Tunable characteristics of bending resonance frequency in magnetoelectric laminated composites*

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(Received 10 October 2012; revised manuscript received 27 December 2012)

As the magnetoelectric (ME) effect in piezoelectric/magnetostrictive laminated composites is mediated by mechanical deformation, the ME effect is significantly enhanced in the vicinity of resonance frequency. The bending resonance frequency (f_r) of bilayered Terfenol-D/PZT (MP) laminated composites is studied, and our analysis predicts that (i) the bending resonance frequency of an MP laminated composite can be tuned by an applied dc magnetic bias (H_{dc}) due to the ΔE effect; (ii) the bending resonance frequency of the MP laminated composite can be controlled by incorporating FeCuNbSiB layers with different thicknesses. The experimental results show that with H_{dc} increasing from 0 Oe (1 Oe=79.5775 A/m) to 700 Oe, the bending resonance frequency can be shifted in a range of 32.68 kHz $\leqslant f_r \leqslant$ 33.96 kHz. In addition, with the thickness of the FeCuNbSiB layer increasing from 0 μm to 90 μm, the bending resonance frequency of the MP laminated composite gradually increases from 33.66 kHz to 39.18 kHz. This study offers a method of adjusting the strength of dc magnetic bias or the thicknesses of the FeCuNbSiB layer to tune the bending resonance frequency for ME composite, which plays a guiding role in the ME composite design for real applications.

Keywords: magnetoelectric effect, bending resonance frequency, composite materials

PACS: 75.85.+t, 75.80.+q, 85.50.–n, 77.84.Lf **DOI:** 10.1088/1674-1056/22/7/077505

1. Introduction

In a magnetostrictive/piezoelectric composite, the magnetoelectric (ME) effect is the result of a "product property", i.e., the mechanical deformation due to magnetostriction results in a dielectric polarization due to the piezoelectric effect.[1] Such an ME effect is dependent on the frequency of the applied ac magnetic field.[2–5] Recent research on the frequency-dependent ME response in the ME composite revealed that the value of the ME voltage coefficient (MEVC) at resonance exceeds the low-frequency value by a factor from several tens to hundreds due to magnetomechanical or electromechanical resonance.[6–10] It has been proved that the large MEVC at the resonance frequency makes the ME composites suitable for applications in magnetic field sensors, transformers, actuators, and transducers.[11–16]

However, for the usual ME laminated composite, the resonance bandwidth is narrow, and the resonant peak is sharp and fixed. Any small deviation from the resonance point will cause a remarkable decrease of the ME voltage coefficient and a corresponding severe degradation of the ME composite's performance. This fact restricts wider applications of ME resonant mode devices. Typically, by selecting materials with a lower mechanical quality factor, a wide-band frequency response can be obtained. Unfortunately, this will result in a notable decrease in the maximum ME voltage. Furthermore, Yu *et al.*[17] have demonstrated the wide-band ME response by combining several Terfenol-D/epoxy-Pb(Zr,Ti)O_3 bilayers in parallel and series electrical connections. However, the overall magnitude of the MEVC at the resonance frequency decreases significantly, and the effective peak is not smooth. Wang *et al.*[18] have studied piezoelectric frequency-tunable transducer. Due to the effect of electric load on the characteristics of piezoelectric vibration system, the frequency-tuning is achieved by adjusting the electric load. Similarly, the resonance frequency for an ME composite strongly depends on the average sound velocity of the composite. The average sound velocity changes continually with the size of ME composite and the applied dc bias magnetic field. Correspondingly, its resonance frequency can be tuned. To date, studies have focused on the tunable characteristics of resonance frequency in ME composites.[19–21] Bi *et al.*[19,20] have reported that the resonance frequency can be controlled by varying the length of a rectangular Ni–PZT–Ni layered composite and the diameter of a cylindrical Ni–PZT–Ni layered composite. This characteristic widens the application scope of ME composites. However, quite a low magnetostriction ($\lambda_s \approx 2.7$ ppm) of Ni results in a small ME voltage coefficient for the Ni–PZT–Ni layered composite. Zhao *et al.*[21] have found that for a trilayered Terfenol-D/PZT/Terfenol-D laminated composite, the resonance frequency can be shifted with the increase of state magnetic field (i.e., dc-bias magnetic field) and a high MEVC can be obtained. However, a disadvantage of the trilayered Terfenol-D/PZT/Terfenol-D laminated composite is that the resonance frequency in the length vibration mode is usually

*Project supported by the National Natural Science Foundation of China (Grant Nos. 50830202 and 61071042) and the National High Technology Research and Development Program of China (Grant No. 2012AA040602).

