OPTIMIZATION OF MAGNETOELECTRIC EFFECT IN MULTIFERROIC COMPOSITES

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Summary We propose a formulation to optimize the effective magnetoelectric voltage coefficient of fibrous/particulate composites made of piezoelectric and piezomagnetic phases. The optimization of magnetoelectricity is with respect to the crystallographic orientations and the volume fractions for the two materials. We show that the coupling constants can be enhanced many-fold at the optimal orientation compared to those at normal orientation. The predictions are in good agreement with the finite element analysis.

INTRODUCTION

This work is concerned with the magnetoelectric (ME) effect of a fibrous/particulate piezoelectric-piezomagnetic composite. ME materials, which simultaneously show two or more types of ferroelectric, magnetic, or elastic orderings, have been the focus of research due to the varieties of their microstructural phenomena and macroscopic properties. These make them promising for a wide range of applications, such as magnetic field sensors, electrically controlled microwave phase shifters, four-state memories, etc. However, this coupling is weak in single-phase materials, and is often observed only at a very low temperatures. Composites materials, on the other hand, offer an alternative option for improvement of the ME coupling. This much stronger ME effect could be realized in a composite made of piezoelectric and piezomagnetic phases using product properties: an applied electric field creates strain in the piezoelectric material which in turn creates a strain in the piezomagnetic material, resulting in a magnetization [1],[2].

In the work of Kuo et al. [3], they proposed a simple framework to optimize the effective magnetoelectric response of a piezoelectric-magnetostrictive bilayer. The essence of the concept is that the induced electric field in the piezoelectric phase could be increased if the orientation and volume fraction of the piezoelectric layer can be carefully chosen. Motivated by this advance, in this paper we optimize the effective ME voltage coefficient of a multiferroic fibrous/particulate composite without any assumptions on the symmetry of the underlying materials and without any assumptions on the crystallographic orientations of the materials.

MICROMECHANICAL MODEL

Consider a perfectly bonded magnetoelectric composite made of piezoelectric and piezomagetic materials. The constitutive laws, generalized strain-displacement and equilibrium equations in a Cartesian frame with the x_3 direction normal to the plane can be described by the following general relations

$$\Sigma_{iJ} = L_{iJMn} Z_{Mn}, \quad Z_{Mn} = U_{M,n}, \quad \Sigma_{iJ,i} = 0, \tag{1}$$

where

$$\Sigma_{iJ} = \begin{cases} \sigma_{ij}, & J = 1,2,3, \\ D_i, & J = 4, \\ B_i, & J = 5, \end{cases} \quad Z_{Mn} = \begin{cases} \varepsilon_{mn}, & M = 1,2,3, \\ -E_n, & M = 4, \\ -H_n, & M = 5, \end{cases} \quad U_M = \begin{cases} u_m, & M = 1,2,3, \\ \phi, & M = 4, \\ \psi, & M = 5. \end{cases} \tag{2}$$

The magnetoelectroelastic moduli are expressed as

$$L_{iJMn} = \begin{cases} C_{ijmn}, \quad J,M = 1,2,3; & e_{imn}, \quad J = 4, M = 1,2,3; & q_{imn}, \quad J = 5, M = 1,2,3; \\ e_{ijn}, \quad M = 4, J = 1,2,3; & -\kappa_{in}, \quad J = 4, M = 4; & -\lambda_{in}, \quad J = 5, M = 4; \\ q_{ijn}, \quad M = 5, J = 1,2,3; & -\lambda_{in}, \quad J = 4, M = 5; & -\mu_{in}, \quad J = 5, M = 5. \end{cases} \tag{3}$$

Here σ_{ij} and ε_{ij} are the stress and strain; D_i and E_i are the electric displacement and electric fields; B_i and H_i are the magnetic flux and magnetic fields; u_i, ϕ, and ψ are the displacement, electric and magnetic potentials; C_{ijkl} is the elastic stiffness, e_{ijk} is the piezoelectric moduli, q_{ijk} is the piezomagnetic moduli, κ_{ij} is the permittivity, μ_{ij} is the permeability and λ_{ij} is the magnetoelectric coefficient.

