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Study on the Characteristics of a Vibration-Excited Magnetoelectric Generator

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Abstract

To collect environmental vibration energy for powering low-power electronic devices, a magnetoelectric vibration power generation device based on E-shaped silicon steel sheets is designed. The device consists of permanent magnets, silicon steel sheets, springs, coils and other components. Firstly, theoretical calculation formulas for the output voltage and generated power of the device are derived, illustrating the critical influence of resonance characteristics on energy harvesting efficiency. Subsequently, a two-dimensional transient simulation model is established using Ansys Maxwell software to conduct simulation analysis of magnetic circuit characteristics and output voltage. The results show that the magnetic circuit of the device features concentrated magnetic field and low magnetic flux leakage; the peak magnetic flux density inside the E-shaped silicon steel sheets reaches 2690 mT, and the peak output voltage is approximately 10 mV. Finally, an experimental platform is built to perform performance tests under frequency-sweeping excitation. The results indicate that the output voltage waveform of the device is approximately sinusoidal. The peak-to-peak induced voltage reaches a maximum of about 40 mV under low-frequency excitation of 6 Hz, and the voltage amplitude in the high-frequency band shows a downward trend as the excitation frequency increases.

Keywords

Vibration Power Generation Device; Electromagnetic Type; E-shaped Silicon Steel Sheets; Simulation Analysis.

1. Introduction

With the rapid development of the Internet of Things and low-power electronic devices, harvesting vibration energy from the ambient environment to power miniature electronic systems has emerged as a highly effective approach. In comparison with new energy sources such as wind power and photovoltaic power generation, vibration energy harvesting has attracted considerable attention due to its independence from spatial and temporal constraints. In recent years, researchers have conducted extensive studies on vibration energy harvesting and developed various types of vibration-powered generators, including piezoelectric vibration energy harvesters [1,2], electrostatic vibration energy harvesters [3], and electromagnetic vibration energy harvesters [4,5], among others. The electrical energy generated by these devices during operation can meet the power supply requirements of low-power electronic products.

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Among various types of vibration energy harvesters, electromagnetic vibration energy harvesters exhibit advantages such as low cost, strong environmental adaptability, and diverse configurations, thereby gradually demonstrating promising application prospects. Relevant researchers have proposed numerous valuable design schemes with high reference significance [6,7].

Beeby et al. focused on the development of a miniature electromagnetic vibration energy harvester targeted at low-level ambient vibrations [8]. The fabricated micro electromagnetic energy harvester achieved an output power of 46 μW under vibrations at 52 Hz and 0.59 m/s^2, verifying the feasibility of extracting usable electrical energy from low-amplitude ambient vibrations using compact devices. Sun et al. designed a dual electromagnetic energy harvester for ultra-low-frequency vibration energy harvesting [9]. A rotary electromagnetic energy harvester was employed to capture oscillatory energy, while a linear-moving electromagnetic energy harvester was utilized to harvest linear vibration energy. A maximum output energy of 0.75 W was obtained under 0.2 g excitation. Li et al. proposed an X-shaped configuration, which effectively broadened the operating bandwidth of conventional cantilever-beam structures and exhibited better adaptability to low-frequency working conditions [10]. Zhang et al. investigated the influences of structural parameters and magnet dimensions on the calculation accuracy of magnetic force in a magnetic dipole model, and analyzed the effect of magnetic force on multistable energy harvesters [11]. Wang et al. presented a rolling-magnet electromagnetic induction energy harvester for energy recovery over a wide frequency range [12]. The harvester was designed based on a magnetically suspended rolling magnet, featuring the advantage of low damping.

From the above research, it can be seen that numerous structural configurations have been investigated for electromagnetic vibration power generation devices, but new structural forms still merit further exploration. This paper proposes a structure based on an E-shaped magnet, presents a theoretical calculation method for the output voltage, and carries out simulation calculations as well as experimental tests.

2. Basic Principle of Electromagnetic Vibration Power Generation Device

When the device is subjected to external excitation, the movable mass undergoes forced vibration, causing the coil to move and cut magnetic field lines. According to Faraday's law of electromagnetic induction, as shown in Equations (1) and (2), an induced current is generated in the coil, thereby realizing the conversion of mechanical vibration energy into electrical energy in the device.

$$\varepsilon = -\frac{d\Psi}{dt} = -N\frac{d\phi}{dt} \tag{1}$$

$$\phi = BS \tag{2}$$

Where ϕ denotes the magnetic flux through each turn of the coil, in webers (Wb); Ψ is the magnetic flux linkage, in webers (Wb); ε represents the induced electromotive force, in volts (V); S is the effective area through which magnetic flux passes across each coil turn; and B is the magnetic flux density, in tesla (T).

