



Design of a piezoelectric–electromagnetic hybrid vibration energy harvester operating under ultra-low frequency excitation

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Abstract

In this paper, we proposed a novel piezoelectric–electromagnetic hybrid vibration energy harvester (HVEH). The HVEH has a unique structure, which enables it to work in an ultra-low frequency environment. An amplification structure amplifies the input displacement, increasing the displacement distance of the magnets. The motion of the magnets causes the frequency up-conversion of the piezoelectric cantilever beam. As the magnets move back and forth, the piezoelectric vibration energy harvester (PVEH) generates a stable output energy. A closed magnetic circuit is designed for electromagnetic vibration energy harvester (EVEH) with a pair of magnets and a soft magnetic core. The pair of magnets with opposite polarities changes the direction of magnetic flux in the coil by 180°, resulting the EVEH to harvest more energy. The combination of piezoelectric and electromagnetic energy harvesters makes the energy harvester obtain higher output energy. The experimental results show that, in the cycle experiments with a frequency of 5 Hz, the maximum peak-to-peak open-circuit voltage of the PVEH and the EVEH is 40.39 V and 36.87 V, respectively. The optimal load resistance and the maximum output power of the PVEH are 398.7 kΩ and 87.9 μW, while the EVEH's are 3.2 kΩ and 2.173 mW, respectively. In addition, the charging characteristics of the HVEH through a 3300 uF capacitor indicated that the voltage growth of the HVEH is faster than that of the single energy harvester at the same time. The experimental results demonstrate great potential of the proposed energy harvester in various applications.

1 Introduction

With the development of low-power electronic devices, converting environment energy into electrical energy for powering devices becomes more possible. At present, energy harvesting as a promising technique has attracted immense interest to power low-power electrical

components, such as wireless sensor networks, implantable biomedical sensor and wearable devices (Lueke et al. 2011; Roundy et al. 2003; Ren et al. 2018). Ambient energy that can be utilized mainly includes thermal energy, kinetic energy, electromagnetic energy, and so on (Zeadally et al. 2020). Among these energy resources, vibration energy is available almost in everywhere, like in buildings, vehicles, industrial vibration, and human motion (Arroyo et al. 2012; Xia et al. 2015), and independent on weather, so it shows a broad application prospect in supplies for devices.

To convert ambient vibration energy into electrical energy, three common electromechanical energy conversion mechanisms have been developed, including piezoelectric, electromagnetic and electrostatic effects (Wang et al. 2021), which provide the basis for designing the vibration energy harvester. The conversion efficiency depends on the applications and on the specific operating conditions (Beeby et al. 2006). Among these vibration energy harvesters, piezoelectric and electromagnetic energy harvesters have been widely studied and realized

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due to their advantages of harvesting high power levels and simple implementations.

Piezoelectric vibration energy harvester (PVEH) generally consists of a metal cantilever beam and one or several piezoelectric patches, which are bonded on the beam (Fang et al. and Lefeuvre et al. 2006; Marzencki et al. 2008; Roundy et al. 2004, 2005). A tip mass is usually added at the free end of the cantilever to reduce natural frequency (Li et al. 2010). Only vibrations near the natural frequency of energy harvesters can be efficiently harvested (Kecik 2021). However, environmental vibrations are mostly low-frequency. Therefore, amounts of researchers have devoted to proposing effective schemes to make energy harvesters work under a wider operating frequency band (Zhang et al. 2019a). For instance, Sampath et al. (2018), Salunke et al. (2018), and Uddin et al. (2016) have analyzed the effect of proof mass on piezoelectric cantilever beams to reduce resonant frequency, while Zhao et al. (2018) has analyzed the relationship between the dimension of piezoelectric cantilever beams and the natural frequencies, and changed the natural frequencies of energy harvesters by changing the dimension. In the following, Wang et al. (2017) presented a compact PVEH using multiple nonlinear techniques to tuning the resonant frequency and broadening the bandwidth. Meanwhile, Usharani et al. (2017) presented a new piezoelectric-patched cantilever beam with a step section, which widens the operating frequency range. What's more, A compact two-degree-of-freedom energy harvester with cut-out cantilever beam was proposed by Wu et al. (2012) who achieved that the first two resonances can be tuned close to each other by varying the proof masses, while maintaining significant magnitudes, thus providing a useful bandwidth for energy harvesting. And Xiong et al. (2020) designed a novel piezoelectric energy harvester, with a rectangular hole in the metal substrate, which reduced the natural frequency and improved the output performance.

