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Optimal configuration of magnetoelectric composites under various mechanical boundary conditions

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A B S T R A C T

The magnetoelectric (ME) coupling effect of magneto-electro-elastic composites is generated by the product property of magnetostriction and piezoelectricity via elastic deformation. Since mechanical deformation and interlayer stress interaction directly influence the extrinsic ME effect, composite configurations between magnetostrictive and piezoelectric materials critically influence the energy conversion efficiency of ME composites, as also do the imposed mechanical boundary conditions (BCs). Here, we aim to identify the material configurations in the composites under different BCs, in order to maximize their ME effects. The problem is set up as optimization problems solved by a genetic algorithm while the required multiphysics simulation is performed by finite element analysis. For five major mechanical BCs, we determined optimal ME laminate layer configurations and compared their magnetoelectric conversion efficiency with that by typical sandwiched laminate composites. We also investigated how much the efficiency can be increased if arbitrary-arranged material distributions are allowed. The present study is expected to provide useful guidelines for the design of ME composites, and offers the possibility of finding new ME composite structures.

1. Introduction

Magnetoelectric (ME) effects, defined as induced electric polarization under a magnetic field or a magnetization under an electric field, have promising device applications such as magnetic field sensors, transformers, energy harvesters, microwave devices, and biomedical applications [1–5]. An artificial combination of magnetostrictive and piezoelectric materials produces the strong ME effects observed in multiferroic composites [6]. If the composites are under external magnetic fields, their mechanical deformation induced by magnetostriction is mediated by mechanical stress, and thus electric fields are induced in the composites due to piezoelectricity. That is, this ME effect in such composites is an extrinsic effect resulting from the product of magnetostrictive and piezoelectric effects through mechanical coupling.

Many investigations have been conducted to predict the multiphysics behavior of ME composites and enhance the magnetoelectric effect via mechanical boundary condition, composite shape and size-dependent material properties. Shi et al. [7] considered ME particulate composites to investigate the influence of mechanical BCs and microstructural features on their magnetoelectric behavior. Pan and Wang [8] proposed a three-dimensional finite element method to examine the effects of geometric size and mechanical BCs for ME bilayer plates. Pan et al. [9] investigated size-dependent material properties to enhance the ME effect in a multiferroic fibrous nanocomposite and Wang et al. [10] showed that the curvature of a ME composite cylinder can substantially affect the ME effect. Nguyen et al. [11] also investigated how mechanical BCs affect the sensitivity of ME sensors. Sun and Kim [12,13] previously proposed a method to find optimal ME composite layouts based on the numerical implementation of topology optimization, and also showed the effectiveness of 1–3 type nanostructured multiferroic composites. Recently, Loja et al. [14] optimized magneto-electro-elastic structures using differential evolution of functionally graded materials, while Huang et al. [15] investigated the free edge stress of laminate composites by using the stress function based equivalent single layer theory. Although

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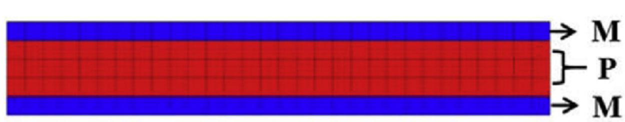
various methods have been proposed to study the multiphysics behaviors of ME composites and the effects of mechanical BCs, studies on the design of ME composites considering the effects of mechanical BCs have, as yet, not been fully explored.

Since the ME coupling in composites is directly produced by the mechanical deformation and interlayer stress interaction, it may be asked which composite structures and mechanical BCs will be effective for strong ME coupling. For example, we can consider the influence of mechanical BCs on the performance of ME coupling as shown in Fig. 1. The composite sample in Fig. 1 has a typical parallel sandwiched layer sequence (M/P/M) [6], which is composed of the piezomagnetic phase (denoted by ‘M’) in the top and bottom layers, and the piezoelectric phase (denoted by ‘P’) in the middle layer. In the sample, five different mechanical BCs are considered, and the ME coupling factor (k_{ME}^2) that indicates the efficiency of energy conversion is calculated for each BC (the detailed modeling and calculation procedure will be addressed in Sec. 2). It is clear that the composite has different values of ME coupling factor according to the imposed mechanical BCs. Based on this observation, it can be recognized that the mechanical BCs strongly influence the ME coupling. Therefore, different optimal configurations of ME composites for different mechanical BCs will indeed exist.

In this study, we propose an effective design method, and provide the optimal layer configurations of ME laminate composites under various mechanical BCs. Furthermore, the optimal distribution in the ME composites that has the greatest ME coupling is also investigated. This study presents useful guidelines for the design of ME composites, and physically interprets the effects of mechanical BCs on the ME coupling.

