Current–voltage characteristics of lead zirconate titanate/nickel bilayered hollow cylindrical magnetoelectric composites*

Pan De-An(潘德安)[a)†], Zhang Shen-Gen(张深根)[a)], Tian Jian-Jun(田建军)[a)], Sun Jun-Sai(孙俊赛)[b)], Alex A. Volinsky[c)], and Qiao Li-Jie(乔利杰)[a)]

[a)] *School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing* 100083, *China*

[b)] *Faculty of Materials and Metallurgical Engineering, Kunming University of Science and Technology, Kunming* 650093, *China*

[c)] *Department of Mechanical Engineering, University of South Florida, Tampa FL* 33620, *USA*

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Current–voltage measurements obtained from lead zirconate titanate/nickel bilayered hollow cylindrical magnetoelectric composite showed that a sinusoidal current applied to the copper coil wrapped around the hollow cylinder circumference induces voltage across the lead zirconate titanate layer thickness. The current–voltage coefficient and the maximum induced voltage in lead zirconate titanate at 1 kHz and resonance (60.1 kHz) frequencies increased linearly with the number of the coil turns and the applied current. The resonance frequency corresponds to the electromechanical resonance frequency. The current–voltage coefficient can be significantly improved by optimizing the magnetoelectric structure geometry and/or increasing the number of coil turns. Hollow cylindrical lead zirconate titanate/nickel structures can be potentially used as current sensors.

Keywords: current–voltage coefficient, bilayered cylindrical composites, electromechanical resonance, current sensor

PACC: 7220M, 8160H, 7430G

1. Introduction

Recently, bulk magnetoelectric (ME) materials have drawn increased attention due to their ME effect, which provides significant advantages for applications in devices operating at low frequencies such as a pico-Tesla sensitivity magnetometer,[1,2] and at microwave frequencies such as an electrostatically tunable band-pass filter,[3] a band-stop filter,[4] a resonator,[5] and a phase shifter,[6] etc. Most of these devices are based on layered ME composites that exhibit stronger ME effect in comparison with the particulate ME materials.[7]

In previous studies plate and cylindrical layered ME composites made by electro-deposition were considered.[8−11] Electrodeposited plate layered ME composites have comparable ME performance to the $Tb_{1-x}Dy_xFe_{2-y}$(Terfenol-D)/[lead zirconate titanate (PZT)] prepared by the gluing method.[8,9] Trilayered Ni/PZT/Ni composites also have some novel ME properties,[10] while PZT/Ni bilayered cylindrical composites exhibit high gain ME effect at resonant frequency under high magnetic field induced by the volume magnetostriction.[11] Cylindrical layered ME composites have a significant potential for applications in high magnetic field detection. However, the ME effects are only suitable for detecting magnetic fields of constant direction, but not rotating or vortex magnetic fields, excited by metal wires carrying current. Moreover, previous studies focused on the relationship between the magnetic fields (bias magnetic field $H_{\rm DC}$ and AC field δH) and the ME coefficient. This paper focuses on an electric polarization in the inner PZT layer induced by the current applied to the copper coil wrapped around the ME composite, which is denoted as the current–voltage characteristics.

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†Corresponding author. E-mail: pandean@mater.ustb.edu.cn

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2. Experimental details

A hollow $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT-5H) cylinder (supplied by the Institute of Acoustics, Chinese Academy of Sciences) was cut to a height of 3 mm, with an inner diameter of 18 mm and an outer diameter of 20 mm (1 mm PZT cylinder wall thickness). The PZT was polarized at 425 K in a 50-kV/cm electric field along the radial directions after being coated with conductive plastic. The poled PZT cylinder was cleaned from the plastic prior to Ni deposition on its surface. After the cylinder inner wall was protected by silicone rubber, it was bathed in nickel aminosulfonate plating solution to electro-deposit Ni layer on the outer PZT cylinder side.[11] The plating solution composition is described in detail elsewhere.[8–12] After 20 hours of electro-deposition, the thickness of Ni layer reached 1 mm. Cylinder was placed in a nylon clamp shown schematically in Fig. 1(a). The groove in the clamp is 3.5 mm wide, 15 mm deep and 20 mm high. The clamp was fixed at the bottom and the sample was hanging from its top supported by the wires measuring voltage. Two ME voltage coefficients, $\alpha_{\mathrm{E,A}}$ and $\alpha_{\mathrm{E,V}}$ were obtained, corresponding to two conditions, where H_{DC} and δH were applied either along or perpendicular to the groove, as shown in Fig. 1(a). In previous experiments, two corresponding ME voltage coefficients were obtained and studied.[10] In this work, lacquered copper wire coil (0.55 mm wire diameter) was wrapped around the bilayered hollow composite circumference, and a sinusoidal current I_{in} was passed through it as illustrated in Fig. 1(b). The number of the coil turns was varied. Magnetic field induced by the coil caused Ni layer to change its dimensions and strain the inner PZT ring, which caused an electrical potential across its thickness. During the measurements, sample was placed in a nylon clamp shown schematically in Fig. 1(a) inside a pure permalloy screening box and subjected to a sinusoidal current I_{in} (1–120 kHz frequency range). The screening box was used to protect the sample from the Earth magnetic field. Maximum voltage, V_{out}, generated across the PZT thickness was amplified and measured with an oscilloscope. The current–voltage coefficient was calculated as $\alpha_{\mathrm{E,C}} = V_{\mathrm{out}}/(t_{\mathrm{PZT}} \cdot I_{\mathrm{in}})$, where t_{PZT} is the thickness of PZT and I_{in} is the maximum applied current.