Electromagnetic vibration energy harvester (EVEH) usually consists of permanent magnets and coils harvest energy from ambient vibrations either by a relative movement between a coil and a magnet, or via a stationary coil in a changing magnetic field (Halim et al. 2018; Zhang et al. 2019b). For example, Zhang et al. (2019b) designed a high-efficiency EVEH based on a rolling magnet. This energy harvester can greatly increase the magnetic flux rate when cutting the coil and hence uprate the harvesting performance compared to that of the harvester with a sliding magnet. Halim et al. (2015) designed a human-limb driven, frequency up-converted EVEH, which can generate significant power from human-limb motion (hand-shaking). Mallick et al. (2017) reported multi-frequency MEMS EVEHs employing two different topologies. The both substantially increased output power compared to the

reported MEMS scale electromagnetic generators. More recently, Liu et al. (2019) first proposed a new concept of speed amplified nonlinear EVEH through fixed pulley wheel mechanisms and magnetic springs, which enhanced the performance of the energy harvester. Khan et al. (2019) presented a novel flow type electromagnetic based energy harvester for pipeline health monitoring system. The harvester can produce an open circuit DC voltage of 2.5 V and a DC output power of 367.5 μW at load resistance of 3 k Ω .

In order to effectively harvest ambient vibrational energy for sustainably powering electronic devices, hybrid vibration energy harvesters (HVEHs) were designed, fabricated and studied by researchers. For instance, Iqbal et al. (2018) reported a novel multimodal hybrid bridge energy harvester using combined piezoelectric and electromagnetic conversion achieving for the health monitoring of bridges. Moreover, a vibration-based multimodal hybrid piezoelectric–electromagnetic energy harvester with multiple mechanical degrees-of-freedom is proposed by Toyabur et al. (2018) Hybridization of the two conversion mechanisms in a single system improved the functionality of the harvester in the low frequency range. In addition, Javed et al. (2019) proposed a piezoelectric-electromagnetic energy harvester harvesting energy from vortex-induced oscillations. After this study, Bolat et al. (2019) investigated a novel hybrid energy harvesting system harvesting energy from flow-induced vibrations.

Reviewing the previous mentioned studies, piezoelectric and electromagnetic energy harvesters were widely investigated, while piezoelectric-electromagnetic HVEHs had also attracted immense interest as a promising scheme. At present, piezoelectric- electromagnetic HVEHs with only a few studies, still need to be improved so that it is enough to harvest energy for powering electronics.

In this paper, a novel piezoelectric-electromagnetic HVEH is proposed combining the merit of displacement amplification, frequency up-conversion, and closed magnetic circuit. Through a simple displacement amplifying structure, the input displacement is amplified to push magnets to move. The cantilever beam adsorbed by magnets is released due to the movement of the magnets, resulting in frequency up-conversion. The well-designed closed magnetic circuit is achieved with a pair of permanent magnets of opposite polarities and an iron core of soft magnetic material. Therefore, this energy harvester can be exploited to improve output power and operating frequency bandwidth, simultaneously.

The remainder of this paper is organized as follows. Section 2 introduces the design concept and working principle of the energy harvester. In Sect. 3, the proposed HVEH is modeled by lumped parameter model to predict the output performance. The prototype fabrication and experimental setup are described in the Sect. 4. In Sect. 5, a

series of experiments are carried out, and the results are described and discussed. Finally, the conclusions are drawn in Sect. 6.

2 Architecture and working principle of the energy harvester

2.1 Structure design

Figure 1 shows the schematic diagram of the proposed HVEH, where Fig. 1a shows the energy harvester with a top plate and four springs. In order to show the internal structure clearly, Fig. 1b is without the top plate and springs. This HVEH mainly consists of a PVEH and an EVEH, where the PVEH is produced by PZTs pasted on the surface of the metal substrate and a mass on the tip end of the cantilever beam, and the EVEH is provided by a combination of magnets, an iron core and a coil.

