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Model of resonance mechanical loss that considers bias field and pre-stress in magnetostricitve/piezoelectric sandwich laminate

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ABSTRACT

A nonlinear mechanical loss model of magnetoelectric laminated composite that fully considers the static magnetic field and pre-stress is established. The proposed model effectively predicts variations in the resonance frequency, anti-resonance frequency, and mechanical loss of magnetostricitve/piezoelectric sandwich laminate as functions of the magnetic field and pre-stress. The degradation model can effectively predict experimental results, confirming the model's validity, when the pre-stress is taken as 0 MPa. By this model, it is found that the mechanical loss can be significantly reduced by applying a static magnetic field less than the critical resonance magnetic field when the resonance frequency is less than the resonance frequency corresponding to no magnetic field; also, when the resonance frequency is larger than the resonance frequency corresponding to no magnetic field, the mechanical loss can be significantly reduced by applying compressive stress.

1. Introduction

Laminated magnetoelectric composites made of magnetostrictive materials and piezoelectric materials have stronger magnetoelectric coupling than do single-phase magnetoelectric materials. Magnetoelectric coupling with stress as a medium is very attractive in many applications, including multifunctional sensors, filters, and power harvesters [1–5]. To obtain the giant magnetoelectric effect, research has concentrated on laminates with ferrite, shape-memory alloys, or Terfenol-D as the magnetostrictive component, and PZT or PMN–PT as the piezoelectric phase. Laminates composed of Terfenol-D have been extensively studied because of its large piezomagnetic coefficient and relatively low cost; also, its magnetoelectric voltage coefficient is as high as $V\,cm^{-1}\,Oe^{-1}$ at a quasi-static frequency, and the magnetoelectric coupling effect of a laminated structure in a resonance state is 1–2 orders of magnitude stronger than in a quasi-static state [6–8]. For example, Duan et al. [6] found the resonance ME coefficient (α_{ME}) of Terfenol-D/PVDF/Terfenol-D at a magnetic bias of 600 Oe to be ~20 times higher than that in a non-resonance state.

In the resonance ME effect, the magnetoelectric coefficient is not only determined by the structure and operating mode, but also by resonance energy losses. These losses include the magnetic loss of the magnetostrictive layer caused by eddy current; hysteresis and magnetization relaxation; conduction loss of the piezoelectric layer caused by conduction current; dielectric loss caused by electric displacement hysteresis; and mechanical loss of the laminate in the resonant state. Wen et al. [9] found that, of these energy losses, mechanical loss of the laminates dominates; the others are often negligible. Magnetomechanical loss in Terfenol-D is mostly caused by non-180° ferromagnetic domain wall movement under external magnetic fields and stress fields, while mechanical loss in PZT stems largely from irreversible ferroelectric domain wall movement. Mechanical loss in the laminates made of Terfenol-D and PZT is a major factor in the resonance magnetoelectric effect. Even when comparing similar resonance frequencies, differing mechanical losses will cause large changes in the resonance magnetoelectric coefficient; for example, Yao et al. [8] found that the measured peak of magnetoelectric coefficients of Terfenol-D/PZT/Terfenol-D at a resonance frequency of 110 kHz was 1.5 times bigger than that at 97.5 kHz. Using the equivalent circuit method, Dong et al. [10–11] established a resonance magnetoelectric coefficient model and found that the resonance magnetoelectric coefficient was proportional to the mechanical quality factor (reciprocal of mechanical loss). When analyzing the magnetoelectric effect, researchers often use a constant mechanical loss of 0.02 [12], making the magnetoelectric coefficient model unable to explain great changes in the magnetoelectric coefficient at different resonance frequencies.

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Attempting to address these problems, Wen et al. [9,13] suggested that the effective mechanical loss of these laminates should comprise the mechanical losses of magnetic layers and piezoelectric layer weighted by their volume fractions, keeping the mechanical loss constant because the relations between mechanical loss of each phase and frequency have not been found. Recently, Yao et al. [8,14] experimentally studied a magnetoelectric laminated composite; they found that, as the bias magnetic field (or resonance frequency) increased, the mechanical loss rapidly increased, then decreased, and eventually stabilized. This stable value of mechanical loss is consistent with the constant value of 0.02 given by Dong et al. [12]. Nonlinear variation of mechanical loss with magnetic field bias causes the resonance magnetoelectric coefficient to vary much with resonance frequency, and also affects the relationship between the magnetodielectric effect of the laminates and magnetic field bias. Based on the model of effective mechanical loss proposed by Wen et al. [9,13], they further considered the impact of interface loss between the ferromagnetic and piezoelectric materials, namely, the total mechanical energy dissipation is mainly composed of the mechanical damping of magnetostrictive layers, mechanical damping of piezoelectric layer, and the loss at the interface mechanical coupling between magnetostrictive and piezoelectric layers. Considering the mechanical loss of laminates with interdigitated electrodes, Wang et al. [7] selected Yao's term of effective mechanical loss [8]. Both expressions of effective mechanical loss by Wen et al. [9,13] and Yao et al. [8,14] considered the effective mechanical losses of the laminates as the weighted sum of both phases' mechanical loss; the mechanical loss of the piezoelectric phase usually has a classic expression, while the mechanical loss of the magnetostrictive phase has no expression, meaning the effective mechanical loss has no exact expression. These cases still consider the effective mechanical loss as a constant or rely on experimental results for qualitative or quantitative analysis. Even with an expression of mechanical loss of the magnetostrictive material, a simple weighted expression cannot accurately reflect the variation of effective mechanical loss with the resonance frequency and magnetic field in the laminates: the resonance frequency and anti-resonance frequency of the laminates differ much from those of the individual piezoelectric layer and magnetostrictive layers. To directly consider the whole laminate, a new method that no longer separates the mechanical losses of the ferromagnetic and piezoelectric phases, using the equivalent circuit of the laminates to deduce a model of mechanical loss that depends on the resonance and anti-resonance frequency is developed. This model can be used to describe the variation of mechanical loss with both bias magnetic field and pre-stress, as well as the variation of the magnetoelectric coefficient with magnetic field bias and the resonance frequency. It can also be used to analyze the laminates with applied self-stress [15], and it can explain how applying tensile stress [16] along the longitudinal direction of Terfenol-D reduces mechanical loss in the magnetoelectric coupling effect, allowing us to use pre-stress to reduce the mechanical loss and improve both the magnetoelectric coupling effect and magnetodielectric effect.