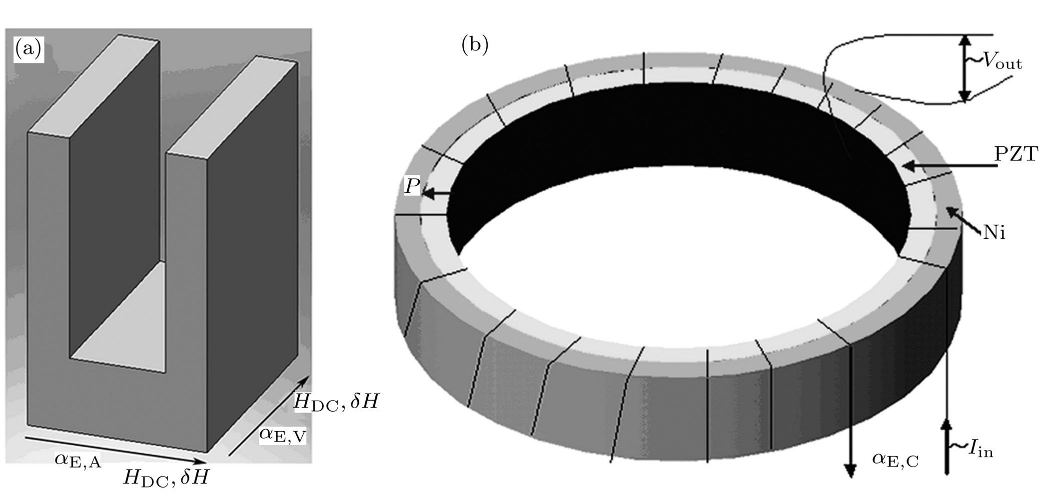

Fig. 1. (a) Schematic diagram of the clamp and (b) current–voltage Ni–PZT bilayered cylindrical composite structure. Here, $\alpha_{\mathrm{E,A}}$ and $\alpha_{\mathrm{E,V}}$ are the ME voltage coefficients of the cylinder when H_{DC} and δH are applied either along or perpendicular to the groove.

3. Results and discussion

The dependence of current–voltage coefficient $\alpha_{\mathrm{E,C}}$ on the applied current frequency for the PZT/Ni bilayered cylindrical composite with the number of coil turns $N = 330$ is shown in Fig. 2 (hollow dots). There is one resonance peak at about 60.1 kHz in the current–voltage coefficient curve plotted as a function of the applied current frequency in the 1–120 kHz range. The ME voltage coefficients due to axially and vertically applied magnetic fields, $\alpha_{E,A}$ and $\alpha_{E,V}$, of the same cylinder were studied previously.[11] The dependence of the vertical ME voltage coefficient $\alpha_{E,V}$ on the applied AC magnetic field is also shown in Fig. 2 (solid dots). The positions of the resonance peaks coincide for $\alpha_{E,C}$ and $\alpha_{E,V}$.

