Enhanced magnetoelectric torque effect in Pb(Zr,Ti)O$_3$/NdFeB bi-cantilever composites

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ABSTRACT

A piezoelectric/ferromagnetic bicantilever composite, constructed with a Pb(Zr,Ti)O$_3$ beam fixed at the middle point and NdFeB magnets attached at both free ends, has been designed and exhibited a giant magnetoelectric torque (MET) effect. The low-frequency and resonant MET effect in the bicantilever composite is more than twice as much as that in the single cantilever composite with the same components and geometry dimension. As the magnet mass increases, the MET effect first increases nearly linearly and then tends to saturate while the resonant frequency decreases. When the magnets are attached asymmetrically at the tip, the MET effect is stronger than that of the symmetric attachment. Our results will give more choices for preparing the magnetoelectric device used as an ac magnetic field sensor, energy harvester, etc.

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I. INTRODUCTION

Magnetoelectric (ME) composites, composed of piezoelectric and magnetostrictive phases, have received continuously increasing attention in the past decades due to their larger ME effect compared with that in single phase multiferroic materials and potential applications in magnetic sensors, energy harvesters, etc. The ME effect in current composites originates from the existence of a strong product effect of the magnetostrictive and piezoelectric effects, and its coupling mechanism is as follows: with the application of an ac magnetic field superimposed on the dc bias magnetic field, strain is produced in the magnetostrictive phase and then transmitted to the piezoelectric phase due to interfacial elastic mechanical coupling, resulting in a polarization or voltage via piezoelectricity. As the giant ME effect is necessary for its application, people have been working to enhance the ME effect in composites by various measures, such as improving interfacial coupling, optimizing structure design, and selecting components of excellent piezoelectric or magnetostrictive properties. To date, the highest record of the ME voltage coefficient for magnetostrictive/piezoelectric laminated composites is 1800 V cm$^{-1}$ Oe$^{-1}$ at resonance and 20 V cm$^{-1}$ Oe$^{-1}$ at low frequency. However, further improvement of the ME effect in magnetostrictive/piezoelectric laminated composites becomes much more difficult due to the restriction of their operating mechanism and composite configurations. The ME effect in current composites largely depends on the magnetostrictive effect of components, but research on magnetostrictive materials has not made much progress in the past few decades, and the commonly used giant magnetostrictive materials are still rare earth alloys discovered in the 1960s, such as Tb$_{0.3}$Dy$_{0.7}$Fe$_{1.92}$ (Terfenol-D) and FeGaB (Gafenol). Then, some researchers turned to seek a new ME coupling mechanism. Recently, Xing et al. proposed a new type of ME composite consisting of a piezoelectric cantilever beam and tip magnets in which the magnetic force moment due to magnets under an applied ac magnetic field drives the piezoelectric cantilever to vibrate and the giant ME effect was obtained by this magneto-mechanical-electric coupling, i.e., a product effect of the magnetic torque effect and piezoelectric effect. Later, Liu et al. further optimized this type of ME composite and obtained a colossal ME effect in a three-phase composite of piezofiber/elastic/magnet. They also investigated the magnetoelectric torque (MET) coupling theoretically based on the equivalent circuit method and elastic mechanics method. In addition, Zhang et al. used the magnetic force between high permeability ferrites to drive the piezoelectric cantilever to vibrate and obtained a strong magnetic force driven ME effect in Mn-Zn-ferrite/piezoelectric composites.
In this work, a piezoelectric/magnets’ bicantilever structure with free vibration at both ends is designed to make full use of bending strain. The enhanced MET effect has been observed compared to that in the single cantilever beam with the same geometric size. In addition, the dependence of the MET effect on the magnets’ position and placement symmetry at the piezoelectric beam is also investigated.

II. EXPERIMENT

The designed bicantilever structure of the piezoelectric/magnet MET device is shown in Fig. 1(a). The piezoelectric phase is a Pb(Zr$_{1-x}$Ti$_x$)O$_3$ (PZT) bimorph plate with Ag electrodes pasted on the top and bottom planes, polarized along its thickness direction. The PZT bimorph is 70 mm in length, 10 mm in width, and 0.5 mm in thickness, constructed with one 0.1 mm-thick copper layer sandwiched between two 0.2 mm-thick PZT layers. The PZT bimorph is fixed at the middle point with NdFeB permanent magnets attached on the two free tip ends using their own magnetic attraction force. The sizes of the used magnets are 10.0 mm (diameter) × 1.0 mm (height). For the sake of comparison, a single cantilever MET device with one end fixed and the other end free was fabricated using the same material and was of the same geometry size, as shown in Fig. 1(b).

