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Effects of hysteresis and temperature on magnetoelectric effect in giant magnetostrictive/piezoelectric composites

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ABSTRACT

A nonlinear dynamic hysteretic theoretical model on magnetoelectric effect of tri-layered composites is built based on a nonlinear constitutive relation for magnetostrictive material and a linear piezoelectric model for piezoelectric material. And a finite element analysis is implemented to investigate quantitatively the influences of hysteresis and temperature on the ME effect of the layered composites. The model also can explain the “self-biased” response caused by the hysteretic characteristics of the ME composites. Then the distribution of the true displacement along the longitudinal direction is revealed by numerical calculation. The increment of temperature due to the magnetic hysteresis loss is investigated. The temperature, the AC magnetic field and the bias field on the induced electric field and the ME effect are studied, respectively. The results show that the bigger the magnetic frequency, the larger the energy loss of the ME composites. The initial temperature has little effect on the induced electric field at low magnetic field region, but significant effect on the induced electric field at high magnetic field region. The frequency multiplying behavior will disappear when the bias field is strong. In addition, the bias magnetic field also affects the shape of $E_3 \sim H_{AC}$ curve, with the increase of the bias field, the shape of $E_3 \sim H_{AC}$ curve changes from symmetry to asymmetry. The frequency mixing of the induced electric field is also discussed.

1. Introduction

Magnetostrictive/piezoelectric composite is a new type of functional composite, which enables the energy conversion between magnetic energy and electric energy by interfacial strain transfer (Gao and Zhang, 2012, 2013; Nan et al., 2008; Wang and Zhou, 2011b; Wang et al., 2010). It has important applications in such areas as magnetoelectric memories, energy harvesters, gyrators, sensors, and actuators (Bibes and Barthelemy, 2008; Israel et al., 2008; Li et al., 2011; Nan et al., 2008; Scott, 2012). The magnetoelectric (ME) coefficient is an important parameter for describing of the ME effect in magnetostrictive/piezoelectric composites. It usually has two forms, the ME field coefficient α_E ($\alpha_E = \partial E/\partial H$) and the ME voltage coefficient α_V ($\alpha_V = \partial V/\partial H$), in which E, V and H are the induced electric field, the induced voltage field and the applied magnetic field, respectively (Dong et al., 2005; Gao and Zhang, 2012, 2013; Wang and Zhou, 2011b). The ME effect in magnetostrictive/piezoelectric composites is called product effect (Nan et al., 2008). It is one of the major topics that how to obtain larger ME coefficient in the entire research area.

As for the advanced composite materials, there are usually three categories to classify ME composites according to the characteristics of the reinforcement. They are 0–3 particulate composites, 2–2 laminate composites and 1–3 fiber/rod composites, respectively (Nan et al., 2008; Wang et al., 2010). Because of a higher ME coefficient and simple fabrication technologies in 2–2 type, it has received more and more concerns in recent years. Many experiments have already been conducted to study the influence factors on the ME effect of 2–2 laminated composites. The experimental researches are mainly shown in the following aspects: (1) changing the thickness ratio (Chen et al., 2013; Fang et al., 2011), the geometry size and the shape of components (Pan et al., 2008, 2009); (2) changing the component of ME composites (Dong et al., 2003, 2004a, 2005); (3) selecting different methods of the samples fabrication (Fang et al., 2013; Hao et al., 2013; Pan et al., 2009; Zhou et al., 2012a); (4) designing the ME composites by different bonding ways (Bi et al., 2011, 2013; Lu et al., 2013a); (5) changing the experimental conditions, such as the forms of applied magnetic field, temperature, or the static and dynamic response mode (Burdin et al., 2014; Fang et al., 2012; Gao et al., 2012; Zhang

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et al., 2012a). Those experimental results show that all the factors include characteristic of structure itself, material parameters, constraint conditions, experimental conditions and so on, which may affect the ME response of ME composites.

Meanwhile, the theoretical studies get development based on some experimental results. The mainly theoretical methods are the elastic mechanics method (Bichurin and Petrov, 2012; Bichurin et al., 2003; Harshe et al., 1993a,b), the Green's function method (Nan et al., 2001, 2005), the equivalent circuit method (Dong and Zhai, 2008; Zhou et al., 2011, 2013), the energy method (Lu and Li, 2011; Lu et al., 2011) and the finite element method (Nguyen et al., 2011; Wang and Atulasimha, 2012). Depending upon the theoretical models, researchers expect providing reasonable explanations and predicting results on ME composites.

