PMN–PT single crystal and Terfenol-D alloy magnetolectric laminated composites for electromagnetic device applications

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Magnetolectric laminated composites of a length-magnetized magnetostrictive $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.92}$ (Terfenol-D) alloy plate sandwiched between two thickness-polarized, electro-parallel-connected piezoelectric $0.7\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ – 0.3PbTiO_3 (PMN–PT) single crystal plates were fabricated and their converse magnetolectric properties were evaluated. An electromagnetic control device using a laminated composite as the control element and an Alnico biasing magnet, two Mn–Zn F-yokes and a Mu-metal movable plate as the magnetic circuit was developed and characterized. The distribution of the dc magnetic flux lines and magnetic inductions of the device were analyzed using a finite element method. The quasistatic and dynamic magnetic inductions of the device were measured, together with the generative forces. The results revealed that the device has linear voltage-controlled magnetic inductions in excess of 0.6 G/V with flat responses in the measured frequency range of 0.1–40 kHz and large generative forces over 0.7 N at 160 V at the designated gaps of 1.0–1.2 mm. This coil-free device could be useful in broadband and precision magnetic flux/force control applications with negligible Joule heating losses.

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1. Introduction

The direct magnetolectric (DME) effect is an electric polarization response of a magnetolectric (ME) material to an applied magnetic field, while the converse magnetolectric (CME) effect is a magnetization response of the material to an applied electric field.¹⁾ In the past decades, considerable research efforts have been put on the DME effect, first in single-phase materials, then in two-phase bulk composites, and lately in two-/three-phase laminated composites.^{2)–6)} To date, it is known that laminated composites of piezoelectric $0.7\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ – 0.3PbTiO_3 (PMN–PT) single crystal and magnetostrictive $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.92}$ (Terfenol-D) alloy possess superior DME effect due to their greater product effect of the direct piezoelectric effect and the direct magnetostrictive effect.⁴⁾ In particular, their ultrahigh DME voltage coefficients ($\alpha_V \sim 0.11$ V/Oe), defined by an induced electrical voltage in response to an applied magnetic field (dV/dH), have led to the commercial development of power-free magnetic field sensing devices.⁷⁾

By contrast, few of information has been available for the CME effect in ME materials in general and in the laminated composites in specific.^{8),9)} In fact, it is both physically interesting and technologically important to quantitatively characterize the CME effect in terms of the CME flux coefficient (α_B) defined by a magnetic induction in response to an applied ac voltage (dB/dV). From the perspective of applications, ME materials with high α_B are crucial to the direct realization of core-free electro-magnetic control devices. Since the traditional devices for magnetic flux/force control are essentially constructed from coil-wound electromagnets and operated according to Faraday's law

of electromagnetic induction, they suffer intrinsically from Joule heating losses, bandwidth limitations and precision problems.¹⁰⁾ Electromagnetic control devices based on the CME effect in ME materials do not need any magnetic coil, and thus have reduced Joule heating losses, improved operating bandwidths and increased control preciseness.

In this paper, we report a prominent CME effect in laminated composites consisting of one Terfenol-D alloy plate bonded between two electro-parallel-connected PMN–PT single crystal plates in the thickness direction, and present the development and performance of a coil-less electromagnetic control device formed by such a laminated composite, an Alnico biasing magnet, two Mn–Zn F-yokes and a Mu-metal movable plate.

2. PMN-PT and Terfenol-D magnetolectric laminated composites

2.1 Structure and working principle

Figure 1 shows the schematic diagram and photograph of the proposed ME laminated composites with the CME effect. The composite has one layer of magnetostrictive Terfenol-D alloy sandwiched between two layers of piezoelectric PMN–PT single crystal arranged in reverse polarization (P) directions and connected electrically in parallel to form the input terminals. The PMN–PT plates were cut from a PMN–PT ingot grown in-house using a modified Bridgman technique.¹¹⁾ The dimensions of the plates were 12 mm long, 6 mm wide and 1 mm thick. Their $\langle 001 \rangle$ and $\langle 011 \rangle$ crystallographic axes were arranged along the length and thickness directions, respectively. Polarization was induced using the $\langle 011 \rangle$ axis in the thickness direction so as to impart a high transverse piezoelectric response to the plates with deformations along the length direction when excited electrically in the thickness direction. The piezoelectric coefficient ($d_{31,p}$) and

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Fig. 1. Schematic diagram and photograph (the inset) of the proposed ME laminated composites with the CME effect.

elastic compliance coefficient at constant electric field (s_{11}^E) of the PMN-PT plates were measured to be -1630 pC/N and $125 \text{ pm}^2/\text{N}$, respectively. The Terfenol-D plate was commercially supplied with the same dimensions as the PMN-PT plates (Baotou Rare Earth Research Institute, China). It had the highly magnetostrictive [112] crystallographic axis along the length direction so that magnetization (M) was relatively easy in this direction. The piezomagnetic coefficient ($d_{33,M}$), elastic compliance coefficient at constant magnetic field strength (s_{33}^H) and relative magnetic permeability at constant stress (μ_{33}^T/μ_0) of the Terfenol-D plate were evaluated to be 7.8 nm/A , $27.6 \text{ pm}^2/\text{N}$ and 4.5 , respectively, at an optimal magnetic bias field of 350 Oe .

