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Size effects in strip–ring piezoelectric/magnetostrictive structures observed in magnetically tuned resonance frequency

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ABSTRACT

In this article we present a theory describing the influence of the magnetostrictive component size on magnetically tuned electromechanical resonance frequencies (EMRs) for ferromagnetic–piezoelectric heterostructures. An analytical model to evaluate the magnetically tuned EMRs offset in strip–ring magnetoelectric composite structures is introduced. The model is applied to the specific case of PZT (ferrite-lead zirconate titanate)-strip/TDF (Terfenol-D)-ring composite. Numerical simulation of magnetically tuned EMRs offset indicated that the magnetically tuned EMRs depend significantly on the ratio of outer and inner radii of the magnetostrictive ring. A maximum value for the magnetically tuned EMRs offset Δf of -2.139×10^5 Hz is found in a magnetic field $H = 8.641 \times 10^{-2}$ T for $b = 1.2a$ (b and a are outer and inner radius of magnetostrictive ring). This theoretical work is significant for designing ME devices and understanding the magnetically tuned EMRs in strip–ring composite structures.

1. Introduction

In recent years, magnetically tuned electromechanical resonances (EMRs) in magnetoelectric (ME) composites have attracted increasing interest because of their promising applications as magnetic field sensors, tunable devices, and as transducers [1–6]. Magnetically excited EMRs in multilayer capacitors (MLCs) that comprise magnetostrictive nickel electrodes and piezoelectric layers $BaTiO_3$ (BTO) were considered by Srinivasan et al. These authors investigate the influence of an applied magnetic field H on the resonant frequencies $f_n(H)$, and attribute the resonant frequency shift to the ΔE_Y effect [7]. C. Israel and co-workers based on strain-mediated magnetoelectric (ME) effect theory and the equation of medium motion approximation for solving the relationship between the piezoelectric capacitance and external magnetic field, have simulated the resonant frequency in multilayer capacitors (MLCs) [8]. We have also used this principle to calculate the relationship between capacitance and external magnetic field and the resonant frequency in sandwich magnetoelectric composite structure [9]. However, because these studies were all focused on layered structures, the interaction force between magnetostrictive and dielectric materials was shear stress [10–12] and consequently only in a limited number of cases a resonant frequency shift has been observed. For example, the largest experimental value for the resonance frequency shift reported was $\Delta f = 1.25 \times 10^3$ Hz ($\Delta f = f_H - f_0$, where f_H is the resonant frequency in the magnetic field H and f_0 is the resonant frequency in zero magnetic field) [8]. Generally, magnetically tuned EMRs is similar in nature to the magnetoelectric effects. The change of compliance coefficients (ΔE effect) in the ferromagnetic phase allows the resonance frequency of the ME composite to be tunable via the external magnetic field [7].

Recently, Wu [13,14] theoretically predicted stronger ME effect in disk-ring structures. Therefore, it is interesting to investigate the influence of magnetic field H on the resonant frequencies in samples with special-shape geometry. We previously studied magnetically tuned EMRs in strip–ring magnetoelectric composites, the magnetostrictive (Ni–Zn ferrite ring) and piezoelectric (PZT strip) phases being coupled through normal stresses, but the largest experimental value for the resonance frequency shift was only $\Delta f = 0.9 \times 10^3$ Hz, and the theoretically predicted value was $\Delta f = 1.58 \times 10^3$ Hz [15]. The motivation for these results can be detailed as follows: (1) The influence of small magnetostrictive coefficient for the ferromagnetic material (Ni–Zn ferrite). The problem could be eliminated by using ferromagnetic materials with large magnetostrictive coefficient (such as Terfenol-D). (2) In the theoretical model of strip–ring magnetoelectric composites, we found that the size of the material will influence the magnetically tuned resonant frequency offset, especially the size of the

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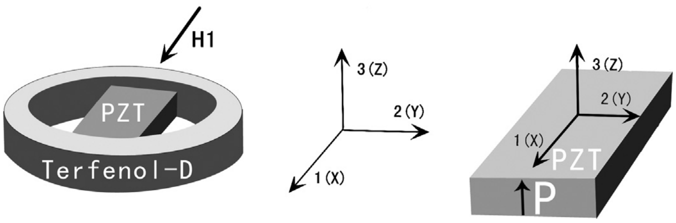

Fig. 1. Schematic of strip–ring magnetoelectric composite structure.

magnetostrictive component. Therefore, in this paper, we focus on optimizing magnetostrictive material size in order to achieve maximum frequency deviation.

