MAGNETOELECTRIC RESPONSE OF MAGNETOSTRICTIVE/PIEZOELECTRIC LAMINATE COMPOSITE IN CONSIDERATION OF DEMAGNETIZATION EFFECT AND MAGNETIC LOSS

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Abstract: In this paper, an analytical model is proposed to predict the magnetoelectric (ME) effect of magnetostrictive/piezoelectric laminate composite using equivalent circuit method, in which the shape demagnetization effect and the magnetic loss are both taken into account. The theoretical and experimental results indicate that the ME effect at low frequency depends on the in-plane size owing to the shape demagnetization effect of the magnetostrictive layer, and the ME effect at resonance is related to the in-plane size owing to not only the shape demagnetization effect but also the magnetic loss. Thus, one should optimize the in-plane sizes in order to obtain the maximum ME effect.

Keywords: Magnetoelectric effect, shape demagnetization effect, magnetic loss

INTRODUCTION

Magnetostrictive/piezoelectric laminate composites (MPLCs) were originally intended for use in magnetic field sensors but have recently been used in energy-harvesting [1]. The ME effect of MPLC is realized by the "product property", i.e., in a magnetic field (H), mechanical stresses arise in the magnetostrictive (M) layer due to magnetostriction and are transferred to the piezoelectric (P) layer, where they produce an electric field (E) due to the inverse piezoelectric effect. The ME effect is characterized by the magnetoelectric voltage coefficient. In previous reports [1-2], theoretical analyses of the ME effect have been performed using constitutive equations and equivalent circuit methods. They focused on selecting materials with good performance and optimizing the layer thickness to maximize the ME effect. However, these works paid little attention to the influence of in-plane sizes of the MPLCs on ME effect. In fact, the in-plane sizes, which are relative to the demagnetizing effect and magnetic loss of the magnetostrictive layer, will influence the ME effect. Recently, the demagnetization effect has been considered to predict the ME effect [3-4]. However, the magnetic loss is ignored in these studies, and the theoretical results about the influence of in-plane sizes on ME effect at resonance frequency are not agree with the experimental results. In this paper, an analytical model is proposed to predict the ME effect of magnetostrictive/piezoelectric laminate composites using equivalent circuit method, in which the shape demagnetization effect and the magnetic loss in the magnetostrictive (M) layer are both taken into account.

THEORETICAL ANALYSIS

Demagnetizing Effect in Magnetostrictive Layer

It is well known that the surface divergence of the magnetization vectors gives rise to a magnetic field, usually termed the "demagnetizing filed" [5]. For predicting the influence of demagnetization, the magnetic field inside the magnetostrictive layer can be expressed as

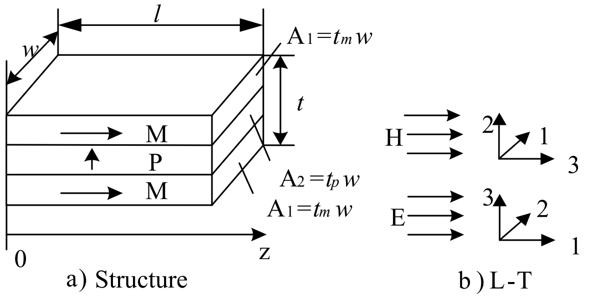
$$\mathbf{H}_{in}(r_i) = \mathbf{H}_{app} + \mathbf{H}_d(r_i) \qquad (1)$$

where, $\mathbf{H}_{in}(r_i)$ is the effective magnetic field with an external magnetic field of $\mathbf{H}_{app}$, $\mathbf{H}_d(r_i) = -\mathbf{N}(r_i)\cdot\mathbf{M}$ is the nonuniform demagnetizing field, $\mathbf{N}(r_i)$ is the diagonal demagnetizing tensor which is a function of sample geometry, $\mathbf{M}$ is the uniform magnetization, $r_i = (x_i, y_i, z_i)$ is the field point location.

From equation (1), the magnetic field inside the magnetostrictive layer $\mathbf{H}_{in}(r_i)$ is altered due to demagnetization [4]. Because the magnetostrictive strain is actually determined by the effective field inside magnetostrictive material, the demagnetizing effect will influence the response of the MPLCs.

Operating Model

As a model, we consider a sample in the form of a plate prepared form a sandwich MPM laminate composite (Fig.1), i.e. the magnetostrictive layers are magnetized along the longitudinal direction (L mode), and the piezoelectric layer is polarized in its thickness direction (T mode). When an external magnetic field (including bias magnetic field and alternating magnetic field) is applied along the longitudinal direction, a strain in magnetostrictive layers will be generated by magnetostrictive effect that is transferred to the bonded piezoelectric layer. Then, the ME voltage is generated by piezoelectric effect.



a) Structure b) L-T

Fig. 1: LT mode of laminate composite.