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quite high, which could bring about significant eddy current loss for the large magnetostrictive earth rare alloy Terfenol-D, correspondingly reducing the conversion efficiency of the magnetoelectric energy severely.[22] In fact, an alternative solution is to reduce the operating frequency by using an ME composite with an asymmetrical structure.

Due to the asymmetrical stress distributions in the magnetostrictive and piezoelectric layers, flexural deformation will occur when an external magnetic field is applied to the bilayered magnetostrictive/piezoelectric composite. A bending vibration is also observed in a bilayered ME composite besides the length vibration mode that usually exists in the symmetrical composites such as trilayered and multilayered composites. The bilayer composite operating in the bending vibration mode has lower resonance frequency and stronger ME coupling compared with operating only in the length vibration mode, which enables a tuning frequency with large an MEVC and quite lower eddy current loss.

In this paper, we report on the tunability of the bending resonant frequency of bilayered Terfenol-D/PZT (MP) laminated composite by an applied dc magnetic bias and controlling the frequency shift for an MP laminated composite by incorporating a soft magnetic amorphous alloy FeCuNbSiB. The MP laminated composite with an FeCuNbSiB layer not only yields a giant ME output, but also keeps its size small. It makes these ME composites suitable for practical applications.

Figures 1(a) and 1(b) show the two configurations of the MP and Terfenol-D/PZT/FeCuNbSiB (MPF) laminated composites, respectively. The sizes of Terfenol-D and PZT are 12 mm × 6 mm × 1 mm and 12 mm × 6 mm × 0.8 mm respectively. The dimensions of FeCuNbSiB ribbon (International standard trademark 1K107) are 12 mm in length, 6 mm in width and 30 μm in thickness. Figures 1(c) and 1(d) show the definitions of local coordinates in PZT and Terfenol-D. The PZT plate is polarized in the thickness direction (direction 3). The Terfenol-D plates are magnetized along the longitudinal direction (direction 3).

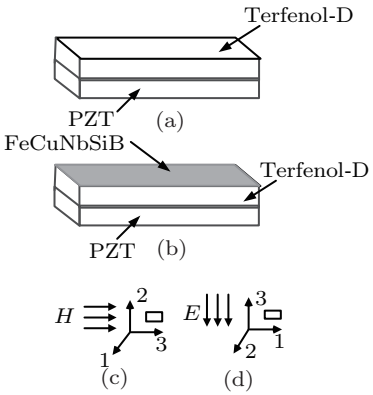


Fig. 1. (a) Configurations of Terfenol-D/PZT laminated composite, (b) Terfenol-D/PZT/FeCuNbSiB laminated composite, and definitions of local coordinates in (c) Terfenol-D and (d) PZT8, respectively.

2. Theoretical analysis

The bending resonance frequency of the bilayered ME laminated composite is given by[22]

$$f_n^{\mathrm{B}} = \frac{\pi d}{2\sqrt{12}l^2}\overline{V}\beta_n^2, \tag{1}$$

where $\beta_n \approx n + 1/2$, $\overline{V}$ is the average sound velocity, d is the thickness, and l is the length, n is the order bending vibration mode. When $n = 1$, it is the first-order bending vibration mode.

The average sound velocity $\overline{V}$ of the ME laminated composite can be derived from the classical plate theory combined with a simple composite principle[22]

$$\overline{V} = \sqrt{\frac{\bar{E}}{\bar{\rho}}}, \tag{2}$$

where $\bar{\rho}$ and $\bar{E}$ are the average density and the average Young's modulus of the ME laminated composite, respectively.

