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A High-sensitivity Passive Magnetic Transducer Based on PZT Plates and a Fe-Ni Fork Substrate

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This paper proposes a magnetoelectric (ME) composite transducer structure consisting of a magnetostrictive H-type Fe-Ni fork substrate and piezoelectric PZT plates. The fork composite structure has a higher ME voltage coefficient compared to other ME composite structures due to the higher quality (Q) factor. The ME sensitivity of the fork structure reaches 12 V/Oe (i.e., 150 V/cm Oe). The fork composite with two PZT plates electrically connected in series exhibits over 5 times higher ME voltage coefficient than the output of the rectangle structure in the same size. The experiment shows the composite of a Fe-Ni fork substrate and PZT plates has a significantly enhanced ME voltage coefficient and a higher ME sensitivity relative to the prior sandwiched composite laminates. By the use of a lock-in amplifier with 10 nV resolution, this transducer can detect a weak magnetic field of less than 10^{-12} T. This transducer can also be designed for a magnetoelectric energy harvester due to its passive high-efficiency ME energy conversion.

Keywords: magnetoelectric composite, H-type Fe-Ni fork structure, magnetic transducer, high quality factor

1. Introduction

The magnetic sensors have attracted much interest in recent years due to its wide range of applications, such as magnetic measurement [1-4], magnetic information acquisition and control [5-7]. The power supply and driving signal are of crucial importance to most of the high-sensitivity magnetic sensors. In general, low power-consumption, small size and high sensitivity are desirable properties of magnetic sensors, since such sensors would be able to offer distinctive advantages over other traditional magnetic sensors. For instance, the coil-type passive magnetic sensors with low magnetic sensitivity are limited to only some of the weak magnetic detection. Therefore, a considerable amount of effort has been devoted to improving the sensitivity of magnetic sensors. Of which, a promising solution is to use the passive piezoelectric/magnetostrictive composite sensors that have very high magnetoelectric conversion coefficient [1-6].

It is reported that piezoelectric/magnetostrictive composites have better ME properties than single phase materials [8]. The maximum ME sensitivity of the three-phase laminated composites at their resonant frequency can reach 2.7-8.70 V/Oe (~10-100 V/cm Oe) [9, 10]. Most of the previous investigations have focused on laminated composites of Terfenol-D and piezoelectric materials (e.g. PZT/PVDF/PMN-PT) in different polarized/magnetized directions, and the giant magnetoelectric (GME) sensitivity has been observed [8-12]. However, for these previous studied composites laminates with low mechanical quality (Q) factor (from 49.9 to 100), difficulties in further enhancing the ME voltage coefficient has been suggested, since the voltage gain is directly proportional to the Q value [2, 10, 13, 14].

This paper proposes a Fe-Ni/PZT H-type fork magnetoelectric composite structure with a higher Q value that generates a higher electric output voltage and a higher ME sensitivity than other prior sandwiched transducers with composite laminates. This passive sensor with a weak signal processing circuit [15] can thus be used in many fields including magnetic detecting and magnetoelectric energy harvesting.

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2. Fe-Ni/PZT H-type Fork ME Transducer Principle

The structures of the rectangle ME composite and the H-type fork ME transducer are shown in Figure 1(a) and (b), respectively. The H-type fork magnetoelectric composite is composed of two identical-sized rectangle composites each with dimensions of 40.0 mm × 6.0 mm × 0.6 mm. The material of the fork substrate is a ferro-nickel iron alloy (3J53) which exhibits a high Q value and a high magnetostrictive strain coefficient. The major components of the ferro-nickel iron are listed in Table 1. For convenient fabrication, a fork shaped ferro-nickel iron alloy substrate with a Q value of 422 is made using the numerical controlled linear cutting machine as shown in Fig. 1(b). The piezoelectric Pb(Zr,Ti)O_3 (PZT-8H) plates with dimensions of 12.0 mm × 6.0 mm × 0.8 mm are symmetrically located at the mechanical anchors of the elastic Fe-Ni alloy substrate where the displacement is zero. Two PZT-8H plates are glued on the elastic Fe-Ni alloy substrate by using α-cyanaloc acrylic resin adhesive. The Fe-Ni alloy is magnetized and oriented along the longitudinal direction, where the highest longitudinal magnetostrictive strain ($\lambda \sim 100$ ppm) can be achieved under a DC magnetic bias (H_{dc}) of 100 Oe. The PZT-8H works at d_{31} model, which is polarized along the thickness direction.

