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Effect of Bias Magnetic Field on Magnetoelectric Characteristics in Magnetostrictive/Piezoelectric Laminate Composites

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The magnetoelectric (ME) characteristics for Terfenol-D/PZT laminate composite dependence on bias magnetic field is investigated. At low frequency, ME response is determined by the piezomagnetic coefficient $d_{33,m}$ and the elastic compliance s_{33}^{H} of magnetostrictive material, $d_{33,m}$ and s_{33}^{H} for Terfenol-D are inherently nonlinear and dependent on H_{dc}, leading to the influence of H_{dc} on low-frequency ME voltage coefficient. At resonance, the mechanical quality factor Q_m dependences on H_{dc} results in the differences between the low-frequency and resonant ME voltage coefficient with H_{dc}. In terms of ΔE effect, the resonant frequency shift is derived with respect to the bias magnetic field. Considering the nonlinear effect of magnetostrictive material and Q_m dependence on H_{dc}, it predicts the low-frequency and resonant ME voltage coefficients as a function of the dc bias magnetic field. A good agreement between the theoretical results and experimental data is obtained and it is found that ME characteristics dependence on H_{dc} are mainly influenced by the nonlinear effect of magnetostrictive material.

Keywords : composite materials, mechanical quality factor, bias magnetic field, Magnetoelectric (ME)

1. Introduction

The magnetoelectric (ME) effect is defined as the electric polarization of ME composite material upon application of a magnetic field or inversely the magnetization of ME composite material upon application of an electric field [1]. The ME effect provides a transduction method between magnetic and electric field signals. Consequently, ME composite materials can be used as transducers in wireless powering systems, energy harvesting and magnetic field sensors, with the main advantage being that they require no external power to operate. Especially, the ME laminate composite has a relative higher ME voltage coefficient and a simpler fabricating procedure, which has attracted wide concern [2-10].

The ME response of ME laminate composite is influenced by many factors, and the traditional ME theories only pay attentions to the relationship between ME voltage coefficient ($\alpha_{ME} = dV/dH$, where V and H are the induced voltage and applied magnetic field, respectively) and the material parameters as well as thickness ratio [3, 4]. In recent years most experimental results have confirmed that ME characteristics in magnetostrictive/piezoelectric laminate composites are intensively dependent on the dc bias magnetic field H_{dc}, because magnetostrictive material exhibits nonlinear behaviors. The traditional ME theories on the basis of the linear constitutive relationships of magnetostrictive material is inappropriate to describe the nonlinear ME response in a broad range of the bias magnetic field. Therefore, some theoretical researches about the influence of bias magnetic field on ME response are reported [5-9]. Liu *et al*. tried to explain the problem by numerical and finite element methods, but it's still not enough to reveal the inherence of the dependence [6]. Nan *et al*. predicted the dependence of ME response on H_{dc} by using the Green's function technique and taking into consideration the nonlinear dependence of the magnetostriction of Terfenol-D on H_{dc}, but the model is not in an explicit form [5, 8]. Zhou *et al*. proposed a numerical model of ME conversion characteristics for

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ME composites based on a nonlinear magnetostrictive constitutive relation, but it is obviously inconvenient for practical applications due to adopting five fitting parameters to fit the experimental results [7]. Besides that, significant increase in the ME voltage coefficient is observed at resonance due to the strain by a factor called the mechanical quality factor Q_m of the composites, but the research on the connection of bias magnetic field and Q_m is rare [11].

Considering these situations, we research the dependence of ME characteristics for Terfenol-D/PZT laminate composite on H_{dc}. It further analyzes the ME effect for the magnetic–mechanical–electric multi-field coupling effect with a theoretical model based on the nonlinear constitutive relationships of magnetostrictive material, motion equation for the composite plate, and ME equivalent circuit method. In this theoretical model, the interface coupling parameter and the H_{dc} dependence of Q_m are taken into consideration. Because piezomagnetic coefficient $d_{33,m}$ and the elastic compliance s_{33}^H of magnetostrictive material is vital to the ME response, $d_{33,m}$ and s_{33}^H for Terfenol-D are inherently nonlinear and dependent on H_{dc}, leading to the influence of H_{dc} on low-frequency ME voltage coefficient. It indicates that the optimization H_{dc} at low frequency can be determined by the piezomagnetic coefficient and the elastic compliance curves of Terfenol-D. Additionally, Q_m exhibits very sensitive dependences on H_{dc}, which results in the differences between the low-frequency and resonant ME voltage coefficient with H_{dc}. The resonant frequency shift is derived with respect to the bias magnetic field due to changes in Young's modulus. This study plays a guiding role in the ME composites design for real applications.

