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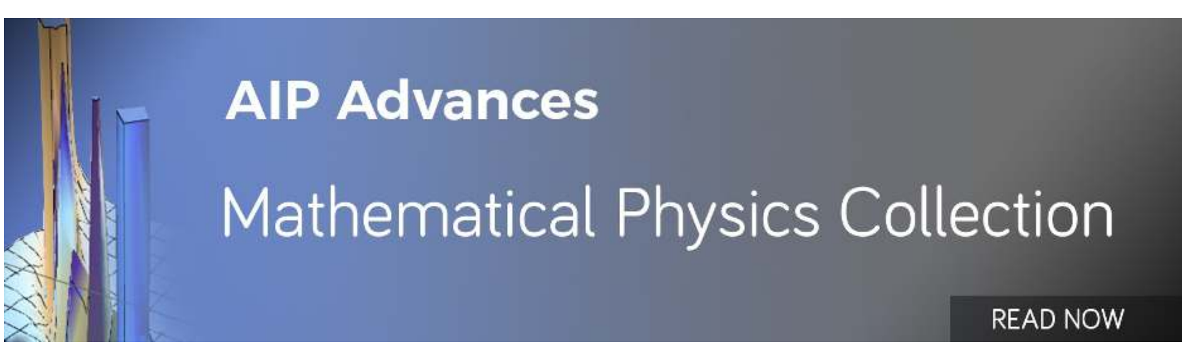

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Longfei Niu,[1,a)] Yang Shi,[2,a)] and Yuanwen Gao[3]

AFFILIATIONS

[1] Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang 621900, PR China
[2] School of Mechano-Electronic Engineering, Xidian University, Xi'an, Shanxi 710071, PR China
[3] Department of Mechanics and Engineering Sciences, College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, Gansu 730000, PR China

[a)] **Corresponding authors:** Longfei Niu: niulf@caep.cn, Yang Shi: shiyang@xidian.edu.cn

ABSTRACT

Magnetoelectric (ME) effect in a Ni/PZT/Terfenol-D composite cantilever was tested under three different magnetic loading modes. The frequency-dependent ME effect and dual-peak phenomenon were observed in the experiment. The influence of orientations of magnetic fields on the dual-peak phenomenon of ME coupling was investigated. Magnetic field distribution inside the ME composite structure was simulated, which agrees well with experimental data. The experiment results indicate that ME coefficient versus bias magnetic field curve presents a novel dual-peak phenomenon near the resonant frequency, and the ME coefficient which depends upon the amplitude and orientation of magnetic field presents a nonlinear shift whether at the resonant frequency or not. In addition, the optimal angle corresponding to the largest ME coefficient for different bias fields were obtained. The proposed ME composites-based sensors can be used for detecting or harvesting magnetic signals of uncertain orientations and amplitudes in complex environments.

I. INTRODUCTION

Inside magnetoelectric (ME) materials, an electric field can be induced under an external magnetic field, or conversely, a magnetic field can be generated by applying an external polarization, which are termed as the direct or converse ME effect, respectively.[1–3] ME coefficient is an important performance index to evaluate the conversion efficiency. Compared to single phase ME materials, the laminated ME composites consisting of magnetostrictive materials and piezoelectric ceramics present relatively larger ME coupling coefficient at room temperature, which has attracted much attention in past decades.[4–8]

Until now, giant ME effects and the resonance properties for different configuration structures have been reported.[9–11] It was shown that a tremendous enhancement of ME effect near the resonant frequency can be achieved. Compared with the conventional layered ME composite, the resonant frequency of ME cantilevers in bending mode is not only relatively low, but also easier to control. Thus the ME cantilevers are advantageous for sensing/harvesting the low-frequency magnetic signals, which have been widely introduced in previous researches. For example, Lu et al.[12] reported a FeCuNbSiB/Ni/PZT cantilever structure as a new type of ME current sensors with mass tips on the end, which can enlarge the bending deformation and reduce the resonant frequency. Metglas/PZT laminate composite cantilever was fabricated to capture the electromagnetic energy in low frequency by Gao et al.,[13] Liu et al.[14] and Zhang et al.[15] experimentally revealed that the ferromagnetic/elastic/piezoelectric cantilever presents an excellent ME performance at low resonant frequency. These works have successfully reduced and tuned the resonant frequency of ME composite. On the other hand, another feature of ambient fields is random distribution in directions, which also hinders potential applications of ME devices. In other words, it is difficult to apply the external magnetic fields along the appointed direction strictly. Consequently, magnetic-field orientation may influence

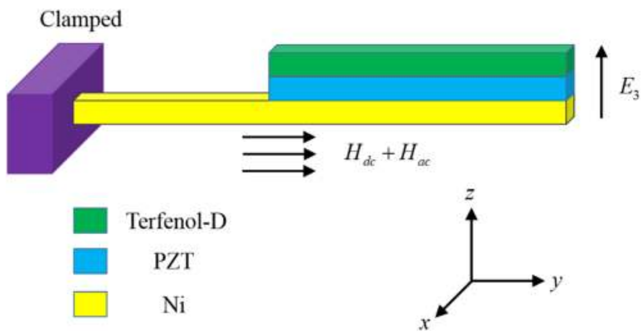

FIG. 1. Configuration of laminated Terfenol-D/PZT/Ni composites cantilever.

