Modeling of giant magnetostrictive vibration energy harvesting

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Abstract. Vibration energy recovery technology, as an important way to alleviate energy pressure, has a broad application prospect in the electromechanical field. With the excellent performance of giant magnetostrictive materials (GMM), the giant magnetostrictive vibration energy recovery technology has attracted attention. In view of the shortcomings of current giant magnetostrictive vibration energy recovery research, this paper designs a column-rod vibration energy recovery device based on the material properties of giant magnetostrictive materials, and introduces its working principles. Combined with the structural characteristics of the device, this paper establishes the output model of the energy recovery process, calculates and analyzes the voltage output of the energy recovery, and obtains the output curves under different excitation energies were obtained, providing reference for the optimal design of the device and its further engineering application.

1. Introduction
Vibration energy recovery refers to the technology that converts vibration energy into usable energy such as hydraulic energy or electric energy by using a specific vibration energy recovery device. It is of great significance in improving the utilization rate of energy systems [1-3]. The giant magnetostrictive vibration energy recovery device converts mechanical vibration energy into electric energy based on the Villari effect of GMM, which has the advantages of high output power and strong working stability. It can provide electricity for electromechanical systems and even the commonly used small-and medium-sized power devices, therefore, it has great development potential [4]. Current research on giant magnetostrictive actuators is comprehensive and the study system is mature, but there is not much research on energy recovery. According to the characteristics of actual mechanical vibration, this paper designs an energy recovery device based on giant magnetostrictive rod. In order to calculate more accurately the electromotive force generated by energy recovery, this paper establishes a output model of the system, and calculates the output curves under different excitation forces, which is helpful for further research and application.

2. Energy recovery device and its working principle

2.1 Basic structure of the device
The giant magnetostrictive vibration energy recovery device is shown in Figure 1. The core component is a GMM rod. The permanent magnet acts as a bias magnet to provide a bias magnetic field, enabling the system to operate in a linear interval with a high electromechanical coupling coefficient. By adjusting the size of the bias magnet, the bias magnetic field strength can be changed...
accordingly [5-6]. The super magnetostrictive rod is not resistant to compression and has high brittleness, so it is necessary to design the pre-stressed bearing rod in practical application [7]. The pre-tightening spring provides pre-tightening force for the GMM rod, and the pre-tightening force can be adjusted by changing the thread between the cap and the sleeve. The cap, the sleeve and the support are all processed with high magnetic permeability material, and the whole device constitutes a closed magnetic circuit, thus maximized output efficiency.

![Figure 1. Structure of the energy recovery device](image)

2.2 Working principles
The stress and strain generated by the material under mechanical stress will cause the change of internal magnetization state of the GMM rod. This phenomenon is called magnetostrictive inverse effect, also known as the Villari effect.

According to the Villari effect, as shown in Figure 2, under external pressure, the shape of the GMM rod changes, and the internal magnetic domain is deflected at the same time, causing the change of the internal magnetic field distribution of the GMM rod, that is to say, the magnetic flux changes. If the GMM rod is covered by induction coil, induced electromotive force will generate [8].

![Figure 2. Diagram of working principles](image)

3. Establishment and solution of device model
Energy recovery is a process of transforming mechanical energy to magnetic field energy and to potential energy. Therefore, the model shall establish the relationship between the input force and the output electromotive force. The vibration process and magnetization of the GMM rod under the bias magnetic field are more complicated, therefore this paper puts forward the following assumptions for modeling:

1. The cross section of the GMM rod always maintains as a plane and moves as a whole when vibrating, and the lateral deformation caused by its longitudinal expansion and contraction is omitted;
2. The stress on the GMM rod $\sigma$, the generated compressive strain $\varepsilon$, and the magnetic field strength $H$ are evenly distributed;
3. The GMM rod is equivalent to the mass-spring-damping model, and it is assumed that the equivalent damping coefficient $c$ and the elastic modulus $E$ do not change with the change of the external force;
4. Ignore the influence of the preload spring on the system; the GMM rod can completely gain the
input of external force.

3.1 Dynamics model
Based on the above assumptions, the giant magnetostrictive energy recovery device is simplified to a single degree of freedom vibration system, as shown in Figure 3.

Figure 3 Device equivalent model

F is the external force received by the GMM rod, m, k, and c represent the mass, equivalent stiffness, and equivalent damping of the GMM rod respectively. Take the center balance point of the GMM rod as the coordinate origin and the positive direction of the x-axis as the vertical downward direction; thereby obtain the dynamic differential equation of the system:

\[ m\ddot{x} + c\dot{x} + kx = F \] (1)

3.2 Strain model
The strain \( \lambda \) can be obtained from the displacement of the GMM rod:

\[ \lambda = \frac{x}{l} \] (2)

l is the length of the GMM.