Due to the symmetrical H-type composite structure, vibrational waves (with the same wavelength or frequency) are induced from two beams of the Fe-Ni alloy substrate under a DC magnetic field of 100 Oe and an AC magnetic field of 1 Oe. Therefore the vibrational-to-electric energy conversion can be achieved by energy harvesting devices, in this case, the PZT plates. Additionally, the vibration of two beams can be described as the interference of two wave sources. In the vibrating beam of the resonant fork structure, the phase of the vibrating wave induced by beam 2 is identical to that of beam 1 as indicated in Fig. 1(b). Fig. 2 shows the vibrational modes and the waveform of two in-phase vibrational waves on the H-type magnetostrictive elastic substrate. The waves of the beams are superimposed and intensified at the resonant frequency as a result of their identical phase and amplitude. Furthermore, higher amplitude can still be managed in the resonant fork structure due to the higher quality value.

The wave equation of two beams can be expressed as

$$\frac{\partial^2 y(x,t)}{\partial t^2} = v^2 \frac{\partial^2 y(x,t)}{\partial x^2}, \tag{1}$$

where v is the velocity of the transverse wave in the elastic substrate.

In the high-Q resonant structure, the fixed point has to locate at the wave node. The minimum amplitude at two fixed points is

$$y(\mathrm{x} = -d,\, t) = y(x = x_0 + d,\, t) = 0, \tag{2}$$

where d is the length of the fixed beam. Combining Eqs. (1) and (2), we may re-write the wave equation into

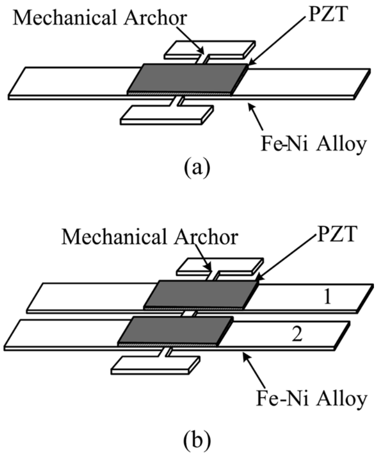

Fig. 1. ME composite structures: (a) a rectangle structure and (b) an H-type fork structure.

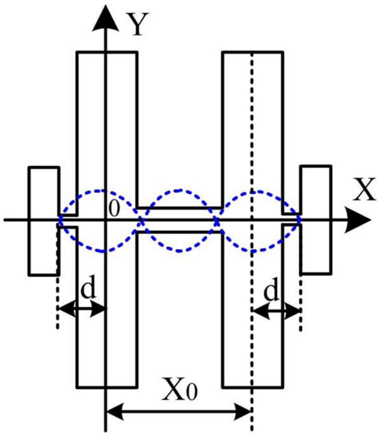

Fig. 2. (Color online) Vibration modality of the H-type elastic substrate structure.

Table 1. Main Components of Ferro-nickel Iron 3J53.

Component	Ni	Cr	Ti	Al	C	Mn	Si	P	S	Fe
Content (%)	41.5-43	5.2-5.8	2.3-2.7	0.5-0.8	≤ 0.05	≤ 0.8	≤ 0.8	≤ 0.02	≤ 0.02	margin

$$y(x,t) = A_0\left|\csc\left(\frac{\omega d}{v}\right)\right|\sin\left(\frac{\omega x-\omega d}{v}\right)\cos\omega t\,. \qquad (3)$$

Two transverse waves are superimposed on x axis. The maximum vibrational amplitude of the H-type fork structure induced from two in-phase vibrational waves is given by

$$y(x = 0,\, t) = A_0\cos\omega t, \qquad (4)$$

where x_0 is the distance between two beams, A_0 is the vibrational amplitude, and ω is the vibrational angular frequency.

Compared with Eq. (3), this can be rearranged into

$$\left|\csc\left(\frac{\omega d}{\upsilon}\right)\right|\sin\left(\frac{\omega x-\omega d}{\upsilon}\right) = 1\,. \qquad (5)$$

Solving Eq. (5),

$$\begin{cases} x_0 = 2d + k\lambda & \text{at } k\lambda < d < (k\lambda + 1/2\lambda) \\ x_0 = k\lambda & \text{at } (k\lambda - 1/2\lambda) < d < k\lambda \end{cases}. \qquad (6)$$

where λ is the wavelength of the transverse wave and k is an integer. The optimal fixed point and the distance between two beams can therefore be located. However, according to Eq. (6), the length of the composite structure on x axis is very long compared to the length of the fixed beam (d). In order to decrease this distance, the structure needs to fulfill a basic resonant condition that the amplitudes of in-phase waves in two beams are more than zero. From Eq. (3), the amplitude can thus be expressed as

$$A_0\left|\csc\left(\frac{\omega d}{v}\right)\right|\sin\left(\frac{\omega x_0-\omega d}{v}\right) > 0\,. \qquad (7)$$

