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ARTICLE

Modeling of Piezomagnetic Effect for Magnetostrictive-Electromagnetic Hybrid Vibration Energy Harvester

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Abstract: A simplified computational model for obtaining large piezomagnetic effect of magnetostrictive-electromagnetic hybrid vibration energy harvester was presented. During the model establishment, the influence of compressive stress $\Delta\sigma$ and magnetic field ΔH on the piezomagnetic effect of $Tb_{0.3}Dy_{0.7}Fe_2$ alloy was studied, and their separate influence on magnetic flux density ΔB of magnetostrictive material was investigated. Then, two methods, pre-loads-based method and impact stress-based method, were used to discuss the optimal criterion of hybrid piezomagnetic effect for the fabrication of magnetostrictive-electromagnetic generator. Finally, the modeling accuracy for obtaining large piezomagnetic effect was testified, and the experiment and theoretical results were in good agreement. Results show that the modeling can efficiently and accurately obtain the piezomagnetic effect for hybrid magnetostrictive material-based harvester under different application environments, which is of significance for design and fabrication of magnetostrictive-electromagnetic hybrid vibration energy harvester for obtaining large piezomagnetic effect.

Key words: vibration energy harvester; model and design; magnetostrictive-electromagnetic hybrid; piezomagnetic effect

Vibration energy of human activities, such as walking and running, is the by-product of everyday life, which can be generated from any perceivable activity. Vibration energy harvesting is a process of converting vibrational energy to electrical energy, which attracts much global attention and becomes a growing field[1-3]. Magnetostrictive energy harvester using magnetostrictive material $Tb_{0.3}Dy_{0.7}Fe_2$ alloy (Terfenol-D) exhibits high power density and efficiency and can be safely used to harvest low-frequency and huge-impact vibration from human walking[4-7]. But the single source magnetostrictive harvester has poor harvesting effect (its piezomagnetic effect $\Delta B/\Delta\sigma$ is 0.005~0.01 T/MPa), and its magnitude of electric power generated is always very low[8-10].

Magnetostrictive-electromagnetic hybrid harvester has better harvesting effect, which can generate more electricity and is suitable for obtaining larger power density of broadband vibration impact[5]. Due to its hybrid harvesting effect, the modeling of piezomagnetic effects is divided into two parts: impact-induced modeling and magnetic field-induced modeling. However, a suitable model for design and fabrication of magnetostrictive-electromagnetic hybrid harvester is still scarce. A simple harvester model can be obtained through the calculation of piezomagnetic effect by linear piezomagnetic equations[11-13], but it cannot consider the non-linear effects and can only be used in small linear effects area. Some modified models[14-16] considered the non-linear behavior, and many significant results have been acquired[17]. But the modified models are complex and computation-intensive, which are applied difficultly for constructing the hybrid harvester model. Park et al[18] introduced a cantilever-based hybrid energy harvester, but its harvesting effect and modeling was limited.

In this research, a simplified computational model for design of magnetostrictive-electromagnetic hybrid energy harvester to obtain large piezomagnetic effect was presented. The effects of single and hybrid operating conditions on the performance of the harvester were calculated and discussed. A prototype of hybrid harvester was designed and tested to verify the validity of the harvesting model.

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1 Model Development and Discussion

1.1 Model development

Piezomagnetic effect, namely Villari effect, indicates the change in magnetization which can be obtained by the stress σ and magnetic field H. It is a typical physical characteristic of magnetostrictive materials. The magnetic induction can be expressed by Eq.(1) as follows:

$$B = d_{33}^{*}\sigma + \mu^{\sigma}H \tag{1}$$

where d_{33}^{*} is a parameter of magneto-mechanical effect, and μ^{σ} is the relative magnetic permeability of a material at a constant stress. According to Eq.(1), the magnetic induction B can be calculated as a function of the magnetic field H and the compressive stress σ, which is expressed as $B(\sigma, H)$. So the piezomagnetic effect ($\Delta B/\Delta\sigma$) in magnetostrictive materials can be expressed by Eq.(2) as follows:

$$\Delta B/\Delta\sigma = \frac{\partial B}{\partial\sigma} + \frac{\partial B}{\partial H}\Delta H/\Delta\sigma = d_{33}^{*} + \mu\Delta H/\Delta\sigma \tag{2}$$