2.2 Frequency up-conversion

For the PVEH, it generates maximum voltages and power when ambient vibration frequency is equal to the natural frequency of the PVEH. A problem is a large amount of energy that is from low-frequency excitations, which significantly reduces the performance of devices. To address this challenge, the novel energy harvester presented in this paper adopts magnetic attraction to achieve frequency up-conversion.

Figure 2a, b illustrate the frequency up-conversion harvesting scheme with magnets sliding back and forth. In the initial state, shown in Fig. 2a, the tip end of the cantilever beam is pulled into contact with the magnets. When the top plate, shown in Fig. 1a, moves downward by the external excitation force, the magnets are pushed forward by the displacement amplifying structure, and the cantilever beam abruptly releases from the magnets to cause free resonance and generate electricity for a while, as

shown in Fig. 1b. When the force disappears, the magnets slide backward, and the cantilever beam is attracted by magnets again. When the magnetic force surpasses the restoring force of the cantilever, the cantilever beam will pull-in onto the magnets to form a beam with one end clamped and the other simply supported. Excited by the external force, the beam will resonate at a much higher resonant frequency. Therefore, this energy harvester has higher performance.

2.3 Closed magnetic circuit

For electromagnetic energy harvesting, it is one of the oldest techniques for energy harvesting (Elvin et al. 2011). Its principle of generating electricity is mainly based on Faraday’s law, and the performance of EVEH depends on the magnetic flux rate. To improve the efficiency of harvesting energy, in this paper, a closed magnetic circuit is designed with a pair of magnets and a soft magnetic core, as shown in Fig. 2. The polarities of two magnets placed side by side are opposite. In the initial state, as seen in Fig. 2a, the direction of the magnetic flux is counter-clockwise. When the magnets move forward to the position shown in Fig. 2b, the direction of the magnetic flux is clockwise. Thus, due to a cycle of back and forth movement of the magnets, the direction of the magnetic flux is changed by 180°, resulting in a maximum magnetic flux change in the coil. The change of the magnetic flux was simulated with COMSOL software, as seen in Fig. 3. The simulated results are consistent with the expected intention. Therefore, this energy harvester with closed magnetic circuit can more efficiently convert energy into electricity.

2.4 Displacement amplification

There is a problem here, that is, under the influence of excitation, the displacement of the top plate is relatively small, while the sliding distance of the magnets need to be relatively large. Therefore, a displacement amplifying

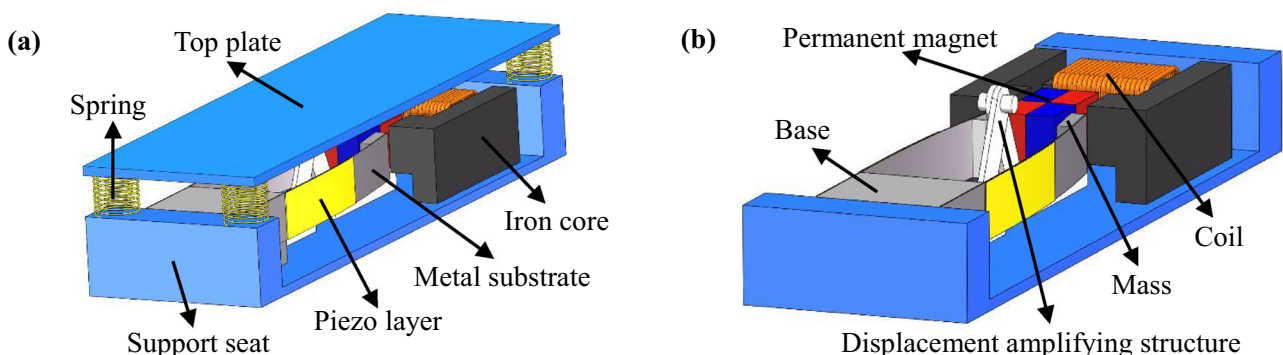


Fig. 1 Schematic diagram of the proposed HVEH: a with a top plate and springs; b without a top plate and springs

