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Zero-biased magnetoelectric composite $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$/Ni/$Pb(Zr_{1-x},Ti_x)O_3$ for current sensing

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ABSTRACT

This paper presents a sensitive electric current sensor employing a magnetoelectric (ME) composite with a large zero-biased ME response. The composite consists of the Fe-based nanocrystalline alloy $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ (FeCuNbSiB) foils with positive magnetosriction, a Nickel (Ni) plate with negative magnetostriction and a piezoelectric $Pb(Zr_{1-x},Ti_x)O_3$ (PZT) plate. Due to the different magnetic characteristics between FeCuNbSiB and Ni (such as permeability, saturation magnetization and magnetostriction), an internal magnetic bias field are formed in the compound magnetostrictive layer FeCuNbSiB/Ni. Consequently, by coupling the vortex magnetic field around a current-carrying cable, the proposed sensor has a large output voltage and electric current sensitivity without additional DC bias magnetic field. The experimental results indicate that the maximum zero-biased ME voltage and current sensitivity for FeCuNbSiB/Ni/PZT are ~8.25 times and ~7.9 times larger than those of hysteretic Ni/PZT composite, respectively. As measuring 50 Hz electric current in power-line, the proposed sensor has a giant zero-biased current sensitivity (330 mV/A) and excellent linearity. The proposed miniature sensor can be used for power-line current measurement.

1. Introduction

A small vortex magnetic field is generated around a straight cable carrying an alternating electric current. Through coupling the vortex magnetic field, the magnetic field sensor can be used as an electric current sensor. But there are some limitations to the applications of the conventional magnetic sensors. For example, Hall and magnetoresistive sensor require external power. Without doubt, the current sensor that transfers magnetic energy to electrical signals is suggested to be a self-powered magnetic field sensor without additional power. Interestingly, this self-powered magnetic field sensor can be obtained by magnetoelectric (ME) effect [1–7]. To date, much research effort has been devoted to the ME materials and their ME properties [1–7]. The ME effects in laminate composites are known to be much higher than those in single phase and particulate composites [1–7]. Thus the ME laminate composite can be potentially used as an electric current sensor through inducing the vortex magnetic field around a current-carrying cable.

Recently, a ME current sensor with a universal tunable bias magnetic circuit has a current sensitivity of ~0.042 mV/A at the power-line frequency of 50 Hz [8]. A ring-type ME current sensor with a large resonance sensitivity of 92.2 mV/A at the fundamental shape resonance of 67 kHz has been developed [9]. For enhancing the sensitivity of this ring-type current sensor, a piezoelectric transformer is combined with this sensor. Then an enhanced sensitivity of 157 mV/A at 68 kHz is obtained [10]. A current sensor with a flux-concentration magnetic ring has an enhanced current sensitivity of ~46.2 mV/A at a power-line frequency of 50 Hz [11]. However, the most previous proposed current sensors require an external DC magnetic bias field H_{dc} to obtain a larger ME response and current sensitivity. For example, a bias magnetic circuit has been designed for generating a tunable H_{dc} for the ME current sensor in Ref. [8]. The four NdFeB magnets have been inset into the ring-type ME current sensors to supply the needs of H_{dc} in Refs. [9,10]. Unfortunately, the need for H_{dc} is of significant disadvantage for ME current sensor. For instance, the presence of H_{dc} increases the required space. The installation of the permanent magnets is troublesome and hard to control. And the permanent magnets for generating H_{dc} interfere with the current-carrying cable and the neighbouring sensors, which add a potential noise source.

In order to eliminate these severe limitations arising from the need of H_{dc}, the ME composite with a build-in bias magnetic field is in demand. There are several approaches to eliminate the need of H_{dc}, such as the use of hysteresis behavior in magnetostrictive materials, antiferromagnetic–ferromagnetic exchange coupling effect and magnetization-graded magnetostrictive materials [12–16]. For the magnetoelectric composite based electric current

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sensor, the remanence magnetization in a hysteretic magnetostrictive material has been used for obtaining a zero-biased ME current sensor or vortex magnetic field sensor [11,17]. But because of the small magnetic hysteresis for the magnetostrictive materials, the zero-biased ME responses of these current sensors driven by vortex magnetic fields are still small [11,17]. In this paper, we propose a self-powered high-sensitivity electric current sensor using a ME composite FeCuNbSiB/Ni/PZT (FNP) with a giant zero-biased ME response. When the zero-biased composite FNP induces the vortex magnetic fields around a current-carrying cable, the proposed sensor can detect the AC electric current.