Substituting Eq. (2) into Eq. (1) yields

$$f_n^{\mathrm{B}} = \frac{\pi d}{2\sqrt{12}l^2}\sqrt{\frac{\bar{E}}{\bar{\rho}}}\beta_n^2. \tag{3}$$

According to Eq. (3), the bending resonance frequency of the ME composites depends on the Young's modulus E. For the magnetostrictive material, the Young's modulus E varies with applied dc magnetic field. Clark and Savage[23] have reported that the largest $\Delta E/E$ for Terfenol-D reaches 161% at a dc magnetic field of 4.3 kOe. The fact is that the dependence of Young's modulus on H_{dc} is related to the different domain magnetizing behaviors under various values of the applied dc magnetic field. The ΔE effect of magnetostrictive material (ΔE) in an applied dc magnetic bias H_{dc} is expressed as[24]

$$\frac{\Delta E}{E_{\mathrm{m}}} = \frac{9M_{\mathrm{s}}^2\lambda_{\mathrm{s}}^2}{8K_{\mathrm{u}}^3}H_{\mathrm{dc}}^2 E_{\mathrm{m}}, \tag{4}$$

where E_{m}, M_{s}, and λ_{s} are Young's modulus, saturation magnetization, and saturation magnetostriction constant, respectively, and K_u is the uniaxial anisotropy with the easy axis vertical to H_{dc}.

For the MP composite, the equivalent Young's modulus $\bar{E}$ and the average density $\bar{\rho}$ are respectively determined by

$$\bar{E} = n_{\mathrm{m}}E_{\mathrm{m}} + n_{\mathrm{p}}E_{\mathrm{p}}, \tag{5}$$

and

$$\bar{\rho} = n_{\mathrm{m}}\rho_{\mathrm{m}} + n_{\mathrm{p}}\rho_{\mathrm{p}}, \tag{6}$$

where E_{p} and E_{m} are the Young's moduli of PZT and Terfenol-D, respectively, ρ_{p} and ρ_{m} are the densities of PZT and Terfenol-D, respectively, n_{m} and n_{p} are the geometrical factors

describing the cross-sectional area ratios (or volume fraction) of PZT and Terfenol-D, respectively.

The dependence of H_{dc} on E_m results in the dependence of H_{dc} on $\bar{E}$ according to Eqs. (4) and (5). Correspondingly, the bending resonance frequency of the ME composite strongly depends on the dc magnetic field.

On the other hand, the bending resonance frequency can be shifted by changing the average Young's modulus $\bar{E}$ of the ME composite. The equivalent Young's modulus $\bar{E}$ and the average density $\bar{\rho}$ for the MPF composite, are respectively determined by

$$\bar{E} = n_m E_m + n_p E_p + (1 - n_m - n_p) E_f, \tag{7}$$

and

$$\bar{\rho} = n_m \rho_m + n_p \rho_p + (1 - n_m - n_p) \rho_f, \tag{8}$$

where E_f is the Young's modulus of FeCuNbSiB, and ρ_f is the density of FeCuNbSiB.

Because the Young's modulus of FeCuNbSiB is higher than the Young's moduli of PZT and Terfenol-D, by incorporating a soft magnetic amorphous alloy FeCuNbSiB, the $\bar{E}$ of Terfenol-D/PZT composite increases. Moreover, the $\bar{\rho}$ of Terfenol-D/PZT composite decreases due to the small density of FeCuNbSiB. Consequently, the bending resonance frequency increases with the thickness of the FeCuNbSiB layer increasing according to Eq. (3).

Substituting the parameters in Table 1 into Eq. (3), the bending resonance frequencies in MPF and MP laminated composites are calculated to be 33.754 kHz and 32.9 kHz, respectively. By incorporating an FeCuNbSiB layer, the bending resonant frequency of MP laminated composite increases 0.854 kHz.

Table 1. Material performances of PZT, Terfenol-D, and FeCuNbSiB.

Material	Density/kg·m^{-3}	Young's modulus/GPa
PZT	7600	90.9
Terfenol-D	9200	29
FeCuNbSiB	7250	110

The calculated bending resonant frequencies for MPF laminated composites at different thicknesses of FeCuNbSiB layer are also shown in Fig. 2. The resonant frequency of layered MPF composite strongly depends on the thickness of FeCuNbSiB layer. It increases almost linearly with the thickness of FeCuNbSiB increasing from 0 μm to 120 μm.