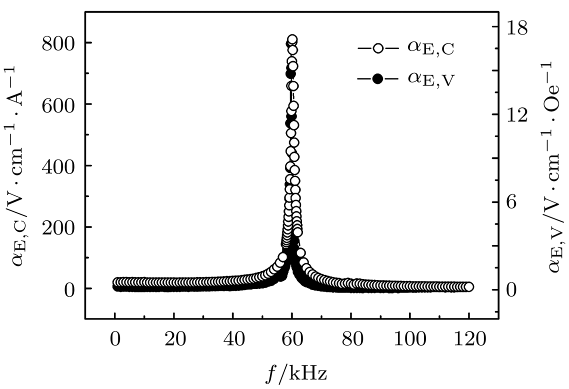

Fig. 2. The dependence of current–voltage coefficient $\alpha_{E,C}$ (hollow dots) and the magnetoelectric coefficient $\alpha_{E,V}$ (solid dots) on the applied current or magnetic field frequency with the number of coil turns $N = 330$ for the PZT/Ni bilayered cylindrical composite (1 Oe = 1 Gb/cm).

In a previous report, the layered cylinder was simplified as a self-bound plate layered composite using the method of differential coefficients along the direction of the toroidal cylinder, as shown in Fig. 3.[13] According to this analysis, the vertical coupling mode of the cylindrical bilayered ME composite can be simplified as a plate mode of the bilayered ME composite with $h \times L^{\rm eff} \times t$ dimensions. The effective magnetic fields are along the directions of the thickness (t) and the effective length ($L^{\rm eff}$) of the plate, simultaneously, and their values are $2/\pi$ times of the applied and measured magnetic fields (Fig. 4(a)). Similarly, the cylindrical bilayered ME composite circumferential coupling mode can be simplified as an $h \times L^{\rm eff} \times t$ plate bilayered ME composite (Fig. 4(b)). Since $H_{\rm DC}$ and δH, as well as $\delta H^{\rm eff}$ (effective sinusoidal magnetic field) and $H^{\rm eff}$ (effective bias magnetic field), are parallel to the differential coefficient face, i.e. along the dL direction (Fig. 5), the effective values of the magnetic fields are the same as the measured and the applied magnetic fields. In the current–voltage composite, the applied sinusoidal current $I_{\rm in}$ would generate a sinusoidal magnetic field along the circumference of the cylinder. That is to say, the current–voltage composite is equal to a circumferential coupling mode of a cylindrical layered ME composite.

Based on this analysis, both the current–voltage and the vertical cylindrical layered composites can be simplified as the bilayered plate ME composite of the same shape and size. The agreement between the dependences of the $\alpha_{E,V}$ and $\alpha_{E,C}$ curves on the applied AC signal and the simplified results indicate that the current–voltage characteristics are based on the ME effect and the resonance peak is associated with the electromechanical resonance (EMR) of the hollow cylindrical bilayered composite structure.

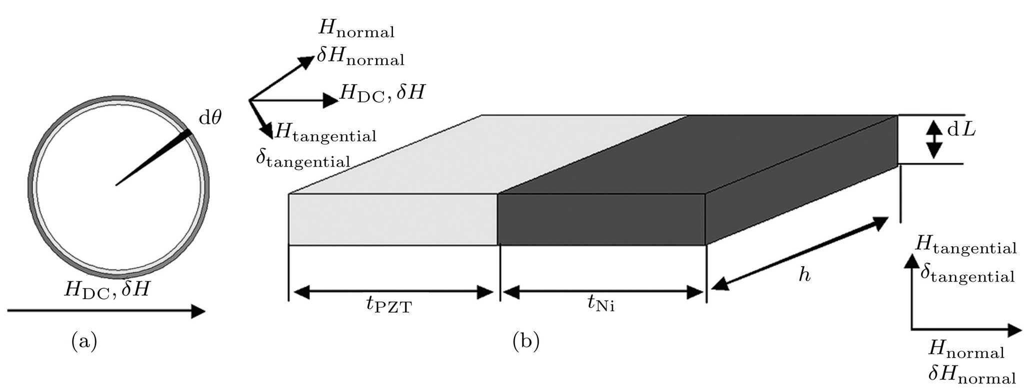

Fig. 3. (a) Schematic diagram of the differential coefficient method in vertical coupling mode of cylindrical layered composite; (b) schematic diagram of the corresponding simple model for the differential coefficient.