When a compressive stress is applied to a GMM rod, its magnetic domains will be distributed mainly along the direction of easy magnetization of the vertical axis. At this time, the relationship between the strain \( \lambda \) and magnetization of the GMM rod \( M \) is approximately the energy-based secondary domain transfer model:

\[ \lambda = \frac{3}{2} \frac{\lambda_s}{M_s^2} M^2 \] (3)

\( \lambda_s \) is the saturation magnetostriction of the GMM rod and \( M_s \) is the saturation magnetization of the GMM rod.

3.3 Magnetic field model
The external force affects the effective magnetic field inside the GMM rod by affecting magnetostriction. According to thermodynamics, the Helmholtz free energy density in the rod \( \rho \) is:

\[ \rho = \mu_0 H_0 M + \frac{1}{2} \mu_0 \alpha M^2 + \frac{3}{2} \sigma \lambda + TS \] (4)

\( \mu_0 \) is the vacuum permeability; \( H_0 \) is the bias magnetic field strength; \( \alpha \) is the domain wall interaction coefficient; \( \sigma \) is the external stress; \( T \) is the internal temperature; \( S \) is the entropy.

Differentiate Helmholtz free energy density \( \rho \) by magnetic density \( M \) to obtain the effective magnetic field. Differentiate the equation (4) and get:

\[ H = H_0 + \sigma \frac{3}{2} \frac{\lambda_s}{\mu_0} \left( \frac{d\lambda}{dM} \right) \] (5)

Differentiate \( M \) on both sides of equation (3):

\[ \frac{d\lambda}{dM} = \frac{3\lambda_s}{M_s^2} M \] (6)
Substitute equation (6) into equation (5):

$$H = H_0 + \left( \alpha + \frac{9\lambda_s \sigma}{2\mu_0 M_s^2} \right) M$$

(7)

3.4 Electromotive force model

The magnetic induction in-rod $B$ is obtained by electromagnetic principle according to the hysteresis nonlinearity inherent in GMM materials:

$$B = \mu_0 (M + H)$$

(8)

Then calculate the induced electromotive force $e$ according to Faraday’s law of electromagnetic induction:

$$e = \frac{d\Phi}{dt} = \frac{d(nBA)}{dt} = nA \frac{dB}{dt}$$

(9)

$\Phi$ is the magnetic flux passing through the GMM; $n$ is the number of turns of the coil; $A$ is the cross-sectional area of the GMM rod.

Substitute equation (8) into equation (9):

$$e = nA\mu_0 \left( \frac{dM}{dt} + \frac{dH}{dt} \right)$$

(10)

Substitute equations (2), (3) and (7) in:

$$e = nA\mu_0 (1 + \alpha + \frac{9\lambda_s F}{2\mu_0 AM_s^2}) \frac{M_s}{\sqrt{6\lambda_s l x}} \frac{dx}{dt}$$

(11)

4. Model solving

When the external force $F$ is determined, the electromotive force $e$ output curve can be directly obtained. The parameter values are shown in Table 1.

Table 1. Value of parameter

| Name and symbol                        | Unit       | Size       |
|----------------------------------------|------------|------------|
| Turns per coil $n$                     | turn       | 100        |
| Cross-sectional area of GMM rod $A$    | m$^2$      | 2.5$\pi \times 10^{-5}$ |
| GMM length $l$                         | m          | 0.03       |
| GMM bar mass $m$                       | kg         | 0.015      |
| Equivalent stiffness of GMM rod $k$   | N/m        | 0.785$\times 10^7$ |
| GMM rod damping $c$                    | N$\cdot$s/m | 400         |
| Vacuum permeability                    | —          | 4$\pi \times 10^{-7}$ |
| Magnetostriction rate of GMM rod $d$   | m/A        | 1.0$\times 10^7$ |
| Interaction coefficient of GMM domain wall domain wall $\alpha$ | — | 0.065 |
| GMM saturation magnetostriction $\lambda_s$ | — | 0.001 |
| GMM saturation magnetization $M_s$     | A/m        | 7.65$\times 10^5$ |

4.1 Sinusoidal force excitation

Since there is no practical significance to apply an upward external force to the device, this paper adjusts the standard sinusoidal function. From the calculation of equations (1) and (12), the output curve of the system under sinusoidal excitation force is obtained, as shown in Figure 4.
4.2 Unit pulse force excitation
For pulse excitation, use the $\delta$ function, and when $t=0$, take $F=\delta(t)$, through equations (1) and (12), the output curve of the system under pulse excitation force can be obtained, as shown in Figure 5.

4.3 Unit step force excitation
Set the unit step force function $F(t)$:

$$ F(t) = \begin{cases} 1 & (t > 0) \\ 0 & (t < 0) \end{cases} $$

Through equations (1) and (12), the output curve of the system under the unit step force excitation force can be obtained, as shown in Figure 6.

5. Conclusion
This paper designs a column-type giant magnetostrictive energy recovery device and establishes the output voltage model based on the structural characteristics of the device. By selecting three different excitation forces, corresponding output curves are obtained, which provides some theoretical basis for
further research.

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