2. Theoretical model development

Fig. 1(a) shows a typical L–T mode magnetostricitve/piezoelectric sandwich laminate, for which Terfenol-D is selected as magnetostricitve phase and PZT is selected as piezoelectric phase. Terfenol-D/PZT/Terfenol-D is fabricated by placing a PZT layer (thickness of t_p) between two Terfenol-D layers (thickness of t_m), where l and w are the length and width of the laminate, respectively.

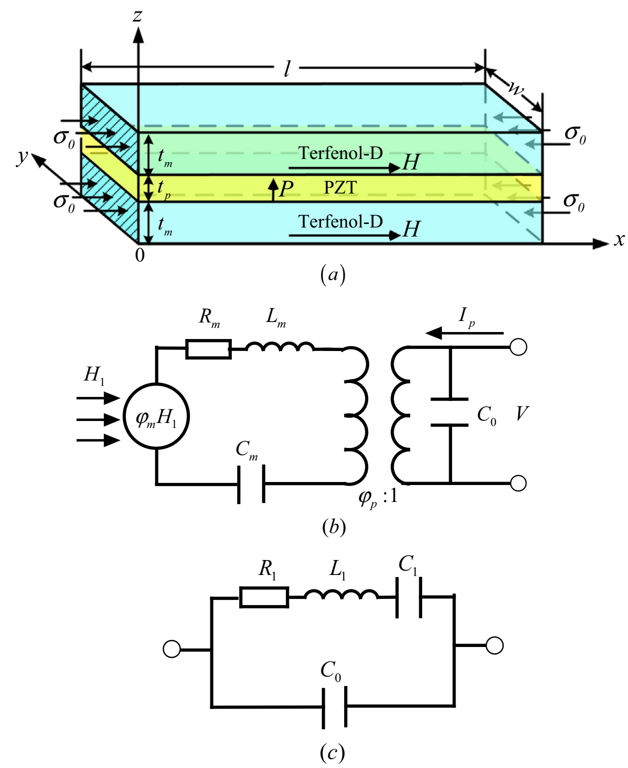

Fig. 1. (a) Schematic diagram, (b) equivalent circuit under resonance drive and (c) equivalent circuit of shorted-input of L–T mode Terfenol-D/PZT/Terfenol-D magnetoelectric composite.

Because the stress passing from the magnetostrictive layer is relatively low, the piezoelectric effect of the piezoelectric layer can be described as linear constitutive relations:

$$\varepsilon_1^p = s_{11}^p \sigma_1^p + d_{31}^p E_3 \tag{1}$$

$$D_3 = d_{31}^p \sigma_1^p + \varepsilon_{33}^p E_3 \tag{2}$$

where the superscript p denotes the piezoelectric layer; ε_1^p, σ_1^p, E_3, and D_3 are the strain, stress, electric field, and electric displacement, respectively, of the piezoelectric layer; d_{31}^p, s_{11}^p, and ε_{33}^p are the piezoelectric coefficient, compliance coefficient in an electrical short-circuit, and relative permittivity, respectively.

The constitutive relations of the Terfenol-D layer should be nonlinear and consider the ΔE effect; these requirements are fulfilled by the Zheng–Liu constitutive model [17]. However, it is difficult to build an equivalent circuit based on the Zheng–Liu model because it contains an inverse function. To avoid this problem, the nonlinear constitutive equations established in Zheng–Liu model can be rewritten in constitutive equations with variable coefficients [16]:

$$\varepsilon_1^m = s_{11}^m(H_1, \sigma_1^m)\sigma_1^m + d_{11}^m(H_1, \sigma_1^m)H_1 \tag{3}$$

$$B_1 = d_{11}^m(H_1, \sigma_1^m)\sigma_1^m + \mu_{11}^m(H_1, \sigma_1^m)H_1 \tag{4}$$

where the superscript m denotes the magnetostrictive layer; H_1, B_1, ε_1^m, and σ_1^m are the applied magnetic field, magnetic induction, and strain and stress along the longitudinal direction of the laminate. Here, H_1 is the applied magnetic field. $d_{11}^m(H_1, \sigma_1^m)$, $s_{11}^m(H_1, \sigma_1^m)$, and $\mu_{11}^m(H_1, \sigma_1^m)$ are the piezomagnetic coefficient, elastic compliance coefficient, and the permeability, respectively, which are functions of the bias magnetic field and pre-stress reflecting the nonlinearity of this constitutive, and their specific expressions can be given as