Ring-type electric current sensor based on ring-shaped magnetoelectric laminate of epoxy-bonded $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ short-fiber/NdFeB magnet magnetostrictive composite and Pb(Zr, Ti)O_3 piezoelectric ceramic

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(Presented 19 January 2010; received 1 November 2009; accepted 16 December 2009; published online 14 May 2010)

A ring-type electric current sensor operated in vortex magnetic field detection mode is developed based on a ring-shaped magnetoelectric laminate of an axially polarized Pb(Zr, Ti)O_3 (PZT) piezoelectric ceramic ring bonded between two circumferentially magnetized epoxy-bonded $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (Terfenol-D) short-fiber/NdFeB magnet magnetostrictive composite rings. The electric current sensitivity of the sensor was evaluated, both theoretically and experimentally. The sensor showed a high nonresonance sensitivity of ~12.6 mV/A over a flat frequency range of 1 Hz–30 kHz and a large resonance sensitivity of 92.2 mV/A at the fundamental shape resonance of 67 kHz, besides an excellent linear relationship between the input electric current and the output magnetoelectrically induced voltage. The power-free, bias-free, high-sensitive, and wide-bandwidth natures of the sensor make it great potential for real-time condition monitoring of engineering systems having electric current-carrying cables or conductors. © *2010 American Institute of Physics*. [doi:10.1063/1.3360349]

Conventional electric current sensors, which are operated on the basis of detection of electric current-induced magnetic fields, are best represented by Hall and reluctance devices. Hall devices need to be powered by highly stable constant-current supplies, and their inherently weak Hall voltages (5–40 μV/Oe) impose great demands on signal conditioners.[1] Reluctance devices require being interfaced with highly precise integrators and real-time measurements are generally inhibited at low frequencies (<100 Hz).[2] By contrast, electric current sensors based on magnetoelectric (ME) materials do not suffer from these problems due to the intrinsic or extrinsic ME effect exhibited by the materials.[3]

The ME effect is defined as an electric polarization response to an applied magnetic field. In the past decade, much research effort has been devoted to the ME materials and their ME effect. These include intrinsic ME effect in single-phase materials and extrinsic ME effect in bulk and laminated composites.[3] Because of better property tailorability and greater extrinsic ME effect arisen from the product effect of the magnetostrictive and piezoelectric effects, laminated composites based on magnetostrictive [e.g., $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (Terfenol-D) alloy] and piezoelectric [e.g., Pb(Zr, Ti)O_3 (PZT) ceramics, 0.7Pb(Mg1/3Nb2/3)O_3—0.3PbTiO_3 (PMN-PT) single crystals, etc.] materials have been the main research focus.[3–11] Accordingly, various configurations in the shape of plate or disk have been studied, including longitudinally or transversely magnetized, longitudinally or transversely polarized plates,[3,6–11] radially or axially magnetized, radially or axially polarized disks,[3–5] etc. However, these plate- or disk-shaped ME laminates are only suitable for detecting magnetic fields of constant direction, indeed, they fall short of detecting vortex magnetic fields associated with current-carrying cables or conductors in real-life applications.[2]

In this paper, we report a promising ring-type electric current sensor designated to detect vortex magnetic fields of current-carrying cables or conductors by using a ring-shaped ME laminate having an axially polarized PZT piezoelectric ceramic ring sandwiched between two circumferentially magnetized, epoxy-bonded Terfenol-D short-fiber/NdFeB magnet magnetostrictive composite rings. These specifically prepared epoxy-bonded Terfenol-D short-fiber/NdFeB magnet magnetostrictive composite rings feature a circumferential magnetization, an internal magnetic biasing, an improved operational bandwidth, and a reduced brittleness compared to mondithic Terfenol-D.[12–14]

Figure 1 illustrates the schematic diagram and photograph of the proposed ring-type electric current sensor based on a ring-shaped ME laminate and operated in vortex magnetic field detection mode. The ring-shaped ME laminate basically consists of a piezoelectric ceramic ring sandwiched

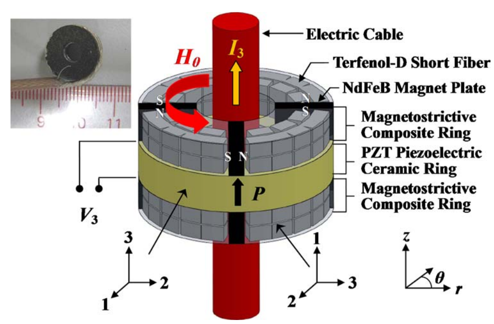

FIG. 1. (Color online) Schematic diagram and photograph of the proposed ring-type electric current sensor operated in vortex magnetic field detection mode. The arrow *P* denotes the electric polarization direction of the PZT piezoelectric ceramic ring, while N and S indicate the north and south poles of the NdFeB magnet plates.

