composites Terfenol-D/PZT/Terfenol-D in using an equivalent circuit approach under resonance drive according to different transversal (T) or longitudinal (L) magnetization–polarization modes (T–T, T–L, L–T, L–L). The works of Dong et al. are revealed that the mode L–T (resp. L–L) is approximately five times higher than the mode T–T (resp. T–L) for Terfenol-D/PZT laminate composites. It is interesting to note that the Dong's model α_V can be established in transposing the 2D models of Harsh, Bichurin in 1D. Recently Dongs models have been enriched in adding a mechanical quality factor Qmech [11,12] and newly they have been adjusted to integrate the effective magnetic field in constitutive equations, the nonlinear magnetostrictive effect due to piezomagnetic coefficient d_{33m}, [13] and the non-uniform magnetic field from the permeability influence [14,15]. Despite these recent adjusting, all models do not include the global nonlinearity of each piezomagnetic coefficient and do not take account the real mechanical impact when a resin layer (like Epoxy) is used to stuck the magnetrostrictive and piezoelectric layers or the mechanical damping in harmonic case. They do not take account neither the electrical impact when the structure is loaded by electrodes or by an electrical impedance. Moreover they are not necessarily adapted to study specific structures incorporating different polarization and magnetization modes (L–T + T–T for example) or thin layer structures exploiting ferromagnetic alloy having an extremely high-permeability to achieved better ME properties [16,17]. Thus, the use of rigorous numerical modeling such as the Finite Element Method (FEM) is essential for the design and

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optimization of devices based on magnetoelectric laminate composites. Moreover, the simulation of the mechanical-magneto-electric field distributions allows deeper understanding of the physical phenomena and is helpful for design optimization.

In the context of energy harvesting application, this paper proposes a 2D finite element model to investigate the performance of a magnetic–electric energy transducer using conventional ME trilayer laminate composite. The nonlinearity of magnetic and piezomagnetic coefficient as well as the load effect representing the electronic circuit that collect and store the energy are considered. The paper is organized as follows. Firstly, the general governing equations and the constitutive laws as well as the finite element formulation with the applied boundary conditions are presented. Secondly the static FEM problem is solved in considering the nonlinear behavior of both magnetic and magnetostrictive materials for various magnetic biases. This allows determining the incremental magnetic and piezomagnetic properties for small signal analysis. Thirdly, the harmonic problem is performed in considering a small signal ac field, H_{ac} around a polarization point of the static case. A harmonic mechanical damping is added with Rayleighs coefficients. To verify the influence of volume fraction, a comparison to Dongs analytical model is done. Fourthly, the load effect between the electrodes is taking into account in adding an electrical equation in the harmonic problem. The simulation results are validated in comparison with experimental results available in the literature. Finally the performances of ME composite are studied according to the estimation of the output power in function of the externally applied dc magnetic bias field, the frequency work and the load value.

2. Physics equations and finite element discretization

2.1. General constitutive laws

Fig. 1 shows the configuration of the trilayer laminate composite Terfernol-D/PZT-5A/Terfernol-D (with the local and global coordinates) proposed to realize an energy transducer. The 2D FEM formulation of this composite is based on the thermodynamical approach presented in [18–23] that combine the mechanical equilibrium equation and the magnetostatic and electrostatic equations, respectively given by (1) and (5), (6) with the electro-magneto-mechanical constitutive equations given in (6).

$$div\mathbf{T} + \mathbf{f} = \rho_m \frac{\partial \mathbf{u}}{\partial t^2} \tag{1}$$

where $\mathbf{T}$ is the mechanical stress tensor, $\mathbf{u}$ the mechanical displacement, $\mathbf{f}$ the externally applied volume force, ρ_m the mass density of the medium.

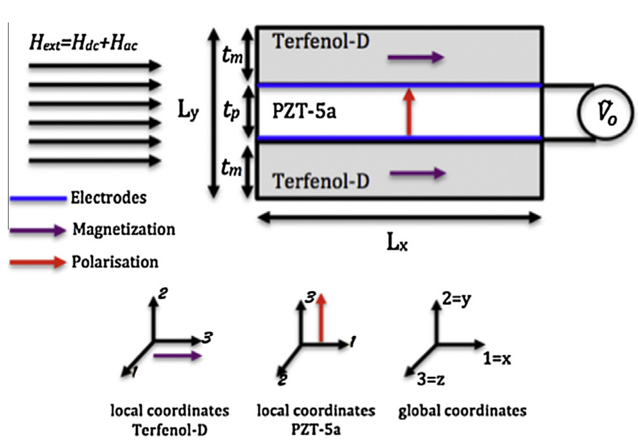

Fig. 1. Trilayer laminate composite in L–T mode.