Obviously, the bending resonant frequency of the MP laminated composite can be controlled by incorporating FeCuNbSiB layer and be tunable by an applied dc magnetic bias.

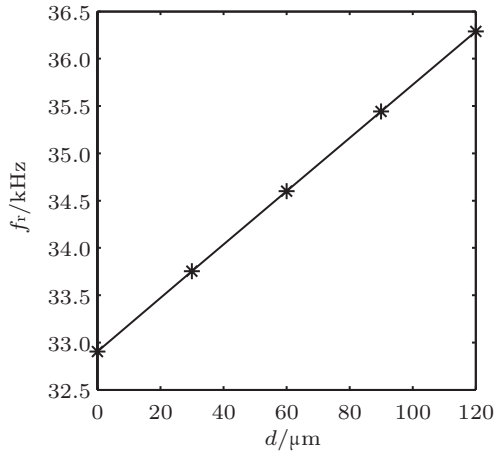


Fig. 2. Calculated bending resonant frequencies f_r at different thicknesses d of FeCuNbSiB.

3. Experiment

The MP and MPF composites were fabricated by the following steps. First, the Terfenol-D plate, PZT plate, and multiple FeCuNbSiB ribbon plates were dipped in an organic impregnant to clean them. After that, the samples were prepared by stacking and then bonding the multiple plates with epoxy (as shown in Figs. 1(a) and 1(b). The samples were cured at 80 °C for 1 h for good mechanical coupling.

When the Terfenol-D plate was vibrating, as induced by ac magnetic field, it would force PZT to vibrate. Consequently, the ME laminate composites would generate an output voltage. The electric current in the coil was monitored by measuring the voltage across the resistor which was connected in series with the long straight solenoid. The bias dc magnetic field applied to the ME laminated composite was generated by using a pair of annular permanent magnets (Nd–Fe–B), and measured by a Gauss meter. Both the ac magnetic field and the dc magnetic bias were parallel to the longitudinal direction of the device. For detecting the ME voltage, the ac magnetic field was generated by applying a sine signal to the solenoid. The induced ME voltage dV across the two electrodes of the PZT plate was measured by an oscilloscope (Tektronix, TDS2022B). The MEVC was calculated according to $\alpha = \mathrm{d}V/\mathrm{d}H$, where d$H$ is kept as 1 Oe. All the experiments were carried out at room temperature and ambient pressure.

4. Results and discussion

The variations in the MEVC with the bending resonance frequency f_r for different values of dc magnetic bias are displayed in Fig. 3. A sharp resonance peak is observed for each H_{dc}. In the resonant peak there occurs a shift with the magnetic field increasing from 0 Oe to 700 Oe. The resonant frequency f_r and resonant MEVC exhibit a significant dependence on dc magnetic bias as shown in Fig. 4. It is seen that as applied bias field increases, f_r first goes down quickly to a critical value

f_{min} (32.68 kHz) and then slightly increases. As mentioned previously, the value of f_r varies with dc bias increasing due to the change of elastic stiffness induced by magnetostriction. The experimental result is in agreement with the theoretical prediction. Figure 4 demonstrates a pronounced shifting of the resonance frequency from $f_r = 33.96$ kHz for H_{dc} =0 Oe to $f_r = 32.68$ kHz for $H_{dc} = 373$ Oe. This means that f_r is adjustable by simply changing the dc magnetic bias. Furthermore, the resonant MEVC increases with applied bias field increasing up to 700 Oe. And the maximum resonant MEVC achieves 1.85 V/Oe [23.125 V/(cm·Oe)] under $H_{dc} = 700$ Oe.

