Magnetic coupled ultra-low frequency piezoelectric energy harvester for self-powered sensors

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Abstract. Harvesting human motion energy to power various sensors has attracted more and more attention of researchers. Aiming to harvest the ultra-low frequency vibration energy generated by human motion, this paper proposes a magnetic coupled scheme which consists of two flextensional transducers with two endmost magnets, a center magnet, and a tube. Through magnetic coupling effect, the ultra-low frequency vibration energy is amplified and effectively harvested, and the output voltage amplitude at 5Hz reaches 22V under the initial distance of 48mm and the acceleration of 1g. The output voltage amplitude of the harvester is related to the initial distance and excitation acceleration which are theoretically analyzed in this paper.

1. Introduction

Energy harvesting technology is to convert all kinds of energy in the environment into electrical energy through various electromechanical conversion mechanisms to supply power for intelligent sensors. Due to the characteristics of ultra-low frequency in human motions, the vibration energy cannot be harvested efficiently by conventional piezoelectric energy harvester, human motion energy harvesting mainly adopts triboelectric [1, 2], electromagnetic [3, 4], thermoelectric [5, 6] and other electromechanical mechanisms. In order to harvest ultra-low frequency vibration energy by piezoelectric mechanism, researchers have developed various energy conversion structures, such as magnetic coupling [7-10] is used to couple the external vibration energy into the piezoelectric cantilever beam, rolling beads are used to impact the piezoelectric patches in different directions [11], and a spring-mass system is used to sense the external vibration [12].

In this paper, a magnetic coupled piezoelectric energy harvester with flextensional transducer is proposed. A center magnet is used to sense the vibration of human motion and generates a changing magnetic force. Therefore, the vibration is coupled to the flextensional transducer which outputs the electrical energy. The working principle of the proposed harvester is illustrated, and the energy harvesting performance of the proposed harvester is theoretically analyzed.

2. The proposed piezoelectric energy harvester

The proposed harvester consists of two flextensional transducers with two endmost magnets attached at the free ends respectively, a center magnet which is cylindrical in shape is placed between the two
endmost magnets and oriented to repel them, a tube for suspending the center magnet, and a substrate which is excited by human motion, as schematically illustrated in Figure 1. The two flextensional transducers and the tube are fixed on the substrate. The flextensional transducer includes a piezoelectric layer and two metal layers, and the metal layer is raised shape, which is composed of two bonded planes, two inclined plane, and an upper plane. As illustrated in Figure 2, the energy conversion process of the proposed energy harvester can be explained as follows: the vibration of human motion is transmitted to the displacement of the center magnet which produces a reciprocating motion. The distance between the center magnet and the endmost magnet varies periodically or randomly, which will change the repulsive force between the two magnets. The magnetic force is transmitted to the piezoelectric layer through the flextensional structure and outputs the electrical energy.

Figure 1. Configuration of the proposed harvester. (a) Conceptual diagram. (b) Top view.

Figure 2. Energy conversion process of the proposed energy harvester.

Figure 3. Schematics of force analysis and geometric parameters of the proposed harvester.

The force analysis and geometric parameters of the proposed harvester are shown in Figure 3. Ignoring the damping in the motion of the center magnet, the dynamic equation of the system can be established as follows. Equation (1) is the mechanical dynamic equation of the center magnet. Equation (2) and Equation (3) are the open-circuit voltages of the harvesting circuits given by reference [13].

\[ m\ddot{x} + F_{mag1} - F_{mag2} = ma \cos \omega t \]  

\[ V_{out1} = \frac{F_{mag1}}{R_{1}} \]  

\[ V_{out2} = \frac{F_{mag2}}{R_{2}} \]
\[ V_1 = \frac{d_{\text{eff}}}{C_p} F_{\text{mag1}} \]  \hspace{1cm} (2)

\[ V_2 = \frac{d_{\text{eff}}}{C_p} F_{\text{mag2}} \]  \hspace{1cm} (3)