On the basis of our experimental studies, the purpose of this article is going to discuss theoretically the influence of the size of the magnetostrictive materials on the frequency offset by means of simulation. The simulation process and conclusion can help us to understand the frequency offset, and predict the performance of the device, and optimize the geometry of the device. In this paper, using the strip–ring composite structure model (the piezoelectric and magnetostrictive material are ferrite-lead zirconate titanate (PZT) and Terfenol-D, where PZT and Terfenol-D are strip and ring respectively) and the relationship between the piezoelectric capacitance and external magnetic field, we have calculated the resonant frequency in strip–ring composite structure. Essentially, we have studied the influence of the magnetostrictive element size on resonant frequency offset in applied magnetic field.

In the next section one presents the theoretical model for the strip–ring composite structure analyzed in this paper. The theoretical model is developed in the following section and the results obtained in the simulations are presented and discussed in the final section.

2. The piezoelectric phase capacitance in strip–ring composite structure

The piezoelectric and magnetostrictive materials were used for the strip and ring, respectively, as shown in Fig. 1. The magnetostrictive and piezoelectric phases are coupled through normal stresses [13,14]. The PZT pole direction is along the thickness direction (direction 3 in Fig. 1). This configuration enables the piezoelectric phases to operate in longitudinal resonance mode. The magnetostrictive direction is along the radius direction. Dc magnetic field is applied along the direction 1 (Fig. 1). An orthogonal coordinate system and a cylindrical coordinate system are used for the piezoelectric and the magnetostrictive phases, respectively. The generalized Hooke's law and corresponding constitutive equations are given by [13,15]

$$ {}^pS_1 = {}^ps_{11}{}^pT_1 + {}^pd_{31}{}^pE_3 \tag{1} $$

$$ {}^pD_3 = {}^pd_{31}{}^pT_1 + {}^p\varepsilon_{33}{}^pE_3 \tag{2} $$

$$ {}^mS_r = {}^ms_{11}^B{}^mT_r + {}^ms_{12}^B{}^mT_\theta + {}^mq_{11}H_1 \tag{3} $$

$$ {}^mS_\theta = {}^ms_{12}^B{}^mT_r + {}^ms_{11}^B{}^mT_\theta + {}^mq_{12}H_1 \tag{4} $$

where p and m are indicating piezoelectric and magnetostrictive, respectively. ${}^pS_1$, ${}^pT_1$, ${}^pD_3$ are the components of the strain tensor, stress tensor and electric displacement under orthogonal coordinate system; ${}^mS_r$, ${}^mS_\theta$, ${}^mT_r$, ${}^mT_\theta$, are the components of the strain tensor, stress tensor are obtained in the cylindrical coordinate system of r, θ; ${}^pE_3$ and H_1 are electric and magnetic fields, ${}^pd_{31}$ and ${}^p\varepsilon_{33}$ are piezoelectric coefficient and permittivity, ${}^ps_{11}$ is the compliance coefficients of piezoelectric phase in constant electric field. ${}^mS_{11}^B$ and ${}^mS_{12}^B$ are the compliance coefficients of the magnetostrictive phase. It should be noted that for the magnetic field directed along 1, ${}^mS_{11}^B$ and ${}^mS_{12}^B$ should be replaced by following equations [8]

$$ {}^ms_{11}^B = {}^ms_{11} - \frac{{}^mq_{11}^2(H) + {}^mq_{12}^2(H)}{u_{11}} \tag{5} $$

$$ {}^ms_{12}^B = {}^ms_{12} - \frac{{}^mq_{11}^2(H) + {}^mq_{12}^2(H)}{u_{11}} \tag{6} $$

where ${}^mq_{11} = d\lambda_{11}/dH_1$, ${}^mq_{12} = d\lambda_{12}/dH_1$ are piezomagnetic coefficients, λ_{11} and λ_{12} are the magnetostrictive coefficients, and μ_{11} is the permeability.