ME effect. Therefore, it is essential to consider the magnetic-field orientation in the study of ME coupling effect.[16–18]

Though many experiments have been conducted on ME composites cantilever, most of them were performed on special conditions that ac and dc fields are applied along transverse or longitudinal direction of the sample. To date, few studies have reported the dependences of the ME coefficient in traditional composites on the orientation angle of fields, and they were not successful in predicting magnetic-fields-orientation dependent ME effect of ME cantilever. In addition, it has been proved that the combined effect of magnitude and frequency of magnetic fields on ME coupling may induce some novel features, such as resonance frequency shift[19] and dual-peak phenomenon,[20] which can broaden the potential application of the devices using ME cantilever structure. Therefore, it is significant to evaluate ME performance of ME cantilever under magnetic signals of random orientations. For this purpose, we report a Ni/PZT/Terfenol-D cantilever and measure its ME coupling effect. The dual-peak phenomenon is obtained and the effect of magnetic-field orientation on peak values of ME coefficient is investigated.

II. EXPERIMENTAL DETAILS

We selected Terfenol-D (Gansu Tianxing Rare Earth Functional Materials Co., Ltd.) and Ni as magnetostrictive phase, PZT-5X (Zibo Yuhai Electronic Ceramic Co., Ltd) as piezoelectric phase, and fabricated a ME tri-layered composite consisting of three main components. Terfenol-D and Ni were magnetized along the longitudinal direction, and PZT was polarized in the transverse direction with a piezoelectric coefficient of 750pC/N. We first bonded Terfenol-D slice ($16 \times 5 \times 0.5$ mm^3) and PZT slice ($16 \times 5 \times 0.5$ mm^3) together. Afterwards, the Terfenol-D/PZT composite was bonded to the surface of a long Ni-sheet beam ($20 \times 5 \times 0.5$ mm^3) using epoxy resin as shown in Fig. 1. Note that the conductive magnetostrictive layers (Terfenol-D and Ni) were separated from the adjacent piezoelectric one by thin insulating layers, the eddy currents in the Terfenol-D layer can be effectively eliminated due to its low permeability. However, Ni is electrically conductive and has a large permeability, so the eddy currents in Ni layer should be non-negligible. The sample was cured for 24 hours under room temperature to achieve a good mechanical coupling and clamped at the end to act as a cantilever beam. Two conductive wires were welded to the surfaces of PZT plate for measuring the induced voltage.

In the experiment, ac magnetic field is provided by a pair of Helmholtz coils driven by a function wave form generator (ATF20B) coupled with a HFVA-62 power amplifier, and bias magnetic field is supplied by a pair of WD-130 electromagnets, which is driven by a power supply. The radius of the Helmholtz coil is R=60mm. The sample is located in the region of [x<0.1R, y<0.1R] along the axial line of the coils. The relative error between the produced magnetic field in the sample and that at the center is just about 0.1%. Thus, we consider that the ac field in the zone is approximately uniform and it will not affect experimental situation. The output ME voltage was measured by a digital oscilloscope (Agilent DSO9064A). The magnitude of ac and bias magnetic field were measured by a digital signal processing gauss meter Lakeshore 475. ME coefficient α_E is estimated by $\alpha_E = V_{p-p}/H_{ac}t$, where V_{p-p} and H_{ac} refer to the peak-to-peak value of the output voltage and ac magnetic field, respectively, and t is the thickness of PZT plate. The ME measurement system is shown in Fig. 2. The ac field in the whole experiments was fixed at H_{ac}=0.5Oe, and the beam is parallel to the table top.

Three loading modes corresponding to the field orientation adjustments are performed as follows (shown in Fig. 3): (i) keeping the direction of the bias field restricted, while changing the orientation of the ac field from length to width direction (Scheme-I); (ii) keeping the direction of the ac field fixed along the length direction

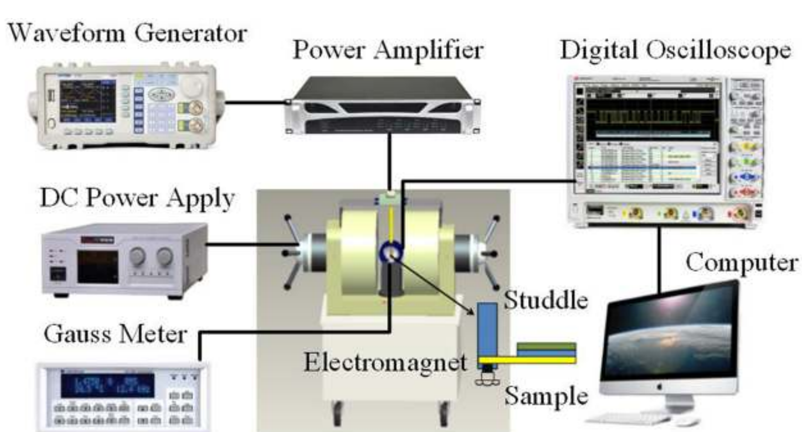

FIG. 2. Schematic diagram of ME measurement system.