According to Eq. (2), the piezomagnetic effect in magnetostrictive material has two parts: impact-induced part (d_{33}^{*}) and magnetic field induced part ($\mu\Delta H/\Delta\sigma$). For the traditional magnetostrictive harvester, magnetic field is always considered as a constant parameter in the action of compressive stress, as expressed by $\Delta H/\Delta\sigma=0$. Its value of piezomagnetic effect obtained by traditional harvester can be calculated as $\Delta B/\Delta\sigma=d_{33}^{*}$. But for the magnetostrictive-electromagnetic hybrid energy harvester, magnetic field change is caused by the compressive stress with the mathematical relationship of $\Delta H/\Delta\sigma\neq0$. Also, its value of piezomagnetic effect obtained by hybrid harvester can be expressed by $\Delta B/\Delta\sigma=d_{33}^{*}+\mu\Delta H/\Delta\sigma$, which is larger than that obtained by traditional harvester (if $\Delta H/\Delta\sigma>0$ is selected in hybrid harvester fabrication). So, magnetostrictive-electromagnetic hybrid configuration is selected to improve the harvesting effect, especially for the harvest of low frequency and broadband vibration.

To design a hybrid harvester for obtaining large piezomagnetic effect, a simplified computational model was presented in this research. In the modeling, the free energy formulation acquired by SW model[19,20] was used to discuss the composite piezomagnetic effect. The magnetic free energy of a unit volume of magnetization M in a single crystal with magnetocrystalline anisotropy under compressive stress and magnetic field can be expressed by Eq.(3) as follows:

$$\begin{aligned} E = {} & K_1(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_1^2\alpha_3^2)+K_2(\alpha_1^2\alpha_2^2\alpha_3^2)- \\ & \frac{3}{2}\lambda_{100}\sigma(\alpha_1^2\beta_1^2+\alpha_2^2\beta_2^2+\alpha_3^2\beta_3^2)- \\ & 3\lambda_{111}\sigma(\alpha_1\alpha_2\beta_1\beta_2+\alpha_2\alpha_3\beta_2\beta_3+\alpha_1\alpha_3\beta_1\beta_3)- \\ & \mu_0 M_s H_e(\alpha_1\gamma_1+\alpha_2\gamma_2+\alpha_3\gamma_3) \end{aligned} \tag{3}$$

where α_i (i=1, 2, 3) is the direction cosine of magnetization $M(\theta, \varphi)$ (θ and φ are the spherical polar orientation parameters of magnetization M); β_i (i=1, 2, 3) is the direction cosine of compressive stress σ; γ_i (i=1, 2, 3) is the direction cosine of magnetic field H; K_1 and K_2 are the magnetocrystalline anisotropy constants of alloy; λ_{100} and λ_{111} are saturation magnetostriction coefficients along <100> and <111> directions, respectively; μ_0 is permeability of vacuum; M_s is the saturation magnetization of alloy; H_e is magnetic field in alloy. Due to the rod structure of magnetostrictive materials, compressive stress and magnetic field are always applied along the same direction, which is [110] direction for $Tb_{0.3}Dy_{0.7}Fe_2$ alloy, and the direction cosine $\beta_i=\gamma_i$. Based on Ref. [21-26] and experiment behavior of magnetostrictive materials, the properties of $Tb_{0.3}Dy_{0.7}Fe_2$ alloy are: $a\lambda_{111}$=1273 μm/m (a is a modified coefficient of strain), K_1=−60 000 J/m^3, K_2=−340 000 J/m^3, M_s=765 000 A/m, distribution factor ω= 10 000.