The current–voltage coefficient $\alpha_{E,C}$ and the maximum generated voltage $V_{\rm max}$ across the PZT both depend on the maximum current $I_{\rm in}$ at 1 kHz and the resonant frequency of the PZT/Ni cylindrical composite as shown in Figs. 6(a) and 6(b). At 1 kHz $I_{\rm in}$ was varied from 0 to 120 mA, and the current–voltage coefficient was almost constant, about 20 V/(cm·A). However, the measured maximum voltage $V_{\max}$ increased linearly with the rise in the applied current ($R = 0.99994$). The 120-mA current could induce a voltage of about 250 mV across the PZT. Because of the measuring range limit of the oscilloscope, the applied current $I_{\rm in}$ was only varied from 0 mA to 40 mA at the resonance frequency, as shown in Fig. 3(b). Variations of the current–voltage coefficient and the induced maximum voltage as a function of the applied current at the resonance frequency are similar to those obtained at 1 kHz. For the 40-mA applied current, the induced voltage across the PZT reached 3 V, and the current voltage coefficient remained almost constant at 820 V/(cm·A). The current–voltage coefficient and the induced voltage for the same applied current at the resonance frequency are about 40 times larger than those at 1 kHz. This voltage enhancement effect at the resonant frequency in comparison with the non-resonant frequency is similar to the ME effect enhancement of the ME composites, which is associated with the EMR.[14]

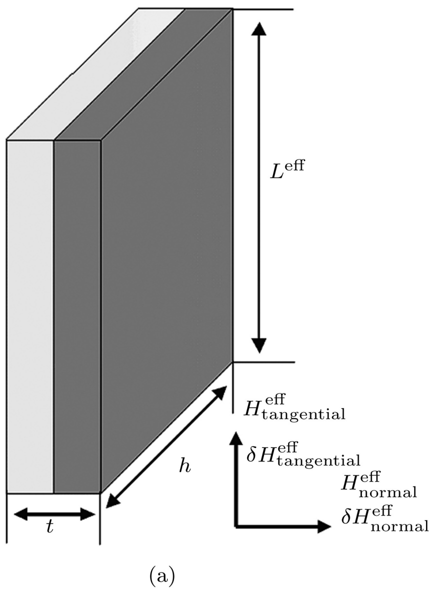

Fig. 4. (a) Bilayered plate composite simple bound state applied for the cylindrical layered composite in the vertical coupling mode and (b) in the circumferential coupling mode (current–voltage composite).

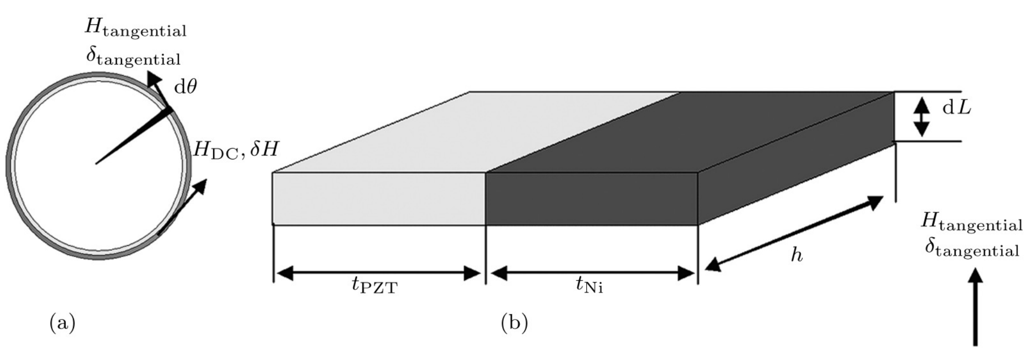

Fig. 5. (a) Schematic diagram of the differential coefficient method in circumferential coupling mode of cylindrical layered composite; (b) schematic diagram of the corresponding simple model for the differential coefficient.

Figure 7 shows the current–voltage coefficient $\alpha_{\rm E,C}$ as a function of the number of coil turns N varied from 75 to 330 at 1 kHz and the resonance frequency, respectively. The current–voltage coefficient increased linearly with the number of coil turns at 1 kHz applied current frequency ($R = 0.9993$), as shown in Fig. 7(a), due to the higher applied magnetic field, which increases with the number of coil turns.

At the resonant frequency, the current–voltage coefficient also increased with the number of coil turns, but did not exhibit linearity. The Boltzmann function was used and provided a better fit. The equation of the fitted

Boltzmann function curve (solid curve) is shown in the insert of Fig. 7(b) (left) ($R^2 = 0.97201$). One can use the Boltzmann function for predicting the dependence of the current–voltage coefficient on frequency.