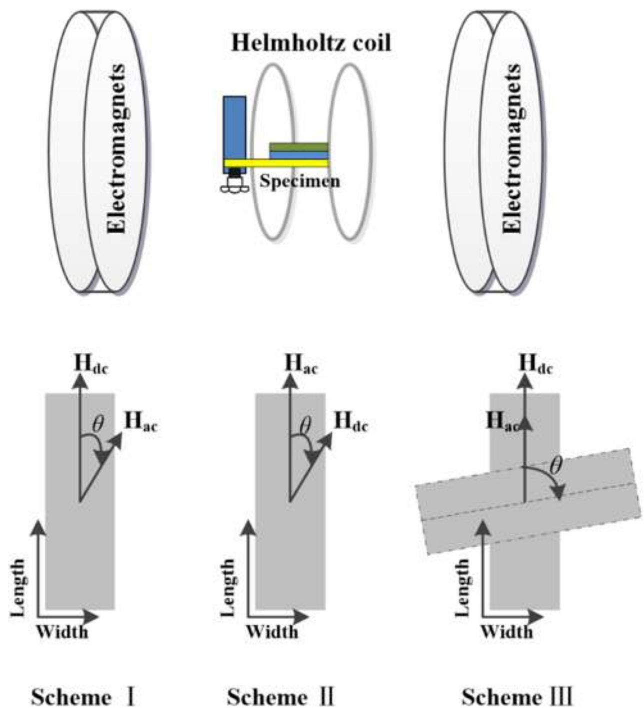

FIG. 3. Schematic diagram of three different field-loading modes.

of the sample, while spatially reorienting the bias field from length to width direction (Scheme-II); and (iii) keeping the direction of the ac and bias fields restricted, while changing the orientation of the sample, resulting in the reorientation of the ac and bias fields relative to the specimen together (Scheme-III). Note that all of the rotations are shifted in-plane.

III. RESULTS AND DISCUSSIONS

The longitudinal magnetostrictive strain and effective piezomagnetic coefficient of the Terfenol-D layer were measured as a function of the magnitude of the dc field with the orientation angle being 0°, 15°, 30°, 45°, 60°, 75°, and 90°, which is plotted in Fig. 4.

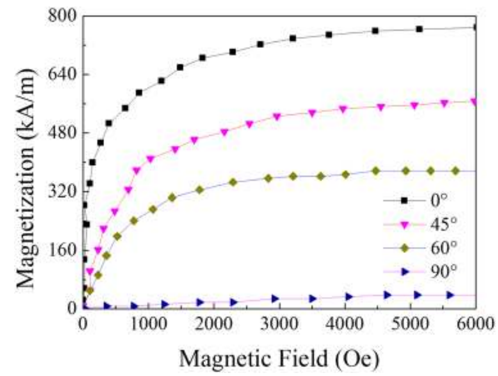

FIG. 5. The measured magnetization of Terfenol-D varying with bias field at different orientation angles.

Clearly, the magnetostrictive strain of Terfenol-D is changed with orientation angle.[21] As the orientation angle increases, the magnetostrictive strain presents an approximately monotonic change. Particularly, when the angle is large enough (>75°) negative magnetostrictive strain induced in magnetostrictive layer. Fig. 4(b) shows that piezomagnetic coefficient of Terfenol-D increases before the optimal magnetic field, but decreases after the optimal magnetic field. When the orientation angle of magnetic field is fixed at 90°, the piezomagnetic coefficient has negative value under any magnetic field. The measured magnetization of Terfenol-D at different orientation angles is plotted in Fig. 5, which shows that the magnetization decreases with increasing the angle. The longitudinal magnetostrictive strain of Ni layer were measured as a function of the magnitude of dc field and plotted in Fig. 6. Comparing with Terfenol-D layer, the magnetostrictive strain of Ni layer is relatively small, thus ME coupling effect in ME composites consisting of both Terfenol-D and Ni mainly originates from magnetostrictive effect of Terfenol-D. The added Ni layer is beneficial to reduce brittleness of the structure. In addition, tension strain induced in Terfenol-D and compressive strain induced in Ni can reduce the radii of curvature of the composite and enhance the bending effect, which may be beneficial to reduce mechanical resonant frequency.