The magnetization in the $Tb_{0.3}Dy_{0.7}Fe_2$ alloy can be obtained by integrating the magnetization contribution from all the possible magnetization orientations, as expressed by Eq.(4):

$$M = \frac{\int_{\varphi=0}^{\varphi=2\pi}\int_{\theta=0}^{\theta=\pi} M_s\cos\theta\exp(-E_{total}/\omega)\sin\theta\,d\theta\,d\varphi}{\int_{\varphi=0}^{\varphi=2\pi}\int_{\theta=0}^{\theta=\pi}\exp(-E_{total}/\omega)\sin\theta\,d\theta\,d\varphi} \tag{4}$$

Then, the hybrid piezomagnetic effect introduced in Eq.(2) can be calculated by Eq.(5), as follows:

$$\begin{aligned} \Delta B/\Delta\sigma &= \frac{B_1(H_0+\Delta H,\sigma_0+\Delta\sigma)-B_0(H_0,\sigma_0)}{\Delta\sigma} \\ &= \mu_0(\Delta M+\Delta H)/\Delta\sigma \\ &= \mu_0[\partial M/\partial\sigma+(\partial M/\partial H+1)\Delta H/\Delta\sigma] \\ &= b_1+b_2\Delta H/\Delta\sigma = b_1+kb_2 \end{aligned} \tag{5}$$

where H_0 is basic magnetic field; σ_0 is pre-stress in the harvester; $\Delta\sigma$ is the impact stress in the vibration; ΔH is the change of magnetic field in alloy induced by impact stress $\Delta\sigma$; $b_1=\mu_0\partial M/\partial\sigma$ and $b_2=\mu_0(\partial M/\partial H+1)$ are the stress-induced and magnetic field-induced piezomagnetic effects, respectively. The magnetization contribution from the rotation of magnetic domain can be calculated by Eq. (4), and then the results of magnetization curves under different magnetic fields and stresses were obtained, as shown in Fig. 1. The hybrid harvester has larger piezomagnetic effect than single effect harvester does. But the modeling of hybrid harvester is more complicated. The piezomagnetic effect $\Delta B/\Delta\sigma$ is a function of basic magnetic field H_0, pre-stress σ_0, impact stress $\Delta\sigma$, and induced-magnetic field ΔH, as expressed by $\Delta B/\Delta\sigma(H_0, \sigma_0, \Delta\sigma, \Delta H)$. This research designed a simplified computational model

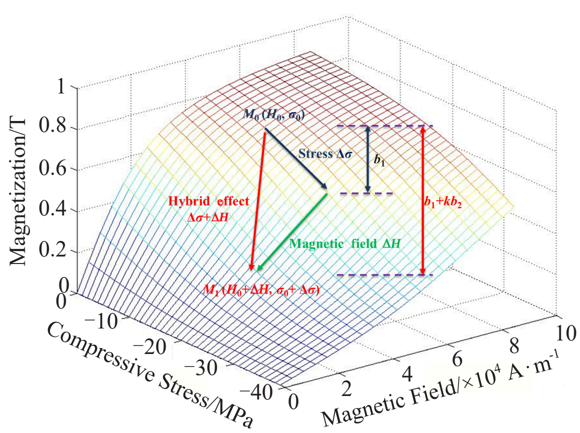

Fig.1 Magnetization curves under different input loads

to calculate the large piezomagnetic effect for the hybrid harvester under vibration impact stress.

According to Eq. (2) and Eq. (5), the relationship between $b_1=d_{33}^*$ and $b_2=\mu$ can be obtained. For traditional harvester, the value of parameter $b_1=d_{33}^*$ is always 0.005~0.01 T/MPa[8-10]. Select the magnetostrictive effect and electromagnetic effect values with their ratio of 1:1 for calculation, the value of $\Delta H/\Delta\sigma$ can be optimally designed as k=0.44~0.88 kA·m^{-1}·MPa^{-1}. Also, four important parameters (H_0, σ_0, $\Delta\sigma$, k) are optimized in the design and fabrication of hybrid harvester based on two methods. (1) Pre-loads-based method: select suitable pre-loads (H_0, σ_0), and then optimize the impact loads ($\Delta\sigma$, k) to obtain larger piezomagnetic effect. (2) Impact-stress-based method: calculate the effect of impact stress $\Delta\sigma$ depending on vibration, and then optimize the selection of (H_0, σ_0, k).