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between two specifically designed magnetostrictive composite rings and with their interfaces being bonded using a conductive epoxy adhesive. The piezoelectric ceramic ring was a hard PZT, PKI804, with an outer diameter of 12.5 mm, an inner diameter of 5 mm, and a thickness of 2.5 mm. It had full fired silver electrodes on the two major surfaces perpendicular to the axial (or z- or 3-) direction and an electric polarization along the axial direction. The material properties of the piezoelectric ceramic ring are available in Piezo Kinetics Inc.[15] The magnetostrictive composite rings were prepared in house.[16,17] [112]-oriented Terfenol-D short fibers of 1–1.5 mm long and 0.5 mm wide were cut along the length of a [112]-textured monolithic Terfenol-D using an electrical discharge machining technique. Four pieces of plate-shaped NdFeB magnets, each having dimensions 3.75 mm (length) $\times 1$ mm (width) $\times 2.5$ mm (thickness) and with the north (N) and south (S) poles normal to its major surfaces of cross-sectional area 3.75×2.5 mm^2, were arranged in the 0°, 90°, 180°, and 270° directions in a ring-shaped aluminum mold cavity of dimensions the same as the PZT piezoelectric ceramic ring so as to create a dc magnetic field of ~ 25 kA/m along the circumferential (or θ-) direction of the mold. Importantly, when a predetermined quantity of Terfenol-D short fibers was placed in the mold, this dc magnetic field not only caused the short fibers to align with the magnetic flux lines and produce short-fiber chains along the circumferential direction of the mold, but also provided an optimal magnetic bias to maximize the magnetostrictive effect of the aligned Terfenol-D short fibers.[16,17] With the NdFeB magnets in place and the Terfenol-D short fibers aligned, the predegassed Araldite LY5210/HY2954 epoxy was transferred into the mold and degassed inside the mold again. The mold was then sealed and placed in an oven at 80 °C for 9 h to ensure full cure of the epoxy. The resulting magnetostrictive composite rings were circumferentially magnetized and magnetically biased without the need of an external biasing means as in the previous works.[3–11] The as-prepared magnetostrictive composite rings were evaluated using an in-house automated magnetostrictive characterization system,[13,16,17] and their material properties were reported elsewhere.[16,17]

The working principle of the ring-type electric current sensor is as follows. When an ac electric current (I_3) is applied to an electric cable in the axial (or z- or 3-) direction as shown in Fig. 1, an ac vortex magnetic field (H_θ) is induced along the length of the electric cable in accordance with Ampère's law.[2] Because of the nonuniform distribution of H_θ over the volume (v_{vol}) of the ring-type electric current sensor, an average ac vortex magnetic field ($H_{\theta,\mathrm{avg}}$) is detected instead, causing the two circumferentially magnetized magnetostrictive composite rings to produce circumferential and also radial motions due to the magnetostrictive effect. As the magnetostrictive composite rings are coupled mechanically to the sandwiched piezoelectric ceramic ring, these magnetostrictive strains subsequently stress the piezoelectric ceramic ring to generate an electric voltage (V_3) across the thickness of the piezoelectric ceramic ring in the axial (or 3-) direction owing to the piezoelectric effect.

The relation between I_3 and $H_{\theta,\mathrm{avg}}$ can be expressed as[2]

$$H_{\theta,\mathrm{avg}} = \frac{1}{v_{\mathrm{vol}}}\int_{r_{\mathrm{in}}}^{r_{\mathrm{out}}} H_\theta \mathrm{d}v_{\mathrm{vol}} = \frac{I_3(r_{\mathrm{out}}-r_{\mathrm{in}})}{\pi(r_{\mathrm{out}}^2-r_{\mathrm{in}}^2)}, \tag{1}$$

where r_{out} and r_{in} are the outer and inner radii of the ring-type electric current sensor, respectively. Using the constitutive piezomagnetic equations for the circumferentially magnetized magnetostrictive composite rings[12] and the constitutive piezoelectric equations for the axially polarized piezoelectric ceramic ring,[15,18] the ME voltage coefficient (α_V) of the ring-shaped ME laminate is found to be