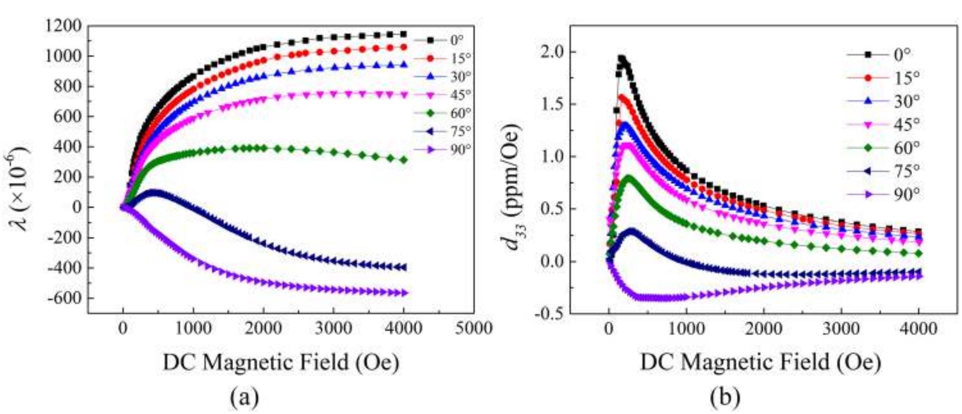

FIG. 4. The measured (a) longitudinal magnetostrictive strain and (b) piezomagnetic coefficient of Terfenol-D layer varying with bias field at different orientation angles.

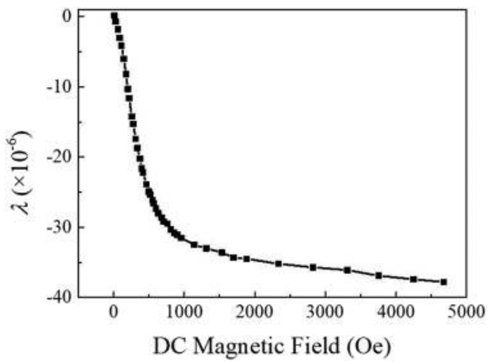

FIG. 6. The measured longitudinal magnetostrictive strain of Ni layer in 0-degree orientation.

The dependence of ME coefficients α_E on bias field H_{dc} with varying frequency are plotted in Fig. 7. When the frequency of ac field is below 12.2 kHz, ME coefficient increases firstly and then decreases with the increase of dc magnetic field, and a single-peak in ME coefficient curve appears. The optimal ME coefficient emerged a quick increase when the value of the frequency is gradually loaded ranging from 3 kHz to 12.2 kHz. Specifically, the maximum ME coefficient raised from 0.7V/cm Oe to 4.63V/cm Oe with its amplification being enhanced more than six times. However, when the frequency of ac field is beyond 12.4 kH, the curve of ME coefficient varying with the dc field exhibits a dual-peak phenomenon, namely, the ME coefficient presents two maximum values with the increase of bias field. With the increasing frequency, the first peak shifts left slightly while the second peak moves toward right obviously. At the same time, both decrease gradually. Comparing Figs. 7(a) and 7(b), one can deduce that the dual-peak phenomenon may be related to both the magnitude and frequency of bias field. To elucidate the origin and mechanism of the dual-peak phenomenon, investigations on combined effect of the frequency of ac field and the magnitude of the dc field are required. The dependence of ME coefficient on frequency at different optimal H_{dc} is plotted in Figs. 7(c) and 7(d). It can be observed that each dc field corresponds to a resonance peak, and the position of the resonance peak and the value of the peak will be changed with dc field. It is noted that the position of the resonant frequency is almost consistent with the excitation frequency of the bimodal tests in this case. The previous works indicated that ME coupling is proportional to piezomagnetic coefficient, so the maximum value of ME coefficient occurs at an optimal magnetic field corresponding to the maximal piezomagnetic coefficient.[22] The first peak in the curve of ME coefficient versus magnetic field occurs due to the maximum of piezomagnetic coefficient. As shown in Figs. 7(c) and 7(d), the ME coupling maximizes at a certain frequency when the value of the bias field is fixed, which is caused by the mechanical resonance of the composites under the applied ac magnetic field. In addition, the second peaks of ME coefficient in figure 7(b) are very close to the peak values at the resonance frequencies, which indicates that the occurrence of the second peak is related to the resonance under a certain value of magnetic field. Due to the ΔE effect of ferromagnetic materials, Young's modulus of the magnetostrictive layers is changed with magnetic field, and then the resonance frequency of ME composites will be changed. That is why the position of second peak is changed with the frequency. For example, Fig. 7(b) shows that as the frequency increases, the position of the second peak will move toward a higher value of bias field. Therefore, the two-peak phenomenon would manifest as long as magnetic materials with the ΔE effect, such as the Terfenol-D and Ni plates, are used as the magnetic layers of the ME composites. From this point of view, the dual-peak phenomenon can be exploited for detection of magnetic materials. In addition, the dual-peak phenomenon has potential applications in optimal performance for ME devices sensing a large DC bias. When the values of two optimal magnetic fields are close to each other, overlapping of the first and second peaks would