1.2 Pre-loads-based method

Through Eq. (3~5), the equal potential curves of single and hybrid piezomagnetic coefficient ($\Delta B/\Delta\sigma$) are obtained, as shown in Fig. 2 and Fig. 3, respectively. As shown in Fig. 2a, there is a largest value point (A) in the equal potential curve of coefficient b_1, and the single piezomagnetic effect d_{33}^* has the largest value at this point. Considering the effect of impact stress $\Delta\sigma$, the larger value change area of magnetization ΔB is marked by red dash line in Fig. 2a, which is a better selection for the pre-loads (H_0, σ_0) design. For the calculation of coefficient b_2, the largest value change of magnetization ΔB appears under the situation of σ_0=0.

Considering the effects of coefficient b_1 and b_2 on piezomagnetic effect of magnetostrictive materials, Fig. 3 shows the results of equal potential curves of piezomagnetic coefficient. As shown in Fig. 3, the larger value change region is reduced with increasing the coefficient k, indicating that the influence of changes of magnetic field ΔH is enhanced. After comparing the results shown in Fig. 2 and Fig. 3, the optimized pre-loads (H_0, σ_0) under the coefficient k=0.44~0.66 kA·m^{-1}·MPa^{-1} are selected in the region of H_0=20~40 kA/m and $|\sigma_0|$ =0~10 MPa. The pre-stress is set as σ_0=−5 MPa for the harvester, and basic magnetic field is set as H_0=30 kA/m for further discussion.

Then, the coefficient of piezomagnetic effect in Eq. (5) can be described by Eq. (6) as follows:

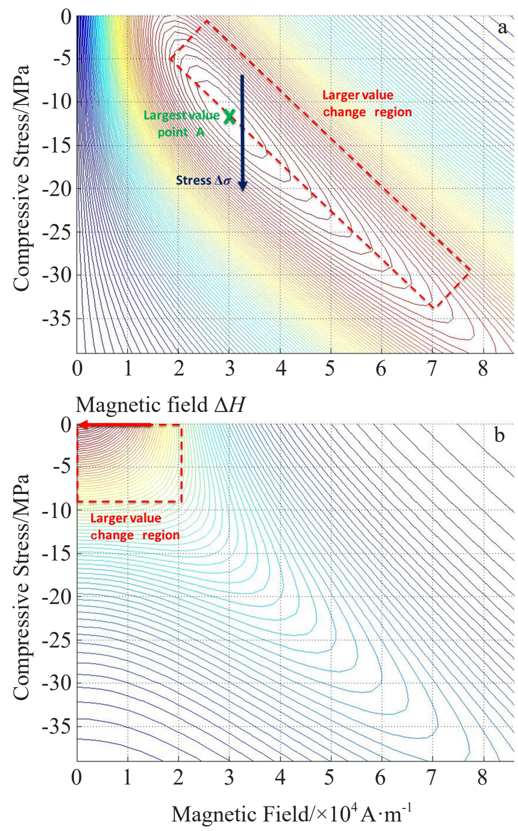

Fig.2 Equal potential curves of coefficient b_1 (a) and b_2 (b) under different loads

$$\begin{aligned}\Delta B/\Delta\sigma &= \mu_0(\Delta M+\Delta H)/\Delta\sigma \\ &= \mu_0[M_1(H_0+k\Delta\sigma,\sigma_0+\Delta\sigma)- \\ &\quad M_0(H_0,\sigma_0)]/\Delta\sigma+\mu_0 k \end{aligned} \tag{6}$$

where k is the coefficient of induced changes in magnetic field under different impact stresses. According to Eq. (3), Eq. (4), and Eq. (6), the equal potential curves of the piezomagnetic coefficients as a function of ΔH and $\Delta\sigma$ can be obtained, as shown in Fig. 4. The larger value of piezomagnetic effect appears at impact stress $\Delta\sigma$=−8 MPa, and the piezomagnetic effect is increased quickly with increasing the coefficient k.