2. Experiment details

2.1. Structure and working principle

The proposed self-biased electric current sensor operated in vortex magnetic field detection mode is shown in Fig. 1. When an AC electric current passes through a cable, the vortex magnetic field around the cable is induced by magnetostrictive layer FeCuNbSiB/Ni. Then the FeCuNbSiB/Ni layer exerts a stress to the PZT plate. As a result, an output voltage is generated across the two electrodes of the PZT plate for the direct piezoelectric effect. With the use of negative magnetostriction Ni and positive magnetostriction FeCuNbSiB, a magnetization-grading magnetostrictive layer FeCuNbSiB/Ni is formed. The different magnetic characteristics (such as magnetostriction and saturation magnetization) between Ni and FeCuNbSiB result in a build-in magnetic bias field in the FeCuNbSiB/Ni layer. The direction of build-in magnetic bias field is opposite to magnetic field created by cable. Hence, a large self-biased ME response can be obtained in FNP. And due to this build-in magnetic bias field, the FNP has a far larger zero-biased ME response than the hysteretic Ni/PZT composite. For obtaining an adjustable resonant frequency current sensor, the usage of a seismic mass to reduce the resonance frequency of a magnetoelectric sensor is used [18]. Through adding a suitable tungsten block at the free end of cantilever FNP, the resonant frequency of the sensor can be adjusted to the frequency of the power-line, for instance, 60 Hz in USA or 50 Hz in China. Therefore, this ME current sensor without magnetic bias field is suitable for power-line current measurement.

2.2. Measurement setup

The piezoelectric material was PZT-5 poled along the thickness direction. The silver electrodes of PZT were painted on the two surfaces perpendicular to the thickness direction. The Ni and FeCuNbSiB were magnetized along the length directions. The PZT plate ($15 \times 6 \times 0.2$ mm^3), Ni plate ($40 \times 6 \times 0.4$ mm^3) and FeCuNbSiB foils ($40 \times 6 \times 0.03$ mm^3) were bonded together using epoxy adhesives.

The experimental setup was presented as follows. The applied dc bias magnetic field (H_{dc}) was generated by a pair of neodymium permanent magnets (NbFeB). The different values of $H_{dc} = -100$ to 100 Oe were realized by adjusting the distances of the two NbFeB magnets, and were measured by a Gauss meter. A small AC signal was generated by a signal generator (Tektronix AFG3021B) and inputted to a power amplifier (200 W with a magnification of 15.2). A 5.1 Ω resistor and a current-carrying power-line cable were series connected to the output of the power amplifier. Through monitoring the signals from the signal generator, the large AC electric currents with different frequencies and magnitudes were generated in the power-line cable. The induced output voltages of the sensor were detected by an oscilloscope (TektronixModel TDS2012B) and a lock-in amplifier (Signal recovery 7280). For a straight cable carrying an alternating electric current, a small vortex magnetic field $H_{ac} = I/(2\pi a)$ is generated. When $I = 2$ A, the distance between the neutral line of FeCuNbSiB/Ni and neutral line of electric cable a is approx. 3.8 mm, thus, $H_{ac} = I/(2\pi a) = 1.05$ Oe. The ME voltage coefficient ($\alpha_{ME} = V/(t_p \times H_{ac})$, where V is the output voltage of sensor, t_p is thickness of PZT plate).

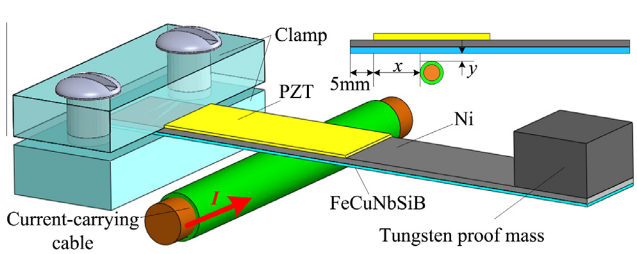

Fig. 1. Schematic diagram of the proposed ME electric current sensor. The single current-carrying cable is located under FNP, where x is tunable and $y = 2$ mm. The current-carrying cable is a copper core of diameter 1.8 mm with an insulating layer of thickness 0.8 mm around the copper core.