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The equations above refer the material properties to the global composite frame. However, the material properties are commonly described in the crystallographic frame and we need to transform them to the composite frame. This is given in terms of three Euler angles (α,β,γ). For the change of frame, the material parameters then follow the tensor transformation rules for second-, third- and fourth- order tensors.

Further, we are interested in the effective behaviour for a situation where we have a large number of inclusions. The effective moduli can be determined for a two-phase composite as

$$L^*_{iJAb} = L^{(m)}_{iJAb} + f\left(L^{(i)}_{iJMn} + L^{(m)}_{iJMn}\right) A_{MnAb}. \qquad (4)$$

Here f is the volume fraction of the inclusion and the superscripts m and i denote the matrix and inclusion, respectively. The concentration tensor A_{MnAb} can be determined by the Mori-Tanaka's approach as

$$A_{MnAb} = A^{\mathrm{dil}}_{MnAb}\left[(1-f)\, I_{JiAb} + f A^{\mathrm{dil}}_{JiAb}\right]^{-1}, \; A^{\mathrm{dil}}_{MnAb} = \left[I_{MnAb} + S_{MnLk} L^{(m),-1}_{LkiJ}\left(L^{(i)}_{iJAb} - L^{(m)}_{iJAb}\right)\right]^{-1}, \qquad (5)$$

where S_{MnIk} is the magnetoelectroelastic Eshelby tensor, which can be calculated through the numerical method [4].

NUMERICAL RESULTS AND OPTIMIZATION

As a numerical example, we choose the widely used $BaTiO_3$ ceramic as the piezoelectric phase, while we choose $CoFe_2O_4$ as the piezomagnetic phase. Both of them are with 6mm symmetry. We seek to optimize the ME voltage coefficient $\alpha^*_{E,ij} = \lambda^*_{ij}/\kappa^*_{ij}$ with respect to the crystallographic orientation of the materials. The following figures show the ME voltage coefficient $\alpha^*_{E,11}$ with respect to the crystallographic orientation of CFO fibers in a BTO matrix. It happens to be optimal when the poling direction of piezoelectric phase coincides with the magnetic axis of the piezomagnetic phase. We observe that the maximum of -2.4823V/cmOe occurs at Euler angles $(\alpha,\beta,\gamma) = (\alpha, 90^0, 90^0)$, where α is arbitrary. Significantly, the optimized value is almost *one hundred and one* times higher than -0.0244 V/cmOe, which is the value of the normal cut where the c axis of the CFO and BTO is along the fiber axis.

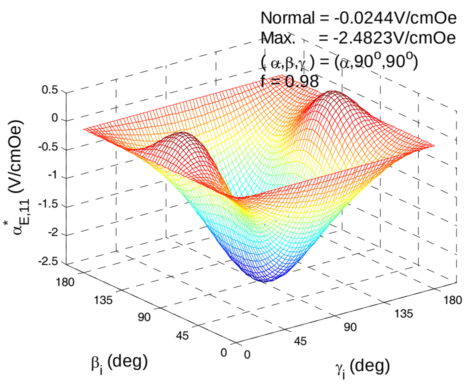

Figure 1(a)

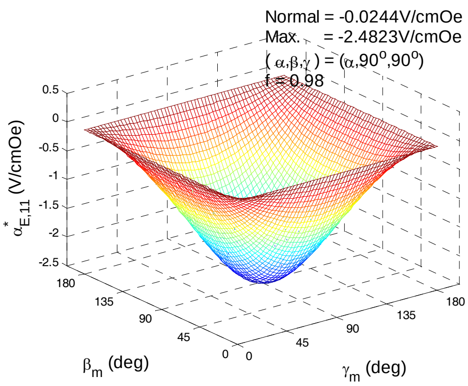

Figure 1(b)

CONCLUSIONS

In summary, we have proposed a theoretical framework to compute the effective magnetoelectric response of piezoelecitric-piezomagnetic fibrous/particulate composites. We have used it to show that, for anisotropic materials as in single crystals, the optimal ME response is obtained for non-trivial orientations. The dependence of the magnetoelectric voltage coefficient with respect to the inclusion volume fraction was also determined when both phases poled along the optimized directions. Finally, the results are compared to finite element analysis and show good agreement.

References

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