Assuming that $A = A_1 + A_2 = tw$ is the cross-sectional area of the composite, $n = A_1 / A = t_m / t$ the thickness ratio of the composite, $\rho = \left(\rho_m A_1 + \rho_p A_2\right) / A$ the average density of composite, where, t and w are the thickness and width of laminate composite, respectively, $A_1 = t_m w$ and $A_2 = t_p w$ are the cross-sectional area of the magnetostrictive layer and piezoelectric layer, respectively, ρ_p and ρ_m are the densities of piezoelectric and magnetostrictive material, respectively.

ME Coefficients at Low Frequency

Under LT mode, when demagnetization is considered, the constitute equations of piezomagnetic and piezoelectric can be described as [4]

$$S_{3m,eff} = s_{33}^{H} T_{3m} + d_{33,m} H_{3eff} \tag{2a}$$

$$B_{3eff} = d_{33,m} T_{3m} + \mu_{33} H_{3eff} \tag{2b}$$

$$S_{1p} = s_{11}^{E} T_{1p} + d_{31,p} E_3 \tag{3a}$$

$$D_3 = d_{31} T_{1p} + \varepsilon_{33} E_3 \tag{3b}$$

$$H_{3eff} = H_{3app} - N_d M_3 \tag{4}$$

where, H_{3eff} , H_{3app} , N_d and M_3 are the effective magnetic field inside the magnetostrictive layer, the applied magnetic field , the demagnetizing factor and the magnetization along the longitudinal direction, respectively; B_{3eff} is the effective magnetic flux; $S_{3m,eff}$ and T_{3m} are the longitudinal piezomagnetic strain and stress, respectively; s_{33}^{H} , $d_{33,m}$ and μ_{33} are the longitudinal elastic compliance, the piezomagnetic constant, and the magnetic permeability at constant stress, respectively; D_3 and E_3 are the dielectric displacement and electric field; S_{1p} and T_{1p} are the strain and stress along longitudinal direction in piezoelectric layer; and s_{11}^{E} , $d_{31,p}$, and ε_{33} are the piezoelectric elastic compliance, the piezoelectric coefficient, and the dielectric constant, respectively. In equation (4), for the rectangular magnetostrictive layer used in the analytical model, under the assumption that the magnetization is of uniform, the demagnetizing factor N_d was derived by Joseph and Schlomann [5].

For the MPLC shown in Fig.1, the equivalent circuit considering demagnetizing effect can be given in Fig.2.

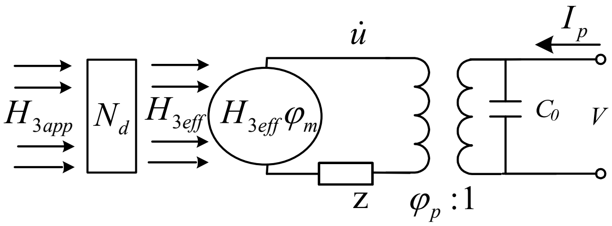


Fig. 2: Magnetoelectricity Equivalent circuit.

In this figure, $\varphi_p = \frac{w d_{31,p}}{s_{11}^{E}}, \varphi_m = \frac{A_1 d_{33,m}}{s_{33}^{H}}, C_0 = \frac{l w \overline{\varepsilon_{33}}}{t_p}$, $Z = -\frac{1}{2} j \rho v A \tan(kl/2)$, where, $\overline{\varepsilon_{33}} = \varepsilon_{33}(1 - k_{31}^2)$, $v^2 = (\frac{n}{s_{33}^{H}} + \frac{1-n}{s_{11}^{E}}) / \rho$, $k = \omega / v$, k_{31} is the electromechanical coupling coefficient of piezoelectric layer.

Applying Ohm's law and impedance conversion method, one obtains

$$\left| \frac{\varphi_p V}{\varphi_m H_{3eff}} \right| = \left| \frac{\dfrac{\varphi_p^2}{j\omega C_0}}{Z + \dfrac{\varphi_p^{2}}{j\omega C_0}} \right| \tag{5}$$

The relationship between $H_{3\mathrm{eff}}$ and $H_{3\mathrm{app}}$ can be expressed as follows [5]

$$H_{3eff} = \frac{H_{3app}}{\left(N_d \left(u_r - 1\right) + 1\right)} \tag{6}$$

where, u_r is the relative permeability of the magnetostrictive layer. Recognizing that the value of tan(kl/2),in the characteristic impedance Z is ~ kl/2 at low frequency [3], and substituting (5) into (6), one obtains the ME voltage coefficient as

$$\alpha_V = \left| \frac{dV}{dH_{3app}} \right| = \frac{n(1-n) t_c d_{33,m} d_{31,p}}{\varepsilon_{33} \left[n(1-k_{31}^2) s_{11}^{E} + (1-n) s_{33}^{H} \right]} \cdot \delta \tag{7}$$

where, $\delta = \frac{1}{N_d(u_r - 1) + 1}$ is related to the demagnetization field. From (7), we can see that, the ME effect at low frequency depends on the in-plane size owing to the shape demagnetization effect.

