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The frequency dependence of harmonic hysteresis effect in magnetoelectric laminated composites

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ABSTRACT

In this study the frequency dependence of harmonic hysteretic magnetoelectric (ME) effect in magnetostrictive-piezoelectric laminate was investigated. Taking into account the nonlinear magnetostrictive effect and the structural vibration, a ME dynamic model was proposed to quantitatively describe the frequency-dependent hysteretic characteristics. The model was validated by comparing the simulated ME response with experiment at both the quasi-static and high frequency conditions. As the frequency increases, the shape evolution of the ME hysteresis loop from crescent to butterfly and ellipse was observed. Moreover, the influences of the magnetic bias field, damping ratio and magnetostrictive loss factor were also investigated. It was found that the dynamic ME hysteresis was the combined result of competition between the first two orders of harmonic components and the corresponding phase shift. The former was controlled by the frequency doubling and the mechanical resonance effect, and the latter was originated from the magnetostrictive loss and mechanical damping.

1. Introduction

Magnetoelectric (ME) effect in laminated composites of magnetostrictive (MS) phase and piezoelectric (PE) phase can be realized by a strain-mediated coupling between MS and PE effect. It has shown great promise for applications in ME sensors [1,2], energy harvesters [3,4], memories [5] and other microwave devices [6]. To satisfy the practical applications, many efforts have been devoted to realize a higher ME coefficient by improving constitutions and configurations of ME composites [7,8]. Moreover, the previous works also show that the ME response can be tuned by external experimental conditions, such as the bias magnetic field, pre-stress and the static or dynamic resonance mode [9–12].

Recently, the hysteresis ME behavior for layered composites has been experimentally investigated [13,14], which can be used to achieve the self-bias ME effect. The self-biased effect, which means that the ME coefficient is nonzero without bias magnetic field, has great advantage in developing miniature magnetic sensor devices [15,16]. Furthermore, motivated by applications of active magnetic sensors and frequency doubling devices, the dynamic nonlinear ME effect has attracted increasing interests, such as the generation of harmonics [17,18] and frequency mixing behaviors [19]. Based on the harmonic nonlinearity, a cross-modulation technique [20] was developed to reduce the low frequency noise of ME sensors by shifting the operating frequency. However, it should be noted that almost all these studies focus on the magnitude of the ME response, but not the details of the hysteretic characteristics.

In theoretical research, the representative theories include the Green's function method [21], equivalent circuit method [22] and elastic mechanics method [23]. These theories are all based on the linear piezomagnetic equations. As the study on nonlinear MS behavior goes deeper, more researches began to model the quasi-static nonlinear ME response [24,25]. Subsequently, without considering the hysteresis, dynamic nonlinear resonant ME response were studied using the equivalent circuit method [26–28]. Zhang et al. developed a dynamic hysteretic model combined with the finite element formulation and investigated the temperature effect on ME response [29], which was suitable for low-frequency range away from the resonance region. Recently, some experimental studies [30,31] reported that the structural mechanical loss and eddy current effect under high frequency conditions had significant influences on ME response, which was rarely theoretical considered. Furthermore, the investigations on dynamic hysteretic ME behaviors are still sparse, no matter in the experimental or theoretical studies.

In this paper, combining a nonlinear hysteretic MS model and the structural vibrating theory, we developed a dynamic harmonic

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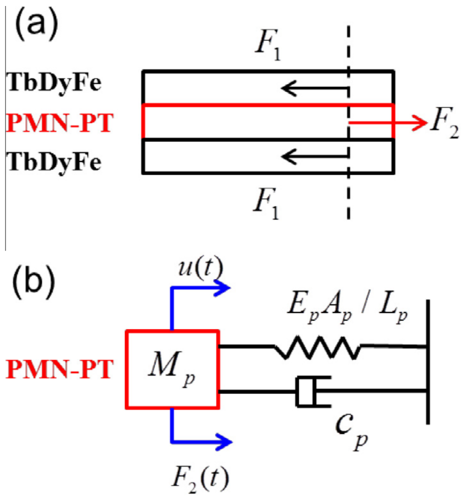

Fig. 1. (a) Illustration of the ME laminated composite. (b) Schematic of the forced damping vibration mechanical model for the PE plate.

model for ME laminate. Both the mechanical loss and the eddy current effect are considered, which are critical to accurately predict the dynamic ME response in a broad range of frequency. Different nonlinear shapes of the dynamic hysteretic ME loops were obtained both experimentally and theoretically, which were proved to be codetermined by the frequency doubling and structural resonance effect. The influences of the magnetic bias field, damping ratio and MS loss factor were also investigated.