Solving Eq. (7), x_0 can be obtained as:

$$\frac{2k\pi\upsilon}{\omega} + d < x_0 < \frac{(2k+1)\pi\upsilon}{\omega} + d, \quad k = 0,1,2,..., \qquad (8)$$

As Eq. (8) suggested, the distance between two beams is related to the position of the fixed point and the vibrational frequency. According to the dynamic theory, the vibrational frequency for the longitudinal vibration of the H-type fork structure is [16]

$$f = \frac{n}{2L}\sqrt{\frac{E}{\rho(1-\sigma^2)}}, \qquad n = 1, 2, 3,..., \qquad (9)$$

where L is the length of the structure, E is the modulus of elasticity for the magnetostrictive material, ρ is the density, σ is the Poisson's ratio, and n is the harmonic number. The length of the H-type fork composite structure is 40 mm. The ferro-nickel iron (3J53) parameters are also included in Table 1. A resonant frequency of 64.69 kHz is calculated from Eq. (9). In this structure, $k = 0$ and $v = \sqrt{G/\rho} = 2.92 \times 10^3$ m/s. Consequently, the distance between two beams can be selected as $x_0 = 14$ mm at $d = 6.5$ mm. Additionally, in the resonant fork structure, the vibrational amplitudes of two in-phase beams can be increased under an AC magnetic field.

3. Experiment

An experimental setup for ME characterization is shown in Fig. 3. The measured sensor is placed at the center of the solenoid, in which AC and DC uniform magnetic fields are generated along the longitudinal direction. Two NdFeB magnets are used to generate the DC bias magnetic field. A peak-to-peak current of 7.26 mA is applied in a helix coil with a turn number of 245, a cylindrical length of 67 mm, and a cylindrical diameter of 41 mm, thus an AC magnetic field with a peak-to-peak magnitude of 0.3 Oe will be excited at the center of the cylindrical shell. An LDV (Polytec OFV-5000, Germany) can be located at two sides to analyze the micro vibrational modes of the sensor structure.

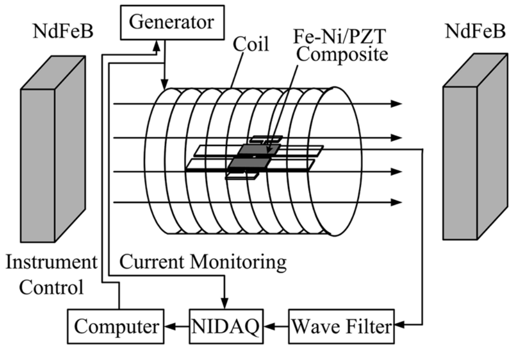

Fig. 3. Experimental setup.

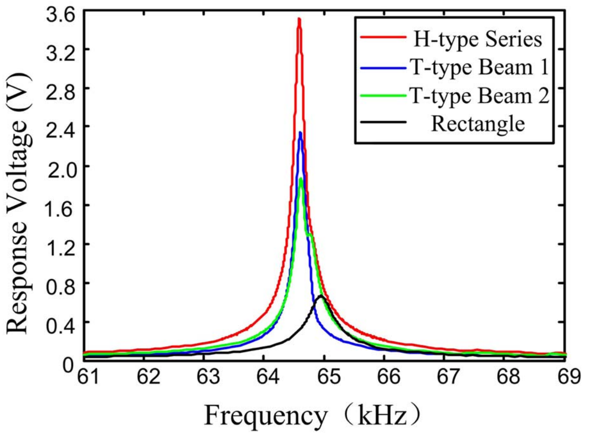

Fig. 4. (Color online) The output voltages of two structures and different connections as a function of frequency (Hdc = 0.3 Oe).

Fig. 4 shows the ME output voltages for different connections of the fork structure and the rectangle structure under an AC magnetic field of 0.3 Oe. The maximum ME conversion coefficient can be obtained at the resonance frequency of the composite structure. In the fork composite structure, the resonant output voltages of one beam and the series output voltage of two beams under an AC magnetic field of 0.3 Oe are 2.35 V and 3.55 V, respectively. In contrast the maximum output voltage of the rectangle composite structure is 0.6 V. Therefore, the output voltage of the fork structure with the series output of two beams is over 5 times higher in ME voltage coefficient than that of the rectangle structure in the same size.

