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The magnetostrictive material effects on magnetic field sensitivity for magnetoelectric sensor

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The magnetic sensitivity to magnetic field for the magnetoelectric (ME) sensor is studied. Theoretical analysis predicts that the ME voltage sensitivity to H_{ac} (i.e., $\partial V_{\mathrm{ME}}/\partial H_{\mathrm{ac}}$ under dc bias field) and the ME voltage sensitivity to H_{dc} (i.e., $\partial V_{\mathrm{ME}}/\partial H_{\mathrm{dc}}$ under ac bias field) for the ME sensor are significantly dependent on the product of the effective mechanical quality factor of the ME sensor Q_{m}, the saturation magnetostriction λ_s of the magnetostrictive material, and the square of magnetic permeability μ_{r}. The experimental results demonstrate that the greatest value of $\partial V_{\mathrm{ME}}/\partial H_{\mathrm{ac}}$ for the FeCuNbSiB/PZT-8/FeCuNbSiB (FePFe) sensor reaches 10 V/Oe due to the largest product of the Q_{m}, λ_s and the square of μ_{r}, relative to FeNi-FACE/PZT-8/FeNi-FACE (FPF) and Terfenol-D/PZT-8/Terfenol-D (MPM) sensors. Meanwhile, the maximum value of $\partial V_{\mathrm{ME}}/\partial H_{\mathrm{dc}}$ for FePFe sensor achieves 242.2 mV/Oe, which is $\sim$10 times higher than that of the FPF sensor and $\sim$4 times higher than that of the MPM sensor. To obtain the high magnetic sensitivity to dc and ac magnetic field, the mechanical quality factor, the magnetic permeability and the saturation magnetostriction should both be taken into account in selecting the suitable magnetostrictive material. © *2012 American Institute of Physics*. [doi:10.1063/1.3670607]

I. INTRODUCTION

The ME laminated composite converting magnetic energy directly into electrical energy has been used as a magnetic field sensor.[1,2] In general, it is an important method to adopt the suitable magnetostrictive material to improve the magnetic sensitivity to the magnetic field. In previous reports,[3,4] most researches have focused on selecting materials with strong magnetostrictive performance and high mechanical quality factor for higher ME sensitivity, and the magnetic permeability of magnetostrictive material have been hardly taken into account. Actually, the magnetic permeability has a noticeable influence on the ME sensitivity for the ME composite.

In this paper, the theoretical analysis indicates that the ME voltage sensitivity to H_{ac} (i.e., ME voltage coefficient (MEVC)) and the ME voltage sensitivity to H_{dc} for the ME composite sensor are significantly dependent on the product of the effective mechanical quality factor of the ME composite sensor Q_{m}, the saturation magnetostriction λ_s of the magnetostrictive material, and the square of the magnetic permeability μ_{r}. So adopting an alternative magnetostrictive material to improve the magnetic sensitivity to dc and ac magnetic field is an important method. The experimental results demonstrate that the highest $\partial V_{\mathrm{ME}}/\partial H_{\mathrm{ac}}$ and $\partial V_{\mathrm{ME}}/\partial H_{\mathrm{dc}}$ for the FePFe sensor are owing to the largest product of the Q_m, λ_s and the square of μ_r, which agree with the theoretical analysis.

II. THEORETICAL ANALYSIS

Figure 1 shows the schematic of the ME composite sensor used in this investigation. The ME composite sensor is a sandwich of one piezoelectric layer bonded between two magnetostrictive layers. The magnetostrictive layers are longitudinally magnetized; the piezoelectric ones are transversely poled. When an external magnetic field H (which consists of the dc bias magnetic field H_{dc} and alternative magnetic field H_{ac}) is aligned along the longitudinal direction and a strain in magnetostrictive layers is generated by the magnetostrictive effect, that is transferred to the bonded piezoelectric layer due to the stress-strain coupling of the interlayer. Then the transverse piezoelectric effect leads to a voltage.

Based on the magneto-elasto-electric equivalent circuit method, the MEVC at resonance α_r can be derived as[5]

$$\alpha_r = \left|\frac{\partial V_{ME}}{\partial H_{ac}}\right| = \frac{8Q_m}{\pi^2}\frac{d_{31,p}d_{33,m}n(1-n)t_c}{\varepsilon_{33}^T[(1-k_{31}^2)ns_{11}^E+(1-n)s_{33}^H]}, \quad (1)$$

where V_{ME} is the induced ME voltage across the thickness of the piezoelectric plate under the drive of H_{ac}, n is the thickness ratio of the magnetostrictive layer in the composite, t_c is the thickness of the magnetostrictive layer, k_{31} is the electromechanical coupling coefficient of the piezoelectric material, $d_{33,m}$ is the piezomagnetic coefficient $d_{31,p}$ is the piezoelectric coefficient, ε_{33}^T is the permittivity under constant stress in the piezoelectric layer, s_{33}^H and s_{11}^E are the longitudinal elastic compliance at constant H_{dc} and the elastic compliance at constant E (electric field), respectively. The effective mechanical quality factor of the ME sensor Q_{m} can be derived as[5]