2. Experiment

We fabricated the Terfenol-D/PZT-8 bi-layered laminate composites, as shown in Fig. 1. The magnetostrictive (M) layer Terfenol-D is grain-oriented in the length direction with the dimension of 12 mm × 6 mm × 1 mm, and the piezoelectric (P) layer PZT is polarized in thickness direction with dimension of 12 mm × 6 mm × 0.8 mm. The Terfenol-D and PZT plates are dipped in organic impregnant to clean at first. After that, the sample is prepared by stacking and then bonding the two plates with conductive sliver epoxy and cured at 100°C 4 hours for good mechanical coupling.

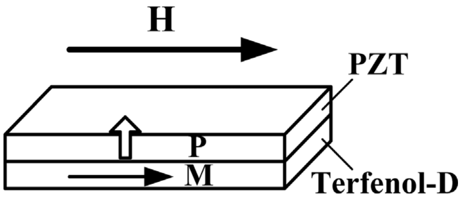

Fig. 1. The schematics of the Terfenol-D/PZT-8 bi-layered laminate composites.

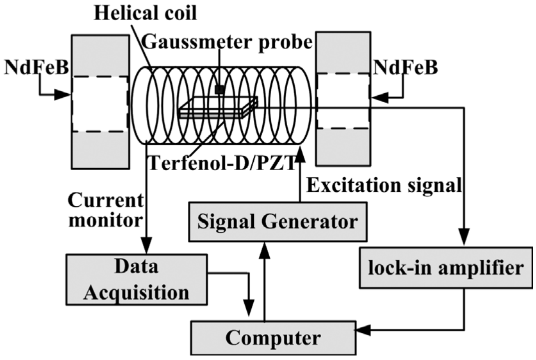

Fig. 2. The experimental setup for the ME characterization.

In our experiments, a helix coil with a turn number of 245, a length of 67 mm and a diameter of 41 mm produces a small ac magnetic field (H_{ac}) with peak-peak value 1 Oe. A signal generator (Tektronix AFG3021B) monitoring by the computer (Labview VI program) generates a controllable excitation current to the helix coil. A pair of NbFeB magnets (commercial brand N50) is located at the two sides of the ME laminate composites along the longitudinal axis, which is used to generate dc bias magnetic field (H_{dc}). The magnitude of H_{dc} is adjusted by varying the distance between NdFeB magnets and measured with a Gauss meter, which ranges from 0 Oe to 700 Oe. The ME composites are placed at the center of the cylindrical shell. Both the H_{ac} and H_{dc} are parallel to the longitudinal direction of the sample. The induced ME voltage across the two electrodes of the piezoelectric material PZT are transferred to a lock-in amplifier (Stanford, SR830), and are then acquired by the data acquisition card (National Instruments Model PCI-6115). The acquired data are stored in the computer with Labview VI program. And the corresponding experimental setup is illustrated in Fig. 2.

3. Results and Discussion

Figure 3 shows the low-frequency ME voltage coefficient α_{ME}^{low} for the Terfenol-D/PZT bi-layered composites at ac driving magnetic field $H_{ac} = 1$ Oe under the frequency of 1 kHz as a function of dc bias magnetic field (H_{dc}). From Fig. 3, it can be seen that the ME voltage coefficient strongly depends on H_{dc}, which increases from approximately zero at $H_{dc} = 0$ Oe to a maximum value 14.63 mV/Oe at an optimum bias magnetic field of 510

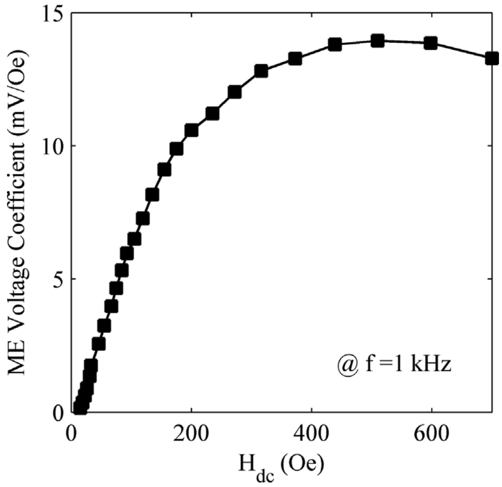

Fig. 3. The low-frequency ME voltage coefficient for the Terfenol-D/PZT laminated composite as a function of H_{dc}.