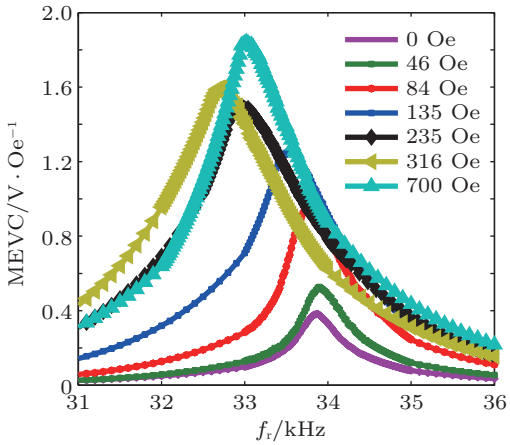


Fig. 3. (color online) Variations of MEVC for Terfenol-D/PZT laminated composite with bending resonant frequency f_r at several different values of H_{dc} ranging from 0 Oe to 700 Oe.

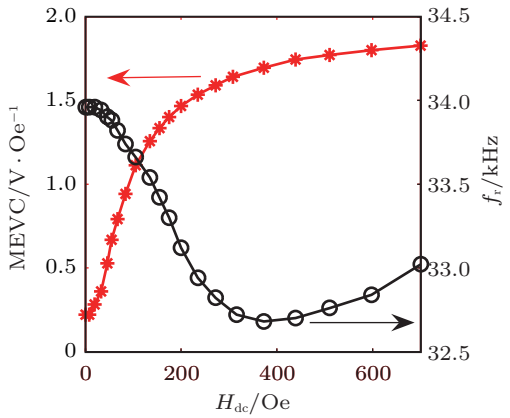


Fig. 4. (color online) Bending resonant frequency and resonant MEVC for the Terfenol-D/PZT laminated composite versus H_{dc} ranging from 0 Oe to 700 Oe.

Figures 5(a)–5(c) show the variations of bending resonant frequencies for the MPF laminated composites with three different thickness values of FeCuNbSiB (t) with dc magnetic field. In all cases, the bending resonant frequency strongly depends on H_{dc}. As H_{dc} increases, bending resonant frequency first increases until it reaches a maximum value, and then goes down quickly to a minimum value, and next slightly increases as the field increases. It can be seen from Figs. 4 and 5 that there are some discrepancies in the change tendency of bending resonant frequencies for the MP and MPF laminated composites. It is mainly because the Young's modulus E for the FeCuNbSiB material varies with the applied dc magnetic field. By incorporating FeCuNbSiB ribbon, the $\bar{E}$ for the MPF composite changes. Correspondingly, there is a change in sound velocity inside the MPF composite. Furthermore, the bending resonant frequency can be seen to notably increase with the thickness of FeCuNbSiB increasing. The maximum bending resonant frequency of the MP laminated composite after incorporating FeCuNbSiB layer increases to 39.227 kHz at $t = 90$ μm.

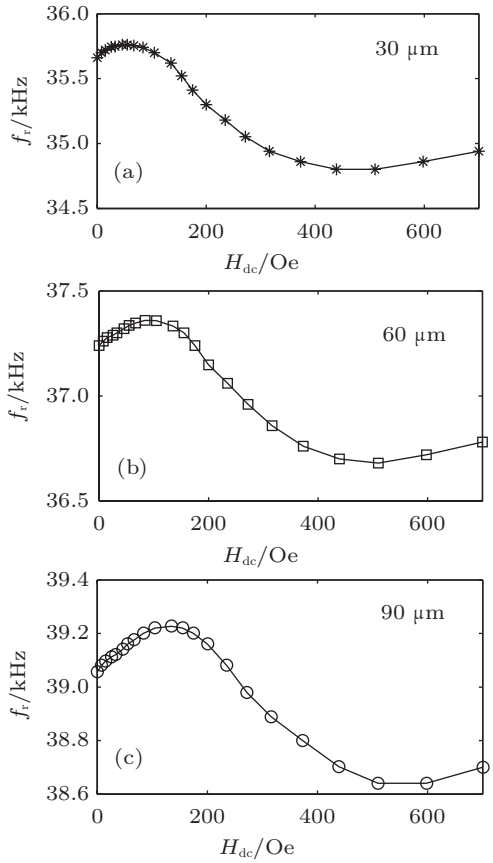


Fig. 5. Variations of bending resonant frequencies for the MPF laminated composites with three different thickness values of FeCuNbSiB with H_{dc} ranging from 0 Oe to 700 Oe: (a) 30 μm, (b) 60 μm, and (c) 90 μm.