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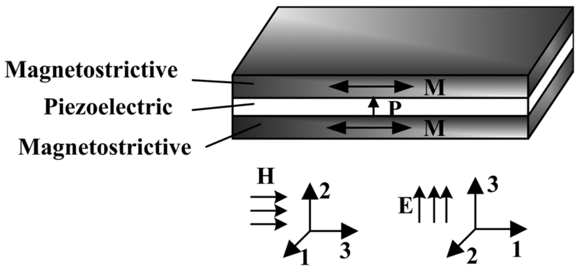

FIG. 1. Schematic diagram of the ME composite sensor.

$$\frac{1}{Q_m} = \frac{n}{Q_{mag}} + \frac{(1-n)}{Q_{piez}}, \tag{2}$$

where $Q_{\rm mag}$ and $Q_{\rm piez}$ are the effective mechanical quality factor of the magnetostrictive material and the piezoelectric material, respectively. From Eq. (2), $Q_{\rm m}$ of ME sensor depends on $Q_{\rm mag}$ of the magnetostrictive material and $Q_{\rm piez}$ of the piezoelectric material. Hence, $Q_{\rm mag}$ and $Q_{\rm piez}$ are the key factors controlling the magnitude of $Q_{\rm m}$.

When the applied $H_{\rm ac}$ is much smaller than the superimposed applied dc magnetic bias $H_{\rm dc}$, the corresponding piezomagnetic coefficient $d_{33,m}$ can be given as[6]

$$d_{33,m} = \frac{3\lambda_s \mu_r^2}{M_S^2} H_{dc}. \tag{3}$$

Substituting Eq. (3) into Eq. (1) yields

$$\alpha_r = \left|\frac{\partial V_{ME}}{\partial H_{ac}}\right| = \frac{8Q_m}{\pi^2}\frac{3\lambda_s\mu_r^2 H_{dc}}{M_S^2}\frac{d_{31,p}n(1-n)t_c}{\varepsilon_{33}^T[(1-k_{31}^2)ns_{11}^E + (1-n)s_{33}^H]}. \tag{4}$$

The prior reported that the induced ME voltage for ME sensor have a linear relationship with $H_{\rm ac}$ at resonance.[7] Hence, V_{ME} can be expressed by

$$V_{ME} = \frac{8Q_m}{\pi^2} d_{33,m} H_{ac} \frac{d_{31,p}n(1-n)t_c}{\varepsilon_{33}^T[(1-k_{31}^2)ns_{11}^E + (1-n)s_{33}^H]}. \tag{5}$$

Due to the strong dependence of ME effect on $H_{\rm dc}$, the dependence of the ME voltage on $H_{\rm dc}$ at resonance can be obtained by the derivative of Eq. (5) with respect to $H_{\rm dc}$, given as

$$\frac{\partial V_{ME}}{\partial H_{dc}} = \frac{8Q_m}{\pi^2}\frac{3\lambda_s\mu_r^2}{M_S^2} H_{ac}\frac{d_{31,p}n(1-n)t_c}{\varepsilon_{33}^T[(1-k_{31}^2)ns_{11}^E + (1-n)s_{33}^H]}. \tag{6}$$

According to Eq. (4), the MEVC at resonance is directly proportional to the product of the mechanical quality factor $Q_{\rm m}$, the saturation magnetostriction λ_s of the magnetostrictive material and the square of magnetic permeability $\mu_{\rm r}$. Hence, the higher product of $\mu_{\rm r}$, λ_s, and $Q_{\rm m}$ results in the higher MEVC of the ME sensor at resonance. Correspondingly, the ME sensitivity (under resonant drive) to $H_{\rm ac}$ is increased. In this case, a constant dc magnetic bias is applied along the length axis of the sensor, and small variations in $H_{\rm ac}$ can be detected. Meanwhile, the ME effect is also strongly dependent on $H_{\rm dc}$. From Eq. (6), the ME sensitivity at resonance to $H_{\rm dc}$ is also directly proportional to the product of λ_s, Q_m and the square of $\mu_{\rm r}$. Clearly, to obtain the higher magnetic sensitivity to dc and ac magnetic field, the mechanical quality factor $Q_{\rm mag}$, the magnetic permeability $\mu_{\rm r}$ and the saturation magnetostriction $\lambda_{\rm s}$ should be taken into account as a whole when it comes to selecting the suitable magnetostrictive material.