Oe, then gradually decreases as H_{dc} increases further. The H_{dc} dependence of the ME voltage coefficient results from the H_{dc} dependence of piezomagnetic coefficient $d_{33,m}$ and the elastic compliance s_{33}^H of Terfenol-D.

According to the magneto-elasto-electric equivalent circuit method, the ME voltage coefficient for ME laminate composite at low frequency can be determined by equation (1), as [4]

$$\alpha_{ME}^{low} = \beta \frac{n(1-n)t d_{33,m} d_{31,p}}{\varepsilon_{33}[n(1-k_{31}^2)s_{11}^E + (1-n)s_{33}^H]}, \tag{1}$$

where $d_{31,p}$ is piezoelectric coefficient, ε_{33} is the permittivity tensor, t is the thickness of ME composite, n is the thickness ratio of magnetostrictive layers in ME composite, β is the interface coupling parameter, k_{31} and s_{11}^E is the electromechanical coupling coefficient and the elastic compliance of piezoelectric material, respectively.

In Eq. (1), ME voltage coefficient is related to the piezomagnetic coefficient $d_{33,m}$ and the elastic compliance s_{33}^H of Terfenol-D. However, $d_{33,m}$ and s_{33}^H of Terfenol-D are not a constant. Many experiments have reported that the magneto-mechanical response of Terfenol-D is nonlinear and coupled [12-15]. It leads to the $d_{33,m}$ and s_{33}^H change with the bias magnetic field. According to Zheng's theory [12], when the pre-stress exerted on a Terfenol-D is zero, the relational expression between piezomagnetic coefficient $d_{33,m}$ and H_{dc} is derived as

$$d_{33,m} = 2\lambda_s\left(\coth(\eta H_{dc}) - \frac{1}{\eta H_{dc}}\right) \times \left(\eta(1-\coth(\eta H_{dc})^2) + \frac{1}{\eta H_{dc}^2}\right), \tag{2}$$

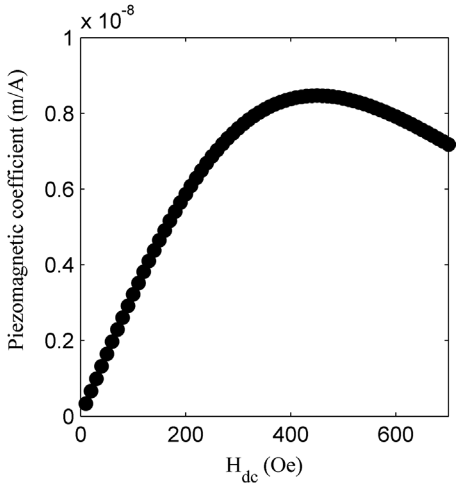

Fig. 4. Calculated piezomagnetic coefficient as a function of the dc bias magnetic field.

where λ_s is the saturation magnetostrictive coefficient, $\eta = 3\chi_m/M_s$, χ_m and M_s are the magnetic susceptibility and the saturated magnetization, respectively. Figure 4. shows the calculated piezomagnetic coefficient on H_{dc}.

The elastic compliance of Terfenol-D at constant magnetic field H_{dc} can be calculated as

$$s_{33}^H = \frac{1}{E} = \frac{\partial\varepsilon}{\partial\sigma}\bigg|_{H_{dc}=const} = \frac{1}{E_{m0}} - \frac{E_{ms}-E_{m0}}{E_{m0}E_{ms}}\left(\coth(\eta H_{dc}) - \frac{1}{\eta H_{dc}}\right)^2, \tag{3}$$

where E_{m0} and E_{ms} are the initial and saturation Young's modules of Terfenol-D, respectively. The reciprocal of the elastic compliance is the Young's module, and one