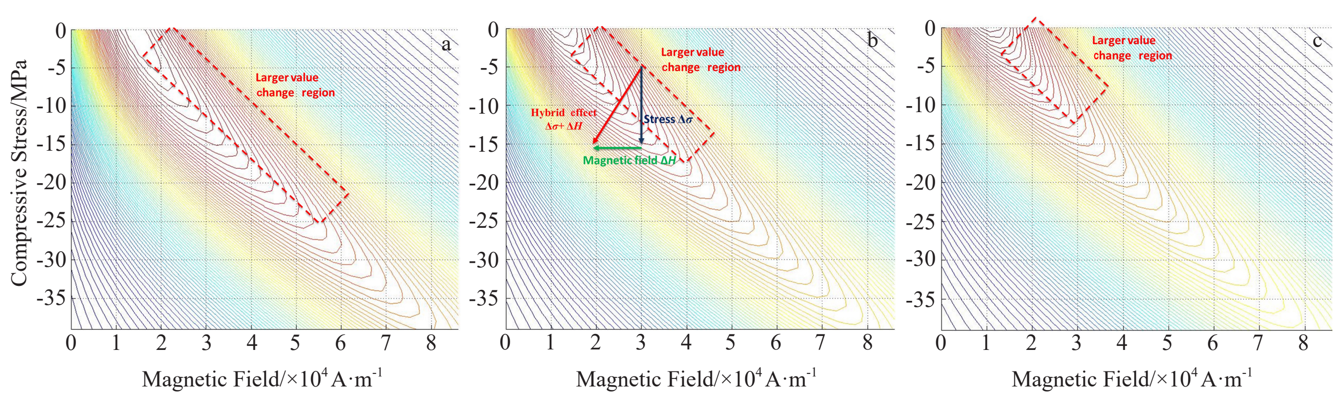

Fig.3 Equal potential curves based on magnetic field ΔH of different piezomagnetic coefficients: (a) k=0.44 kA·m^{-1}·MPa^{-1}; (b) k=0.66 kA·m^{-1}·MPa^{-1}; (c) k=0.88 kA·m^{-1}·MPa^{-1}

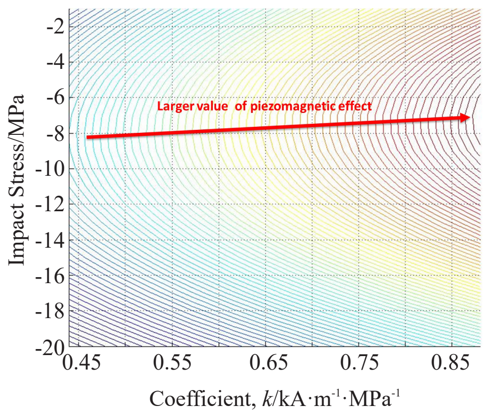

Fig.4 Equal potential curves of piezomagnetic coefficient under impact stress

In general, when the pre-loads (H_0, σ_0) are selected as (30 kA/m, -5 MPa), the larger value of piezomagnetic effect exists at impact stress $\Delta\sigma=-8$ MPa, and coefficient k should be selected as large as possible.

