



Nomograph method for predicting magnetoelectric coupling



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ABSTRACT

Magnetoelectric (ME) composites are known to enable the achievement of ME voltage coefficients many orders of magnitude larger than previously reported values for single phase materials. The advancements have opened up many possibilities in applications of sensors, transformers, and microwave devices. We presented here a new quick test of ME composites using nomographs and showed its use in applications where an approximate answer is appropriate and useful. To draw the graphs for ME voltage coefficients, we derived approximate expressions in explicit form for magnetically induced ME effect for different operational modes and laminate composite configurations including symmetrical and asymmetrical structures.

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1. Introduction

Magnetoelectric (ME) interactions in magnetostrictive-piezoelectric multiferroic structures are intensively studied in recent years for their applications in magnetic field sensors, transducers and energy harvesters [1–11]. ME interaction exhibits itself as inducing the electric field E across the structure in an applied ac magnetic field H and arises as a product property of magnetostriction in magnetic layer and piezoelectricity in piezoelectric layer. ME coupling strength is characterized by the ME voltage coefficient $\alpha_E = E/H$. It is the practice to obtain the estimates of magnetoelectric (ME) voltage coefficients by solving the set of analytic equations. However, it's a difficult problem. Estimates of ME coupling strength can be obtained by using the numerical graphical database presented recently for several compositions for low-frequency [12] and magnetic resonance [13] regions. A model was recently proposed to optimize the design of magnetoelectric composites for low frequency sensor application [14]. The influence of the properties of piezoelectric and piezomagnetic materials, volume fraction, and magnetic field orientation on the induced voltage were evaluated. We suggest using the nomograph method that facilitates the efficient estimates of ME coefficients from given parameters of composite components. To draw the graphs for ME voltage coefficients, we obtained approximate expressions for magnetically induced ME effect in explicit form for different operational modes and laminate composite configurations including symmetrical and asymmetrical (bilayer) structures.

Results from a nomogram can be obtained very quickly and reliably. In addition, nomograms are known to naturally incorporate the domain knowledge into their design. It should be noted that the nomogram's accuracy is limited by the precision of reproducing the physical parameters. Most nomograms are used in applications where an approximate answer is appropriate and useful. On the other hand, a nomogram may be used to verify an estimate obtained from another exact calculation method. Thus a nomogram is designed to perform a specific calculation.

In ME composites, the induced polarization P is related to the magnetic field H by the expression, $P = \alpha H$, where α is the second rank ME-susceptibility tensor. The (static) effect was first observed in antiferromagnetic Cr_2O_3 . The ME effect was first observed in single crystals [15] of single phase materials a little more 50 years ago, and subsequently in polycrystalline single phase materials. The largest value of a ME for a single phase material is that for Cr_2O_3 crystals [16], where $a_{\text{ME}} = 20 \text{ mV/cm-Oe}$. In last few years, strong magneto-elastic and elasto-electric coupling has been achieved through optimization of material properties and proper design of transducer structures. Lead zirconate titanate (PZT)-ferri-rite, PZT-Terfenol-D and PZT-Metglas are the most studied composites to-date. One of largest ME voltage coefficient of 500 Vcm⁻¹ Oe⁻¹ was reported recently for a high permeability magnetostrictive piezofiber laminate [17]. These developments have led to ME structures that provide high sensitivity over a varying range of frequency and DC bias fields enabling the possibility of practical applications [18].

In order to obtain high ME couplings, a layered structure must be insulating, in order that it can be poled to align the electric dipole moments. The poling procedure involved heating the sample to 420 K, and re-cooling to 300 K under an electric field of

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$E=20\text{--}50\text{ kV/cm}$. The samples are then placed between the pole pieces of an electromagnet (0–18 kOe) used for applying a magnetic bias field H . The required AC magnetic field $\delta H=1\text{ Oe}$ at 10 Hz to 100 kHz applied parallel to H is generated with a pair of Helmholtz coils. The AC electric field δE perpendicular to the sample plane is estimated from the measured voltage δV . The ME coefficient a_E is measured for three conditions: (1) transverse or $a_{E,31}$ for H and δH parallel to each other and to the disk plane (1,2) and perpendicular to δE (direction-3), (2) longitudinal or $a_{E,33}$ for all the three fields parallel to each other and perpendicular to sample plane and (3) in-plane $a_{E,11}$ for all the three fields parallel to each other and parallel to sample plane. An ME phenomenon of fundamental and technological interests is an enhancement in the coupling, when the electrical or magnetic sub-system undergoes resonance: i.e., electromechanical resonance (EMR) for PZT and ferromagnetic resonance (FMR) for the ferrite. As the dynamic magnetostriction is responsible for the electromagnetic coupling, EMR leads to significant increasing in the ME voltage coefficients. In case of resonance ME effects at FMR an electric field E produces a mechanical deformation in the piezoelectric phase, resulting in a shift in the resonance field for the ferromagnet. Besides, the peak ME voltage coefficient occurs at the merging point of acoustic resonance and FMR frequencies, i.e., at the magnetoacoustic resonance [19]. Then we discuss the estimations of ME effects in the different frequency ranges.