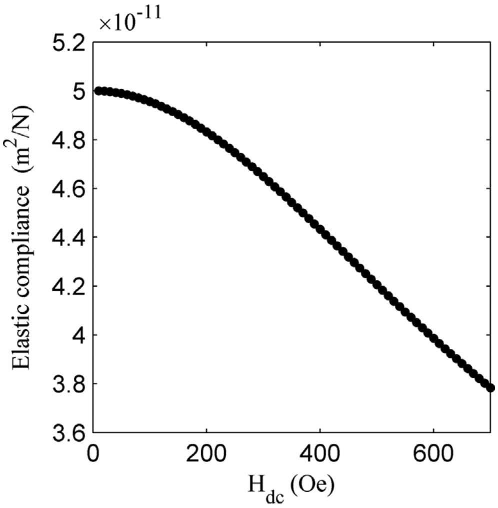

Fig. 5. Calculated elastic compliance as a function of the dc bias magnetic field.

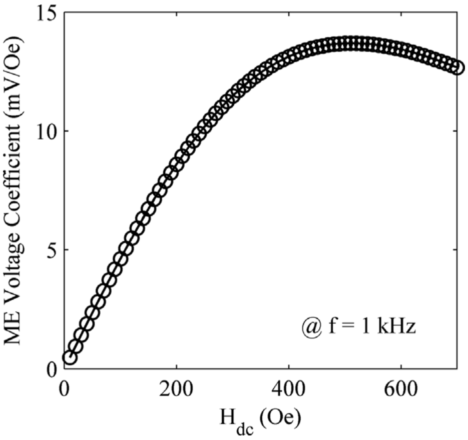

Fig. 6. Calculated low-frequency ME voltage coefficient as a function of the dc bias magnetic field.

famous properties of Terfenol-D is its giant *ΔE* effect, i.e., the Young's module of Terfenol-D varies with the change of H_{dc} [13, 14]. Correspondingly, the elastic compliance change in accordance with the change of dc bias magnetic field (as shown in Fig. 5).

The magnetostrictive material Terfenol-D parameters are $E_{m0} = 20$ Gpa, $E_{ms} = 60$ Gpa, $\chi_m = 20$, $\lambda_s = 0.001$, $\mu_0 M_s = 1.6$ T, $\rho_m = 9200$ kg/m^3. The piezoelectric material PZT parameters are $d_{31,p} = 93$ pC/N, $\varepsilon_{33} = 1000$, $\rho_m = 7600$ kg/m^3, $k_{31} = 0.38$, $s_{11}^E = 11.1 \times 10^{-12}$ m^2/N. The calculated low-frequency ME voltage coefficient on H_{dc} can be plotted as Fig. 6. As seen from the comparison, the experimental result and theoretical value have a good agreement qualitatively and quantitatively in Fig. 3 and Fig. 6. Clearly, because piezomagnetic coefficient and elastic compliance is vital to the ME response, the magneto-mechanical coupling for Terfenol-D is inherently nonlinear and dependent on H_{dc}, leading to the influence of H_{dc} on low-frequency ME voltage coefficient.

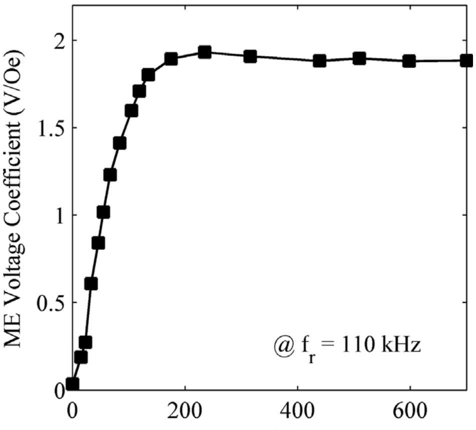

Fig. 7. The resonance ME voltage coefficients for the Terfenol-D/PZT laminated composite as a function of H_{dc}.