2. Theoretical model

Considering the L-T mode ME laminate of symmetric configuration illustrated in Fig. 1(a), a PE layer is poled in the thickness direction sandwiched between two MS layers. An extension vibration is excited in the MS layer under a time-harmonic longitudinal magnetic field. Considering the influences of the inherent damping c_m, the mass of the MS layer and the interface constrained forces F_1, the dynamic total strain can be expressed as

$$\varepsilon_m(t) = \frac{\sigma_m}{E_m} + \lambda - \frac{c_m}{E_m}\dot{\varepsilon}_m - \frac{\rho_m L^2}{3E_m}\ddot{\varepsilon}_m. \tag{1}$$

where $\sigma_m, E_m, \lambda, \rho_m$ and L are the constrained stress, Young's modulus, magnetostriction, density and the length of MS layer, respectively. Therefore the constrained force F_1 can be obtained as

$$F_1(t) = \sigma_m A_m = E_m A_m(\varepsilon_m - \lambda) + A_m c_m \dot{\varepsilon}_m + \frac{\rho_m L^2 A_m}{3}\ddot{\varepsilon}_m, \tag{2}$$

where A_m is the cross-sectional area of the MS layer. Then, the strain is elastically coupled to PE layer and drives it into oscillation, which can be modeled by a lumped-parameter oscillation resonator, as shown in Fig. 1(b). The PE layer acts as an equivalent spring of stiffness E_pA_p/L (E_p and A_p are the Young's modulus and cross-sectional area, respectively) together with an overall damping c_p. Thus the motion equation of PE layer can be written as

$$F_2(t) = -\left(\rho_p A_p L\ddot{u}_p + c_p\dot{u}_p + \frac{E_pA_p}{L}u_p\right). \tag{3}$$

where $F_2(t)$ is the driven force, ρ_p and u_p are the density and displacement of the PE layer.

Assuming a perfect bonding interface, the MS and PE layers undergo the same displacement $u_p = u = \varepsilon_m L$. Then taking into account the force balance condition $F_2(t) = -2F_1(t)$ we can obtain the equivalent vibration equation of the PE layer

$$\tilde{M}\ddot{u} + \tilde{c}\dot{u} + \tilde{k}u = 2E_m A_m \lambda(t). \tag{4}$$

where $\tilde{M} = \rho_p A_p L + 2\rho_m A_m L/3$, $\tilde{c} = c_p + 2A_m c_m/L$ and $\tilde{k} = E_pA_p/L + 2E_mA_m/L$ denote the equivalent mass, damping coefficient and stiffness, respectively. Eq. (4) represents a second-order dynamic system driven by the equivalent force $2E_mA_m\lambda(t)$. For harmonic applied magnetic fields, $\lambda(t)$ can be expressed as the Fourier series [32]

$$\lambda(t) = \sum_{n=0}^{N} |\lambda_n|\cos(2\pi n f_0 t + \phi_n), \tag{5}$$

where $|\lambda_n|$ and ϕ_n respectively represent the magnitude and phase of the n_{th} harmonic of actuation frequency f_0. Therefore, using the

Table 1
Material and model parameters for the ME laminated composite.

$M_s(10^6$ A/m)	0.765	λ_{100}(m/m)	90×10^{-6}
λ_{111}(m/m)	1640×10^{-6}	w(J/m^3)	9000
$\rho(\Omega$/m)	3.5×10^{-6}	K(A/m)	1000
η	6	E_m(GPa)	30
E_p(GPa)	44	ρ_m(kg/m^3)	9200
ρ_p(kg/m^3)	8000	d_{31}(C/ςN)	-1300×10^{-12}
k_{33}/k_0	3864	ς	0.05

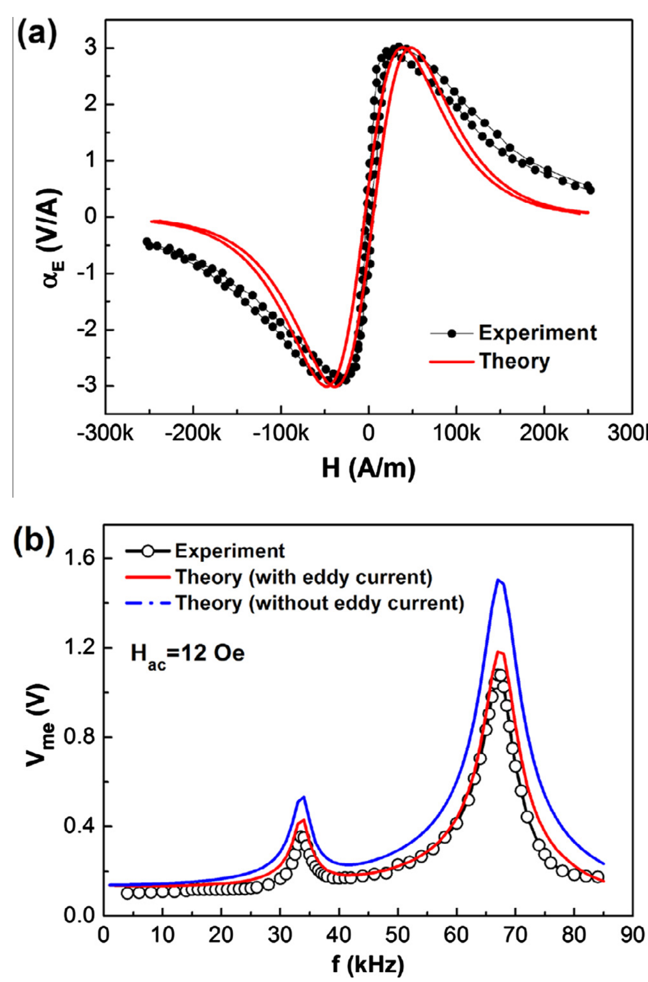

Fig. 2. Comparisons between experiment and theoretical simulation. (a) ME coefficient versus bias magnetic field. (b) The induced ME voltage as a function of applied frequency with zero bias field.