1.3 Impact-stress-based method

In the impact-stress-method, an impact stress value needs to be selected for calculation depending on the harvester application. Based on the above results, this method selected impact stress $\Delta\sigma$=-8 MPa as a constant for modeling, and Eq. (4) could be calculated by Eq.(7) as follows:

$$\Delta B = \mu_0[M_1(H_0 + k\Delta\sigma, \sigma_0 + \Delta\sigma) - M_0(H_0, \sigma_0) + k\Delta\sigma] \quad (7)$$

According to Eq.(3), Eq.(4), and Eq.(7), the equal potential curves of magnetization ΔB as a function of basic magnetic field H_0 and pre-stress σ_0 under different values of coefficient k can be obtained, as shown in Fig. 5. The larger value of piezomagnetic effect regions are marked by red circles, and the peak value exists at pre-stress σ_0=0. But according to the results in Section 1.2 and in Fig. 5, the pre-stress of -5 MPa and basic magnetic field of 25~27 kA/m are the optimized parameters for the hybrid harvester design. Also, the basic magnetic field of 25~27 kA/m in impact-stress-based method is close to the predicted value of 30 kA/m, which verifies the accuracy of these two methods in modeling.

Therefore, for magnetostrictive-electromagnetic hybrid energy harvester, the larger value of piezomagnetic effect appears when pre-loads (H_0, σ_0) = (27 kA/m, -5 MPa) and impact stress $\Delta\sigma$=-8 MPa. The piezomagnetic coefficient $k=\Delta H/\Delta\sigma$=0.44~0.88 kA·m^{-1}·MPa^{-1} is an optimal range for the harvester design.

2 Comparison with Experiment Results

The parameters of designed hybrid harvester are listed in Table 1, and harvester structure and test bench are shown in Fig. 6. The high-permeability material and permanent magnet (PM) are considered as the moving parts installed on cap amplifiers. Terfenol-D rod and the shell are considered as the fixed parts in the middle of the harvester. Also, there are four adjustable air gaps between the moving part and the fixed

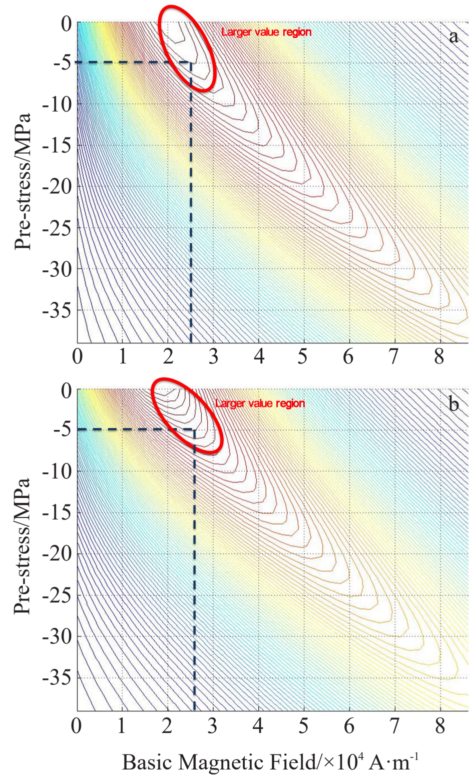

Fig.5 Equal potential curves based on magnetization ΔB of different piezomagnetic coefficients: (a) k=0.44 kA·m^{-1}·MPa^{-1}; (b) k=0.88 kA·m^{-1}·MPa^{-1}