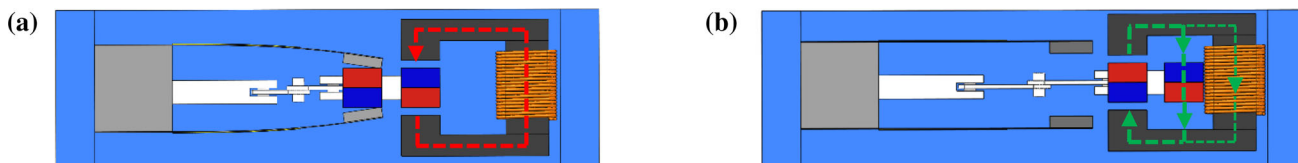


Fig. 2 The top view of this HVEH: **a** counter-clockwise magnetic flux direction when cantilever beams are adsorbed; **b** clockwise magnetic flux direction when cantilever beams are released

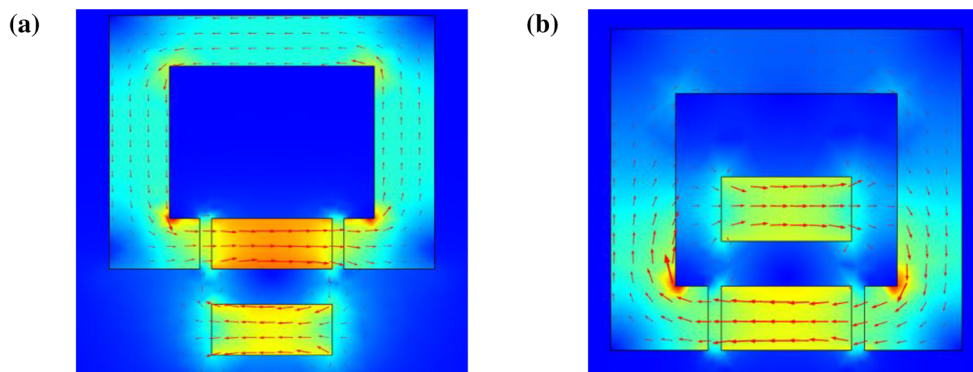


Fig. 3 Simulation of magnetic flux density for the permanent magnets pair and a soft magnetic core from COMSOL software: **a** counter-clockwise magnetic flux direction when cantilever beams are adsorbed; **b** clockwise magnetic flux direction when cantilever beams are released

structure is designed to amplify the small input displacement into a large output displacement. At present, many magnification structures are designed based on the lever magnification mechanism (Cheng et al. 2017; Lu et al. 2016) and the triangular magnification mechanism (Iqbal et al. and Pan et al. 2019; Qi et al. 2015). In this design, since the direction of the excitation force is 90° from the sliding direction of the magnets, a simple triangular amplifying structure can meet the requirements. Figure 4 shows a schematic diagram of the triangular amplifying

structure. According to the reference (Pan et al. 2019), the displacement amplification rate of this structure is obtained by the Eq. (1).

$$\lambda = \frac{B}{A} = 2 \cot \theta \tag{1}$$

From Eq. (1), it can be seen that the displacement amplification rate is only related to the angle θ , not to the size of the structure. Therefore, the displacement amplification rate can be adjusted by changing θ .

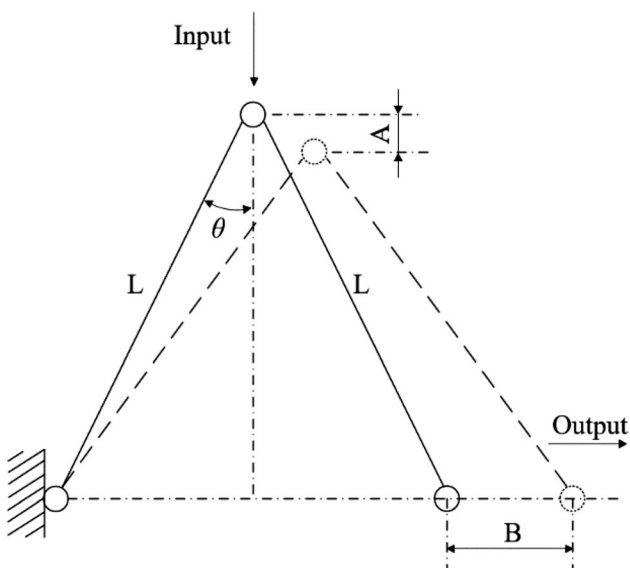


Fig. 4 Schematic diagram of the triangular amplifying structure

3 Theoretical modeling of the HVEH

The purpose of the model developed in this section is to enable a simple analytical calculation of the mechanical variables, as well as the electrical variables. A vibration energy harvester is often modeled as a mass + damper + spring system. Here, the proposed HVEH has modeled as a lumped parameter system, as shown in Fig. 5, which contains a PVEH and an EVEH.