The resonance ME voltage coefficients for Terfenol-D/PZT composite at different bias magnetic fields are measured, as illustrated in Fig. 7. When bias magnetic field H_{dc} is above 175 Oe, the resonance ME voltage coefficient is within the range of 1.88-1.9 V/Oe, and once H_{dc} is below 135 Oe, the coefficient decreases rapidly. In comparison, there are some differences between the varying trend of the low-frequency and resonant ME voltage coefficient with H_{dc}. This is principally because effective mechanical quality factor of ME composite Q_m exhibits very sensitive dependences on H_{dc}. The Q_m directly influences the magneto-elastic-electric coupling effect in the ME composite and the magneto-elastic damping in the magnetostrictive layers, leading to a strong influence on the resonant ME effect.

Based on the magneto-elasto-electric equivalent circuit method, the ME voltage coefficient α_{ME}^{R} at resonance can be derived as

$$\alpha_{ME}^{R} = \frac{8Q_m}{\pi^2}\beta\frac{n(1-n)td_{33,m}d_{31,p}}{\varepsilon_{33}[n(1-k_{31}^2)s_{11}^E+(1-n)s_{33}^H]} \approx \frac{8Q_m}{\pi^2}\alpha_{ME}^{low}$$

$$\approx \frac{4Q_m}{\pi^2}\lambda_s\beta\frac{n(1-n)td_{31,p}}{\varepsilon_{33}\left[\dfrac{n(1-k_{31}^2)s_{11}^E+(1-n)}{\dfrac{1}{E_{m0}}-\dfrac{E_{ms}-E_{m0}}{E_{m0}E_{ms}}\left(\coth(\eta H_{dc})-\dfrac{1}{\eta H_{dc}}\right)^2}\right]}$$

$$\times\,\eta(1-\coth(\eta H_{dc})^2)+\frac{1}{\eta H_{dc}^2}\times\left(\coth(\eta H_{dc})-\frac{1}{\eta H_{dc}}\right). \quad (4)$$

In Eq. (4), the resonant ME voltage coefficient is directly proportional to Q_m and the low ME voltage coefficient. Q_m is an inverse measure of damping in a material (or system). For the ME composite, Q_m^{-1} represents mechanical energy dissipation [11]. According to the frequency dependency for the ME voltage coefficient, it estimates the mechanical energy dissipation (Q_m^{-1}) for ME composite defined as [12]

$$Q_m^{-1} = \frac{\Delta f_r}{f_r}, \quad (5)$$

where f_r and Δf_r are the resonant frequency and the 3dB frequency bandwidth respectively.

The mechanical energy dissipation Q_m^{-1} dependence on H_{dc} can be obtained as Fig. 8. In the previous theoretical research, it is often inappropriate to set a constant value Q_m^{-1} to describe the nonlinear resonant ME response in a broad range of the applied dc magnetic field. From Fig. 8, we can see that as H_{dc} increases, Q_m^{-1} first increases until it reaches a certain maximum at $H_{dc} = 439$ Oe and then decreases past that point. This can be understood as a result of the dependence of the mechanical damping for Terfenol-D on H_{dc}. For the ME composite with PZT and

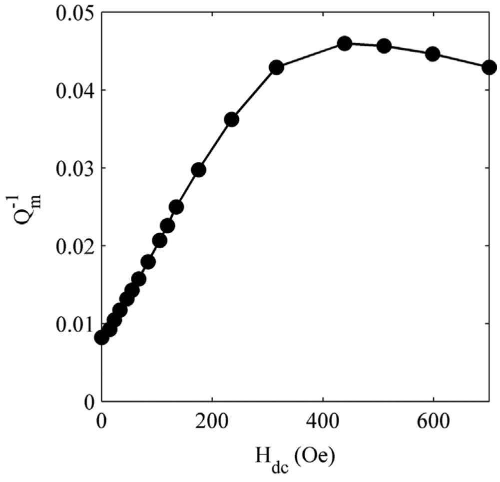

Fig. 8. The mechanical energy dissipation Q_m^{-1} for the Terfenol-D/PZT laminated composite as a function of H_{dc}.

Terfenol-D, Q_m^{-1} can be given by [11]

$$Q_m^{-1} = (1-n)Q_{mech,pzt}^{-1} + nQ_{mech,\,Terfenol-D}^{-1} + Q_{face}^{-1}, \quad (7)$$

where $Q_{mech,pzt}^{-1}$ and $Q_{mech,\,Terfenol-D}^{-1}$ are the mechanical damping of PZT and Terfenol-D, respectively. Q_{face}^{-1} is the loss at the interface of PZT and Terfenol-D layers. n is the volume ratio of the Terfenol-D layer in the ME composite.