The schematic diagram of the ME measurement is shown in Fig. 1(c). The MET device to be measured was placed in a long straight solenoid. A harmonic voltage from the output port of the lock-in amplifier (Zurich Instruments, UHF-DEV2031) with frequency $f = 1–300$ Hz was applied to the solenoid to generate an ac magnetic field, which was measured by using an ac magnetic field gauss meter. The magnetic torque due to interaction between magnets and ac magnetic field drives the PZT bimorph bonded with magnets to vibrate and produce bending strain, resulting in piezoelectric voltage across the top and bottom electrodes, which was recorded by the input port of the lock-in amplifier with an input impedance of 1 MΩ.

III. RESULTS AND DISCUSSION

Figure 2 shows the frequency dependent $V_{out}$ in the bicantilever PZT/NdFeB composite with two NbFeB magnets attached at both free ends. The low frequency $V_{out}$ and resonant $V_{out}$ are 0.002 V and 0.14 V, respectively, and corresponding ME voltage coefficient $\alpha_{ME}$ ($\alpha_{ME} = V_{out}/hH$, where $h$ is the thickness between the electrodes of the piezoelectric phase and $H$ is the applied magnetic field) are 6.7 and 466.7 V cm$^{-1}$ Oe$^{-1}$, respectively, which is very comparable to the highest record in traditional piezoelectric/magnetostrictive ME composites. Moreover, the ME voltage coefficient could be further enhanced by increasing the magnets mass, which will be discussed in detail below. It is believed that if interdigitated electrodes and piezoceramic fibers are adopted to prepare the MET bicantilever device, the obtained ME voltage could be further enhanced and exceed the record in Ref. 13. The result in the single cantilever structure of the same geometry size is also given as a comparison. It can be seen that resonant $V_{out}$ in the bicantilever is more than twice as large as that in the single-cantilever, which can be attributed to increased bending strain due to two free vibration ends of the bicantilever.

In order to investigate the relationship of the working principle between the bicantilever and single-cantilever, the bicantilever device was attached two magnets only at one end and no magnets at the other end. As shown in the inset of Fig. 2, the measured
resonant ME magnitude is reduced by more than half while the resonant frequency remains almost unchanged, which indicates that the bicantilever can be seen as a serial connection of the two same single-cantilevers.

The generated voltage in the PZT/NdFeB MET bicantilever device is due to axial strain $S_1$ of the PZT beam via the piezoelectric effect, which originates from the bending vibrations driven by magnetic torque due to interaction between magnets and the applied ac magnetic field. The axial strain $S_1$ in the cantilever can be expressed in terms of the bending deflection $w_3(x, t)$ as

$$S_1 = -\frac{\partial^2 w_3}{\partial x^2},$$  

(1)

where $w_3(x, t)$ satisfies the governing equation for the bending motion of the PZT beam,

$$\frac{\partial^2 M}{\partial x^2} = bh\rho \frac{\partial^2 w_3}{\partial t^2},$$  

(2)

where $b$ is the width of the piezoelectric phase, $h$ is the thickness between the electrodes of the piezoelectric phase, and $\rho$ is the mass density of the piezoelectric phase. As mentioned above, the bicantilever structure with the middle point fixed and two ends free could be seen as a serial connection of the two same single-cantilevers, so the solution to Eq. (2) for the bicantilever structure will have the same form as that in the single-cantilever structure problem with one end fixed and the other end free, which has been presented in Ref. 15,

$$w_3(x, t) = W(x)\exp(i\omega t) = (A \cos kx + B \sin kx + C \cosh kx + D \sinh kx)\exp(i\omega t),$$  

(3)

with

$$A = -C = \frac{\theta_0}{2k} \left( \frac{\cos kl + \cosh kl}{\sinh kl} - K(\sin kx - \sinh kx) \right),$$  

$$B = -D = \frac{\theta_0}{2k} \left( \frac{\sin kx - \sinh kx}{\sinh kl} + K(\cos kx - \cosh kl) \right),$$  

$$k = \sqrt{\frac{2bh\rho\omega^2}{\Omega^2}}, \quad \Omega = \frac{2bh^3}{3} + \frac{1}{3} \left( \frac{1 - \frac{1}{2}e_{31}^2}{1 - k_{31}^2} \right), \quad K = \frac{m_0\omega^2}{\Omega k^2}, \quad k_{31} = \frac{d_{31}}{\sqrt{\varepsilon_{11}^0\varepsilon_{33}^0}},$$

