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Theoretical analyses of nonlinear magnetoelectric response in self-biased magnetostrictive/piezoelectric laminated composites

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ABSTRACT

A novel nonlinear theoretical model including eddy-current effect and demagnetization effect is presented for predicting magnetoelectric (ME) response in self-biased magnetostrictive/piezoelectric composites with the magnetization-graded ferromagnetic materials. The model is developed based on the nonlinear constitutive relationships of magnetostrictive material, motion equation for the composite plate, and ME equivalent circuit method. In this theoretical model, the equivalent magnetic charge theory is used for analyzing the influence of magnetostrictive material FeCuNbSiB on the effective magnetic field inside the Terfenol-D and the non-zero piezomagnetic coefficient at zero bias, in which the interface coupling parameter £ and the magnetic field dependence of mechanical quality factor are taken into consideration. The theoretical results indicate that the variation of ME voltage coefficients with applied dc magnetic field are in good agreement with the experimental results both under low and resonant frequency conditions. It confirms the validity and reliability of the obtained nonlinear theoretical model. Furthermore, self-biased effect and the difference between the low frequency and resonant ME voltage coefficient with H_{dc} are discussed in details. The theoretical model plays an important role in the comprehensive understandings of dynamic ME response properties for self-biased laminate composites and the designing and fabricating ME devices.

1. Introduction

The magnetoelectric (ME) effect is defined as a polarization response to an applied magnetic field or conversely a magnetization response to an applied electric field [1,2]. Such effect can realize the energy conversion between the electric field and the magnetic field. Currently it has become a hot research field owing to its potential application in new multifunctional devices such as magnetic field sensors, actuators, generators, transformers and transducers [3–7].

The laminated composites of the piezoelectric (e.g., $Pb(Zr,Ti)O_3$, $Pb(Mg_{1/3}Nb_{2/3}O_3–PbTiO_3)$, PVDF, etc.) and magnetostrictive materials (e.g., Galfenol, $Tb_{1-x}Dy_xFe_{2-y}$, Nickle, Permendur, Metglas, etc.) exhibit excellent ME effects at room temperature and meet the demands of application, which is much stronger than that of the traditional particulate ME composites and that of single-phase ME materials [8–17]. In general, the strength of the ME effect is determined by both the piezoelectric and piezomagnetic coefficients for material. However, the values of piezomagnetic coefficients for the most magnetostrictive material are close to zero at zero-biased magnetic field, such ME laminated composites needs to be provided with an external dc bias magnetic field to produce high ME response. Such needs for a magnetic bias field cause some significant disadvantages for the practical application of highly precise, sensitive and miniature magnetic sensor devices, such as adding a potential noise source, reducing the spatial resolution and increasing the device volume and costs. Therefore, more and more interesting researches are being turned to realizing self-biased ME effect for magnetostrictive/piezoelectric laminated composites [18–24]. In the latest work, we have reported that combining traditional magnetostrictive/piezoelectric laminated composites with magnetization-graded ferromagnetic materials can obtain highly zero-biased ME response [23]. And a self-bias ME sensor of FeCuNbSiB/Terfenol-D/PZT8/Terfenol-D/FeCuNbSiB (FeMPMFe) is designed, as shown in Fig. 1 [18]. There are great differences between the ME effect of the FeMPMFe laminated composite with magnetization-graded ferromagnetic materials and the traditional ME laminated composites. From the experimental results, we found that the magnetization-graded ferromagnetic materials produce complex effects on the curves of the ME voltage coefficient and FeMPMFe composites show self-biased effect

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characterized by non-zero ME effect at zero bias. Although the other some researchers have proposed the self-bias ME laminated composites, few articles presented the detailed theoretical analysis. Furthermore, the theoretical analyses are derived based on the linear piezomagnetic model. Many experiments have exhibited that the magnetostrictive effect of magnetostrictive material is inherently nonlinear and dependent on the applied dc magnetic field [25–28]. Thus the ME composites exhibit nonlinear behaviors. Some theoretical studies on the traditional ME laminated composites are conducted on the basis of the nonlinear piezomagnetic model of magnetostrictive materials [29–33]. However, these theoretical studies are not suitable for self-bias laminated composites. Furthermore, they neglected the effect of demagnetization effect and the dominating magnetic loss of eddy in magnetostrictive materials on magnetic-mechanical-electric coupling. The design and fabrication of ME devices needs comprehensive understandings of dynamic ME response properties for self-biased laminated composites. Therefore, it is urgent to establish analysis model which can completely and accurately describe the nonlinear magnetic-mechanical-electric coupling for self-biased ME laminated composites taking into account of eddy-current effect and demagnetization effect.

In this letter, we investigate and analyze FeMPMFe laminate composite with Terfenol-D, PZT, and FeCuNbSiB layers bonded by an epoxy adhesive, as shown in Fig. 1(a). Combing higher permeability FeCuNbSiB with Terfenol-D forms magnetization-graded ferromagnetic materials, which is to increase the ME coupling and keep its size small. The piezomagnetic coefficient of magnetostrictive material are derived based on the nonlinear constitutive model of magnetostrictive material. An analytical model is proposed to predict the ME response of the self-biased laminated composite in consideration of the eddy-current effect, demagnetization effect, and the nonlinear magnetostrictive effect in magnetostrictive layer employing the equivalent circuit method and the equivalent magnetic charge theory. The aim of this study is to establish the complete and accurate analysis model for self-bias laminate composites and facilitate the understanding of the ME properties of the self-bias laminate composites. The comparison between the theoretical data of the analysis model and experimental results indicate that the model can effectively predict the change in ME voltage coefficient with the dc bias magnetic field both qualitatively and quantitatively.

