Dynamic characteristics and response research of low-frequency vibration harvester based on diamagnetic levitation

Kedi Wu, Yufeng Su*, Kun Zhang and Qi Gong
School of Mechanical Engineering, Zhengzhou University, Zhengzhou, China
E-mail: yufengsu@zzu.edu.cn

Abstract. A low-frequency vibration energy harvester used to collect environmental vibration is proposed in this paper. The energy harvester mainly includes a diamagnetic stabilized levitation structure and elastic films as the stoppers. The floating magnet maintains a stable levitation in the vertical direction under the action of gravity, magnetic force and diamagnetic force. The elastic film is introduced to build a piecewise linear system which can increase the resonant frequency and extend the operating bandwidth for the energy harvester. The energy harvester prototype is designed, manufactured and tested. During the experiment, the working frequency range is extended from 2.1 Hz to 5.1 Hz under the excitation amplitude of 5 mm. The output voltage increases steadily from 59 mV to 159 mV within this frequency range. The experimental results under different harmonic excitation show that the harvester has the potential to work at a broadband and low-frequency range. The proposed harvester could power micro and intelligent equipment in a low-frequency vibration environment.

1. Introduction
With the quick development of intelligent society, wireless sensor network, implantable medical equipment, and low-power electronic devices have been applied widely. However, the operation of a number of devices accompanies a major issue of the maintenance cost of replacing or recharging batteries. Therefore, there is considerable research interest in obtaining energy from environmental sources such as heat, wind, and biochemistry as alternative sources of energy for these kinds of equipment. In these sources of energy, environmental vibration energy has become one of the most popular energy sources because it is ubiquitous, inexhaustible and versatile in nature [1]. Generally, there are three main conversion mechanisms used to convert vibrational energy into electric energy: electromagnetic [2-4], electrostatic [5], piezoelectric [6-8] and so on. Based on the principle of electromagnetic induction, the electromagnetic vibration energy harvester generates induced electromotive force by the relative motion of the magnet and coil. Unfortunately, the disadvantages of the traditional electromagnetic vibration energy harvester are limited bandwidth and constant resonant frequency. To solve the shortcomings, some researchers suggest a number of approaches to widen the operating bandwidth, such as multimodal oscillators [9, 10], frequency-up conversion [11, 12] technique and piecewise linear methods [13, 14]. The piecewise linear method is widely concerned because it enables the energy harvester to operate in a wider frequency band. It is not enough to simply increase the bandwidth of the operation to avoid undesirable internal losses. In order to alleviate this problem, the diamagnetic stabilized levitation has been introduced into the energy harvester. The diamagnetic levitation refers to a phenomenon in which a permanent magnet floats stably without any external control or contact by virtue of closely placed diamagnetic materials. A novel energy harvester used diamagnetic levitation structure proposed by Palagummi et al. [15] has good low frequency
characteristics. The experimental result shows that the output power of harvester can reach 3.6 \( \mu \text{W} \) when the excitation acceleration is 0.0434 m/s\(^2\).

This paper introduces a low-frequency energy harvester used diamagnetic levitation structure to scavenge environmental vibration. Following the introduction, Section 2 introduces the diamagnetic levitation structure and working principle in detail. Section 3 introduces the theoretical modeling of piecewise linear vibration system. The experimental equipment and measurement results are introduced in Section 4. Section 5 draws some important conclusions.

2. Structure and working principle
The structural model of diamagnetic levitation system is shown in figure 1, and figure 2 shows the prototype of the harvester. The proposed energy harvester includes a diamagnetic stabilized levitation structure and elastic films as the stoppers. The diamagnetic levitation structure includes a lifting magnet and a floating magnet with the same axial direction magnetization, two pyrolytic graphite discs and planar copper coils distributed on the opposite surfaces of the graphite discs. The elastic film is introduced to build a piecewise linear system which can increase the resonant frequency and extend the operating bandwidth.

![Figure 1. Structural model of diamagnetic levitation system. Figure 2. Energy harvester prototype.](image)

Table 1 shows the list of material and structural parameters of the harvester. The floating magnet and the lifting magnet are both cylindrical and the magnetization directions are both in the axial direction. The floating magnet is pulled by the lifting magnet. Simultaneously, the floating magnet is subjected to the diamagnetic forces by the pyrolytic graphite discs. A stable levitation of the floating magnet is achieved between the two graphite discs. When the harvester is excited by the vibration of the external environment, the floating magnet could move nearby its equilibrium position. Based on the principle of electromagnetic induction, the kinetic energy of floating magnet vibration is converted into electric energy inside the copper coil.

| Component       | Material       | Dimensions(mm) |
|-----------------|----------------|-----------------|
| Lifting magnet  | NdFeB(N52)     | \( \varnothing 12.7 \times 5 \) |
| HOPG disc       | HOPG           | \( \varnothing 25 \times 5 \) |
| Coil            | copper         | \( \varnothing 0.07 \) |
| Floating magnet | NdFeB(N52)     | \( \varnothing 12 \times 4 \) |
| Elastic film    | PVC            | 30×30×0.03 |