Table 1 Parameters of designed hybrid harvester

H_0/kA·m^{-1}	σ_0/MPa	k/kA·m^{-1}·MPa^{-1}	$\Delta\sigma$/MPa
27	−5	0.44~0.88	−8

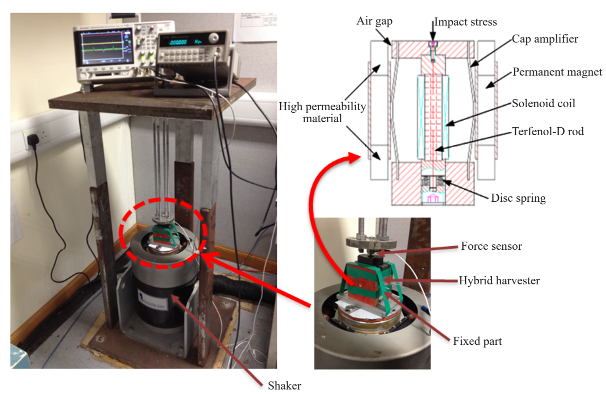

Fig.6 Appearance and schematic diagram of harvester and test beach

part. The Terfenol-D rod is surrounded by a solenoid coil, which is used to measure the magnetization change in Terfenol-D rod. The cap amplifiers are designed not only to load the moving parts, but also to turn and enlarge the axial impact into radial strain vibration. In the harvester, the impact stress applied to the axial direction of Terfenol-D rod and the harvester leads to the appearance of piezomagnetic effect in Terfenol-D rod. During the impact process, the length of air gap elongates, leading to the decrease of magnetic field H in Terfenol-D rod, and inducing more magnetization changes. The values of design parameters of harvester are listed in Table 2.

The magnetic field in Terfenol-D rod is about 26.5 kA/m. The magnification of cap amplifier reaches 3.6 at compressive stress of 8 MPa. The calculated coefficient k of the harvester is about 0.72 kA·m^{-1}·MPa^{-1}, indicating that harvester can generate ΔH=5.76 kA·m^{-1}·MPa^{-1} at impact stress of −8 MPa. The impact frequency of 5 Hz generated by the shaker was selected in the harvester testing.

The results of piezomagnetic effect in hybrid harvester are shown in Fig.7. The piezomagnetic effect has the similar trend in both experimental and calculated results: the piezomagnetic coefficient increases firstly and then decreases with increasing the impact stress. The experimental results agree well with the calculated ones, which verifies the accuracy of the model. Compared with the calculated piezomagnetic effect, the experiment results are smaller at low impact stress but larger at high impact stress, which is influenced by the structure effect of cap amplifier. Because the electromagnetic force between the moving parts and fixed parts is not taken into consideration, the magnification of cap amplifier at low impact stress is smaller than 3.6, which causes smaller changes of magnetic field in Terfenol-D rod. According to Eq. (5), the results of piezomagnetic coefficient are smaller than calculated ones at low impact stress, especially at impact stress of 5 MPa, but are larger than the calculated ones at large impact stress (>20 MPa), which is caused by the larger value changes of magnetic leakage with increasing the length of air-gap. The piezomagnetic effect $\Delta B/\Delta\sigma$ in hybrid harvester can reach 0.02~0.0278 T/MPa, which is larger than that in traditional harvester (0.005~0.01 T/MPa). The large piezomagnetic effect exits at $\Delta\sigma$=−8 MPa, which agrees well with the calculated results.

Fig. 8 shows the results of piezomagnetic effect in hybrid harvester at $\Delta\sigma$=−8 MPa with different basic magnetic fields. The basic magnetic fields in Fig. 8 are the calculated results based on different lengths of air gap (0.5~10 mm). As shown in Fig. 8, the piezomagnetic coefficient increases firstly and then decreases with increasing the basic magnetic field, which reveals the similar trend in both experimental and calculated results. At impact stress of −8 MPa, a larger value of piezomagnetic effect appears at basic magnetic field of 25~26.5 kA/m, which agrees with the result in Section 1.3 and Table 1 (H_0 of designed hybrid harvester is 27 kA/m). With the consideration of electromagnetic force in harvester and introduction of the magnification in cap amplifier at low impact stress (<3.6), the experiment results are smaller than the calculated ones. The results shown in Fig. 7 and Fig. 8 verify the modeling and design of the hybrid harvester.