In this basic approach, the PVEH is composed of a mass M_p , a damper of coefficient D_p , and a spring of effective stiffness K_p . For the EVEH, it contains a mass M_e , a damper of coefficient D_e , and a spring of effective stiffness K_e .

For the EVEH, the external force F results from the mechanical excitation applied to the mass M_e . The governing equation of motion for the electromagnetic system is given by Eq. (2) in which M_e is the mass of the magnets, u_1

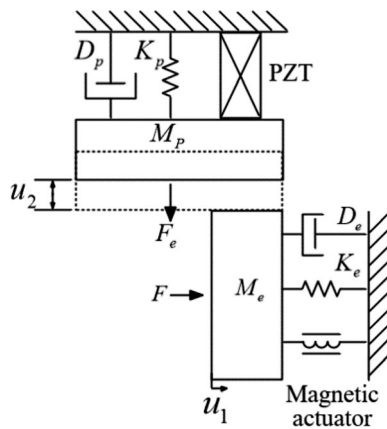


Fig. 5 Equivalent mechanical model of the proposed energy harvester

is the displacement of the magnets, β is the electromagnetic force-current factor, V_e and I_e are the load voltage and the coil current, respectively, and r and L_e are the internal resistance and inductance of the coil. These parameters are listed in Table 1. If we apply Kirchhoff’s voltage law for the electrical model of the EVEH, the voltage governing equation can be given by Eq. (3).

$$M_e \ddot{u}_1 + D_e \dot{u}_1 + K_e u_1 = F - \beta I_e \tag{2}$$

$$V_e = \beta \dot{u}_1 - r I_e - L_e \dot{I}_e \tag{3}$$

In the similar way, the governing equation of motion for PVEH is given by Eq. (4), and the current governing equation can be given by Eq. (5).

$$M_p \ddot{u}_2 + D_p \dot{u}_2 + K_p u_2 = F_e - \alpha V_p \tag{4}$$

$$I_p = \alpha \dot{u}_2 - C_p \dot{V}_p \tag{5}$$

where M_p is the modal mass of the PVEH, u_2 is the displacement of the mass M_p , F_e is the magnetic force of the permanent magnets to the tip mass of the cantilever beam, α

is the piezoelectric force-voltage factor, V_p and I_p are the piezoelectric voltage and the piezoelectric current, and C_p is the clamped capacitance of the electrical model. These symbols are summarized in Table 1.

During the energy harvesting, part of the energy is absorbed by the loads, so the amplitude of the structure is suppressed. It is assumed that the loads of the EVEH and the PVEH, are pure resistances, which are R_e and R_p , respectively. Then the electrical Eqs. (3) and (5) can be rewritten as Eqs. (6) and (7).

$$\beta \dot{u}_1 = (r + R_e) I_e + L_e \dot{I}_e \tag{6}$$

$$\alpha \dot{u}_2 = \frac{V_p}{R_p} + C_p \dot{V}_p \tag{7}$$

Performing Laplace transformation on Eqs. 6 and 7 under zero initial conditions, then the frequency domain expressions of the output current of the induction coil and the output voltage of the piezoelectric element can be derived as Eqs. (8) and (9).

$$I_e(j\omega_1) = \frac{j\omega_1 \beta}{j\omega_1 L_e + (r + R_e)} U_1(j\omega_1) \tag{8}$$

$$V_p(j\omega_2) = \frac{j\omega_2 \alpha R_p}{j\omega_2 R_p C_p + 1} U_2(j\omega_2) \tag{9}$$

where ω_1 and ω_2 are the angular frequencies of the EVEH and the PVEH, respectively. The power harvested from this device is equal to the power consumed in the load resistances R_e and R_p , as shown in Eq. (10). Therefore, the expression of the RMS power delivered by the device is given in Eqs. (11) and (12).