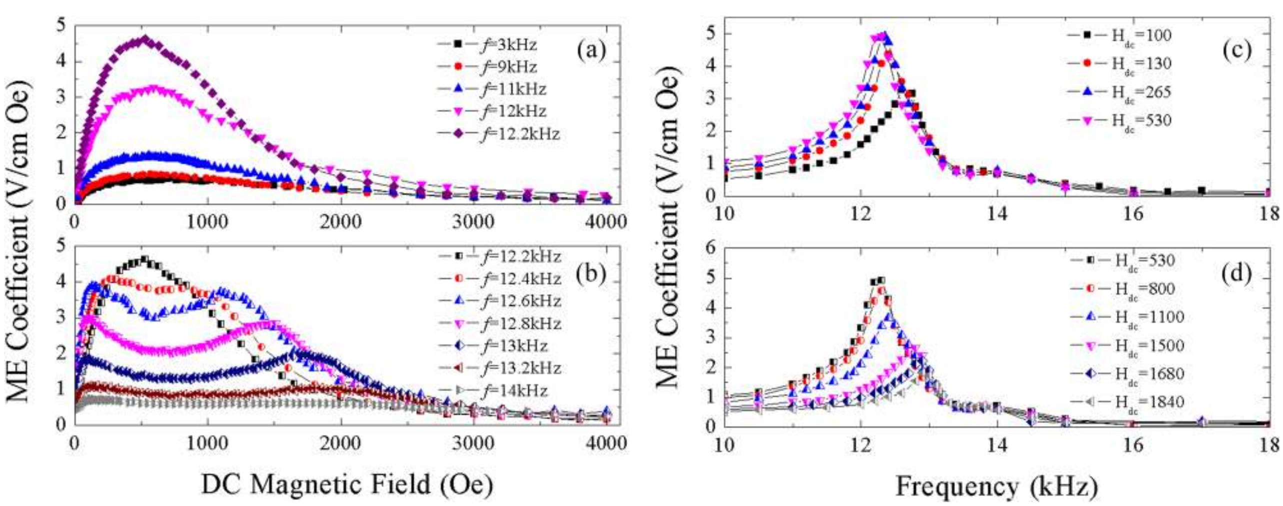

FIG. 7. Dependence of ME coefficient on bias field with varying the driven frequency: (a) 3~12.2kHz; (b) 12.2~14kHz, and dependence of ME coefficient on the driven frequency with varying bias field: (c) 100~530Oe; (d) 530~1840Oe.

cause enhancement of the maximum value of ME coefficient. In brief, the dual-peak phenomenon can be interpreted as follows: the maximum value of the piezomagnetic coefficient of magnetostrictive materials are reached under an optimal bias field, which leads to the largest changing rate of the magnetostrictive strain and therefore causes the first peak; The second peak appears under resonant frequency at an exactly certain bias field. The above results and analyses conclude that the dual-peak phenomenon can be observed only at the resonant frequency. Comparing the results in Fig. 7(c) and 7(d) with Fig. 6a in Ref. 20, we observe that the ME coefficient of the proposed system has a sharper drop. For example, when the setup is shifted by ~1 kHz, the magnitude of ME coefficient is dropped by 80%. This difference is mainly caused by eddy-current loss. The sample in the Ref. 20 is a symmetrical structure consisting of PZT and Terfenol-D, and eddy-current loss is very small. Thus the maximum value of ME coefficient has a relatively little change in the range of 90 kHz to 125 kHz. However, according to Porter's dissertation[23] and using the geometry in this paper with nickel's resistivity 7×10^{-8} S/m and moderate permeability from 100 to 300, the predicted eddy currents in the nickel layer of this system are expected to set in around 1 to 3 kHz, which is quite close to the tested frequency range.

The effects of magnetic-field orientation on dual-peak phenomenon is then studied. Fig. 8(a) shows the variations of ME coefficient with bias field at different ac-field orientation angles. It is observed that two peak values of ME coefficient generally exist over the bias field at each given orientation angle. As the orientation angle of ac field increases from 0° to 90°, the overall ME effect gets attenuated. Thus both peaks decrease gradually, and the maximum value of the ME coefficient is obtained at $\theta = 0°$. The first optimal bias field almost keeps unchanged, while the second one shifts left. To clearly examine this excitation-field-orientation effect, the dependence of the ME coefficient on the orientation angle are plotted in Fig. 8(b). It can be seen that with the increase of the orientation angle of ac magnetic field, ME coefficient decreases nonlinearly. The bias field can only change the value of ME coefficient instead of the variation trend. That is to say, the best performance condition in Scheme-I is keeping the ac and dc magnetic fields at the same direction. Based on the previous model, the expression of ME coefficient as a function of angle is derived to confirm the stated results, which is given as:[24]

$$\alpha = \frac{n\left[d_{31}^{m}(\sigma,H) + d_{33}^{m}(\sigma,H)\right]d_{31}^{p}\cos\theta}{\varepsilon_{33}^{T}\left[n\left(s_{11}^{p} + s_{12}^{p}\right) + (1-n)\left(s_{33}^{m} + s_{31}^{m}\right)\right] - 2n\left(d_{31}^{p}\right)^{2}} \quad (1)$$

