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Additional dc magnetic field response of magnetostrictive/piezoelectric magnetoelectric Laminates by Lorentz force effect

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We have discovered that traditional long-type magnetoelectric laminate composite of magnetostrictive $Tb_{1-x}Dy_xFe_{2-y}$ and piezoelectric materials possesses additional ability of detecting dc magnetic field, using the product effect of the Lorentz force effect from Terfenol-D metal strips in dc magnetic field applied with an ac electrical current and the piezoelectric effect from piezoelectric material. The output voltage between the two faces of piezoelectric $(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3-xPbTiO_3$ single crystal shows a good linear response to applied dc magnetic field of 100–1200 Oe under different ac electrical current inputs (0.4–200 mA). The magnetoelectric coefficient is about ~64.1 mV/T A. The additional dc magnetic field response of magnetostrictive/piezoelectric magnetoelectric laminates driven by Lorentz force makes this composite hopeful for application in coil-free ac/dc magnetic-sensitive sensors. At the same time, for this composite, the additional ability will not affect the primal ability for detecting ac magnetic field. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2402099]

The magnetoelectric (ME) effect in materials which are simultaneously ferroelectric and ferromagnetic has been a research topic in recent years.[1–7] From previous reports, ME effects were reported mainly focusing on the ac magnetic field (H_{ac}) response of single phase and multiphase laminates.[5–9] However, it is a pity that it cannot be used to detect dc or quasi-dc magnetic field.[10,11] When it comes to the applications, magnetic sensor for magnetic anomaly detection requires strictly high sensitivity to dc or quasi-dc magnetic field.

Piezoelectric materials such as $(1-x)Pb(Mg_{1/3}Nb_{2/3})\times O_3-xPbTiO_3$ (PMN-PT) crystal, which is one of the most excellent piezoelectric materials up to now,[12] have an excellent ability of transducing force (stress) signals to electrical charge (or voltage) signals. At the same time, normal magnetic sensor based on Lorentz force effect can show an excellent linear response to magnetic field and offer a high sensitivity of 200 nT (excellent ability of transducing magnetic signals to force signals).[13,14] On the basis of the theory of product effect,[15] which demands both of the two effects combined together to accomplish excellent product effect, we expect to obtain excellent magnetic-electric transducing output by combining Lorentz force effect with piezoelectric effect. In this case, we try to detect a constant dc magnetic field using longitudinally magnetized and transversely polarized (or *L*-*T*) laminates of $Tb_{1-x}Dy_xFe_{2-y}$ (Terfenol-D) and piezoelectric single crystal PMN-PT besides their popular function in detecting an ac one.[16] Here, we accomplished to detect dc magnetic field by the product effect of the Lorentz force effect from Terfenol-D metal strips in dc magnetic field applied with an ac electrical current and the piezoelectric effect from piezoelectric material.

Our dc magnetic field detector, whose geometry and working principle have been shown in Fig. 1, is consisted of one *L*-*T* mode ME laminate and one ac current source supplying ac electrical current to Terfenol-D alloy strips. Terfenol-D strips were commercially supplied with dimensions at $1\times1\times23$ mm^3 and easy magnetization axis $\langle 112\rangle$ orientation along the length direction.[17] The PMN-PT piezoelectric crystal was grown in house by using a modified Bridgman technique.[18] As-grown crystal was oriented along the $\langle 001\rangle$ direction and cut with the dimensions of $1\times1\times27$ mm^3. After being electroded with silver and polarized along the thickness direction in silicone oil, the relative dielectric constant $(\varepsilon_{33}^T/\varepsilon_o)$ of the piezoelectric layer was evaluated to be ~4000 at 1 kHz using an HP 4194A imped-

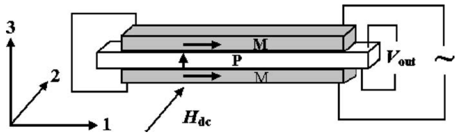

FIG. 1. The geometry and working principle of the ME laminate with a Cartesian coordinates.

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ance analyzer. The piezoelectric charge coefficient (d_{33}) was measured to be ~2000 pC/N using a quasistatic Berlincourt d_{33} meter. The piezoelectric voltage coefficient ($g_{33} = d_{33}/\varepsilon_{33}^T$) was estimated to be 56.5 mV m/N. The PMN-PT piezoelectric layer was bonded between two Terfenol-D layers by insulating epoxy. To avoid the contact between Terfenol-D and the electrode of PMN-PT layer, a thin nonpolarized PMN-PT crystal layer with the thickness of ~80 μm, which is insulating and nonpiezoelectric, is inserted between Terfenol-D strips and piezoelectric PMN-PT crystal strip.