Fig. 9 shows the results of piezomagnetic coefficient under different impact frequencies. As shown in Fig. 9, the experiment results show good agreement with the calculated ones at low frequency. However, larger error appears at high

Table 2 Design parameters of hybrid harvester

Terfenol-D rod	PM	Air gap
Φ10 mm×50 mm	15 mm×10 mm×20 mm	(1.5~10) mm×20 mm×10 mm

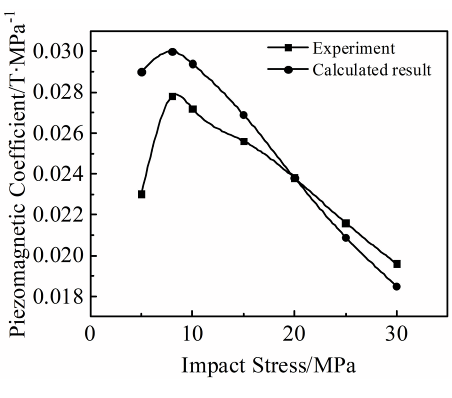

Fig.7 Piezomagnetic coefficient of experiment and calculated results

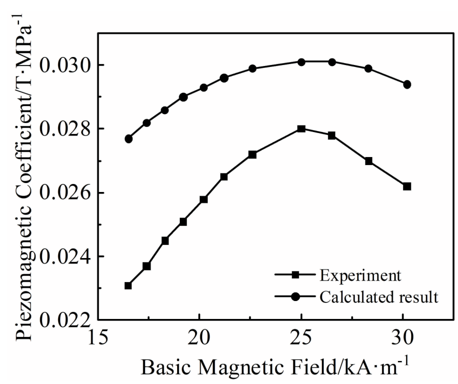

Fig.8 Piezomagnetic coefficient under different basic magnetic fields

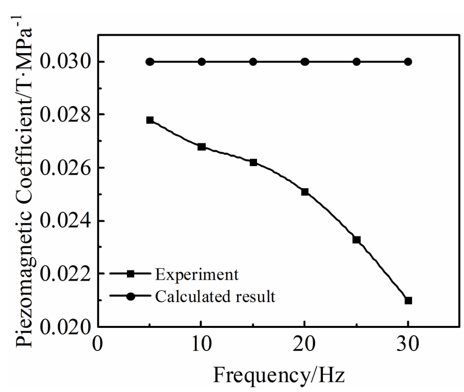

Fig.9 Piezomagnetic coefficient under different impact frequencies

frequency situation (>15 Hz). Because the dynamic effect in Terfenol-D rod and harvester structure is not taken into consideration, the calculated results are regarded as a constant under different frequencies. But the experiment results of piezomagnetic coefficient is decreased with increasing the impact frequency. Therefore, the influence of dynamics and frequency should be considered in modeling.

So, the model in this research is a static or quasi-static model, which can be used for the design of hybrid harvester for obtaining larger piezomagnetic effect and output effect calculation.

3 Conclusions

1) A simplified computational model applied for the design of magnetostrictive-electromagnetic hybrid harvester for obtainment of larger piezomagnetic effect was established.

2) Calculated results by the model agree well with the experimental results, especially at low impact frequency.

3) The model is suitable for both the pre-loads-based method and impact-stress-based method used in the hybrid harvester fabrication, which is helpful for the harvester design and optimization in harvesting vibration energy of human walking.

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面向磁致伸缩-电磁复合式能量采集器的压磁效应模型

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摘　要：提出了一种简化的、能指导复合式能量采集器中磁致伸缩发电效应、电磁发电效应的最优性能输出的理论模型。在模型的建立过程中，首先研究了应力和磁场对$Tb_{0.3}Dy_{0.7}Fe_2$合金压磁效应的影响，讨论了单独应力和单独磁场作用下磁致伸缩材料内磁通密度的变化特性；其次，提出了基于预加载荷方法和基于冲击应力方法的理论模型思路，并分别探讨了2种模型建立方法在复合式能量采集器设计中最大压磁系数获取的准则；最后，完成了能量采集器的大压磁系数获取方法的可靠性试验，实验结果与理论设计的结果吻合较好。该模型能够快速、准确地获得不同应用环境下复合式能量采集器的压磁特性，并可用于获取大压磁系数的复合式能量采集器构造及设计。

关键词：振动能量采集器；模型与设计；磁致伸缩-电磁；压磁效应

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