In considering small mechanical deformation, the mechanical displacement u and the mechanical strain $\mathbf{S}$ is related to the cross-section defined by the global coordinate directions 1 and 2:

$$\mathbf{S} = \hat{\nabla}\mathbf{u} \tag{2}$$

where $\hat{\nabla}$ is a gradient operator define as :

$$\mathbf{S} = \frac{1}{2}(grad\mathbf{u} + grad^T\mathbf{u}) \tag{3}$$

In our 2D problem, we consider the plane stress condition which satisfies the following properties:

$$T_{33} = T_{13} = T_{23} = 0 \tag{4a}$$

$$S_{13} = S_{23} = 0, S_{33} = \frac{\upsilon}{E}(T_{11} + T_{22}) \tag{4b}$$

where E and υ are the Young's module and the Poisson ratio, respectively. As shown in Fig. 1, the directions 1, 2, 3 represent the global Cartesian coordinates x, y, z.

Magnetostatic equations:

$$\begin{cases} curl(\mathbf{H}) = \mathbf{J} \\ div(\mathbf{B}) = 0 \end{cases} \tag{5}$$

where $\mathbf{H}$ the magnetic field, $\mathbf{B}$ the magnetic induction and $\mathbf{J}$ the current density.

Electrostatic equations:

$$\begin{cases} curl(\mathbf{E}) = 0 \\ div(\mathbf{B}) = \rho \end{cases} \tag{6}$$

where $\mathbf{E}$ is the electric field, $\mathbf{D}$ the displacement field and ρ the volume density of the free electric charge.

The magnetic induction $\mathbf{B}$ and the electric field $\mathbf{E}$ are considered in the cross-section defined by the global coordinate directions 1 and 2. The magnetic induction $\mathbf{B}$ can be expressed as the curl of the magnetic vector potential $\mathbf{a}$. In 2D only the component a_3 of $\mathbf{a}$ subsists and it is independent of the direction 3. Using the potential variables, the electric field and the magnetic induction become:

$$\begin{cases} \mathbf{E} = -grad(V) \\ \mathbf{B} = r^* grad(a_3) \end{cases} \tag{7}$$

with r^* a rotation matrix in Cartesian coordinates:

$$r^* = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \tag{8}$$

The electro–magneto-mechanical constitutive laws for the composite material are the combination between the electro-mechanical and the magneto-mechanical constitutive laws:

$$\begin{aligned} \mathbf{D} &= \epsilon\mathbf{E} - \mathbb{e}\mathbf{S} \\ \mathbf{H} &= \mathbb{v}\mathbf{B} - \mathbb{h}\mathbf{S} \\ \mathbf{T} &= \mathbb{c}\mathbf{S} - \mathbb{e}^t\mathbf{E} - \mathbb{h}^t\mathbf{B} \end{aligned} \tag{9}$$

where ϵ is the permittivity matrix, $\mathbb{e}$ is the piezoelectric coefficients matrix, $\mathbb{v}$ the reluctivity matrix, $\mathbb{h} = \mathbb{q}v$, with $\mathbb{q}$ the piezomagnetic coefficients matrix and $\mathbb{c}$ the elasticity matrix.

In considering the applied magnetic field along 1-direction in respect to global Cartesian coordinates defined in Fig. 1, the tensor representations in L–T mode of the magnetostrictive and piezoelectric layers in 2D are, respectively: Magnetostrictive material in L magnetization:

$$\mathbb{q}^t = \begin{bmatrix} q_{33} & 0 \\ q_{31} & 0 \\ 0 & q_{15} \end{bmatrix}, \mathbb{v} = \begin{bmatrix} v_{33}^S & 0 \\ 0 & v_{11}^S \end{bmatrix}, \mathbb{h}^t = \begin{bmatrix} q_{33}v_{33}^S & 0 \\ q_{31}v_{33}^S & 0 \\ 0 & q_{15}v_{11}^S \end{bmatrix}, \tag{10a}$$