Recently, the hysteretic characteristics of ME effect for layered composites composed of ferromagnetic/piezoelectric phases were experimentally investigated. For example, Zhou et al. (2012b) reported that the curve of $\alpha_E \sim H$ in Ni-PMT bilayer showed a hysteretic behavior, and the value of α_E at zero DC magnetic field is ~72.5% of the maximum value of α_E. Patil et al. (2013) investigated the frequency dependence of ME coefficient for magnetic field and obtained two wide frequency windows of a giant ME voltage coefficient of over 16 V/cm Oe in series-connected Ni/PMN-PZT/Ni laminates with different thickness ratios. The hysteretic curves of α_E vs. H were shown in their experimental results. Shi et al. (2013) also measured ME coefficient loops of the bilayer and tri-layer ME composites. Although the ME effect with hysteretic characteristics has been observed in many experiments, and there are many theoretical studies on ME effect of ME composites, there still lack the corresponding theoretical model of ME effect to predict and describe those hysteretic characteristics for ME composites in experimental results. Because ME composites are widely applied in some microelectromechanical systems, in some cases the hysteretic characteristics for ME composites are efficiently used, but sometimes they need to be inhibited (Bibes and Barthelemy, 2008; Dong et al., 2004b; Eerenstein et al., 2006; Israel et al., 2008; Li et al., 2011; Nan et al., 2008; Scott, 2012). In addition, due to the hysteretic characteristics of ME composites, the concept 'self-biased' is proposed. The self-biased effect is that the ME coefficient is nonzero under zero magnetic field, which is directly related to the nature of magnetization and can be tuned by variation in demagnetization state and the resultant differential magnetic flux distribution. The self-biased effect has great advantage in integration with zero-biased magnetic field sensors and MEMS-scalable energy harvesting components (Zhou et al., 2012; Li et al., 2013; Lu et al., 2013). Wang et al. point out self-biased with higher ME coefficients should be a research issue in the future, which is a new research area in broad application of ME composites (Li et al., 2013; Lu et al., 2013b; Wang et al., 2014; Zhou et al., 2012b). However, up to now there are few theoretical studies on this aspect. Thus it is necessary to build a nonlinear dynamic hysteretic theoretical model on ME effect for ME composites and accurately predict the ME effect with hysteretic characteristics. Fortunately, many dynamic hysteretic theoretical models on the magnetostrictive materials have already been proposed (Chwastek, 2009; Fang et al., 2008; Jiles, 1994; Jin et al., 2011; Wang and Zhou, 2010, 2011a; Xu et al., 2013; Zheng and Sun, 2007), which make it possible to build a dynamic hysteretic theoretical model on ME response of ME layered composites.

In addition, as a smart device or an important part of some smart structures, the ME material or structure is often required to work in some special conditions. So the environment temperature is always a very important factor in the applications of ME composites or structures. Vaz et al. (2010) reported that the temperature has a great influence on the ME response of PZT/LSMO multiferroic heterostructures. Fang et al. (2012) measured the ME field coefficients for three kinds of tri-layered laminates at different temperature fields. The result showed that the peak value of the ME field coefficient decreased with the increase of temperature at a range of 25–80 °C. It can be noticed that the studies including the temperature effect on the ME response are still sparse, no matter in the experimental or theoretical studies.

The primary aim of this study is to investigate the influences of hysteresis and temperature effect on the ME effect of layered ME composites, a dynamic hysteretic nonlinear theoretical model on ME effect is thus proposed to predict the induced electric field and the ME effect. A coupling finite element formulation and an in-house code are developed to describe the transient dynamic response, the transient induced electric field and displacement distribution characteristics of tri-layered ME composites. The deformation characteristics, the increment of temperature due to the hysteresis loss and the induced electric field response are investigated by the numerical simulation. The frequency mixing of the induced electric field is also discussed for a tri-layered composite in two AC magnetic fields with different frequencies.

2. Theoretical analysis model

Consider a tri-layered ME composite consisting of magnetostrictive material and piezoelectric material in a time-dependent magnetic field, the direction of magnetic field is along the longitudinal direction. The structures are shown in Fig. 1. M and P denote the magnetostrictive material and the piezoelectric material, respectively. L is the length of the composite, t_m, t_p are the thickness of magnetostrictive and piezoelectric layers, respectively.

Here a nonlinear constitutive relation for magnetostrictive material is provided.

The relationship between stress and strain of magnetostrictive materials can be expressed as

$$\begin{aligned} {}^mS_1 &= {}^ms_{11}{}^mT_1 + {}^ms_{13}{}^mT_3 + \lambda_1 + {}^m\alpha\Delta T \\ {}^mS_3 &= {}^ms_{31}{}^mT_1 + {}^ms_{33}{}^mT_3 + \lambda_3 + {}^m\alpha\Delta T \end{aligned} \tag{1}$$

where, the strains of magnetostrictive material include the elastic strain, the magnetostrictive strain caused by the magnetic field, and the temperature strain caused by the change of temperature. ${}^mS_1$ and ${}^mS_3$ are the strains along the longitudinal direction and the thickness direction of M-layer, respectively. ${}^mT_1$ and ${}^mT_3$ are the stresses along the longitudinal direction and the thickness direction of M-layer, respectively. ${}^ms_{11}$, ${}^ms_{13}$, ${}^ms_{31}$ and ${}^ms_{33}$ are the components of the flexibility matrix of M-layer, ${}^m\alpha$ is the thermal expansion coefficient of M-layer. ΔT is the change of temperature. For the simplicity of computation, we assume that: (i) the applied magnetic field is parallel to the longitudinal direction and the magnetization direction is along the magnetic field direction; (ii)

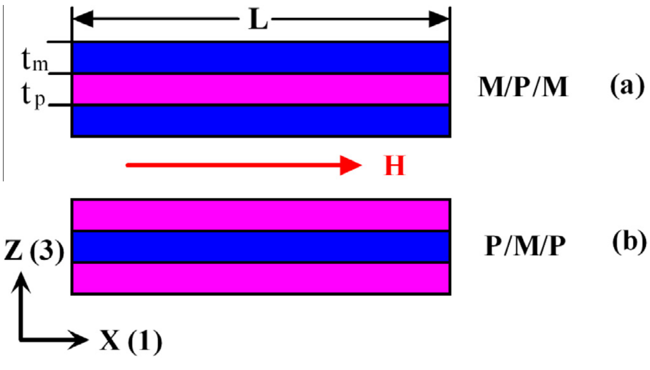

Fig. 1. Two different structures of giant magnetostrictive/piezoelectric composites. (a) M/P/M structure; (b) P/M/P structure.

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