III. EXPERIMENT

For validating the theoretical analysis, the three different magnetostrictive materials of the soft magnetic amorphous ribbon FeCuNbSiB ($Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$), ferromagnetic alloy with constant elasticity (FeNi-FACE) and giant magnetostrictive material (Terfenol-D) are prepared. Table I summarizes the magnetostrictive material characteristics of FeCuNbSiB, FeNi-FACE and Terfenol-D. It can be seen that FeCuNbSiB exhibits the highest relative permeability ($\mu_{\rm r} > 100\,000$ (f = 1 kHz)), Terfenol-D has the largest saturation magnetostriction ($\lambda_{\rm s} = 2000$ ppm) and FeNi-FACE presents the greatest mechanical quality factor ($Q_{\rm mag} = 2282$).

We design and fabricate three sensors of FPF, MPM, and FePFe. The dimensions of FeNi-FACE, Terfenol-D, and PZT-8 are $12 \times 6 \times 0.6$ mm^3, $12 \times 6 \times 1$ mm^3, and $12 \times 6 \times 0.8$ mm^3, respectively. The dimensions of the FeCuNbSiB ribbon are 12 mm in length, 6 mm in width, and 30 μm in thickness. The FeCuNbSiB ($12 \times 6 \times 0.18$ mm^3) layer is prepared by stacking and bonding six FeCuNbSiB ribbons. The ME sensors are bonded with an insulated epoxy adhesive (as shown in Fig. 1).

For the ME voltage coefficient measurement, a pair of annular permanent magnets is used to apply dc magnetic field, and the samples are placed in the center of the long straight solenoid under an ac magnetic field $H_{\rm ac}$. The ME voltage V_{ME} is monitored over resonant frequency under various $H_{\rm dc}$ superimposed $H_{\rm ac}$ using a lock-in amplifier (Stanford, SR830). The resonant MEVC is calculated by $\alpha_r = \Delta V_{ME}/\Delta H_{ac}$ based on the fact that induced ME voltage has a linear relationship with $H_{\rm ac}$. All the experiments are carried out at room temperature and ambient pressure.

IV. RESULTS AND DISCUSSION

The ME voltage coefficient spectrum near resonance of the ME sensors with different magnetostrictive materials under $H_{\rm dc} = 84$ Oe are illustrated in Fig. 2. From the ME voltage coefficient spectrum, the effective mechanical quality factor of ME sensors $Q_{\rm m}$ can be evaluated by 3-dB

TABLE I. The material performance of FeCuNbSiB, Terfenol-D, and FeNi-FACE.

Material	Performance parameters		
	λ_s (ppm)	$\mu_{\rm r}$	$Q_{\rm mag}$
FeCuNbSiB[a]	2.7	>100 000	>1000
Terfenol-D[b]	2000	<20	<40
FeNi-FACE[c]	11	30	2282

[a]Cited from Foshan Huaxin Microlite Metal Co., Ltd., China.
[b]Cited from Taizhou Jiaoguang Rare Earth Materials Co., Ltd., China.
[c]Cited from Chongqing Instrument Materials Research Institute, China.

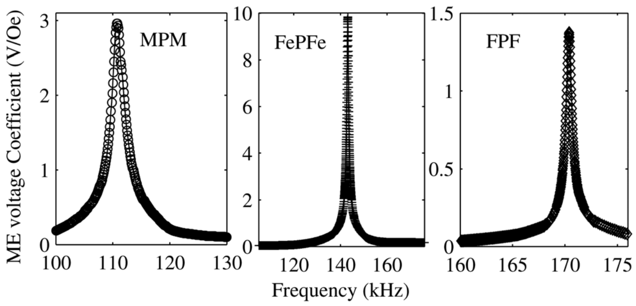

FIG. 2. The ME voltage coefficient spectrum near resonance at 84 Oe dc magnetic bias.

bandwidth method.[8] The FPF sensor obtains the largest Q_m of 370.43 due to the high mechanical quality factor in FeNi-FACE ($Q_{mag} = 2282$), which is ~ 3.82 times higher than that of the MPM sensor and ~ 1.55 times higher than that of the FePFe sensor. But it is found that the product of the effective Q_m, λ_s and the square of μ_r is the greatest for the FePFe sensor among all three samples, which indicates its $\partial V_{ME}/\partial H_{ac}$ and $\partial V_{ME}/\partial H_{dc}$ should be the largest.