Where \( m \) is the mass of the center magnet; \( F_{\text{mag1}} \) and \( F_{\text{mag2}} \) are the magnetic forces, which are related to the displacement between the center magnet and the endmost magnet; \( a \) is the acceleration of the external excitation; \( \omega \) is the frequency of the external excitation; \( V_1, V_2 \) are the output voltages of the two piezoelectric layers, respectively; \( C_p \) the equivalent capacitance of the piezoelectric layer; \( d_{\text{eff}} \) represents the equivalent piezoelectric coefficient, and can be written as:

\[ d_{\text{eff}} = -d_{33} + \frac{\mu_0 l_1^2 (2l_2 \cos \theta + l_3) \sin \theta \cos \theta}{t_p l_1^2 \sin^2 \theta + 3s_{11} D (2l_2 \cos \theta + l_3)} d_{11} \]

where \( d_{33} \) and \( d_{11} \) are the piezoelectric constants; \( l_1, l_2, l_3 \) are the lengths of bonded plane, inclined plane, and upper plane, respectively; \( \theta \) is the included angle between the bonded plane and the inclined plane; \( t_p \) is the thickness of the piezoelectric layer; \( s_{11} \) is the elastic compliance of the piezoelectric layer; \( D \) is the bending stiffness of the metal layer, and \( D = E_m t_m^3 / 12(1-\nu_m^2) \), in which \( t_m \) is the thickness of the metal layer, \( E_m \) and \( \nu_m \) are the elastic modulus and Poisson’s ratio of the metal layer, respectively.

The magnetic forces can be written as:

\[ F_{\text{mag1}} = \frac{3 \mu_0 M^2}{2 \pi d_1^4} \]  \hspace{1cm} (4)

\[ F_{\text{mag2}} = \frac{3 \mu_0 M^2}{2 \pi d_2^4} \]  \hspace{1cm} (5)

where \( \mu_0 \) is the vacuum permeability, and \( \mu_0 = 4 \pi \times 10^{-7} \text{ H m}^{-1} \); \( M \) is the moment of the magnetic dipole; \( d_1 \) and \( d_2 \) are the distance between the magnetic dipoles, by ignoring the deformation of the metal layer, \( d_1 \) and \( d_2 \) can be written as \( d_1 = d_0 + x \) and \( d_2 = d_0 - x \), in which \( d_0 \) is the initial distance between the magnetic dipoles.

3. Analytical study

According to the theoretical formula, whether the center magnet can realize reciprocating motion depends on the resultant force of the magnetic forces and the external excitation force. Therefore, the harvesting performance is analyzed from two aspects: geometric parameters and external excitation. The analysis parameters of the proposed harvester are shown in Table 1.

Figure 4 shows the output voltage of the piezoelectric layer under different initial distances. The frequency and acceleration of the excitation are 5Hz and 1g respectively. The proposed harvester shows different characteristics with the initial distance, and the output voltage is directly related to the displacement of the center magnet. As shown in Figure 4(a), when the initial distance \( d_0 \) equals 20mm, the output voltage and the displacement of the center magnet vary periodically in a small interval, this is because the small initial distance \( d_0 \) leading two large repulsive forces \( F_{\text{mag1}} \) and \( F_{\text{mag2}} \), the external excitation force cannot overcome the repulsive forces and cannot make the center magnet produce large reciprocating motion. As shown in Figure 4(b), when the initial distance \( d_0 \) equals 48mm, the output voltage and the displacement of the center magnet vary randomly in a large interval, the amplitudes of the output voltage and the displacement are 22V and 41mm respectively, resulting in large magnetic coupling effect. As shown in Figure 4(c), when the initial distance \( d_0 \) equals 60mm, the magnetic coupling effect becomes weak and the center magnet can only move periodically with a slight fluctuation in a small interval with an amplitude of 20mm. Therefore, the amplitude of the output voltage is only 0.013V which is far less than that of \( d_0 \) equals 20mm and \( d_0 \) equals 48mm. According to numerous data, when the frequency and acceleration of the excitation are 5Hz and 1g, the optimal value of the initial distance is \( d_0 = 48 \text{mm} \).
Table 1. Parametric values of the proposed harvester.