where $A, B, C,$ and $D$ are the constants determined using the boundary conditions, $l$ is the length of the plate, $\omega$ is the angular frequency of the applied ac magnetic field, $\theta_0$ is the constant dependent on the magnitude of driven magnetic torque, $e_{31}^2$ is the compliance coefficient, $m_0$ is the mass of the magnets, $d_{31}$ is the piezoelectric coefficient, and $\varepsilon_{11}^0$ is the permittivity under free mechanical boundary conditions. Some material parameters are used for numerical calculation: $e_{31}^2 = 15.3 \times 10^{-12}$ m/V, $\rho_p = 7.5 \times 10^{-7}$ kg/m$^3$, $d_{31} = -175 \times 10^{-12}$ m/V, $e_{11} = 1750$, $l = 70 \text{ mm}$, $b = 10 \text{ mm}$, $h = 0.5 \text{ mm}$, and the mass of magnets is $m_0 = 3.4 \text{ g}$. The numerical calculation result is shown in Fig. 3, demonstrating that $\partial^2 W_3/\partial x^2$ is a monotonic decreasing function of $x$, i.e., the bending strain is limited to the region close to the fixed end of the cantilever. This shows that the bicantilever structure with the middle point fixed, seen as a serial connection of two single cantilevers, will have more bending strain than the single cantilever of the same length under equal driving magnetic torque and thus exhibit a larger MET effect.

Since the attached magnets are closer to the fixed point in the bicantilever than those in the single-cantilever, the deformation of the device due to the gravity force will decrease, which is beneficial for the device to maintain stable working conditions.

As shown in Fig. 2, the resonant frequency shifts from ~30 Hz in the single-cantilever to a higher frequency ~102 Hz in the bicantilever. The resonant frequency of the cantilever structure with the tip load could be described as follows:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{1/l^3}{\varepsilon_{31}^0(\rho A + m_0)^2}},$$  

(4)

where $bl$ is a constant dependent on mechanical boundary conditions and the order of the resonance, which is 1.875 for the first order bending vibration of the single cantilever; $l = bh^2/12$ is the inertia moment of the rectangular cantilever with respect to the fixed point; and $A = bh$ is the cross-sectional area of the beam. As the bicantilever structure is fixed at its middle point, the effective length $l$ used for resonant frequency calculation is only half that of the single-cantilever when they have the same total length. The effective length $l$ is 37.5 mm and 70.0 mm, respectively, for our bicantilever and single-cantilever structures. Using the above listed material parameters, the calculated resonant frequency from Eq. (4) is 103 Hz and 32 Hz for the bicantilever and single cantilevers, respectively, which are in good agreement with the experimental results.

Then, the influence of magnet mass on the MET effect was investigated. The magnet mass is tuned by changing the number of the magnets. As shown in Fig. 4, when the magnet mass increases, the resonant frequency decreases, which is due to the tip mass loading contribution, in agreement with Eq. (4) and the result in the single-cantilever.\(^\text{11,20}\) The induced magnetic force torque $M$ is calculated as

$$M = |m \times B| = \mu_0 JVH \sin \theta,$$  

(5)
where \( \mu_0 \) is the permeability of vacuum, \( J \) is the magnetic polarization of the magnet, \( V \) is its volume, and \( \theta \) is the angle between \( J \) and \( H \). Since the magnetic force is proportional to the volume of magnets, the resonant ME effect first increases nearly linearly with the increasing magnet mass, as shown in Fig. 4. However, when the magnets’ mass is increased to a larger range, \( V_{\text{out}} \) tends to saturate, which is due to the fact that the larger mass load makes the piezoelectric plate to vibrate more difficultly and counteract the effect of increased magnetic torque.

Interestingly, it is found that the magnitude of the MET effect could be influenced by the placement symmetry of magnets at the tip. As indicated in Fig. 5, when the number of magnets is fixed as 4, 3-1 placement (3 magnets on the top and 1 magnet at the bottom) will induce a stronger MET effect than 2-2 placement. Consistent result is obtained for the case of 5 magnets. It is speculated that the asymmetric placement of magnets will induce larger magnetic torque and consequently a stronger MET effect.

The influence of the position of the magnets at the beam on the MET effect was also investigated. As shown in Fig. 6, when the magnets were moved from the tip end to the middle of the bicantilever beam, the resonant \( V_{\text{out}} \) decreases, while the resonance frequency increases gradually, which could be attributed to the reason that the acting arm of the bending moment induced by the magnetic torque becomes shorter. Thus, the resonant frequency and resonant ME magnitude can be adjusted not only by the loaded magnet mass but also by the position of magnets on the beam.

IV. CONCLUSION

Our designed bicantilever PZT/NdFeB MET device exhibited a stronger MET effect than that in the single-cantilever device of the same components and geometry size, which results from the increased bending strain due to the bicantilever structure. As the magnets’ mass increases, the resonant frequency decreases, while the resonant ME voltage increases. The asymmetric placement of magnets on the tip ends will bring out more bending strain than the symmetric placement and leads to an enhanced MET effect. When the magnets are moved from the free end to the middle of the bicantilever beam, the acting arm of the bending moment becomes short, resulting in increased resonant frequency and decreased ME voltage. These results are of significance for designing a better MET device and application of sensitive magnetic field sensors and energy harvesters.

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