$$\alpha_V = \frac{dV_3}{dH_{\theta,\mathrm{avg}}} = \frac{A-B}{C-D}\times t_{\mathrm{p}}, \tag{2}$$

where

$$A = d_{33,m}\left[s_{12,p}^E - s_{11,p}^E + \frac{t_p}{2t_m}(s_{13,m}^H - s_{11,m}^H)\right],$$

$$B = d_{31,m}\left[s_{11,\mathrm{p}}^E - s_{12,\mathrm{p}}^E + \frac{t_p}{2t_m}(s_{33,m}^H - s_{13,m}^H)\right],$$

$$C = \left[d_{31,p} - \frac{\varepsilon_{33}^T}{d_{31,p}}\left(s_{12,p}^E + \frac{t_p}{2t_m}s_{13,m}^H\right)\right]\left[s_{12,p}^E - s_{11,p}^E + \frac{t_p}{2t_m}(s_{13,m}^H - s_{11,m}^H)\right],$$

$$D = \left[d_{31,p} - \frac{\varepsilon_{33}^T}{d_{31,p}}\left(s_{11,p}^E + \frac{t_p}{2t_m}s_{11,m}^H\right)\right]\cdot\left[s_{11,p}^E - s_{12,p}^E + \frac{t_p}{2t_m}(s_{33,m}^H - s_{13,m}^H)\right],$$

where s_{11}^H, $s_{13,m}^H$, and $s_{33,m}^H$ are the elastic compliance coefficients at constant magnetic field strength; $d_{31,m}$ and $d_{33,m}$ are the piezomagnetic coefficients; ε_{33}^T is the dielectric permittivity at constant stress; $s_{11,p}^E$ and $s_{12,p}^E$ are the elastic compliance coefficients at constant electric field strength; $d_{31,p}$ is the piezoelectric coefficient; and t_m and t_p are the thickness of the magnetostrictive composite ring and the piezoelectric ceramic ring, respectively. Combining Eqs. (1) and (2), the electric current sensitivity of the sensor (S) is

$$S = \frac{dV_3}{dI_3} = \frac{dV_3}{dH_{\theta,\mathrm{avg}}}\times\frac{dH_{\theta,\mathrm{avg}}}{dI_3} = \alpha_V\frac{dH_{\theta,\mathrm{avg}}}{dI_3} = \frac{A-B}{C-D}\times t_{\mathrm{p}}\times\frac{r_{\mathrm{out}}-r_{\mathrm{in}}}{\pi(r_{\mathrm{out}}^2-r_{\mathrm{in}}^2)}. \tag{3}$$

With the material properties given in Refs. 15–17 and the geometric parameters described in Fig. 1, S of the ring-type electric current sensor and α_V of the ring-shaped ME laminate are predicted to be 14.7 mV/A [Eq. (3)] and 32.16 mV/Oe [Eq. (2)], respectively, at nonresonance frequencies.

The ring-type electric current sensor was inserted in an electric cable of diameter 2.5 mm (Fig. 1), and the sensor-wire assembly was placed in an EMI-shielded chamber for measurement. Figure 2 plots the ac electric voltage (V_3) output from the sensor as a function of both the ac electric current (I_3) applied to the electric cable and its associated average ac vortex magnetic field ($H_{\theta,\mathrm{avg}}$) at the frequency of 1 kHz [Fig. 2(a)] and 67 kHz [Fig. 2(b)]. The values of $H_{\theta,\mathrm{avg}}$ are calculated based on Eq. (1). It is seen that V_3 has good linear responses to I_3 and is very sensitive to the variation of I_3 even at a small I_3 value of 0.01 A. From the slopes of the