It can be seen that the faster the rate of change of magnetic flux, the greater the induced electromotive force in the coil. Therefore, the vibration characteristics of the vibration pickup system directly affect the relative motion between the permanent magnet and the coil, as well as the output voltage of the device. The physical model of the vibration pickup system can be

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simplified as a single-degree-of-freedom vibration system. To capture ambient vibration as effectively as possible, the optimal approach is to utilize resonance.

The vibration power generation device can be simplified as a spring-mass model, as shown in Figure 1. When the external environment vibrates, the mass m moves up and down under the traction of the spring, thereby harvesting external vibration energy. When the vibration pickup system is subjected to external excitation, it first undergoes forced vibration; when the excitation disappears, the system performs free damped motion. Since the energy conversion in free vibration is favorable, only the forced vibration is analyzed here.

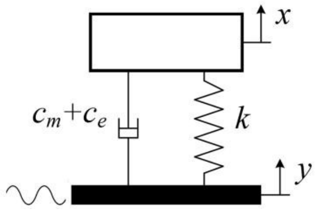

Figure 1. Schematic diagram of the vibration power generation device.

The differential equation of the system can be expressed as Equation (3):

$$m\ddot{x}(t)+(c_m+c_e)\left[\dot{x}(t)-\dot{y}(t)\right]+k\left[x(t)-y(t)\right]=0 \tag{3}$$

Where *m* is the mass of the object, *x* is the displacement of the movable part of the device, *y* is the displacement of the mounting base, *k* is the spring stiffness, c_m is the mechanical damping coefficient, *t* is time, and c_e is the electromechanical damping coefficient.

Assume that the external excitation is $y(t)=Y\sin(\omega t)$, where Y is the amplitude of the external excitation, and ω is the angular frequency.

Let $z=x(t)-y(t)$ represents the displacement of the mover relative to the base in the vibration power generation device. Through derivation, we obtain:

$$z=\frac{\left(\frac{\omega}{\omega_n}\right)}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)\right)^2+\left(2\xi\frac{\omega}{\omega_n}\right)^2}}\cdot Y\sin(\omega t-\varphi) \tag{4}$$

Where, $\varphi=\arctan\frac{2\xi\frac{\omega}{\omega_n}}{1-\left(\frac{\omega}{\omega}\right)^2}$, $\xi=\frac{c_m+c_e}{2\sqrt{mk}}$.

When the excitation frequency ω equals the natural frequency of the spring-mass system, $\omega_n=\sqrt{k/m}$, the maximum vibration energy can be obtained.

During the vibration of the oscillator, c_m+c_e represents the total damping, where c_e denotes the damping induced by the magnetoelectric conversion. Accordingly, the power converted into electrical energy, namely the ideal generated power, is approximately equal to the power absorbed by the magnetoelectric damping c_e, which can be obtained by multiplying the damping force by the vibration velocity, as shown in Equation (5).

$$p_{out} = F_e \cdot z' = c_e \cdot z' \cdot z' = \frac{c_e \left(\frac{\omega}{\omega_n}\right)^4 \omega^2}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2} Y^2 \cos^2(\omega t - \varphi) \tag{5}$$

As mentioned previously, the maximum energy can be extracted when the resonant frequency matches the input frequency, and the vibration-to-electricity conversion system can be designed to resonate at this frequency. In this case, the maximum instantaneous power after conversion is given by Equation (6).

$$p_{out} = \frac{c_e \omega_n^2}{4\zeta^2} Y^2 \tag{6}$$

It can be seen that the power harvested by the vibration power generation device depends on the amplitude of the base vibration on the one hand, and on the magnetoelectric damping on the other. The magnetoelectric damping is affected by the circuit load connected to the coil and the rate of change of flux linkage.

3. Simulation Analysis of Electromagnetic Vibration Power Generation Device

The 3D model of the vibration power generation device is shown in Figure 2. The square component on the middle guide rod is a permanent magnet, which is fixed to the guide rod, and springs are mounted on the guide rod at both ends of the permanent magnet. The E-shaped silicon steel sheets on both sides are connected to the middle housing, and this part constitutes the oscillator in the single-degree-of-freedom model. During vibration, relative motion occurs between the E-shaped silicon steel sheets and the permanent magnet, resulting in the cutting of magnetic induction lines, thereby generating an induced voltage in the coil.