Figure 3 shows the resonant ME voltages for MPM, FePFe, and FPF sensors responding to ac magnetic fields H_{ac}, taken at optimum dc magnetic bias ($H_{dc,opti}$). This figure reveals that the induced ME voltage for ME sensor has a linear relationship with H_{ac} at resonance frequency and the slope is just the dynamic MEVC. The values of $\partial V_{ME}/\partial H_{ac}$ for FePFe, FPF and MPM sensors are evaluated to be 10 V/Oe at $H_{dc,opti} = 84$ Oe, 3.03 V/Oe at $H_{dc,opti} = 316$ Oe, and 3.024 V/Oe at $H_{dc,opti} = 200$ Oe, respectively, which agree with the previous prediction. Although the saturation magnetostriction λ_s of FeCuNbSiB is only 2.7 ppm, the magnetic permeability of FeCuNbSiB directly affects its effective piezomagnetic coefficient according to Eq. (3). The high permeability causes its large effective $d_{33,m}$ due to a low saturation field.[9] At the same time, the FePFe sensor exhibits a high effective mechanical quality factor ($Q_m = 238.5$). Hence, a high $\partial V_{ME}/\partial H_{ac}$ can be achieved.

The ME voltages of the MPM, FePFe, and FPF sensors with dc magnetic field under a resonant excitation $H_{ac} = 1$ Oe are shown in Fig. 4. The maximum value of $\partial V_{ME}/\partial H_{dc}$ for the FePFe sensor is calculated as 242.2 mV/Oe at

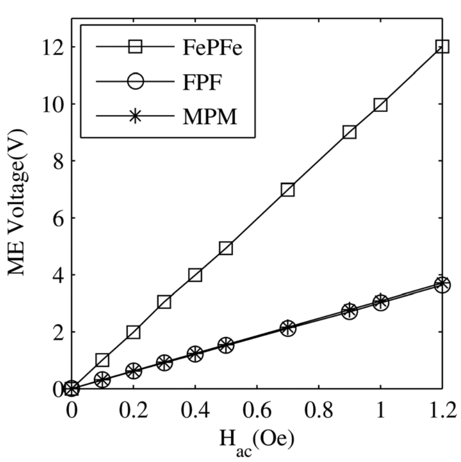

FIG. 3. Resonant ME voltages for MPM, FePFe, and FPF sensors responding to ac magnetic fields H_{ac} at the optimum dc magnetic bias $H_{dc,opti}$.

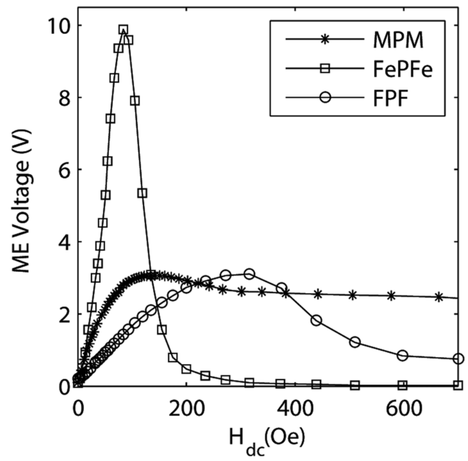

FIG. 4. Resonant ME voltages for MPM, FePFe, and FPF sensor responding to dc magnetic fields under $H_{ac} = 1$ Oe.

$H_{dc} = 55$ Oe, which is ~ 10 times higher than that of the FPF sensor (24.49 mV/Oe) and ~ 4 times higher than that of the MPM sensor (62.68 mV/Oe). The theoretical analysis gives better physical explanations on this result, and it is reasonable that $\partial V_{ME}/\partial H_{dc}$ is directly proportional to the product of the Q_m, λ_s and the square of μ_r. The highest product of Q_m, λ_s and the square of μ_r for the FePFe sensor can achieve the greatest $\partial V_{ME}/\partial H_{dc}$. Correspondingly, it has the highest sensitivity to small dc magnetic field variations, and a minute H-field variation of $H_{dc} = 3$nT at resonant frequency is still detectable for the FePFe sensor by using a lock-in amplifier.

V. SUMMARY

A theoretical analysis of the magnetic sensitivity to dc and ac magnetic field in the ME sensor is presented. The theoretical and experimental results illustrate that the $\partial V_{ME}/\partial H_{ac}$ and $\partial V_{ME}/\partial H_{dc}$ are significantly dependent on the product of the effective mechanical quality factor of the ME sensor Q_m, the saturation magnetostriction λ_s of the magnetostrictive material, and the square of μ_r. When designing high performance ME sensors, the magnetostrictive material with much higher permeability, piezomagnetic coefficient, and mechanical quality factor will be more suitable.

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