3. Results and discussion

As the location of current-carrying cable is changed, the output voltage of the proposed sensor is different. Thus, we focus on finding the optimal location of the cable for obtaining the maximum output voltage of the self-biased ME composite FNP. Fig. 2 shows the resonant output voltage of the FNP ($V_{o,r}$) as a function of the distance x (as shown in Fig. 1). The magnitude of the electric current in cable (I) is set to 2 A and H_{dc} is set to zero. The thickness of FeCuNbSiB foils varies from 0 mm to 0.12 mm (or the number of the FeCuNbSiB layers $L = 0$–4). From the data in this figure, it is obviously that the maximum $V_{o,r}$ is generated when $x = 0.6$ cm or the current-carrying cable is placed at the middle of the PZT plate. Thus, the current-carrying cable is placed at $x = 6$ mm (as shown in Fig. 1) in the following experiments. When $x = 0.6$ cm, the $V_{o,r}$ for FNP with $L = 0$–4 are 126, 556, 828, 1040 and 870 mV (or the α_{ME} are 6, 26.5, 39.4, 49.5 and 41.4 V/cm Oe), respectively.

Fig. 3 shows $V_{o,r}$ as a function of H_{dc} for FNP with $L = 0$–4. For Ni/PZT composite ($L = 0$), the $V_{o,r}$ vs H_{dc} loop is clockwise with a negative remanent $V_{o,r} = -126$ mV and a negative coercive field $H_c = -21$ Oe. The hysteretic behavior in Ni/PZT composite is attributed to the nature of magnetostrictive Ni [15]. After adding FeCuNbSiB foils in Ni/PZT composite, a build-in magnetic field is achieved for the grading of magnetostriction and magnetization in FeCuNbSiB/Ni [14,15]. Therefore, a large self-biased ME effect in FNP composite can be obtained. From Fig. 3, one can see clearly that (i) the $V_{o,r}$ increases greatly after adding FeCuNbSiB foils in Ni/PZT composite, (ii) the $V_{o,r}$ vs H_{dc} loops for FNP with $L = 1$–4 are clockwise with negative remanent $V_{o,r}$ and positive coercive fields, (iii) the loops move along H_{dc} axis with increasing of L, (iv) the largest $V_{o,r}$ is achieved when $L = 3$. One observes that the largest zero-biased $V_{o,r}$ of FNP with $L = 3$ is 1040 mV (or α_{ME} is nearly 49.5 V/cm Oe), which is ~8.25 times larger than that of Ni/PZT composite with 126 mV (or α_{ME} is nearly 6 V/cm Oe). As H_{dc} increases from -100 Oe to 100 Oe, the data in Fig. 3 show a negative peak $V_{o,r}$ of -926 mV (or $\alpha_{ME} = -44.1$ V/cm Oe) at $H_{dc} = -21$ Oe and a positive peak $V_{o,r}$ of 1080 mV (or $\alpha_{ME} = 51.4$ V/cm Oe) at $H_{dc} = 4$ Oe for FNP with $L = 3$.

As the numbers of FeCuNbSiB layer L increase, there is an optimal L for obtaining a maximum effective strain of PZT in FeCuNbSiB/Ni/PZT composite. Due to the direct piezoelectric effect, the output voltage is the largest for the PZT with a maximum effective strain. From Fig. 3, the maximum ME voltage is obtained when $L = 3$. In addition, as L is fixed, the peak positions of $V_{o,r}$ versus H_{dc} in Fig. 3 can be attributed to the maximum values in the magnetostriction versus H_{dc}.

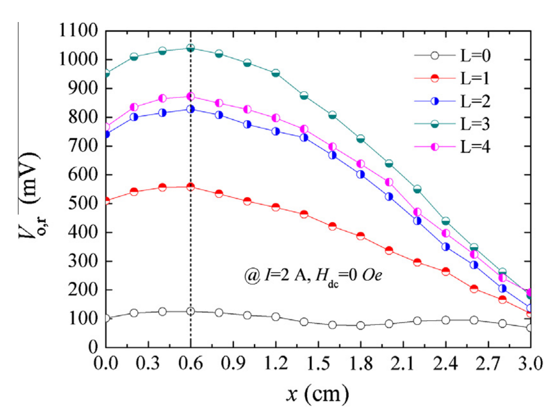

Fig. 2. The resonant output voltage ($V_{o,r}$) as a function of the distance x for FNP with $L = 0$–4. The magnitude of the current (I) is set to 2 A and the H_{dc} is set to 0 Oe.