In the orthogonal coordinate system, as shown in Fig. 1 (on the right), the equation of elastodynamics for the piezoelectric phase, is given by:

$$ {}^pS_1 = \frac{\partial {}^pu_x}{\partial x} \tag{7} $$

$$ {}^p\rho\frac{\partial^2 {}^pu_x}{\partial t^2} = \frac{\partial {}^pT_1}{\partial x} \tag{8} $$

where ${}^pu_x$ and ${}^p\rho$ are displacement and the density of the piezoelectric phase. According to Eq. (1), ${}^pT_1$ can be obtained as:

$$ {}^pT_1 = \frac{{}^pS_1 - {}^pd_{31}{}^pE_3}{{}^pS_{11}}. \tag{9} $$

The general solution of Eq. (8) is given by:

$$ {}^pu_x = A_1\sin(k_Ex) + A_2\cos(k_Ex) \tag{10} $$

Due to the symmetry of the stress tensor, the ${}^pu_x$ should be zero when $x = 0$.

Thus Eq. (9) can be rewritten as:

$$ {}^pu_x = A_1\sin(k_Ex) \tag{11} $$

where $k_E = \sqrt{{}^p\rho{}^pS_{11}\omega}$. ω is angular frequency and A_1 is the coefficient to be determined.

Similarly, in cylindrical coordinate system, the equation of elastodynamic for the magnetostrictive phase can be written as

$$ {}^mS_r = \frac{\partial {}^mu_r}{\partial_r} \tag{12} $$

$$ {}^mS_\theta = \frac{{}^mu_r}{r} \tag{13} $$

$$ \frac{\partial {}^mT_r}{\partial r} + \frac{{}^mT_r - {}^mT_\theta}{r} + \rho\omega^{2m}u_r = 0 \tag{14} $$

From Eqs. (3) and (4), ${}^mT_\theta$, ${}^mT_r$ can be obtained as:

$$ {}^mT_\theta = \frac{{}^ms_{11}^B{}^mS_\theta - {}^ms_{12}^B{}^mS_r - ({}^ms_{11}^Bq_{12} - {}^ms_{12}^Bq_{11})H_1}{{}^ms_{11}^{B2} - {}^ms_{12}^{B2}} \tag{15} $$

$$ {}^mT_r = \frac{{}^ms_{11}^B{}^mS_r - {}^ms_{12}^B{}^mS_\theta - ({}^ms_{11}^Bq_{11} - {}^ms_{12}^Bq_{12})H_1}{{}^ms_{11}^{B2} - {}^ms_{12}^{B2}} \tag{16} $$

The general solution of Eq. (14) is given by:

$$ {}^mu_r = A_3J_1(k_Mr) + A_4Y_1(k_Mr) + \frac{B}{k_M{}^2r} \tag{17} $$

where $k_M = \sqrt{{}^m\rho(({}^ms_{11}^{B2} - {}^ms_{12}^{B2})/{}^ms_{11}^B)}\omega$, $B = (q_{11} - q_{12})(1 + {}^m\nu)H_1$, ${}^m\nu = {}^ms_{12}^B/{}^ms_{11}^B$; J_1 and Y_1 are the first and second kind Bessel functions of order 1, A_3 and A_4 are the coefficients to be determined.

Therefore there are three unknown coefficients, A_1, A_3 and A_4 to be determined by taking into account the three boundary conditions

$$ {}^mu_r|_{r=a} = {}^pu_x|_{x=a} \tag{18} $$

$$ {}^mT_r|_{r=a} = {}^pT_1|_{x=a} \tag{19} $$