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Dynamic Magneto-mechanical Behavior of Magnetization-graded Ferromagnetic Materials

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This study investigates the dynamic magneto-mechanical behavior of magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB (MF). We measure the dynamic magneto-mechanical properties as a function of the DC bias magnetic field (H_{dc}). Our experimental results show that these dynamic magneto-mechanical properties are strongly dependent on the DC bias magnetic field. Furthermore, the dynamic strain coefficient, electromechanical resonance frequency, Young's moduli, and mechanical quality factor of Terfenol-D/FeCuNbSiB are greater than those of Terfenol-D under a lower DC bias magnetic field. The dynamic strain coefficient increases by a factor of between one and three, under the same DC bias magnetic field. In particular, the dynamic strain coefficient of Terfenol-D/FeCuNbSiB at zero bias achieves 48.6 nm/A, which is about 3.05 times larger than that of Terfenol-D. These good performances indicate that magnetization-graded ferromagnetic materials show promise for application in magnetic sensors.

Keywords : dynamic magnetomechanical properties, dynamic strain coefficient, magnetization-graded ferromagnetic materials, magnetic sensor, magnetoelectric effect

1. Introduction

A ferromagnetic material develops large mechanical deformations, and causes them to change their shape when subjected to an external magnetic field. This phenomenon is called magnetostriction [1]. The cause of magnetostrictional change in shape is the result of the rotation of small magnetic domains in the material, which are randomly oriented when the material is not exposed to a magnetic field. The orientation of these small domains by the imposition of a magnetic field creates a strain field, which leads to the stretching or shrinking of the material in the direction of the magnetization, as a function of the applied magnetic field. Typical ferromagnetic materials are Terfenol-D, Nickel, FeNi, Metglas, FeGa and SmFe alloys, which have been successfully used in transducer, sonar, and actuator devices [2-5]. In particular, Terfenol-D ($Tb_xDy_{1-x}Fe_y$) has received significant attention over the past decades, due to its giant magnetostrictive strain (1200 ppm), strain energy density (20 kJ/m^3), and good magneto-mechanical coupling property [3, 6]. However, its small mechanical quality factor (ranging from 3 to 20), and quite low relative permeability (ranging from 3 to 10) lead to a low effective static strain coefficient (piezomagnetic coefficient) and dynamic strain coefficient *(*resonant strain coefficient) for Terfenol-D under a low H_{dc}, and to larger required magnetic biases. This causes difficulties in machining and device fabrication, and limits practical applications. In response to these shortcomings, Dong *et al.* have reported that a higher effective piezomagnetic coefficient can be achieved by incorporating a high permeability $MnZnFe_2O_4$ layer into Terfenol-D, due to magnetic flux concentration [7]. Unfortunately, this will greatly increase the size, which is disadvantageous to practical applications. Recently, Srinivasan *et al.* [8] have proposed an internal magnetic field induced by a spatially varying magnetization in a compositionally graded ferromagnetic material. Taking advantage of this, we prepared magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB (MF), consisting of the two different ferromagnetic materials, Terfenol-D and FeCuNbSiB ($Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$). Due to their different magnetic characteristics, an internal magnetic field (H_{int}) is produced. Accordingly, the

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total DC magnetic bias ($H_{\mathrm{total,dc}}$) consists of an external DC magnetic field (H_{dc}) and H_{int}, which results in large strain coefficients under a low H_{dc}, due to the strain coefficient dependence on the magnetic field. The benefits of using these magnetization-graded ferromagnetic materials are that they increase the strain coefficient under a low field, and maintain its small size.

The behavior of the magnetization-graded ferromagnetic materials in various applications is complex, because the changing conditions during operation cause changes in the material properties. A full understanding of the complexity will enable engineers to use the potential advantages of magnetization-graded ferromagnetic materials. In this paper, we discuss the dynamic behavior of magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB. We investigate the dependence of the dynamic magneto-mechanical properties on the DC bias magnetic field and frequency. We evaluate the dynamic performance by measuring its vibrational characteristics with a laser doppler vibrometer (LDV) [4]. The experimental results show that MF in a low magnetic field can obtain a relatively high dynamic strain coefficient, due to the internal magnetic field, compared with Terfenol-D. In particular, the dynamic strain coefficient for MF can achieve 48.5 nm/A at zero bias. In addition, the dynamic strain coefficient and the mechanical quality factor for MF strongly depend on the DC bias magnetic field. The good performance indicated that Terfenol-D/FeCuNbSiB would be a promising ferromagnetic material for magnetic sensor applications.