In operation, applying an ac voltage (V_3) to the input terminals of the composite produces two equimagnitude, opposite-sign ac electric fields across the thickness of the PMN-PT plates, resulting in transverse piezoelectric strains in the PMN-PT plates owing to the converse piezoelectric effect. These piezoelectrically induced strains lead to mechanical stresses in the sandwiched Terfenol-D plate, giving rise to a magnetic induction (B_3) along the length of the composite because of the converse magnetostrictive effect. To enable description of the composite for magnetic flux/force control applications, one can determine its α_B at frequencies well below its fundamental shape resonance as follows:¹²⁾

$$\alpha_B = \left| \frac{dB_3}{dV_3} \right| = \left| \frac{d_{31,P} d_{33,M}}{s_{11,P}^E t_M + 2s_{33,M}^H t_P - 2 \frac{d_{33,M}^2}{\mu_{33}^T} t_P} \right| \quad (1)$$

where t_M is the thickness of the Terfenol-D plate, t_P the thickness of the PMN-PT plates, and μ_{33}^T the magnetic permeability at constant stress. Substituting the corresponding material and geometric parameters into Eq. (1), α_B of the proposed composite is predicted to be 0.80 G/V at $H_{\text{Bias}} = 350 \text{ Oe}$.

2.2 Converse magnetoelectric properties

The CME properties of the composites were characterized using an in-house automated measurement system.¹³⁾ A composite sample was placed between the pole gap of a water-cooled, U-shaped electromagnet (Mytem PEM-8005K). By energizing the electromagnet with a dc current supply (Sorensen DHP200-15), a magnetic bias field (H_{Bias}) was generated in the pole gap and was measured with a first Hall probe connected to a Gaussmeter (F. W. Bell 7030). A dynamic signal analyzer (Ono Sokki CF5220) connected to a voltage amplifier (NF-HAS 4025) was employed to provide a V_3 at the desired amplitude and frequency for the PMN-PT plates of the sample. The corresponding B_3 induced in the Terfenol-D plate of the sample was measured by

Fig. 2. Measured CME properties of the ME laminated composite in Fig. 1. (a) Waveforms of B_3 due to an applied V_3 of 104 V peak at 1 kHz and with $H_{\text{Bias}} = 350 \text{ Oe}$. (b) B_3 as a function of V_3 for various H_{Bias} at 1 kHz . The inset shows α_B as a function of H_{Bias} .

a second Hall probe attached to the end of the sample and connected to the dynamic signal analyzer via the Gaussmeter. From the slope of B_3 - V_3 plot, α_B was determined. By plotting α_B as a function of H_{Bias} , the H_{Bias} required to optimally operate the sample was obtained.

Figure 2(a) illustrates the waveforms of the measured B_3 due to an applied V_3 of 104 V peak at 1 kHz and with $H_{\text{Bias}} = 350 \text{ Oe}$. It is clear that B_3 follows steadily V_3 and has the maximum amplitude of 81 G when V_3 peaks at 104 V . The fact that B_3 and V_3 are of opposite phase can be explained by the negative sign of the piezoelectric coefficient $d_{31,P}$ in Eq. (1). **Figure 2(b)** plots the measured B_3 as a function of V_3 for various H_{Bias} at 1 kHz . B_3 has good linear responses to V_3 in the entire V_3 range of 10 – 104 V for all H_{Bias} . From the slopes of the B_3 - V_3 plots, α_B at each H_{Bias} is determined and shown in the inset of Fig. 2(b). It is seen that α_B increases initially up to 0.73 G/V at a relatively low H_{Bias} of 350 Oe and then decreases with increasing H_{Bias} . The characteristic variation of α_B with H_{Bias} is mainly attributed to the H_{Bias} -dependent piezomagnetic $d_{33,M}$ contribution from the Terfenol-D plate as a result of the increased and decreased motions of the non- 180° domain walls.¹⁴⁾ Nevertheless, the measured α_B agrees well with the predicted value of 0.80 G/V at $H_{\text{Bias}} = 350 \text{ Oe}$ based on Eq. (1). It is noted that the composite exhibits significantly small variations in α_B (i.e., 0.71 – 0.73 G/V) in the H_{Bias} range of 250 – 450 Oe . In order to obtain a high and stable B_3 in practice, this specific range of H_{Bias} should be utilized in the design and operation of the composite and its associated devices.