| Parameters                              | Values       | Parameters                              | Values       |
|-----------------------------------------|--------------|-----------------------------------------|--------------|
| Material of the metal layer             | Aluminium    | Material of the piezoelectric layer     | PZT-5H       |
| Length of the bonded plane $l_1$ (mm)   | 5            | Piezoelectric constant $d_{31}$ $(10^{10}$CN$^{-1}$) | -3.2         |
| Length of the inclined plane $l_2$ (mm) | 12.9         | Piezoelectric constant $d_{33}$ $(10^{10}$CN$^{-1}$) | 6.5          |
| Length of the upper plane $l_3$ (mm)   | 5            | Thickness of the piezoelectric layer $t_p$ (mm) | 1            |
| Included angle $\theta$ (°)            | 15           | Elastic compliance of the piezoelectric layer $s_{11}$ $(10^{11}$m$^2$N$^{-1}$) | 1.65         |
| Width of the metal layer $b$ (mm)       | 10           | Equivalent capacitance of the piezoelectric layer $C_p$ $(10^9$F$)$ | 6.25         |
| Thickness of the metal layer $t_m$ (mm) | 0.25         | Material of the magnet                 | NdFeB        |
| Elastic modulus of the metal layer $E_m$ (GPa) | 200     | Mass of the center magnet $m$ (Kg)     | 0.005        |
| Poisson’s ratio of the metal layer $\nu_m$ | 0.28       | Magnetic moment $M$ (Am$^2$)            | 0.1          |

Figure 4. The output voltage of the piezoelectric layer under different initial distance $d_0$. (a) $d_0 = 20$mm. (b) $d_0 = 48$mm. (c) $d_0 = 60$mm.

As mentioned above, the reciprocating amplitude of the center magnet is also related to the external excitation acceleration. Figure 5 shows the output voltage of the piezoelectric layer under different excitation accelerations. The excitation frequency and the initial distance are 5Hz and 48mm, respectively. It is found that the output voltage of the piezoelectric layer increases with the excitation acceleration. When the external excitation acceleration are 0.5g, 1.0g and 1.5g, the amplitudes of the
output voltage are 0.018V, 22V and 35V, respectively. Due to the lower level of the excitation acceleration, the displacement of the center magnet is not large enough to produce a high level of magnetic coupling, so the piezoelectric layer cannot produce large output voltage.

Figure 5. The output voltage of the piezoelectric layer under different excitation accelerations. (a) $a=0.5g$. (b) $a=1.0g$. (c) $a=1.5g$.

Figure 6 shows the output voltage amplitude of the piezoelectric layer under different excitation frequencies when the initial distance $d_0$ is 48mm and excitation acceleration is 1g. It can be seen from the figure that the proposed harvester can effectively harvest human motion energy in the range of 1～5Hz, and the energy harvesting efficiency is the highest at 5Hz. When the frequency exceeds 5Hz, as shown in Figure 7, the displacement of the center magnet becomes smaller resulting in a weak magnetic coupling effect, and the output voltage is very low. Therefore, this scheme is very suitable for ultra-low frequency vibration energy harvesting of human motion.

Figure 6. The RMS voltage of the piezoelectric layer under different excitation frequencies.

Figure 7. The output voltage of the piezoelectric layer and the displacement of the center magnet when the frequency is 6Hz.
4. Conclusion
In this paper, a magnetic coupled piezoelectric energy harvester is proposed and theoretically analyzed. The harvester uses the compressive mode of the flextensional transducer to harvest the ultra-low frequency vibration energy of human motion through magnetic coupling. Under the initial distance of 48mm and the acceleration of 1g, the harvester can effectively harvest ultra-low frequency energy in the range of 1~5Hz, and the output voltage amplitude at 5Hz reaches 22V. The output voltage amplitude of the harvester is related to the initial distance, excitation acceleration and other parameters. The greater the acceleration, the greater the output voltage, and the output voltage has different output characteristics at different initial distances. The next research will further explore the influence of system parameters on energy harvesting performance, and carry out experimental verification.

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