Fig. 5 plots the output voltages of two structures as a function of an AC magnetic field. The ME output voltages of the fork structure and the rectangle structure under the AC magnetic fields have a near linear correlation to the AC magnetic intensity. The output peak-to-peak voltage of the H-type ME transducer can reach 12 V under an AC magnetic intensity of 1 Oe. Moreover, the Q values of the H-type fork and rectangle composite structures are 422 and 180, respectively.

4. Magnetic Sensor Detecting System

Fig. 6 presents the magnetic detection scheme of the composite sensor consisting of the H-type fork substrate, the magnetostrictive Terfenol-D plate and the piezoelectric PZT plate. As a function of the magnetic bias field, the ME coefficients of the composite are varied at an AC driving magnetic field of 1 Oe with a fixed driving frequency. A giant ME voltage of ~12 V/Oe (i.e. 150 V/cm Oe) is obtained at an optimized bias magnetic field of ~800 Oe that is set by the computer or DSP.

Since the electric response signal at a weak magnetic field is very weak, a high sensitive detector or conditioning circuit (such as a lock-in amplifier) is necessary for collecting and amplifying the electromagnetic signal. A higher signal/noise ratio (SNR) sensor signal output can be obtained by using the signal acquisition, processing and analysis device, and hence the weak magnetic signal can be detected, as illustrated in Fig. 7. The multiple averages are calculated during the data processing in order to decrease the noise. In the experiments, the measured ME voltage also shows a nearly linear correlation to Hac over the range of 1×10^{-12} T ≤ Hac ≤ 1×10^{-4} T at a bias magnetic field of 800 Oe. Due to the high ME sensitivity (150 V/cm Oe) for the H-type fork substrate composite, a minute H-field variation of Hac = 1×10^{-12} T at the resonant frequency may be detectable by using a lock-in amplifier with a sensitivity of 10 nV.

5. Conclusion

In this paper, an H-type magnetoelectric (ME) composite

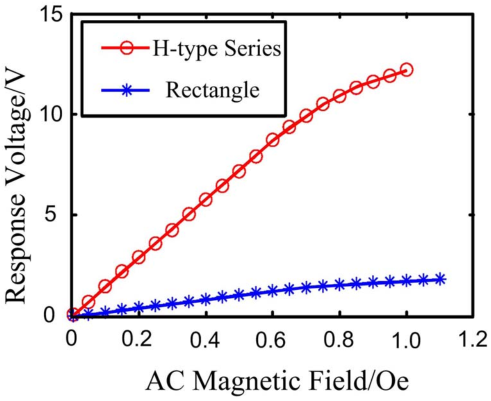

Fig. 5. (Color online) The output voltages of two structures as a function of AC magnetic field.

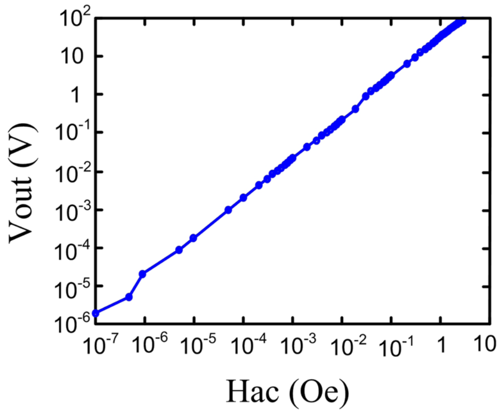

Fig. 7. (Color online) The output voltages of sensor system as a function of AC magnetic field.

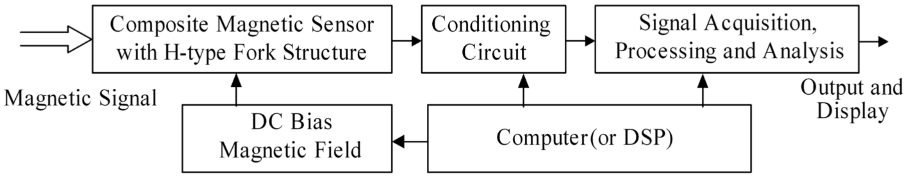

Fig. 6. The magnetic detection scheme of the composite sensor.

transducer structure consisting of a magnetostrictive Fe-Ni fork substrate and piezoelectric PZT plates has been developed. The vibrational waves of the fork beams are superimposed and intensified at the resonant frequency. Higher amplitude can be achieved in the resonant fork structure. Because of its higher quality (Q) factor, the fork composite structure has a higher ME voltage coefficient (150 V/cm Oe) relative to other ME composite structures. By the use of a lock-in amplifier with a 10 nV resolution, this transducer can detect a weak magnetic field of less than 10^{-12} T.

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