2. Experiment

Samples of the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB, employing Fe-based nanocrystalline FeCuNbSiB alloy (International standard trademark 1K107, provided by Foshan Huaxin Microlite Metal Co., Ltd., China) and Terfenol-D (Taizhou Jiaoguang Rare Earth Materials Co., Ltd., China), were prepared, as shown in Fig. 1. The Terfenol-D plate was cut into rectangular plates of dimensions 12 mm × 6 mm × 1 mm. The FeCuNbSiB ribbon is a material of high magnetic permeability ($\mu_r > 10000$), high saturation magnetization ($\mu_0 M_s = 1.45\mathrm{T}$), low magnetostriction ($\lambda = 2.7$ ppm), and large anisotropic constant ($-30000\ \mathrm{J/m^3}$) [9]. Its dimensions are 12 mm × 6 mm × 0.03 mm. The FeCuNbSiB layer was prepared by the stacking and bonding of two FeCuNbSiB ribbons. The magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB was bonded using an epoxy adhesive, and cured at 80 °C for 1 h under load, to provide a strong bond between the layers. The two ferromagnetic materials were both magnetized along the longitudinal direction.

The experimental setup for investigating the dynamic magneto-mechanical behavior is shown in Fig. 2. A pair of annular permanent magnets (NdFeB) was used to generate the DC bias magnetic field (H_{dc}), which was monitored by Gauss meter. A constant current was applied in a helix coil with a turn number of 245, cylindrical length of 67 mm, and cylindrical diameter of 41 mm; correspondingly, an AC magnetic field (H_{ac}) was excited at the center of the cylindrical shell. The measured sample was placed at the center of the solenoid, in which AC and DC uniform magnetic fields were generated along the longitudinal direction. It was driven to vibrate around the $\lambda/2$ longitudinal resonance, by H_{ac} superimposed H_{dc}. The vibration velocity v at the end faces of the samples was measured by Laser Doppler vibrometer (Polytec Model OFV-5000, Germany) [4]. The dynamic strain coefficient of the sample was calculated by the equation $d_{33,\mathrm{m}} = d\lambda/d\mathrm{H} = v/(\pi f l H_{\mathrm{ac}})$, where v is the vibration velocity of the sample induced by the magnetic field, f is the exciting frequency, l is the undeformed length of sample, and H_{ac} is the magnitude of the external AC magnetic field [4]. The experiments were carried out at room temperature and ambient pressure.

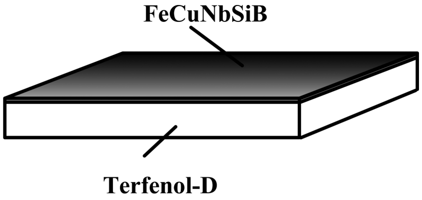

Fig. 1. Schematics of the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB.

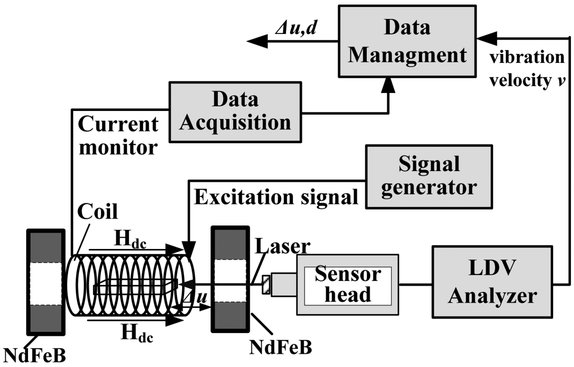

Fig. 2. Schematic diagram of the dynamic measurement setup.

3. Results and Discussion

Fig. 3 shows the measured dynamic strain coefficient as a function of frequency (strain coefficient spectra) for the magnetization-graded ferromagnetic materials MF near resonance, under various magnetic fields H_{dc}.