From Eq. (6), the mechanical energy dissipation is mainly dominated by the mechanical damping of Terfenol-D and PZT. However, the mechanical damping of Terfenol-D arises from the magnetostrictive stress-strain hysteresis loop which is caused by the irreversible motion of magnetic domains and domain walls. Taking into consideration the fact that the shapes and areas of the stress-strain hysteresis loops dependence on H_{dc} results in the mechanical damping of Terfenol-D dependence on H_{dc}, it is easy to understand that the mechanical energy dissipation (Q_m^{-1}) for ME composite strongly depends on H_{dc}.

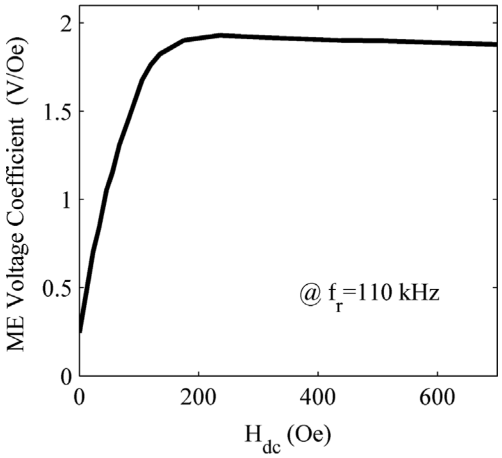

Fig. 9. Calculated resonant ME voltage coefficient as a function of H_{dc}.

Using the above data, we can calculate the dependence of the resonant ME voltage coefficient on H_{dc} according to the Eq. (5) and the results are shown in Fig. 9. The ME voltage coefficient values calculated by Eq. (5) and the experimental result agree with each other quite well (as shown in Fig. 7 and Fig. 9).

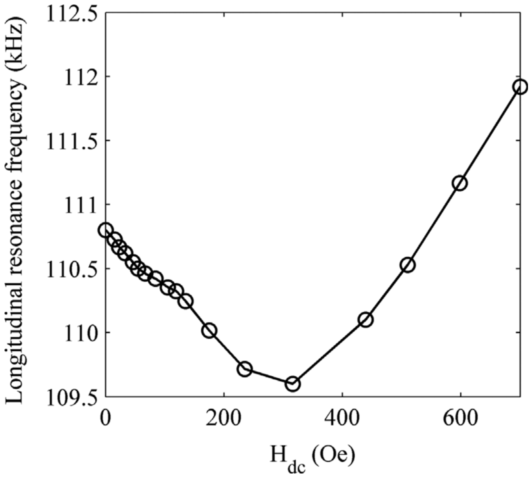

Fig. 10. The longitudinal resonant frequency f_r for the PZT/Terfenol-D laminated composite as a function of H_{dc}.

Figure 10 shows the longitudinal resonant frequency (f_r) for the PZT/Terfenol-D laminated composite as a function of H_{dc} from 0 to 700 Oe. The resonant frequency decreases to a minimum value at $H_{dc} = 316$ Oe, and then increases with H_{dc}, showing a “V” shape in the range of 0-700 Oe. The resonant frequency shift is derived with respect to the bias magnetic field due to changes in Young’s modulus. As mentioned previously, the Young’s modulus E for the magnetostrictive material varies with the applied dc magnetic field. The reciprocal of the elastic compliance is the Young’s module. The resonance frequency is influenced by the elastic compliance, geometry dimension and density of laminate composite. Therefore, the ΔE effect of Terfenol-D induces the resonant frequency shift phenomenon.

4. Conclusions

The significant dependence of dc magnetic bias field on the ME characteristics in Terfenol-D/PZT laminate composite is studied experimentally and theoretically. It has been demonstrated that: 1) The ME voltage coefficient at the low frequency strongly depends on H_{dc}, which is mainly determined by the $d_{33,m}$ and s_{33}^H curves of Terfenol-D with H_{dc}; 2) At the resonant mode, Q_m exhibits very sensitive dependences on H_{dc}, which results in the differences between the low-frequency and resonant ME voltage coefficient with H_{dc}; 3) The resonant frequency of ME laminate composite shifts with the influence of the ΔE effect of Terfenol-D.

Acknowledgements

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