where σ and H represent pre-stress and magnetic field. $d_{31}^{m}(\sigma,H)$ and $d_{33}^{m}(\sigma,H)$ represent the effective piezomagnetic coefficients along the longitudinal and transverse directions, respectively. The reader is referred to Ref. 18 for more details of the materials' constant. The effective piezomagnetic coefficient represents a complex nonlinear variation under combined magnetic field and pre-stress. In this experiment, we did not exert external excitations in our experiment, and the pre-stress was set to zero. Thus, the effective piezomagnetic coefficient is only related to the magnetic field under fixed materials' constants. For Scheme-I, when we fix the dc magnetic field and change the angle of H_{ac}, the values of cosθ in Eq. (1) is changed significantly. At the same time, the components of combined magnetic field along longitudinal and transverse directions are changed slightly because ac field is very small compared to the dc filed, and the effective piezomagnetic coefficient $d_{31}^{m}(\sigma,H)$ and $d_{33}^{m}(\sigma,H)$ present nonlinear variations with the change in components of magnetic field. As a result, the variation of ME coefficient is influenced by both cosine term and the effective piezomagnetic coefficient, which is no longer a strict Cosine law, but a decreasing trend with the change of θ. In addition, the ME coefficient is also slightly affected by the magnetic field-dependent compliance coefficient. That is why the orientation angle influences ME coefficient significantly. From another perspective, the results can be further explained by simulation results of the magnetic flux density in different orientations. We calculate the magnetic field distribution inside the ME composite structure using the software COMSOL. In our simulation, the ME structure is surrounded by a large enough air domain which can not only provide a nature environment but also eliminate effects on magnetic field distribution around the laminated structure. The frequency and magnitude of magnetic fields are fixed at 12 kHz and 1000 Oe, respectively. The magnetic flux density distribution in x-y plane of magnetostrictive layer is presented in Fig. 9. Due to the edge effect and demagnetization effect, the distribution of the magnetic flux density is inhomogeneous and the maximum value happens inside the layer. With increasing the

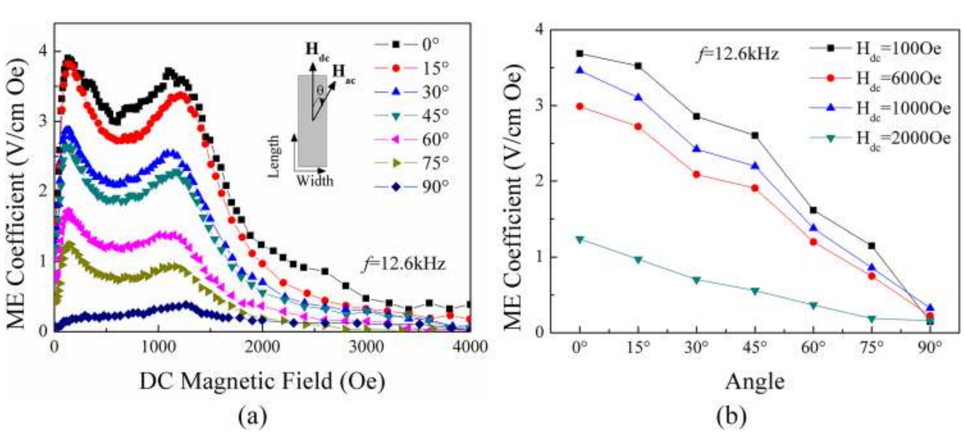

FIG. 8. The effects of ac-field orientation on dual-peak phenomenon.