2. Problem definition and design formulation

For the finite element analysis of ME composites, a fully-coupled magneto-electro-elastic constitutive relation [6] is considered:



Mechanical boundary conditions	ME coupling factor (k_{ME}^2)
BC1: Simply-supported	3.91e-4
BC2: Left side-fixed	4.01e-4
BC3: Left&right side-fixed	5.88e-7
BC4: Bottom-fixed	3.94e-4
BC5: Top&bottom-fixed	1.26e-4

Fig. 1. A ME composite with typical sandwiched layer sequence and its magneto-electric coupling factor k_{ME}^2 under different mechanical boundary conditions (M: piezomagnetic layer (blue color) and P: piezoelectric layer (red color)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$\begin{aligned} T_k &= C_{kl}S_l - e_{jk}E_j - q_{jk}H_j \\ D_i &= e_{il}S_l + \varepsilon_{ij}E_j + m_{ij}H_j \\ B_i &= q_{il}S_l + m_{ij}E_j + \mu_{ij}H_j \end{aligned} \tag{1}$$

where T_k, D_i, and B_i denote the stress, electric displacement, and magnetic induction, respectively; C_{kl}, ε_{ij}, and μ_{ij} are the elastic, dielectric, and magnetic permeability coefficients respectively; e_{jk}, q_{jk}, and m_{ij} are the piezoelectric, piezomagnetic, and magneto-electric coefficient, respectively; S_l, E_j, and H_j denote the strain, electric field, and magnetic field. Here $k, l = 1, \ldots, 6$ and $i, j = 1, \ldots, 3$. The strain, electric field, and magnetic field can be written in terms of the displacement u, electric scalar potential ϕ, and magnetic scalar potential ψ, respectively, as:

$$S_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}), \quad E_i = -\phi_{,i}, \quad H_i = -\psi_{,i} \tag{2}$$

Under a time-invariant condition, the equations of equilibrium including the body force f_j^S, electric charge density f^E, and magnetic charge density f^M are given by

$$T_{ij,j} + f_j^S = 0, \quad D_{j,j} - f^E = 0, \quad B_{j,j} - f^M = 0 \tag{3}$$

Employing the standard weak formulation, the following system equations in the vector/matrix form can be obtained [16]:

$$\begin{aligned} &[K_{uu}]\{u\} + [K_{u\phi}]\{\phi\} + \left[K_{u\psi}\right]\{\psi\} = 0 \\ &[K_{u\phi}]^t\{u\} - [K_{\phi\phi}]\{\phi\} - \left[K_{\phi\psi}\right]\{\psi\} = 0 \\ &\left[K_{u\psi}\right]^t\{u\} - \left[K_{\phi\psi}\right]\{\phi\} - \left[K_{\psi\psi}\right]\{\psi\} = \left\{F_\psi\right\} \end{aligned} \tag{4}$$

where F_ψ is the constant nodal force due to an applied magnetic force and the superscript t denotes the transpose. The system matrices $[K_{uu}]$, $[K_{u\phi}]$ etc. in Eq. (4) are assembled by using the element-level stiffness matrices as

$$\begin{aligned} &[K_{uu}] = \sum_{e=1}^{n_d}\int_{V_e}[B_u]^t\left[\overline{C}\right][B_u]dV, \ [K_{u\phi}] = \sum_{e=1}^{n_d}\int_{V_e}[B_u]^t[\overline{e}]\left[B_\phi\right]dV, \\ &\left[K_{u\psi}\right] = \sum_{e=1}^{n_d}\int_{V_e}[B_u]^t[\overline{q}]\left[B_\psi\right]dV, \ \left[K_{\phi\phi}\right] = \sum_{e=1}^{n_d}\int_{V_e}\left[B_\phi\right]^t[\overline{\varepsilon}]\left[B_\phi\right]dV, \\ &\left[K_{\psi\psi}\right] = \sum_{e=1}^{n_d}\int_{V_e}\left[B_\psi\right]^t[\overline{\mu}]\left[B_\psi\right]dV, \ \left[K_{\phi\psi}\right] = \sum_{e=1}^{n_d}\int_{V_e}\left[B_\phi\right]^t[\overline{m}]\left[B_\psi\right]dV \end{aligned} \tag{5}$$

where n_d is the number of the discretizing finite elements and V_e denotes the element volume. The matrices $[B_u]$, $[B_\phi]$, and $[B_\phi]$ are shape function derivative matrices for strain-displacement, electric field-electric potential, and magnetic field-magnetic potential relations, respectively. In this investigation, the four-points Gauss quadrature is used to evaluate integrals given in Eq. (5). Each element is associated with four degrees of freedom per node: displacements in the horizontal direction (u_x) and the vertical direction (u_z), electric potential (ϕ), and magnetic potential (ψ). In Eq. (5), $[\overline{C}]$, $[\overline{e}]$, $[\overline{q}]$, $[\overline{\varepsilon}]$, $[\overline{\mu}]$ and $[\overline{m}]$ are the reduced elastic, piezoelectric, piezomagnetic, dielectric, magnetic permeability and magneto-electric coefficient matrices, respectively. Under the two-dimensional plane stress condition, the constitutive relation can be written as