3. Electromagnetic control device with magnetolectric laminated composite

3.1 Structure and working principle

Figure 3 shows the solid model and photograph of the proposed electromagnetic control device. The device has a length of 30 mm, a width of 19 mm and a thickness of 5 mm. A ME laminated composite of PMN-PT and Terfenol-D described in Section 2 is used as the control element and integrated into a magnetic circuit composed of an Alnico biasing magnet (14 mm × 7 mm × 2 mm), two Mn-Zn F-yokes and a Mu-metal movable plate (30 mm × 5 mm × 0.25 mm). The magnetic circuit with the composite in place essentially forms two sets of magnetic flux loops: one including the biasing magnet, the upper section of the F-yokes and the composite (Loop 1), and the other containing the biasing magnet, the lower section (or the output poles) of the F-yokes, the air gaps and the movable plate (Loop 2). The type and size of the biasing magnet have been carefully selected to serve two main purposes: (1) It provides an optimal magnetic bias field (H_{Bias}) of 350 Oe to the composite so as to enable a high and stable α_B value (0.71–0.73 G/V) centering the specific H_{Bias} range (250–450 Oe) as discussed in Section 2; and (2) it generates a basis value of dc magnetic induction in the gap (B_{go}) between the output poles of the F-yokes and the movable plate. For a given gap size (g), the sum of magnetic fluxes in the two loops is

Fig. 3. Solid model (upper) and photograph (lower) of the proposed electromagnetic control device. Two sets of magnetic flux loops (Loop 1 and Loop 2) are created. g is the gap between the output poles of the F-yokes and the movable plate.

approximately conserved so that an induced B_3 in the composite due to an applied V_3 leads to a change in the magnetic induction in the gap (B_g) and hence an associated magnetic force acting on the movable plate (F_g). In applications, this movable plate may be adhered on the surface of the object to be controlled.

3.2 DC magnetic analysis

To gain insight into the design of the device with both the composite and magnetic circuit, an ANSYS 10.0 finite element model was created to analyze the distribution of the dc magnetic flux lines of the device, the dc magnetic induction in the gap (B_{go}) and the dc magnetic field strength used to bias the composite (H_{Bias}), all for different gap sizes (g). The SOLID98 element

Table 1. Magnetic Properties of the Constituent Components of the Proposed Electromagnetic Control Device for the dc Magnetic Finite Element Analysis

Constituent components	Materials	Relative magnetic permeability μ_{r3} / μ_0	Coercive field H_c (Oe)
Magnetolectric laminated composite	PMN-PT Terfenol-D	1 4.5	—
Biasing magnet	Alnico	5.3	1,670
F-yoke	Mn-Zn ferrite	2,000	—
Movable plate	Mu-metal	20,000	—
Air gap	Air	1	—

Fig. 4. DC magnetic analysis results. (a) Computed dc magnetic flux lines for a full device model with $g = 1.1$ mm. (b) Comparison between the computed (lines) and measured (symbols) B_{go} and H_{Bias} as a function of g .

was employed for the magnetic analysis. Magnetic properties of the constituent components of the device listed in **Table 1** were input into the model.

Figure 4(a) displays an example of the computed dc magnetic flux lines for a full device model with $g = 1.1$ mm. It is seen that the magnetic circuit incorporated with the composite results in two sets of magnetic flux loops in good agreement with the schematic illustration in Fig. 3. The magnetic circuit is capable of channeling the magnetic fluxes into the composite and the movable plate (via the output poles of the F-yokes). **Figure 4(b)** plots the comparison between the computed and measured B_{go} and H_{Bias} as a function of g . B_{go} and H_{Bias} were measured with two separate Hall probes connected to a Gaussmeter (F. W. Bell 7030). This was achieved by placing a first Hall probe on the surface of the movable plate underneath the output pole of an F-yoke and by attaching a second Hall probe to the end of the composite. It is found that the computed B_{go} and H_{Bias} coincide well with the measured B_{go} and H_{Bias} . There are a gradual decrease in B_{go} and a corresponding increase in H_{Bias} with increasing g . The complementary trends elucidate the conservation nature of the sum of magnetic fluxes in the two loops. The degree of conservation reduces with increasing g as a result of the increased flux leakage and non-uniformity of flux distributions. Nevertheless, when $g = 1.0$ – 1.2 mm is used, the composite will be biasing in the specific H_{Bias} range of 250–450 Oe with a remarkable α_B in excess of 0.7 G/V (Fig. 2).