ME Coefficients at Resonance

In resonance status, the dissipations of magnetic, mechanical and electric sections are introduced to the equivalent circuit, and characterized as resistances, i.e., the magnetic loss R_{mag} of the magnetic section, the mechanical loss R_{mech} of the mechanical section and the electric loss R_e of the electric section. Then the equivalent circuit is given as Fig. k3 [2]. The R_{mag} is caused by various magnetic losses such as hysteresis, eddy current, magnetization relaxation and so on.

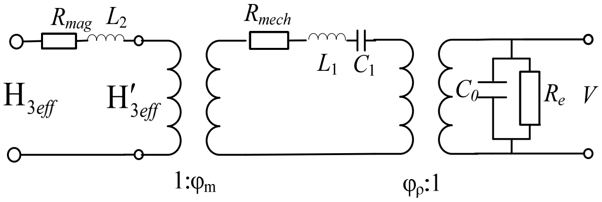


Fig. 3: Equivalent circuit at resonance.

The magnetic field applied to the MPLCs consists of a strong bias DC magnetic field and a small AC magnetic field. Fig.4 is the model of hysteresis loop and definition of several parameters under DC-biased magnetization. ΔB is the value of DC-biased magnetization and B_m is the amplitude of AC magnetization. In Fig.4, a minor-hysteresis-loop is formed around the DC-biased point due to the AC magnetic field. The area surrounded by the loop directly denotes the hysteresis loss, eddy current loss, and so on. It should be noted that the shape and area of the minor-hysteresis-loop changes with the amplitude and frequency of the AC magnetic filed. The magnetic power loss related to the minor-hysteresis-loop in one magnetizing period can be expressed as follows [6]

$$W_{loss} = W\left(B_m^n, \int_{Tmi} \left(\frac{dB}{dt} \right)^2 dt \right) \tag{8a}$$

$$\int_{Tmi} \left(\frac{dB}{dt} \right)^2 dt = 16 B_m^2 \times FF^2 \times f \tag{8b}$$

where, B_m is the induction amplitude of the minor loop, $\left(\frac{dB}{dt} \right)$ is the induced voltage, FF is the form factor of $\left(\frac{dB}{dt} \right)$.

According to the Law of conservation of energy, the effective magnetic power applied to MPLC is

$$W_{eff} = W_{appl} - W_{demg} - W_{loss} \tag{9}$$

where, W_{appl} is the power of the applied magnetic field, W_{demg} is the power of the dogmatization field. Thus, at resonance, the effective magnetic field applied to MPLC is

$$H'_{eff} = \left(\frac{W_{eff}}{\pi \mu_0 \mu_{33}} \right)^{\frac{1}{2}} \tag{10}$$

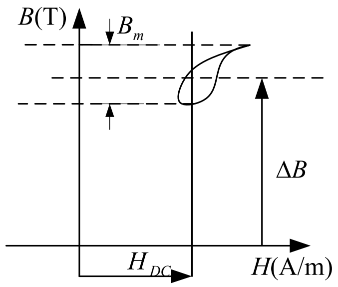


Fig. 4: Model of hysteresis loop and definition of several parameters under DC-biased magnetization.

Refering to [2], the ME voltage coefficient at the resonance can be derived as follows

$$\alpha_V^{reson} = \frac{8 Q_m n(1-n) t d_{33,m} d_{31,p}}{\varepsilon_{33} \left[n\pi^2 (1 - k_{31}^2) s_{11}^E + (1-n)(\pi^2 + (8Q_m - \pi^2) k_{31}^2) s_{33}^H \right]} \times \gamma$$

where, $\gamma = \frac{H'_{3eff}}{H_{3app}}$ is related to the demagnetization field and the magnetic loss, and Q_m is he mechanical quality factor of the laminate composite.