The figure shows the fundamental longitudinal mode resonance of the sample to be approximately 100 kHz. A sharp resonance peak is observed for $H_{\mathrm{dc}} = 19$, 55, 105, 235, 598, and 700Oe. A shift occurs in the resonant peak,

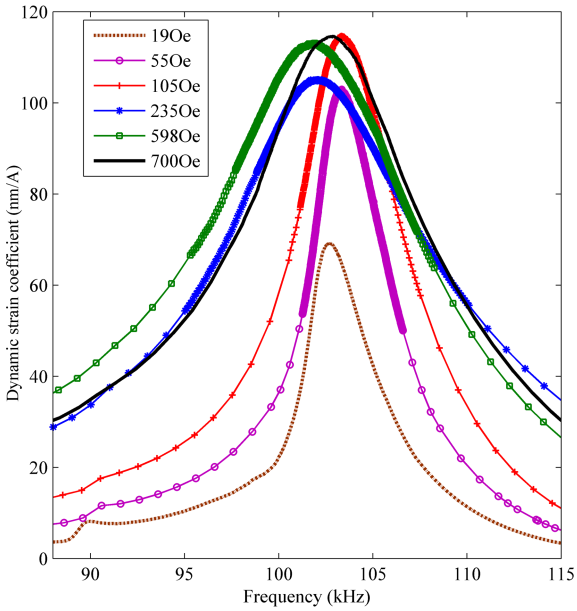

Fig. 3. (Color online) Variations of the dynamic strain coefficient for the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB with resonant frequency f_r, at several different values of H_{dc} ranging from 19 Oe to 700 Oe.

with the DC bias magnetic field increasing from 19 Oe to 700 Oe. As can be seen, the maximum dynamic strain coefficient achieves 114.8 nm/A at the resonance frequency of ~102.86 kHz under H_{dc} = 105 Oe, which is much larger than its non-resonance values.

As shown in Fig. 4 the dynamic strain coefficients for the Terfenol-D and Terfenol-D/FeCuNbSiB exhibit significant dependence on the DC magnetic bias. The dependence of the dynamic strain coefficient on H_{dc} originates from the piezomagnetic coefficient d_{33} dependence on H_{dc}. Generally, the piezomagnetic coefficient for magnetostrictive material increases, and achieves a certain maximum; then decreases slowly, with increasing applied DC bias magnetic field. From Fig. 4, we can see that the dynamic strain coefficient for Terfenol-D increases up to its maximum of 104.6 nm/A, with DC bias magnetic field increasing up to 700 Oe. In comparison, we find that the dynamic strain coefficient for the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB increases dramatically up to a maximum value (114.8 nm/A) near 105Oe, and then slowly decreases until H_{dc} = 235Oe; and next, slightly increases, with increasing DC bias field. Under lower DC magnetic field biases of H_{dc} < 105 Oe, the dynamic strain coefficient for Terfenol-D/FeCuNbSiB is increased by a factor of between one and three under the same DC magnetic field bias, compared with Terfenol-D. In particular, the effective dynamic strain coefficient of Terfenol-D/FeCuNbSiB under H_{dc} = 0 Oe achieves 48.6 nm/A, due to the internal magnetic field induced by the spatially varying magnetization, which is about 3.05 times larger than that of Terfenol-D (as shown in the inset of Fig. 4). There are some significant differences between the trends of the dynamic strain coefficient for Terfenol-D and Terfenol-D/FeCuNbSiB laminated composite with H_{dc}. This is principally because the dynamic strain coefficient is directly proportional to the product of the effective mechanical quality factor Q_m and the piezomagnetic coefficient d_{33} [10]. The mechanical quality factor Q_m strongly depends on H_{dc} (as shown in Fig. 5). On the basis of the dynamic strain coefficient spectrum under various H_{dc}, the effective mechanical quality factor of the Terfenol-D and Terfenol-D/FeCuNbSiB is calculated by:

$$Q_m = \frac{f_r}{\Delta f} \quad (1)$$

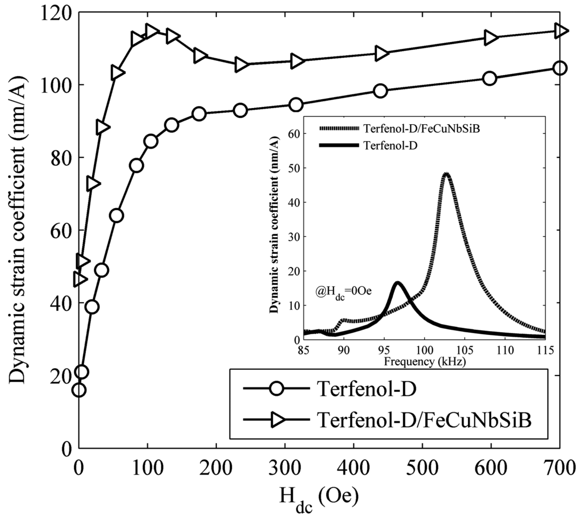

Fig. 4. The dynamic strain coefficient for Terfenol-D and the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB as a function of $H_{dc.}$ The inset shows the dynamic strain coefficient as a function of frequency, around the electromechanical resonance frequency at H_{dc} = 0 Oe.

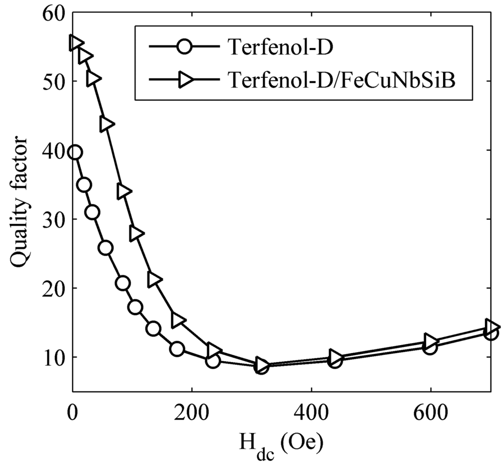

Fig. 5. Mechanical quality factors for Terfenol-D and the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB composite, as a function of H_{dc}.

where, f_r is the resonance frequency, and Δf is the 3-dB bandwidth.

In comparison to the variation of the piezomagnetic coefficient, as H_{dc} increases, Q_m first rapidly decreases, until it reaches a certain minimum; and then it gradually increases (as shown in Fig. 5). We can see that the effective Q_m of the Terfenol-D/FeCuNbSiB is greater than that of Terfenol-D, under the lower DC magnetic field biases of $H_{dc} < 105$ Oe, because Q_m is a measure of mechanical losses or damping in a material, with inversely proportional relationship. These losses can be regarded as mechanical hysteresis losses, which generally limit the dynamic behavior of the material. Obviously, a larger mechanical quality factor Q_m for Terfenol-D/FeCuNbSiB can be obtained, owing to the high Q_m of FeCuNbSiB (of about 1000), resulting in the higher product of the effective mechanical quality factor Q_m and the piezomagnetic coefficient. Correspondingly, the dynamic strain coefficient for the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB increases more rapidly under $H_{dc} < 105$Oe, relative to Terfenol-D.

Fig. 6 shows the DC bias magnetic field H_{dc} dependence of the resonance frequency f_r for Terfenol-D and Terfenol-D/FeCuNbSiB. The resonance frequency depends on H_{dc}, which can be explained by the ΔE effect and motion of the non-180° domain walls. For the Terfenol-D, the resonant frequency f_r reduces quickly to a minimum value at $H_{dc} = 316$ Oe, and then slightly increases with the DC bias magnetic field, showing a “V” shape in the range of 0-700Oe (as shown in Fig. 6(a)). Furthermore, it demonstrates a pronounced shifting of the resonance frequency, from $f_r = 92.93$ kHz for $H_{dc} = 316$ Oe, to $f_r = 98.69$ kHz for $H_{dc} = 700$ Oe. In contrast, as H_{dc} increases, the resonant frequency for the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB first increases, until it reaches a maximum value at $H_{dc} = 84$ Oe; and then it decreases quickly, to a minimum value at $H_{dc} = 439$ Oe; and next, it slowly increases, as the field increases (as shown in Fig. 6(b)). The resonance frequency shifts over the range of 99.54 kHz-103.4 kHz, with increasing H_{dc} from 0 Oe to 700 Oe. Some discrepancies are induced by the variation of Young’s modulus of the FeCuNbSiB material with the applied DC magnetic field. The mechanical resonance frequency for the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB can be written as:

$$f_r = \frac{1}{2l}\sqrt{\frac{\bar{E}}{\bar{\rho}}} \tag{2}$$

where, $\bar{\rho}$ is the average density of the composite determined by $\bar{\rho} = n_f\rho_f + (1 - n_f)\rho_t$, and ρ_f and ρ_t are the Young’s moduli of FeCuNbSiB and Terfenol-D, respectively. The equivalent Young’s modulus $\bar{E}$ is given by

$$\bar{E} = n_f E_f + (1 - n_f)E_t \tag{3}$$

where, E_f and E_m are the Young’s moduli of FeCuNbSiB and Terfenol-D, respectively, and n_f is the volume fraction of the FeCuNbSiB layer.

The equivalent Young’s modulus for the magnetization-graded ferromagnetic materials changes, compared with Terfenol-D (as shown in Figs. 7(a) and (b)). As a result, the resonance frequency for Terfenol-D/FeCuNbSiB changes along with the Young’s modulus. Furthermore, the relatively high Young’s modulus of FeCuNbSiB enhances the equivalent Young’s modulus, and the relatively small density of FeCuNbSiB reduces the average density according to Eqs. (2) and (3). Consequently, the resonance frequency of the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB is higher than that of Terfenol-D.

The magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB is a potentially feasible material for use in high-sensitivity DC or/and AC magnetic field detection. One approach would be to prepare a PZT/Terfenol-D/FeCuNbSiB magnetoelectric (ME) laminated composite, by combining a piezoelectric material PZT with Terfenol-D/FeCuNbSiB. Since the dynamic strain coefficient of the magnetization-graded ferromagnetic materials is intrinsical-

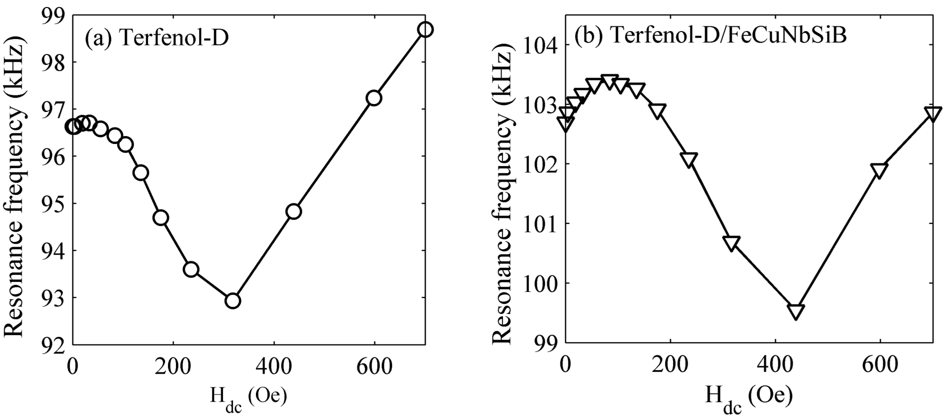

Fig. 6. Variations of resonant frequencies for Terfenol-D and the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB, with H_{dc} ranging from 0 Oe to 700 Oe.

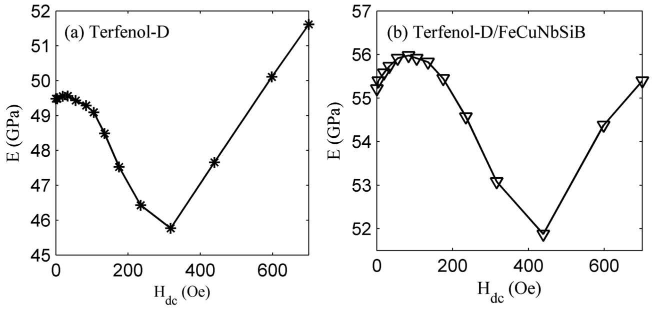

Fig. 7. The Young's moduli for Terfenol-D and the magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB, as a function of the DC bias magnetic field.