For comparison, the dependence of the MEVC on ac magnetic field frequency f_r at $H_{dc} = 105$ Oe for the MPF laminated composites with four different thickness values of FeCuNbSiB layer are shown in Fig. 6. One observes that the bending resonance frequency and MEVC of the MP laminated composite depend strongly on the thickness of FeCuNbSiB layer. With the thicknesses of FeCuNbSiB layer increasing from 0 μm to 90 μm, the bending resonance frequencies of the MP laminated composites gradually increase from 33.66 kHz to 39.18 kHz. Such a variation essentially can be attributed to the changing of the average Young's modulus $\bar{E}$ of the MPF composite. It results in a relatively large frequency shift. Equation (3) gives better physical explanations to the variation in bending resonant frequency. Furthermore, figure 7 shows that resonant frequency for the laminated composite exhibits

a good linearity in the whole range of measurement for all thickness values, which indicates that the resonance frequency of MP laminated composite can be controlled by changing the thickness of the FeCuNbSiB layer. The calculated value is slightly lower than the experimental value. The discrepancy results from the glue plate, which increases the average sound velocity of the laminate. The deviation of the predicted value from the experimental value may result from the bonding effect.

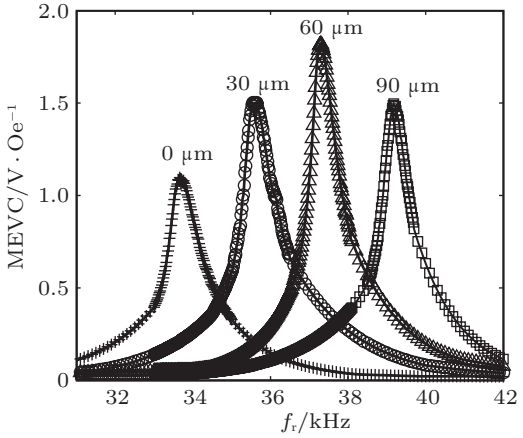


Fig. 6. Variations of ME voltage coefficients for the MPF laminated composites with four different the thickness values of FeCuNbSiB layer with frequency at $H_{dc} = 105$ Oe.

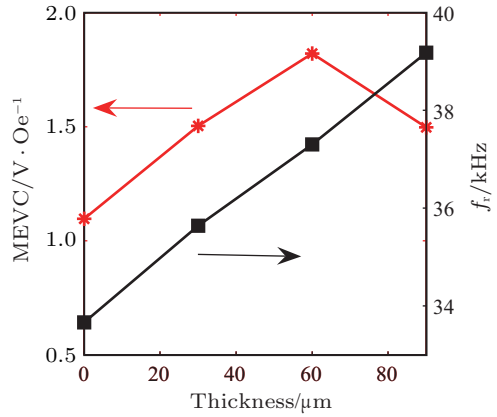


Fig. 7. (color online) Dependence of the bending resonance frequency f_r and the maximum of MEVC on the thickness of FeCuNbSiB d.

The maximum of the MEVC of the composite increases until it reaches a certain maximum value 1.855 V/Oe (23.1875 V/(cm·Oe)) and then decreases (shown in Fig. 7).

5. Conclusion

The bending resonance frequency of Terfenol-D/PZT (MP) laminated composite is investigated. The study demonstrates that (i) the H_{dc} dependence of the Young's modulus results in the H_{dc} dependence of the bending resonance frequency. The bending resonance frequency of an MP laminate can be continuously tuned by an applied dc magnetic field in a wide range from 32.68 kHz to 33.96 kHz; (ii) by incorporating an FeCuNbSiB layer, the bending resonant frequency of the MP laminated composite increases. It increases almost linearly with the thickness of FeCuNbSiB layer increasing. Thus, one can control the bending resonance frequency by changing the strength of H_{dc} and the thickness of the FeCuNbSiB layer, which makes these layered ME composites suitable for practical applications in multifunctional devices such as electromagnetic sensors and transducer devices.

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