Simulation analysis was carried out using Ansys Maxwell software with the two-dimensional transient simulation method. It should be noted that, since strict symmetry cannot be guaranteed in actual fabrication, an offset of approximately 1 mm was reserved during modeling. In the material settings of the simulation software, the permanent magnet was set to NdFe35, the E-shaped silicon steel sheets to steel008, and the coil to copper. The mesh size was set to 0.5 mm. The silicon steel sheets were defined as moving components with linear reciprocating motion along the guide rod, an initial position of -30 mm, and a velocity of 2 m/s.

The final simulation results are shown in Figure 3. It can be observed that the magnetic field lines emanate from the N pole of the permanent magnet and return to the S pole through a pair of yoke teeth of the left and right magnetic yokes, forming a closed magnetic circuit. The magnetic flux density inside the E-shaped silicon steel sheets is relatively high, with a peak value of 2690 mT. Overall, the magnetic field is concentrated with low magnetic flux leakage, which verifies the effectiveness of the magnetic circuit.

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Figure 4 shows the instantaneous voltage waveform of the electromagnetic vibration power generation device. It can be seen that the voltage variation exhibits a nearly sinusoidal form, with a peak voltage of approximately 10 mV.

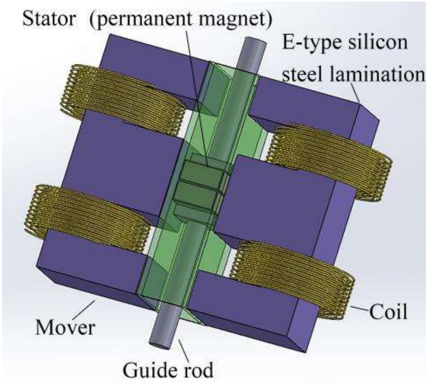

Figure 2. Structure diagram of the vibration power generation device

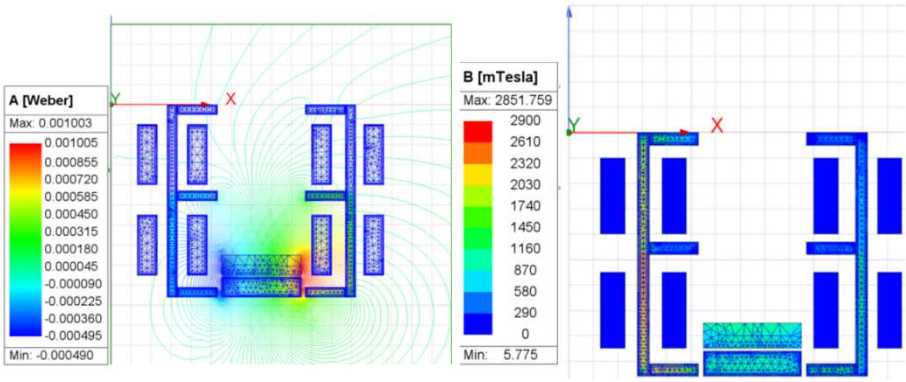

Figure 3. Magnetic field line distribution (left) and magnetic flux distribution (right)

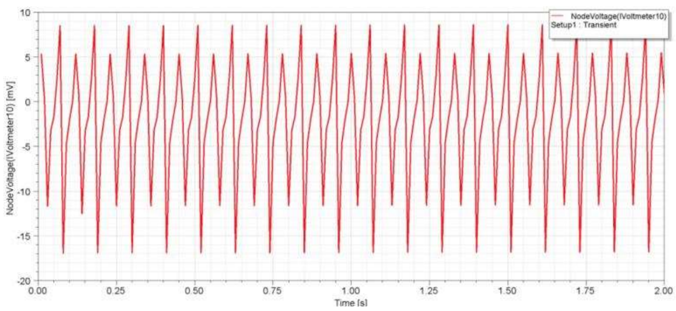

Figure 4. Simulated voltage values

4. Experimental Test of Electromagnetic Vibration Power Generation Device

The shell was fabricated by 3D printing, and then components such as the permanent magnet, E-shaped silicon steel sheets, coil windings, springs, and guide rod were assembled. The length of each E-shaped silicon steel sheet is approximately 4 cm. Two E-shaped silicon steel sheets are joined vertically and stacked to a certain thickness to serve as the magnetic yoke of the device. Copper wire is wound around the middle pillar of the E-shaped silicon steel sheets to form the winding. Permanent magnets are stacked and placed inside the shell, with the iron core inserted, and springs are fitted over the iron core. End caps are mounted on both sides of

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the outer shell. Finally, the E-shaped silicon steel sheets are fixed to the outer periphery of the shell, forming the electromagnetic vibration power generation device. The vibration power generation device and the experimental setup are shown in Figure 5.