Such configuration is similar to that of traditional *L-T* mode magnetostrictive/piezoelectric ME laminates having been reported previously.[6,10] Cartesian coordinates was built as shown in Fig. 1, in which the DC magnetic field is along the width direction (direction "2") and the length and thickness directions of ME samples were defined as direction "1" and direction "3," respectively. The working principle of H_{dc} signal detector is described as follows. Due to Terfenol-D alloy's conductibility, it can be considered as wires in our ME samples. When we apply a small ac electrical current with its range of 0.4–200 mA along direction 2, Terfenol-D strips undergo an ac Lorentz force along the thickness direction (direction 3) in the dc magnetic field. Since the two Terfenol-D strips are boned outside the piezoelectric layer together, the induced Lorentz forces either press or pull the layer inside simultaneously and make it either produce or charge piezoelectric voltages under the piezoelectric effect.

In our laminate, the weak magnetoelectric effect may affect the detection for dc magnetic field which came from the transverse magnetostrictive (d_{32}^M) effect of Terfenol-D and transverse piezoelectric (d_{32}^P) effect. However, the optimal magnetostrictive effect stemmed from the longtitudial $\langle 112 \rangle$ direction for Terfenol-D, so the magnetostrictive effect in width direction is very poor.[19] At the same time, in view of the sizes of Terfenol-D layers and PMN-PT layer selected in our laminate, the transverse d_{32} (magnetostritive or piezoelectric) are very small and can be neglected.[17,20] Therefore, the weak ME effect should have no significant effect for our dc magnetic detection in direction 2. What is more, the inability of the magnetoelectric laminate for dc magnetic field is well known[10,11] even though the existence of weak transverse ME effect is true. In fact, in our experiment, we have found that output voltage signal of dc magnetic field response is hardly observed when we applied dc magnetic field along direction 2 of our laminate under the condition of no ac electric current applied. So, the additional ability of dc magnetic field response comes from Lorentz effect, not from magnetostrictive effect. It can also be proved from the fact of remarkable ME voltage output observed in the composite of metal brass ring (nonmagnetostrictive material) and piezoelectric (PZT) disk under the drive of an ac electrical current in our recent work.[21]

according to Ampere's law, the magnitude of Lorentz force acted on each Terfenol-D alloy trip F_3 is

$$F_3 = (B \times I)L, \tag{1}$$

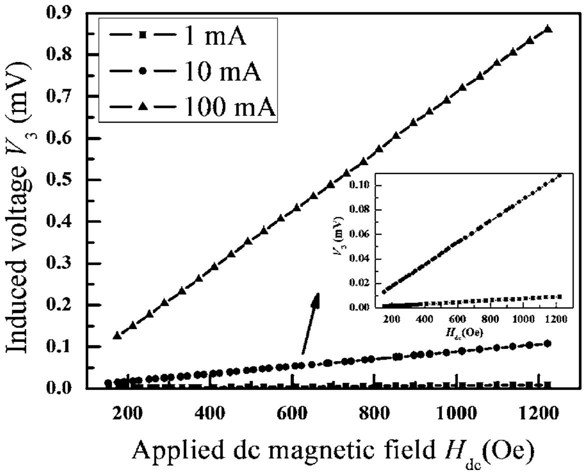

FIG. 2. The induced ME voltage as a function of applied dc magnetic field (H_{dc}) under different ac electrical current drives of 1, 10, and 100 mA at the frequency of 1 kHz.

where I is the direct current vector, L is the length of Terfenol-D strips, and B is the magnetic field vector. The force relationship above is in a vector product form and its direction obeys the right-hand rule. The Lorentz force F reaches a maximum value when the two vectors I and B are positioned at right angles with respect to each other.

As the piezoelectric layer was polarized along the thickness direction, its constitutive equations can be expressed as[20]

$$S_3 = s_{33}^D T_3 + g_{33} D_3, \tag{2a}$$

$$E_3 = - g_{33} T_3 + \beta_{33}^T D_3, \tag{2b}$$

where E_3 and D_3 are the electric field and electric displacement along the polarization direction, respectively; T_3 and S_3 are the stress and strain along the polarization direction, respectively; s_{33}^D is the elastic compliance coefficient at constant electric displacement; g_{33} is the piezoelectric voltage constant; and β_{33}^T is the dielectric permittivity at constant stress. Due to the open circuit condition $D_3 = 0$, an induced open circuit output voltage (V_3) obtained from Eqs. (1) and (2) is

$$V_3 = - g_{33} \frac{t}{w} (B \times I), \tag{3}$$

where t and w are the thickness and width of the piezoelectric PMN-PT crystal layer, respectively. The calculated induced output voltage is about 57.2 mV at $B = 1$ T and $I = 1$ A by substituting the corresponding material parameters of Terfenol-D and PMN-PT piezoelectric crystal layer into Eq. (3).