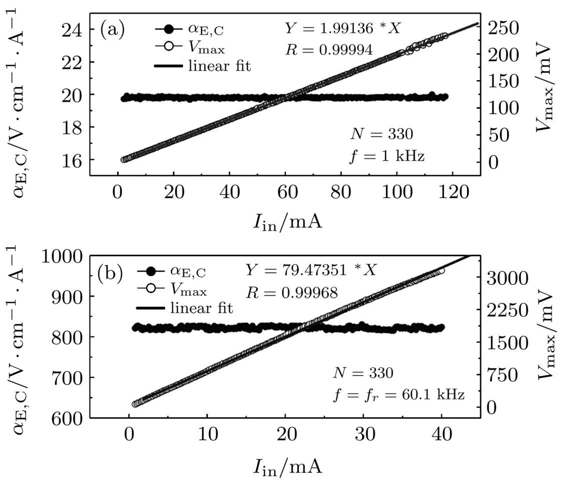

Fig. 6. The dependence of the current–voltage coefficient $\alpha_{\rm E,C}$ and induced maximum voltage $V_{\max}$ on the maximum current $I_{\rm in}$ at (a) 1 kHz and (b) resonant frequency for the PZT/Ni cylindrical composite.

For the current–voltage bilayered cylindrical composite, the current $I_{\rm in}$ applied to the coil will induce a vortex magnetic field $H_{\rm in}$, which is along the circumference of the cylinder, and is directly related to the amplitude of the applied current and the number of coil turns N. The PZT/Ni composite is an ME composite. The applied vortex magnetic field will induce a voltage in the sample because of the ME effect. Therefore, the current–voltage coefficient is directly related to the number of coil turns N. That is the reason why the current–voltage coefficient linearly increases with the number of coil turns at 1 kHz. We believe that at the resonance frequency the dependence of the current–voltage coefficient on the number of coil turns deviates from linearity because of the coil effective mechanical quality factor, $Q_{\rm m}$.[15] The mechanical quality factor is defined as $Q_{\rm m} = f_{\rm r}/\Delta f$, where $f_{\rm r}$ and Δf are the resonant frequency and the full width at half maximum of the coil resonance peak, respectively. As shown in Fig. 7(b) (right), the coil effective mechanical quality factor $Q_{\rm m}$ decreased with the number of coil turns N above 125.

Since the current–voltage composite is based on the ME composite, the improvement in the ME effect may also enhance the current–voltage effect. For the ME composites, one can change their shape and size to improve the ME effect.[16] As for the cylindrical ME composites, the height and the diameter of the cylinder will significantly influence the ME voltage coefficient.[17,18] One can choose an optimal shape and size to obtain the maximum ME effect. Study of the shape and size effects on the cylindrical composites ME and electrical performance is in progress. It is important that the current–voltage coefficient is directly related to the number of coil turns, N, thus it is easy to increase the current–voltage coefficient by simply adding more coil turns. There is lot of room for improvements of the current–voltage coefficient in the bilayered cylindrical hollow structures. Based on the presented results, hollow cylindrical PZT/Ni structures can be potentially used as current sensors.

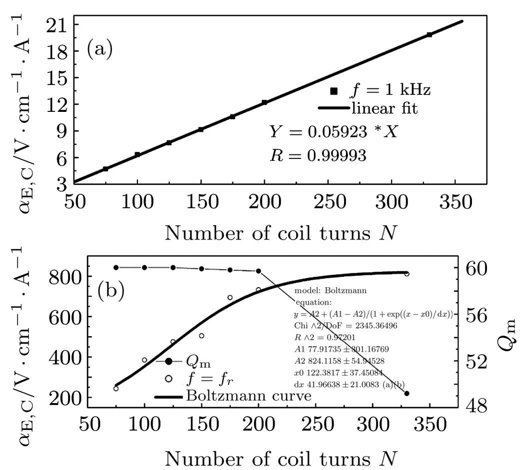

Fig. 7. The dependence of the current–voltage coefficient $\alpha_{\rm E,C}$ (left) and the effective mechanical quality factor Q_m (right) on the number of coil turns N varied from 75 to 330 at (a) 1 kHz and (b) the resonant frequency.

4. Summary

In summary, the current–voltage coefficient of hollow cylindrical PZT/Ni composites is directly related to the number of coil turns N. The induced maximum voltage $V_{\max}$ increased with the rise of applied current $I_{\rm in}$ both at 1 kHz and the resonance frequencies. One can change the shape and size of bilayered cylindrical composites and the number of coil turns to improve the current–voltage coefficient. This study is helpful in identifying applications of these current–voltage structures as current sensors.

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