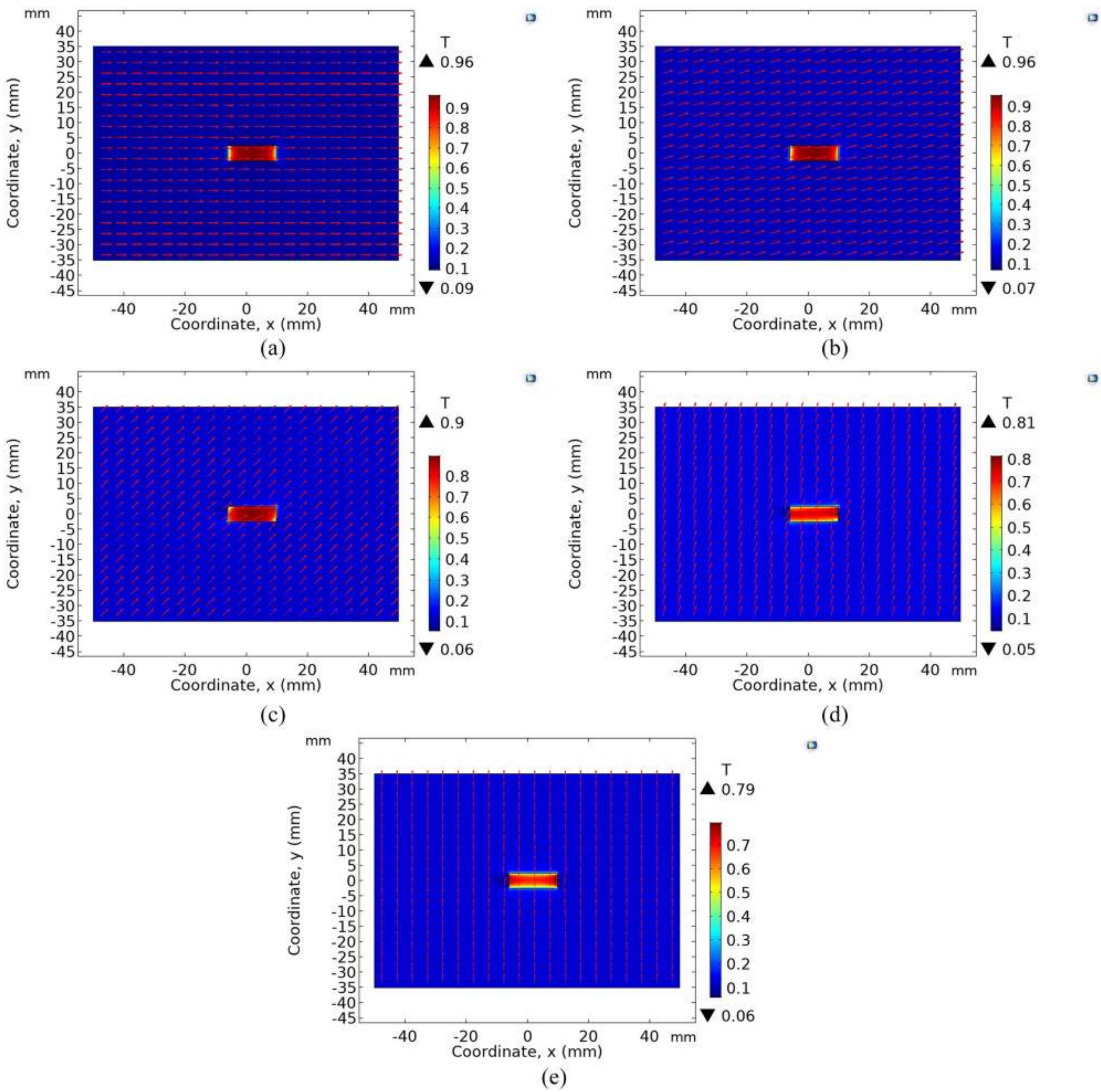

FIG. 9. Magnetic flux density distribution x-y plane of magnetostrictive layer (Terfenol-D) for different dc-field orientations (a) 0° (b) 15° (c) 45° (d) 75° (e) 90°.

orientation of dc field from 0° to 90°, the edge effect becomes more obvious, and the maximum value of magnetic flux density reduces from 0.96 T to 0.79 T. This result reveals that magnetostrictive effect is weakened by changing magnetic-field orientation. Accordingly, ME coefficient is reduced by increasing magnetic-field orientation.

We next investigated the dependence of ME coefficient on the dc-field orientation angle at 12.6 kHz. As shown in Fig. 10(a), the plotted curves show a dual-peak characteristic (except for 90°), with the orientation angle changing from 0° to 90°, the dual peaks are relatively concentrated and accompanied by volatility. The obtained ME coefficient varying with the orientation angle of dc field is shown in Fig. 10(b). One can see from the figure that with the increase of the orientation angle of dc field, the peak value of ME coefficient first decreases, then increases and finally decreases again with the orientation angle increasing from 0° to 90°. In addition, Fig. 10(b) also demonstrates there may exist two optimal orientation angle for a given value of bias field, which can make the ME composites reach

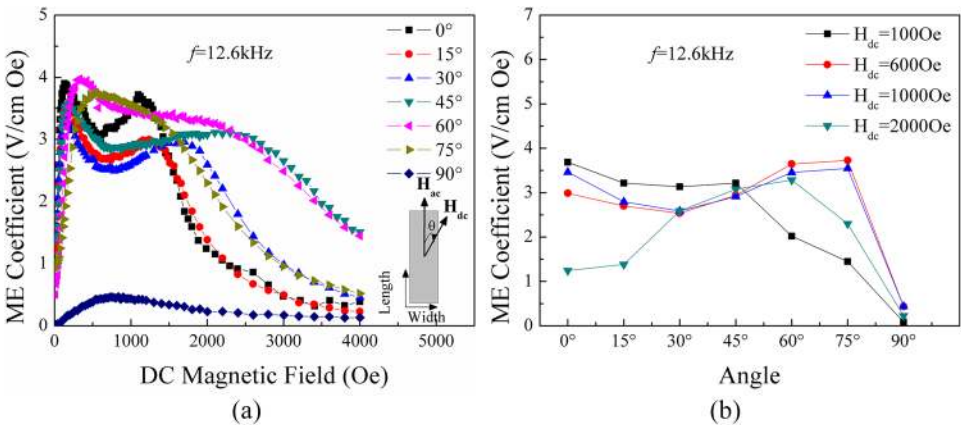

FIG. 10. The effects of dc-field orientation on dual-peak phenomenon.

a better performance. When the bias field is fixed at 100 Oe, the best operating condition is keeping the orientation angle be 0°. However, when the bias field is higher, the optimal angle increases. As shown in Fig. 4(b), the largest effective piezomagnetic coefficient occurs around H_{dc}=300 Oe. When we fix the magnitude of dc field and increase the dc-field orientation angle, the effective magnetic field applied to the sample actually deceases. Due to the nonlinearity of the effective piezomagnetic coefficient shown in Fig. 4(b), the decrease in effective applied field causes a decrease in piezomagnetic coefficient before the optimal magnetic field, whereas an increase in piezomagnetic coefficient after the optimal magnetic field. Thus, as the orientation angle increases the effective applied field decreases, which makes the effective piezomagnetic coefficient reduce gradually when dc field is fixed at 100 Oe. Consequently, the black line in Fig. 10(b) has almost a downward trend. However, when dc field exceeds optimal magnetic field (>300Oe), the effective piezomagnetic coefficient first increases and then decrease with the decrease in effective applied field. That why the ME coefficients have different variation trends with the orientation angle under different dc fields.