$$P = P_{R_e} + P_{R_p} \tag{10}$$

$$P_{R_e} = \frac{|I_e(j\omega_1)|^2 R_e}{2} = \frac{u_{M_1}^2}{2} \frac{\omega_1^2 \beta^2 R_e}{\omega_1^2 L_e^2 + (r + R_e)^2} \tag{11}$$

$$P_{R_p} = \frac{|V_p(j\omega_2)|^2}{2 R_p} = \frac{u_{M_2}^2}{2} \frac{\omega_2^2 \alpha^2 R_p}{\omega_2^2 R_p^2 C_p^2 + 1} \tag{12}$$

where u_{M_1} and u_{M_2} are the relative displacement magnitude of the magnets and the mass, respectively.

4 Prototype fabrication and experimental setup

In order to illustrate the proof of a concept, a macroscale prototype of the HVEH was fabricated, As shown in Fig. 6. The main geometric dimension of the harvester is given in Table 2. For PVEH, the copper sheet is used as the substrate to develop the beam of the prototype, the PZT was attached to the beam, and the cubic stainless steel was fixed

Table 1 Symbols and definitions

Sub-module	Symbol	Name
EVEH	M_e	Mass of the magnets
	D_e	Damping coefficient
	K_e	Spring stiffness
	β	electromagnetic force-current factor
	r	Coil resistance
	L_e	Coil inductance
PVEH	M_p	Modal mass
	D_p	Damping coefficient
	K_p	Spring stiffness
	α	piezoelectric force-voltage factor
	C_p	piezoelectric clamped capacitance

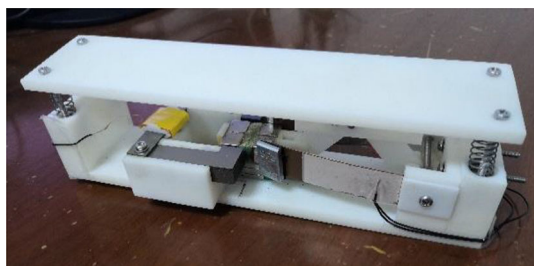


Fig. 6 Photograph of the proposed energy harvester

Table 2 Geometric parameters of the proposed energy harvester prototype

Parameters	Values
Piezo layer	$40 \times 16 \times 0.2 \text{ mm}^3$
Metal substrate	$60 \times 16 \times 0.4 \text{ mm}^3$
Mass	$16 \times 10 \times 5 \text{ mm}^3$
Coil inner dimensions	$17.22 \times 11.21 \times 3 \text{ mm}^3$
Coil outer dimensions	$17.22 \times 14.68 \times 7 \text{ mm}^3$
Magnets	$20 \times 10 \times 10 \text{ mm}^3$
Spring	$\phi 0.6 \times 9 \times 40 \times 12 \text{ N}$



Fig. 7 Photograph of the PVEH

at the tip end of the cantilever beam as the proof mass. Figure 7 The detailed fabrication of PVEH is as follows:

1. Cut the copper sheet to the size shown in Table 2, but its length dimension should be 80 mm, because the extra 20 mm part needs to be fixed on the base. After that, the copper sheet needs to be polished to remove the burrs left by cutting and the oxide film on its surface, and at the same time increase the surface roughness, so as to make the piezoelectric sheet and copper fit better.
2. Select PZT-5H piezoelectric material consistent with the required size, and wipe it to remove dust.
3. Use SINWE 6529 epoxy conductive adhesive to attach the piezoelectric sheet to the copper substrate and then cure for 24 h.
4. The steel mass block is pasted at the free end of the piezoelectric cantilever beam.

For EVEH, two pair of cubic NdFeB magnets were used to absorb the cantilever beam and change the magnetic flux of the EVEH. The magnetic field generated by the NdFeB

magnets is transmitted to the coil via a silicon steel core. The coil is made over a plastic skeleton wound an enameled copper wire of 0.05 mm, which internal resistance is 2.133 k Ω , and the inductance is 140 mH. Since silicon steel is easily attracted by magnets, it is difficult to fix it. In order to solve this problem, this paper designs a fixed base made of ABS material for the iron core, as shown in Fig. 8. In this picture, the NdFeB magnets are fixed on a slide rail to realize the movement of the magnets.