The experimental setup mainly consists of a signal generator, a power amplifier, a vibration exciter, a vibration power generation device, and an oscilloscope. The signal generator serves as the signal source, outputting electrical signals with different frequencies and amplitudes. Connected to the signal generator, the power amplifier amplifies weak electrical signals to drive the vibration exciter, while controlling waveform distortion to ensure the excitation signal remains stable and intact. After receiving the driving signal, the vibration exciter converts the electrical signal into mechanical vibration and applies a stable excitation to the energy harvesting device through a connecting component. The oscilloscope is used to record the output voltage of the energy harvesting device in real time.

Figure 5. Prototype of the vibration power generation device (left) and experimental setup (right)

In the experiment, a frequency-sweeping excitation mode was adopted, with the excitation frequency starting at 5 Hz and ending at 100 Hz. Oscilloscope results show that the output voltage waveform of the energy harvesting device is approximately sinusoidal, and the voltage frequency increases with the rise of the excitation frequency. The voltage amplitude changes slightly in the low-frequency band, but decreases rapidly as the frequency increases. It is speculated that this is due to the significant reduction in the amplitude of the energy harvesting device under high-frequency excitation. According to Equation (6), it can be theoretically concluded that the voltage will also decrease.

Three representative sets of experimental results are selected, as shown in Figure 6, where the excitation frequencies are 6 Hz, 40 Hz, and 100 Hz, respectively. It can be seen that when the vibration frequency is 6 Hz, the peak-to-peak value of the induced voltage is the highest, reaching approximately 40 mV.

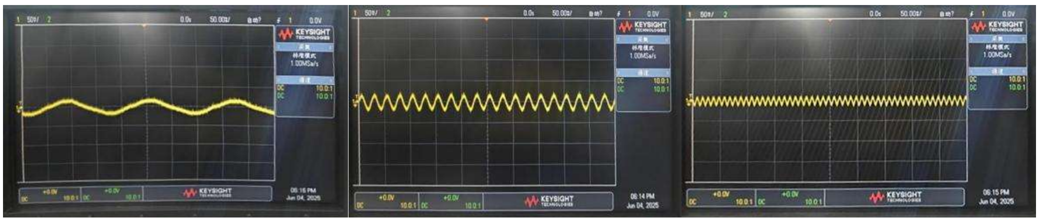

Figure 6. Voltage waveforms of the energy harvesting device under excitations of 6 Hz (left), 40 Hz (middle) and 100 Hz (right)

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5. Conclusion

In this study, aiming at the problem of environmental vibration energy recovery, a magnetoelectric vibration power generation device based on E-shaped silicon steel sheets was designed. Theoretical modeling, simulation analysis and experimental testing were completed, and the magnetic circuit characteristics and power generation performance of the device were systematically investigated. The main conclusions are as follows:

(a) The designed electromagnetic vibration power generation device is based on a single-degree-of-freedom spring-mass vibration system and Faraday's law of electromagnetic induction. It can realize efficient harvesting of vibration energy under resonance conditions. The generated power is jointly affected by the base vibration amplitude and magnetic damping, while magnetic damping is related to coil load and flux linkage variation rate, which provides a theoretical basis for the structural parameter optimization of related devices.

(b) Ansys Maxwell simulations verified the effectiveness of the device's magnetic circuit design. The magnetic lines of force form a closed loop and the magnetic field is highly concentrated in the E-shaped silicon steel sheet region, with significantly reduced magnetic flux leakage. The output voltage of the device varies approximately sinusoidally with a peak value of about 10 mV, showing good magnetoelectric conversion potential.

(c) The prototype experimental results are consistent with the trends of theoretical and simulation analyses. The device can output an approximately sinusoidal voltage waveform under swept excitation from 5 Hz to 100 Hz, and the voltage frequency is positively correlated with the excitation frequency. The voltage amplitude remains stable in the low-frequency range and reaches a maximum peak-to-peak value of 40 mV at 6 Hz. In the high-frequency range, the voltage amplitude decreases due to the reduction in device vibration amplitude, confirming that the optimal operating frequency band of the device is the low-frequency region.

This magnetoelectric vibration power generation device using E-shaped silicon steel sheets features a simple structure and low manufacturing cost. It can realize vibration energy harvesting and vibration reduction simultaneously, effectively reducing energy waste, and can supply auxiliary electric energy for low-power electronic devices. It has practical application prospects in self-powered fields such as Internet of Things terminals and micro sensing systems.

Although this study verified the feasibility and basic performance of the device, there is still room for improvement. In future work, structural parameters can be optimized to broaden the operating frequency band aiming at the performance degradation in the high-frequency range. Meanwhile, performance tests under different vibration amplitudes and load resistances can be carried out to further explore the optimal operating conditions of the device and improve its magnetoelectric conversion efficiency and practical application value.

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