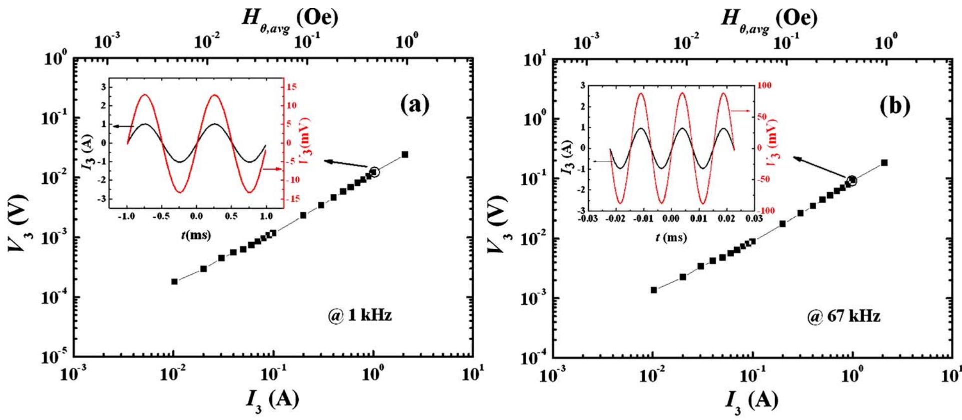

FIG. 2. (Color online) The ac electric voltage (V_3) output from the sensor as a function of both the ac electric current (I_3) applied to an electric cable of diameter 2.5 mm and its associated average ac vortex magnetic field ($H_{\theta,\text{avg}}$) at the frequency of (a) 1 kHz and (b) 67 kHz. The insets show the waveforms of I_3 of 1 A peak and the resulting V_3.

plot, the electric current sensitivity (S) of the sensor and the ME voltage coefficient (α_V) of the ring-shaped ME laminate are determined to be 12.6 mV/A and 27.5 mV/Oe, respectively, at 1 kHz [Fig. 2(a)] as well as 92.2 mV/A and 201.2 mV/Oe, respectively, at 67 kHz [Fig. 2(b)]. The significant enhancement in both S and α_V at 67 kHz compared to those at 1 kHz is due to the occurrence of fundamental shape resonance of the sensor to be discussed in Fig. 3. Nevertheless, the experimental nonresonance S and α_V agree well with the theoretical nonresonance S and α_V of 14.7 mV/A and 32.16 mV/Oe based on Eqs. (2) and (3), respectively. The insets of Figs. 2(a) and 2(b) show the waveforms of I_3 of 1 A peak and the resulting V_3. In line with the working principle described above, both I_3 and V_3 are in phase. Besides, V_3 follows I_3 steadily, indicating the ability of stable signal conversion from I_3 to V_3 in the sensor.

Figure 3 shows the electric current sensitivity (S) of the sensor in the frequency (f) range of 1 Hz–70 kHz with a constant electric current (I_3) of 1 A peak applied to the electric cable. For comparison, a reluctance coil, having the same height as the sensor (i.e., 7.5 mm) and with the turn number of 100, was wrapped around the electric cable to detect I_3. It is clear that S of the sensor has a reasonably flat response to f in the range of 1 Hz–30 kHz. The increase in S beyond 30 kHz is attributed to the fundamental shape resonance of the sensor at 67 kHz. Nevertheless, the eddy current-induced drop in S is not observed, elucidating the wide-bandwidth nature of our magnetostrictive composite ring and hence our sensor. By contrast, the reluctance coil shows a strong inductive effect and its S increases with increasing f, or $f < 50$ Hz, the floor noise level is larger than the induced voltage of the reluctance coil, thus inhibiting the measurement.

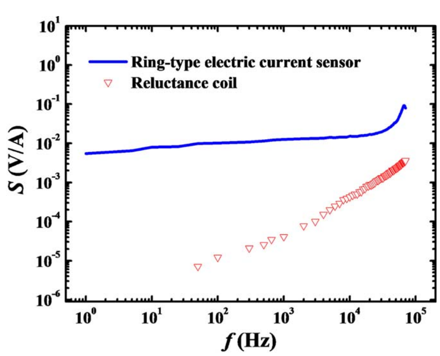

FIG. 3. (Color online) Electric current sensitivity (S) of the sensor in the frequency (f) range of 1 Hz–70 kHz with a constant electric current (I_3) of 1 A peak applied to an electric cable of diameter 2.5 mm. The performance of a reluctance coil, having the same height as the sensor and wrapped around the electric cable, is included for comparison.

We have developed a ring-type electric current sensor for the detection of vortex magnetic fields of current-carrying cables or conductors based on a ring-shaped ME laminate of an axially polarized PZT piezoelectric ceramic ring bonded between two circumferentially magnetized epoxy-bonded Terfenol-D short-fiber/NdFeB magnet magnetostrictive composite rings. The results have demonstrated the existence of a high nonresonance sensitivity of ~12.6 mV/A over a flat frequency range of 1 Hz–30 kHz and a large resonance sensitivity of 92.2 mV/A at 67 kHz in the sensor. The simultaneous power-free, high-sensitive, and wide-bandwidth natures of the sensor compared to conventional Hall or reluctance devices, in conjunction with its bias-free and vortex field detection capabilities, makes the sensor great promise for real-time monitoring of electric currents in electric cables or conductors associated with various engineering systems.

This work was supported by the Research Grants Council of the HKSAR Government (PolyU 5266/08E).

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