The output ME voltage induced by variations of applied dc magnetic field (H_{dc}) performs in a simply magnetically shielded environment, which is realized by the use of μ-metal in lock-in method. A small ac electrical current (I_{ac}) of 0.4–200 mA at a lower frequency (10^3 Hz) was supplied to the Terfenol-D alloy strips.

Figure 2 plots the induced ME voltage as a function of applied dc magnetic field H_{dc} in the field range of 100–1200 Oe under different ac electrical current drives of 1, 10, and 100 mA at the frequency of 1 kHz. From Fig. 2,

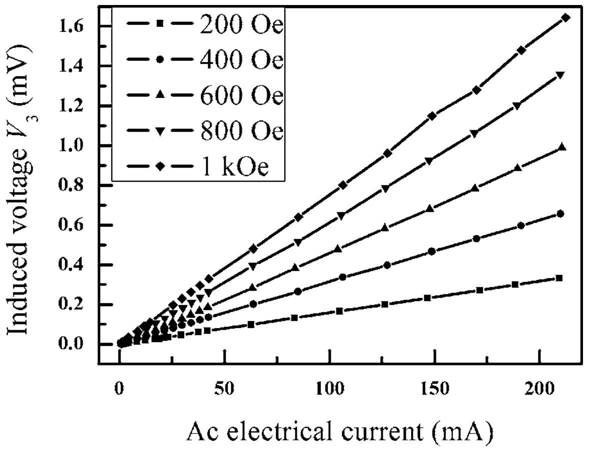

FIG. 3. The induced voltage (V_3) as a function of input ac electrical current with range of 0.4–200 mA at the frequency of 1 kHz under several fixed dc magnetic fields of 200, 400, 600, 800 Oe, and 1 kOe.

we can see that induced ME voltage (V_3) has a good linear response to the applied dc magnetic field (H_{dc}) over this magnetic field range. In addition, with the increasing ac electrical current, the induced voltage increases correspondingly. It could be used to detect smaller dc magnetic field if better shielding of magnetic noises could be adopted and composite fabrication techniques could be improved further.[6,10] From the slope of the plot, the induced voltage is about ~64.1 mV at $B=1$ T and $I=1$ A. The ME coefficient from measurement (64.1 mV/TA) is a bit higher than the calculation result (57.2 mV/TA). This is considered as the result of effect of magnetic noise field (ac and dc) in surroundings.

Figure 3 shows the induced voltage (V_3) as a function of input ac electrical current with range of 0.4–200 mA at the frequency of 1 kHz under several fixed dc magnetic fields of 200, 400, 600, 800 Oe, and 1 kOe. It was found that the induced ME voltage has a good linear response to ac electrical current at various fixed dc magnetic fields. With increasing applied ac electrical current or dc magnetic filed, the induced ME voltage increases correspondingly and such result shows its good accordance with Eq. (3).

It should be noted that, after the magnitude and direction of dc magnetic field are fixed, a maximum ME voltage output can be obtained in a certain position when the laminate is rotated both in plane consisting of directions 1 and 2. In that position, the direction of dc magnetic field is perpendicular to the direction of input ac electrical current (that is the length direction of our ME laminate). Such result shows our long-type ME laminate's potential ability to detect the direction of dc magnetic field.

It is known that when *L*-*T* mode laminate is used to detect ac magnetic field along length direction, a dc bias must be applied to obtain linear and high ME voltage.[2,5–7] While based on Eq. (3), we can conclude that in its practical application in magnetic sensors, the existence of bias dc magnetic field in length direction will not affect the detection for external dc magnetic field along the direction 2. From this conclusion, an edge-cutting ME magnetic-sensitive sensor can be designed integrating both abilities in detecting ac and dc magnetic fields.

In summary, using the product effect of the Lorentz force effect from Terfenol-D metal strips in dc magnetic field applied with an ac electrical current and the piezoelectric effect from piezoelectric material, we successfully completed our work in using the traditional magnetoelectric/piezoelectric ME laminate to detect additional vector dc magnetic field. The output ME voltage has a good linear response to dc magnetic field applied. With increasing applied ac electrical current or dc magnetic field, the induced ME voltage increases correspondingly. The ME coefficient is about ~64.1 mV/T A. The additional dc magnetic field response of magnetostrictive/piezoelectric magnetoelectric laminates driven by Lorentz force makes this composite hopeful for application in coil-free ac/dc magnetic-sensitive sensors. At the same time, for this composite, the additional ability will not affect the primal ability for detecting ac magnetic field.

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