In addition, the support base, top plate, base and displacement amplifier are all made of ABS material by 3D printing. The compression spring in the designed structure is made of stainless steel with a wire diameter of 0.6 mm, its outer diameter is 9 mm, length is 40 mm, and the number of turns is 12.

In this prototype, the maximum input displacement is 7 mm, and the maximum output displacement is 14 mm, which achieves a 2 \times magnification of the input displacement.

The experimental setup for testing the fabricated prototype of the HVEH is illustrated in Fig. 9. This system consists of a Resistance Box (J15026-2), a Multimeter (UT890D +), and an Oscilloscope (Tektronix MDO3012). The experimental parameters of the HVEH are identified and given in Table 3.

5 Experimental results and discussions

In this section, a series of experiments for HVEH is performed to display the harvester's applicability. It should be mentioned that due to uncertainty factors in experiments there is a little bit deviation for measured results. For example, the external force for the harvester was exerted by human hands, so there might be some variation every time.

5.1 Single press experiments

Firstly, to characterize the performance of the HVEH, the open-circuit voltage is measured under single press experiments, as shown in Figs. 8 and 9. Figure 10a shows the test results for open-circuit voltage during one back and

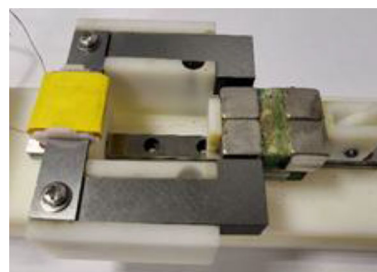


Fig. 8 Photograph of the silicon steel core

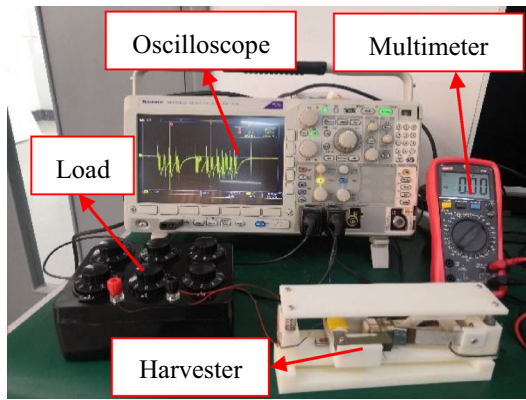


Fig. 9 Experimental setup

Table 3 Experimental parameters identification

Parameters	Values
Piezoelectric force-voltage factor, α	1.88×10^{-4} N/V
Piezoelectric clamped capacitance, C_P	90.6 nF
Electromagnetic force-current factor, β	8.075 N/A
Coil resistance, r	2.133 k Ω
Coil inductance, L_e	140 mH
Displacement of the magnets, u_{M1}	14 mm
Displacement of the beam, u_{M2}	6 mm

forth cycle, clearly demonstrating the two parts for the cantilever beam release process and the clamping process. The force exerted by hands acts on the top plate of the HVEH, causing the magnets to move forward until the cantilever beam is released. During the movement of the magnets, the PVEH generates a negative instantaneous voltage of 18 V just before the cantilever beam is released, as shown in Fig. 10a. Then, the cantilever beam is released and resonates. Due to the effect of damping, the cantilever beam finally stops vibrating.

Figure 10b shows the output voltage generated by the cantilever beam under self-excited resonance. It can be seen from Fig. 10b that the peak voltage generated after the cantilever beam is released is 20.57 V, and then gradually decreases due to the damping. 26.5 Hz. When the external force is removed, the magnets move backwards, clamping the cantilever beam again. At this time, PVEH instantly generates a positive voltage of 23.4 V. It can be found from this figure that the vibration frequency of PVEH is about 26.5 Hz, but it is actually about 38.8 Hz by COMSOL analysis, as shown in Fig. 11. This is because the PVEH is affected by the magnets' attractive force during vibration, resulting in a lower vibration frequency. Meanwhile, due to the attractive force of the magnets, the balanced position of