EXPERIMENT

The experimental composites are fabricated by sandwiching a PZT5H layer between two FeNi-FACE layers (an iron-nickel-based ferromagnetic alloy) (Fig.5). The FeNi-FACE layer is designed with dimensions of 12mm × w × 0.6mm, and the PZT-5H layer is designed with dimensions of 12mm × w × 0.8mm, where w is the width of the MPLC. Table 1 shows the material performances of FeNi-FACE and PZT5H. The experimental setup used for the characterization of the ME effect is shown in Fig. 6. During the experiments, the ME devices are placed at the center of a long-straight solenoid, which generates a small AC magnetic field with a peak–peak value of 1 Oe. An oscilloscope is used to detect the output of the MPLCs.

Table 1: Material characteristics of FeNi-Face and PZT5H.

	$d_{33,m}$ / $\mathrm{nm \cdot A^{-1}}$ $d_{31,p}$ / $\mathrm{pC \cdot N^{-1}}$	s_{33}^{H} or s_{11}^{E} $\times 10^{12}\,\mathrm{nm \cdot A^{-1}}$	ε_{33}	ρ kg/m^3	Q$_\mathrm{m}$
FeNi	0.63	5.37		9200	2282
PZT5H	-274	16.5	3800	7500	65

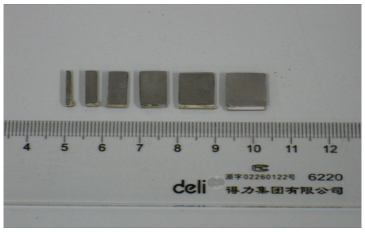


Fig. 5: Laminate composites.

Fig. 6: Experimental setup.

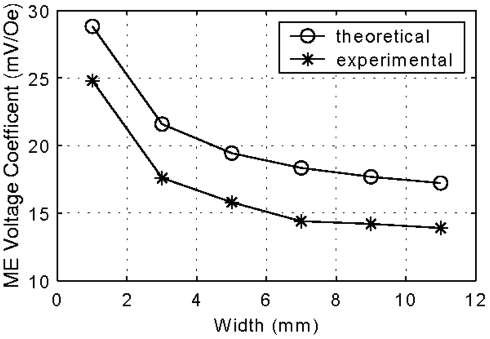


Fig. 7: ME voltage coefficients as a function of the composite width at 1 kHz.

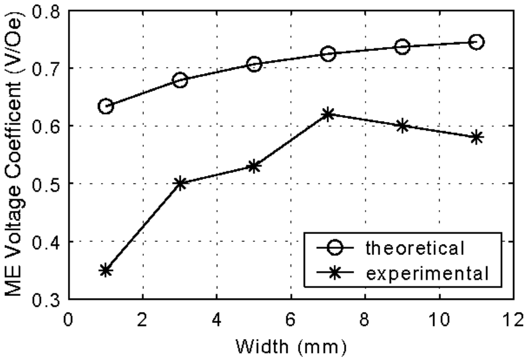


Fig. 8: ME voltage coefficients as a function of the composite width at resonant frequency.

Fig.7 shows ME voltage coefficients as a function of the width at 1 kHz. As expected, the ME voltage coefficients significantly decrease with increasing width until the width is over 7mm, which is attributed to the demagnetization effect. Fig.8 shows ME voltage coefficients as a function of the width at resonant frequency. It can be seen that the ME voltage coefficients increase with increasing width until below 7 mm, which is attributed to not only the demagnetization effect but also the magnetic loss in FeNi layers.

CONCLUSION

In this paper, the shape demagnetization effect and the magnetic loss are both taken into account to investigate the ME effects of MPLCs. The theoretical and experimental results illustrate that the ME effects depend on the in-plane sizes of MPLCs. Great attention must be paid to the in-plane sizes when designing high-performance ME devices.

REFERENCES

[1] S. X. Dong, et al, 2006 Magnetoelectric coupling, efficency, and voltage gain effect in piezoelectric-piezomagnetic laminate composites. *J. Mater. Scien.* **41** 97-106.

[2] F.Yang, Y.M.Wen, et al, 2008 Resonant magneto-electric response of magnetostrictive/ piezoelectric laminate composite in consideration of losses. *Sensors and Actuators A*, **141** 129–135.

[3] D. A. Pan, S. G. Zhang, et al, 2008 Shape and size effects on layered Ni/PZT/Ni composites magnetoelectric performance. *J. Phys. D: Appl. Phys.* **41** 172003.

[4] C. M. Chang, G. P. Carman 2007 Modeling shear lag and demagnetization effects in magneto-electric laminate composites. *Physical review B* **76** 134116.

[5] Amikam Aharoni 1998 Demagnetizing factors for rectangular ferromagnetic prisms. *Jouranl of applied physics* **83**(6) 3432-3434.

[6] Shunji Yanase, Hirotaka Kimata, et al., 2005 A simple predicting method for magnetic losses of electrical steel sheets under arbitrary induction waveform. *IEEE transactions on magnetics* **41**(11) 4365-4367.