In the Scheme-III, the orientation angles of ac and dc fields were aligned with the same direction, the angle of specimen was rotated from 0° to 90° in a plane gradually, and the effects of combined-field orientation on dual-peak phenomenon are displayed in Fig. 11. Like the phenomenon of rotating dc field, Fig. 11(a) shows that when the orientation angle of the specimen was changed and the alternating frequency is fixed at 12.6 kHz the ME coefficient decreases with the increase of orientation angle of specimen from 0° to 75°, and the dual-peak phenomenon disappears completely when the angle approaches to 90°. As shown in Fig. 11(b), the value of the ME coefficient first decreases and then increases in the range from 0° to 90°. This is because that when the orientation angle of specimen is changed, the original "L-T"[25] mode transfers to the "W-T" mode gradually, i.e., the magnetization is induced along width direction, and the polarization is induced along the transverse direction. Since the ac and dc fields have an angle with the specimen simultaneously, the dependence of ME coefficient on bias field indicates a similar super position between the results in Schemes-I and II but more complex. Only when the ac field has the same angle with the bias field and the specimen can the total strain of the composite be expressed by the Eq. (1), in which the ME coefficient shows a nonlinear decrease with the increase of the orientation angle. At the same time, when the bias field has the same angle with the specimen, both d_{31} and d_{33} will be changed due to the variations of bias field induced by the variable angles. These two factors have an interaction effect so that the dependence of ME coefficient on bias field or orientation angle shows a nonlinear variation. For example, Fig. 4(b) shows that the measured d_{33} at θ=90° is larger than at θ=75°. Consequently, in

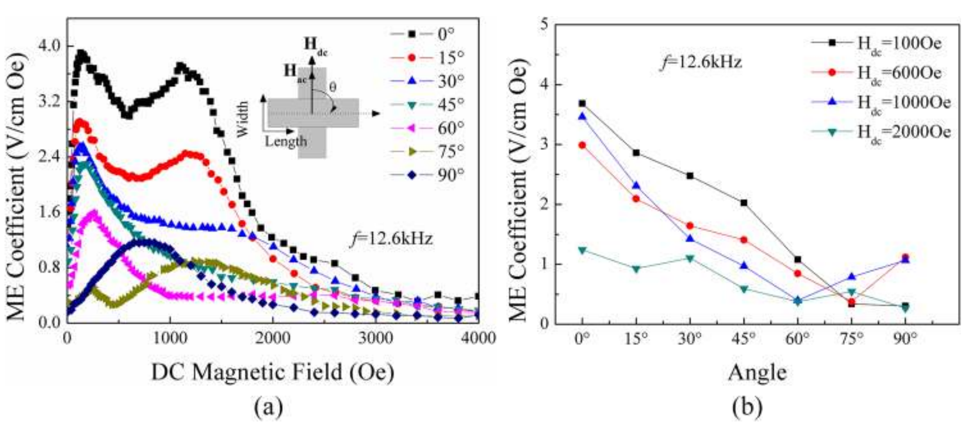

FIG. 11. The effects of combined-field orientation on dual-peak phenomenon.

Fig. 11(b) the ME coefficient value at θ=90° is higher than that at θ=75°. In addition, the composite shows a bending effect because it consists of positive and negative magnetostrictive materials with an intermediate piezoelectric slice.[10]

IV. CONCLUSION

In summary, we have fabricated a Ni/PZT/Terfenol-D trilayer composite cantilever, which presents relatively low resonant frequency due to the bending effect. The dual-peak phenomenon was observed and explained. Then, based on three proposed loading modes, the influence of the orientation of ac and dc fields is investigated in detail. The results show that dual-peak phenomenon occurs only around the resonant frequency and is determined by the combined effect of responsive frequency and the optimal dc field. For Scheme-I, ME coefficient always decreases with the increasing angle, indicating that the best ME performance should be achieved at the condition that both ac and dc fields are applied along the length direction. However, something has been changed for Scheme-II. When ac field is fixed along the length direction and dc field is rotated from length to width direction, the optimal angle is no longer 0°. There exists an optimal angle between 0° and 90°. For instance, the optimal angle is 75° at 12.6 kHz. The optimal angle is almost not altered by bias field. Compared to Schemes-I and II, Scheme-III presents more complex variation trends, ME coupling is reduced with increasing angle firstly, and then enhanced when the angle is beyond 75°. These phenomena are actually caused by the change in the component of magnetic field and nonlinear material characteristics of magnetostrictive materials. The results may provide some useful guidance for ME devices operating under complex ambient magnetic fields.

ACKNOWLEDGMENTS

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