2. Low-frequency magnetoelectric coupling

We consider more often used in practice the transverse fields' orientation that corresponds to E and δE being applied along the X_3 direction, and H and δH along the X_1 direction (in the sample plane). The expression for the transverse ME voltage coefficient is [12]

$$\alpha_{E,31} = \frac{E_3}{H_1} = \frac{-V(1-V)(^mq_{11} + ^mq_{21})^pd_{31}}{p_{\epsilon 33}(^ms_{12} + ^ms_{11})v + p_{\epsilon 33}(^ps_{11} + ^ps_{12})(1-V) - 2^pd_{31}^2(1-V)}. \quad (1)$$

For symmetric trilayer structures, using the 1-D approximations, the expression for transverse ME voltage coefficient takes on the form:

$$\alpha_{E,31} = \frac{V(1-V)x}{\epsilon_0[^ms_{11}V + ^ps_{11}(1-V)]} \quad (2)$$

where $x = ^mq_{11}^pd_{31}/\epsilon_0$, $^ps_{11}$, $^ms_{11}$, $^pd_{31}$ and $^mq_{11}$ are compliance, and piezoelectric and piezomagnetic coupling coefficients for piezoelectric and piezomagnetic layers, respectively, $^p\epsilon_{33}$ is the permittivity of piezoelectric layer. In Eq. (2), the electromechanical coupling factor is assumed to satisfy the condition: $^pK_{31}^2 = ^pd_{31}^2/[^ps_{11}^p\epsilon_{33}] < 1$.

For convenience we suggest using the nomograph method to estimate the ME voltage coefficients from given parameters of composite components.

Figs. 1 and 2 present the ME voltage coefficients as a function of piezoelectric volume fraction. As an example, estimates are obtained for transverse fields' orientation (in-plane ac and dc magnetic fields and out-of-plane ac electric field and poling direction). However, ME voltage coefficients for longitudinal (out-of-plane electric and magnetic fields) and in-plane longitudinal fields orientations can be easily obtained by replacing the piezomagnetic coefficient q_{11} in Eq. (2) with q_{31} for longitudinal and replacing the piezoelectric coefficient d_{31} in Eq. (2) with d_{33} for in-plane longitudinal fields' orientation. The theory predicts the highest ME coupling for in-plane fields.

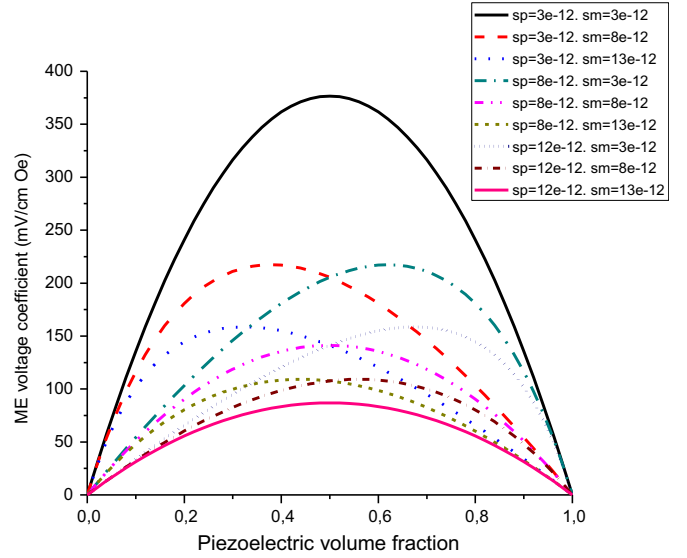


Fig. 1. Piezoelectric volume fraction dependence of transverse ME voltage coefficient for symmetric layered structure of magnetoelectric and piezoelectric components with different compliances for $x=0.5 \cdot 10^{-22}$ (in SI units).

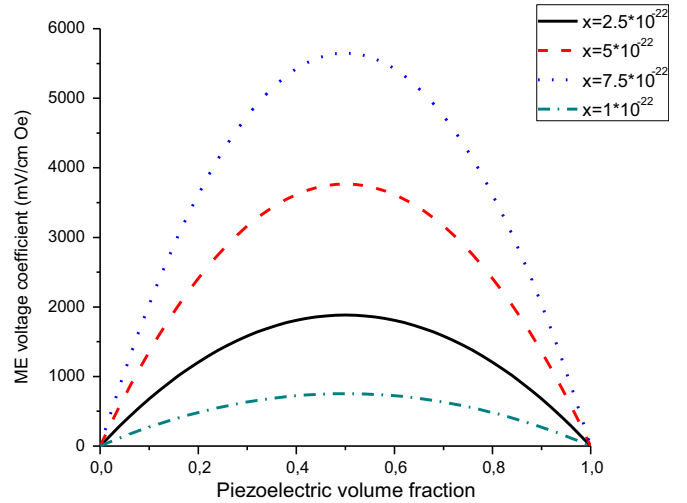


Fig. 2. Piezoelectric volume fraction dependence of transverse ME voltage coefficient for symmetric layered structure of magnetoelectric and piezoelectric components for different x -values.

For the bilayer structure, the ME voltage coefficient should be calculated taking into account the flexural deformations. On the foregoing assumptions, our model enables deriving the explicit expression for ME voltage coefficient:

$$\frac{\delta E_3}{\delta H_1} = \frac{[1^ps_{11} + ^ms_{11}r^3]^mq_{11}^pd_{31}/^p\epsilon_{33}}{^ps_{11}[2^rm_{s11}(2 + 3r + 2r^2) + ^ps_{11}] + ^ms_{11}^2r^4}. \quad (3)$$

where $r = ^pt/^mt$ with pt and mt denoting the thickness of piezoelectric and magnetostrictive layer, correspondingly.

Eq. (3) is written in a simplified form under assumption $^pK_{31}^2 < 1$ similarly to deriving Eq. (2).

Piezoelectric volume dependence of ME voltage coefficient reveals a double maximum that is due to fact that the strain produced by the magnetic component consists of two components: longitudinal and flexural. In the absence of flexural strain the maximum ME coefficient occurs for certain value of volume fraction [12]. Since the flexural strain is of opposite sign relative to

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