2. Theoretical analysis

2.1. Working model

For the proposed model, we consider a sample in the form of a plate prepared form a FeCuNbSiB/Terfenol-D/PZT/Terfenol-D/FeCuNbSiB (FeMPMFe) laminated composite (as shown in Fig. 1), with high-permeability FeCuNbSiB fixed to the up and bottom surfaces of a rectangular sandwich Terfenol-D/PZT/Terfenol-D (MPM) laminated composite. The FeMPMFe laminated composite operates in the L-T mode, which are magnetized in the longitudinal or length *l* direction and poled in the transverse or thickness *t* direction. The sizes of FeCuNbSiB, Terfenol-D and PZT-8 layers are denoted as $l \times w \times t_f$, $l \times w \times t_m$ and $l \times w \times t_p$, respectively, where w is the width, t_p, t_m and t_f are the thicknesses of the PZT, Terfenol-D and FeCuNbSiB layers, respectively. Correspondingly, the total thickness of composite t equals to the sum of the thickness of each layer. ($t = t_p + 2t_f + 2t_m$).

When an external magnetic field H_{app} (including dc bias magnetic field (H_{dc}) and alternating magnetic field (H_{ac})) is applied along the longitudinal direction, a strain in the magnetization-graded ferromagnetic materials will be generated by the magnetostrictive effect that is transferred to the bonded piezoelectric layer. Then a ME voltage is generated by piezoelectric effect.

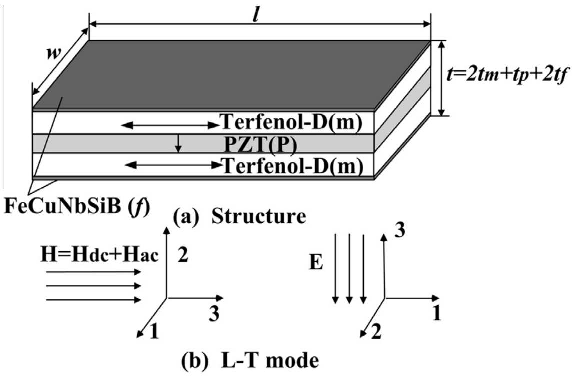

Fig. 1. (a) The structure of FeMPMFe laminated composite. (b) L-T mode FeMPMFe laminated composite.

2.2. The dynamic effective piezomagnetic coefficient of magnetostrictive material

For the magnetization-graded ferromagnetic materials, the internal magnetic field in the magnetostrictive layer of Terfenol-D varies due to the adjacent bonding high-permeability FeCuNbSiB in the low dc bias magnetic field. Van Roy reported that the high-permeability material can be treated as a static magnetic field source which produces high magnetic-field strength in the surrounding space [34]. In this case, high-permeability FeCuNbSiB material yields the additional magnetic field H_f in the Terfenol-D layer due to the flux concentration effect. On the other hand, the demagnetizing field H_d is exactly opposite to the magnetization which will influence the internal magnetic field in the Terfenol-D layer. For predicting the influence of the high-permeability FeCuNbSiB material and the demagnetization effect, the internal effective magnetic field in the magnetostrictive layer of Terfenol-D can be expressed as

$$H_{ineff,m1} = H_{ac} + H_{dc} + H_{d,m} + H_f \tag{1}$$

For the sake of simplicity, we assume a uniform and homogeneous magnetostrictive layer of Terfenol-D. Correspondingly, $H_{d,m} = -N_{d,m} \cdot M$ is the uniform demagnetizing field, where $N_{d,m}$ is a demagnetizing factor for Terfenol-D which is a function of sample geometry, and M is the uniform magnetization of the Terfenol-D layer.

It is assumed that the high-permeability FeCuNbSiB material are homogeneously magnetized with a magnetization $M = M_0$. Then, the magnetic charge density σ_m ($=\mu_0 M \cdot n$) is concentrated on the two transversal surfaces of the FeCuNbSiB material along the longitudinal direction (direction 3), and acts as the source of the static magnetic field. According to the equivalent magnetic charge theory, the additional magnetic field H_f in the Terfenol-D layer produced by the high-permeability FeCuNbSiB material is calculated, given as

$$H_f = \frac{1}{lwt_m} \int_{-\frac{l}{2}}^{\frac{l}{2}} \int_{-\frac{w}{2}}^{\frac{w}{2}} \int_{-\frac{t_m}{2}}^{\frac{t_m}{2}} (H_{f3+} + H_{f3-}) dxdydz \tag{2}$$

where H_{f3+} is the magnetic field in the Terfenol-D produced by positive surface magnetic charge, derived as Eq. (3)

$$H_{f3+} = \frac{\mathbf{H}}{4\pi} \frac{(1 - \mu_{rf,eddy})}{\mu_{rm,eddy}} \int_{-\frac{w}{2}}^{\frac{w}{2}} \int_{-\frac{t_f}{2}}^{\frac{t_f}{2}} \times \frac{(x - l/2)}{\left[(x - l/2)^2 + (y - y_1)^2 + (z - z_1)^2\right]^{3/2}} dy_1 dz_1 \tag{3}$$