3. Theoretical modeling
As shown in figure 3(a), a SDOF spring-mass model is proposed to simulate the piecewise linear vibration system. The system is composed of a floating magnet \( M \) of spring stiffness \( K_i \) and damping
$C_1$, and two elastic films, which work as flexible stoppers, are regarded as mechanical springs with spring stiffness $K_2$ and damping $C_2$. The distance from the floating magnet to the elastic film is $D$. The vibration of the floating magnet relative to the base is $X(t)$ when the system is excited by the external excitation $Y(t)$. According to the relative displacement $X(t)$, the system response could be divided into two phases. In the first phase, when the relative displacement $X(t)$ does not exceed the gap $D$, the elastic film is not impacted by the floating magnet. The equivalent stiffness $K_1$ and damping $C_1$ of the floating magnet do not change. In the second phase, when the relative displacement $X(t)$ exceeds the gap $D$, the floating magnet impacts the elastic film. The equivalent stiffness of the floating magnet becomes $K_1 + K_2$, and the equivalent damping becomes $C_1 + C_2$. Therefore, the movement of the floating magnet changes from linear behavior to non-linear behavior, which broadens the working frequency band of the harvester. Figure 3(b) shows the stiffness change of piecewise linear system motion.

**Figure 3.** Equivalent piecewise linear vibration system.

The general governing equations are shown below:

\[
\begin{align*}
M\dddot{X} + C_1\ddot{X} + K_1X + F(X, \dot{X}) &= -M\dddot{Y} \\
\dot{L}_{\text{coil}} + i(R_{\text{load}} + R_{\text{coil}}) &= V(X, \dot{X}) \\
C_2\ddot{X} + K_2(X - D) &= 0 & (X \geq D) \\
C_2\ddot{X} + K_2(X + D) &= 0 & (X \leq -D)
\end{align*}
\]

(1)

Where $Y(t) = A\sin(\omega_0 t)$; $A$ and $\omega_0$ represent the excitation amplitude and the excitation frequency respectively; $L_{\text{coil}}$ depends on the inductance of the copper coil, the resistances of the load and the copper coil are represented by $R_{\text{load}}$ and $R_{\text{coil}}$ respectively. $V(X, \dot{X})$ represents the induced electromotive force.

Combining equation (1) with equation (2), the general governing equations are written as

\[
\begin{align*}
M\dddot{X} + C_1\ddot{X} + K_1X &= -M\dddot{Y} & [X] \leq D \\
M\dddot{X} + (C_1 + C_2)\dddot{X} + (K_1 + K_2)X - K_1D &= -M\dddot{Y} & [X] > D \\
\dot{L}_{\text{coil}} + i(R_{\text{load}} + R_{\text{coil}}) &= V(X, \dot{X})
\end{align*}
\]

(3)

The induced voltage could be calculated using Faraday's law of electromagnetic induction.

4. Experiment

4.1. Experimental device

Figure 4(a) shows the connection diagram of the experimental device, and the experimental platform is constructed to study the output characteristics of the harvester in figure 4(b). The energy harvester prototype is excited by a vibration exciter (LT-50-ST250; ECON). A power amplifier (LSA-V5000A; ECON) incorporating a vibration controller (VT9002; ECON) is connected to the vibration exciter. An
An accelerometer (EA-YD-188; ECON) is placed on the vibration exciter to directly sense the amplitude of the output vibration. The signals obtained from the accelerometer are transmitted to a computer by a signal analyzer. To measure its output voltage, an oscilloscope (Tektronix TBS 1052-B-EDU) is connected to the prototype.

4.2. Experimental results
The relationship between the output characteristics of the harvester and the excitation frequency is shown in figure 5. As shown in figure 5(a), the RMS voltage first increases to a certain value and then decreases under various excitation amplitudes as the frequency increases. At the same time, the RMS voltage and the resonant frequency gradually enlarge when the excitation amplitude increases. The RMS voltage reaches the maximum value (159 mV) under the excitation amplitude of 5 mm. It is also found that under the excitation amplitude of 5 mm, the working frequency range was increased from 2.1 Hz to 5.1 Hz, and the bandwidth was widened above 3 Hz. Compared with figure 5(a), the output power shows the same change trend which increases at first and then decreases in figure 5(b). The output power of the energy harvester at 5.1 Hz could reach 225.72 µW under an amplitude of 5 mm.

5. Conclusions
A low-frequency energy harvester used diamagnetic levitation structure is tested and researched. The energy harvester can enlarge the working frequency range in a low-frequency vibration environment. The working frequency is from 2.1 Hz to 5.1 Hz, and its bandwidth is widened to the range above 3 Hz. The output voltage increases steadily from 59 mV to 159 mV within this frequency range when the excitation amplitude is 5 mm. The maximum power generated by the energy harvester at 5.1 Hz is 225.72 µW under an amplitude of 5 mm. It's verified that the elastic film could effectively improve the
output characteristics under low frequency and small displacement conditions. The proposed harvester could power micro and intelligent equipment in a low-frequency vibration environment.

6. References
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