ly dependent on the DC bias magnetic field H_{dc}, such a sensor can detect a small H_{dc} signal, by using the operational mode proposed in Ref. [11]. In the ME measurement, the Terfenol-D/FeCuNbSiB (the easy direction is along the longitudinal direction) is magnetized in the longitudinal (length) direction, and the PZT is polarized in the transverse (thickness) direction. Fig. 8 shows the induced ME voltage for PZT/Terfenol-D/FeCuNbSiB, and the phase shift as a function of the dc magnetic field, when an ac magnetic field (H_{ac}) with a peak–peak value of 1 Oe and a resonance frequency of 36 kHz is applied. The measured ME voltage shows an unexpected 180° phase shift, upon reversal of the sign of H_{dc}. Such reversals are found under small dc magnetic fields of $H_{dc} = \pm 67$ Oe. The phase shift reveals the tendency of the applied dc field variation [11]. According to Fig. 8, the maximum ME sensitivity of the ME voltage V_{ME} to H_{dc} (i.e., dV_{ME}/dH_{dc} under AC bias field) reaches 125.9 mV/Oe under a resonant drive of $H_{ac} = 1$ Oe, which is about 5 times higher than that of PZT/Terfenol-D sensor (25.7 mV/Oe). The higher sensitivity of the ME sensor is mainly due to a higher dynamic strain coefficient for Terfenol-D/FeCuNbSiB, which results in a higher output voltage in response to a small variation of H_{dc}. Furthermore, we can clearly see that the zero-biased ME voltage of the ME composite has a giant value of 1.362 V. Correspondingly, the ME sensitivity of the ME voltage V_{ME} to H_{ac} (i.e., dV_{ME}/dH_{ac} under a DC bias field) is calculated as 1.362 V/Oe (17.025(V/cm Oe)). This indicates the possibility of using the PZT/Terfenol-D/FeCuNbSiB ME sensor for low-level ac magnetic field detection without bias, which can greatly reduce the size, relative to the traditional ME sensor. Obviously, this ME sensor can sense not only an AC magnetic field, but also, and in particular, a DC magnetic field.

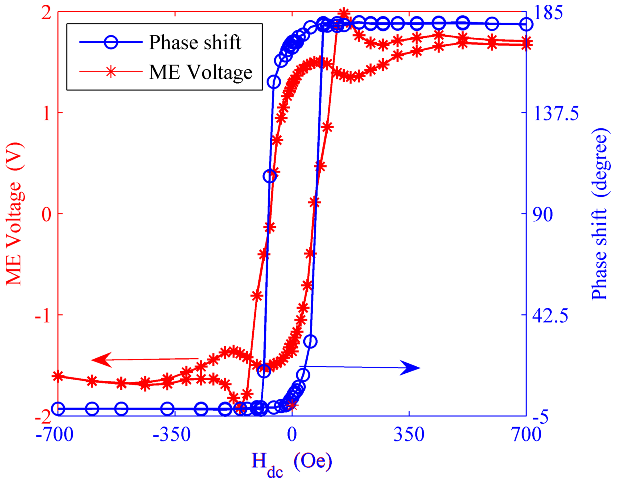

Fig. 8. (Color online) The ME voltage and phase shift as a function of the DC magnetic field bias for ME sensor, under a resonant drive of H_{ac} = 1 Oe.

4. Conclusion

We investigate the dynamic magneto-mechanical behavior of magnetization-graded ferromagnetic materials Terfenol-D/FeCuNbSiB (MF) relative to a DC bias magnetic field. The dynamic strain coefficient, mechanical resonance frequency, Young's modulus, and mechanical quality factor are strongly dependent on the DC bias magnetic field. The MF displays a significantly high dynamic strain coefficient, and a large effective mechanical quality factor, compared with Terfenol-D. In particular, the dynamic strain coefficient for MF can achieve 48.5 nm/A at zero bias. Based on dynamic magneto-mechanical characteristics, we fabricate a new type of sensor with PZT/Terfenol-D/FeCuNbSiB. The maximum ME sensitivity of the ME voltage V_{ME} to H_{dc} reaches 125.9 mV/Oe under a resonant drive of $H_{ac} = 1$ Oe, which about 5 times higher than that of PZT/Terfenol-D sensor (25.7 mV/Oe). The ME sensitivity of the ME voltage V_{ME} to H_{ac} achieves 1.362V/Oe (17.025(V/cm Oe)) at zero bias. These properties are promising for use in magnetic field sensing.

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