3.3 Performance measurements

The dynamic performance of the fabricated electromagnetic control device in Fig. 3 was characterized by measuring its ac magnetic induction in the gap (B_g) and the associated generative force exerted on the movable plate (F_g) as functions of V_3 , g and frequency (f). **Figure 5** shows the measurement setup. The device was mounted on a z -manipulator and positioned right above its movable plate affixed to a load cell (KISTLER Type 9222). V_3 (and f) were supplied by a dynamic signal analyzer (Ono Sokki CF5220) via a voltage amplifier (NF-HAS 4025). B_g and F_g were measured using a Hall probe connected to a Gaussmeter (F. W. Bell 7030) and the load cell linked to a signal conditioner (VISHAY 3800), respectively. The acquired B_g and F_g signals were gathered by the dynamic signal analyzer. The exact value of g was confirmed by a laser displacement sensor (Keyence LK-G82) with a controller (Keyence LK-G3001).

Figure 6(a) shows the waveforms of the measured B_g and its excitation V_3 of 160 V peak at 1 kHz for $g = 1.1$ mm. Similar to the observation on the waveforms of B_3 and V_3 of the composite

(Fig. 2(a)), B_g and V_3 of the device, while stable, are of opposite phase with the maximum amplitudes of 104 G and 160 V, respectively. This indicates that an applied positively phased V_3 produces a negatively phased B_3 in the composite and hence a negatively phased B_g in the device. **Figure 6(b)** plots B_g as a function of V_3 for various g at 1 kHz. As expected, B_g has an essentially linear relationship with V_3 in the measured range of 10–160 V for all g . The inset of Fig. 6(b) relates the CME flux coefficient of the device (α_{Bg}), defined by a magnetic induction in a given gap in response to an applied ac voltage (dB_g/dV_3), with g . It is obvious that α_{Bg} attains its generally high value in excess of 0.6 G/V in the g range of 1.0–1.2 mm. This range of g corresponds

Fig. 6. Measured dynamic magnetic flux results. (a) Waveforms of B_g and its excitation V_3 of 160 V peak at 1 kHz for $g = 1.1$ mm. (b) B_g as a function of V_3 for various g at 1 kHz. The inset relates α_{Bg} with g . (c) f dependence of α_{Bg} at three different g of 1.0, 1.1 and 1.2 mm.

Fig. 5. Measurement setup for characterizing the dynamic performance of the fabricated electromagnetic control device in Fig. 3.

Fig. 7. Measured generative force results: F_g versus V_3 for various g at 1 kHz. The inset shows the variation of F_g with g at three different V_3 of 60, 100 and 160 V.

to biasing the composite in the H_{Bias} range of 250–450 Oe with a generally high and stable α_{Bg} of 0.71–0.73 G/V. Figure 6(c) illustrates the f dependence of α_{Bg} for three different g of 1.0, 1.1 and 1.2 mm. It is noted that α_{Bg} has essentially flat responses in the measured f range of 0.1–40 kHz with no observable dispersion of the CME effect.

Figure 7 shows the relationship between F_g and V_3 for various g at 1 kHz. Instead of exhibiting a highly linear relationship with V_3 as in Fig. 2(b) for B_3 and in Fig. 6(b) for B_g , F_g demonstrates nonlinear increasing trends with V_3 . These nonlinear trends may be explained by Eq. (2) in which F_g is a function of both B_g and B_{g0} rather than a function of B_g .¹⁰⁾

$$F_g = \frac{2B_g B_{g0} A_g}{\mu_0} \quad (2)$$

where A_g is the cross-section area of the output poles of the F-yokes and μ_0 ($= 4\pi \times 10^{-7}$ H/m) the magnetic permeability at free space. From the inset of Fig. 7, it is known that F_g is capable of maintaining stable and high values at the designated gaps of 1.0–1.2 mm.

4. Conclusions

We have developed, analyzed and characterized a coil-free electromagnetic control device based on the CME in a ME laminated composite of a Terfenol-D alloy plate sandwiched between two electro-parallel-connected PMN-PT single crystal plates in the thickness direction. The composite demonstrates a high α_{B} of 0.73 G/V at a relatively low H_{Bias} of 350 Oe, together

with an excellent linear relationship between B_3 and V_3 in the measured V_3 range of 10–104 V for H_{Bias} varying from 0 to 1200 Oe. The device shows generally high α_{Bg} over 0.6 G/V with flat frequency responses in the measured range of 0.1–40 kHz and with large generative forces in excess of 0.7 N at 160 V at the designated gaps of 1.0–1.2 mm. Comparing to conventional coil-wound electromagnetic devices based on Faraday's law of electromagnetic induction, our device has the distinct advantage of no magnetic coil, and is thus suitable for magnetic flux/force control applications where reduced Joule heating losses, improved operating bandwidths and increased control preciseness are of great concern/interest.

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