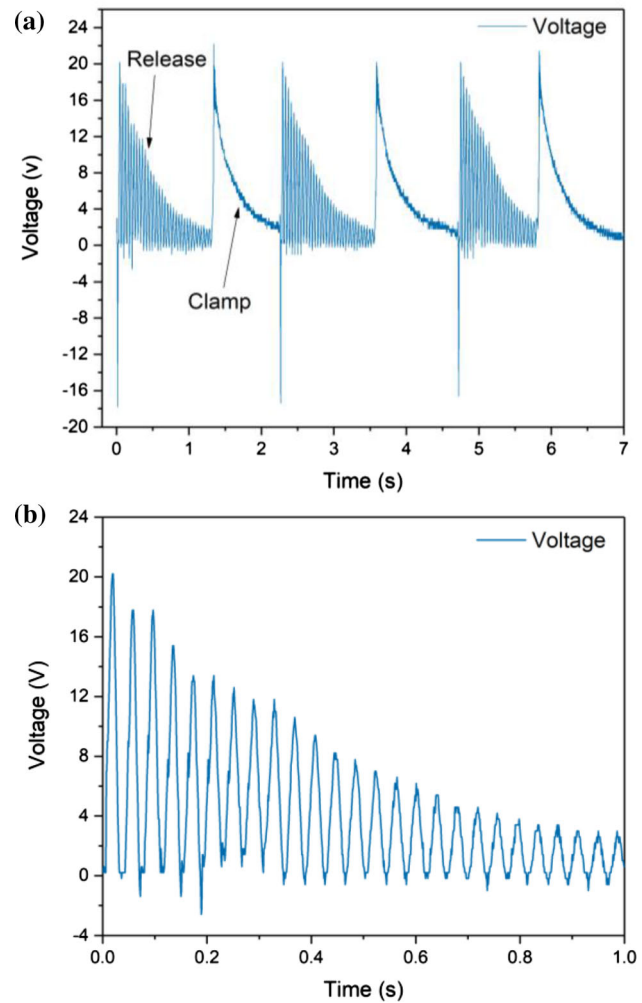


Fig. 10 Test results of the PVEH. a Time-domain test results for voltage waves during one back and forth cycle. b Time-domain test results of the generated voltage when the cantilever beam is released

Fig. 11 Eigenfrequency of the PVEH

Eigenfrequency (Hz)
38.862
284.01
368.25
997.15
1183.2
1641.1

PVEH is shifted, resulting in almost only positive values and few negative values.

Figure 12 represents the instantaneous open-circuit voltage waveforms generated by the EVEH during one back and forth cycle. As the magnets move forward, the coil generates a positive voltage of 26.7 V. When the magnets move backward, the coil generates a negative voltage of 11.3 V.

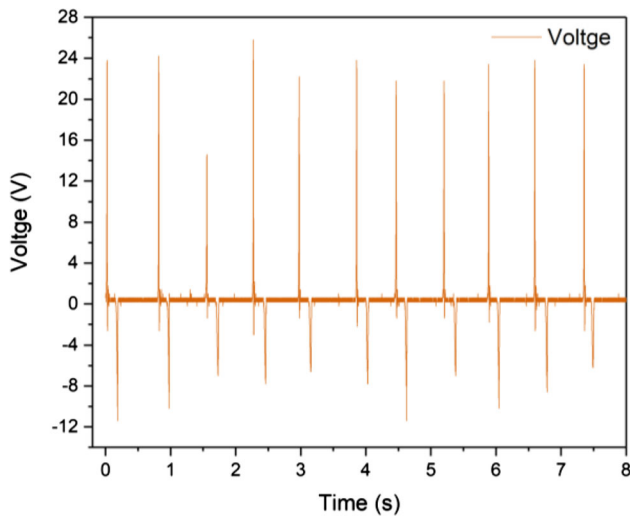


Fig. 12 Test results of the EVEH for instantaneous voltage waveforms during one back and forth cycle

5.2 Cycle experiments

Next, cycle experiments are performed on the energy harvester. The open-circuit voltage waveforms shown in Fig. 11 are obtained by exciting the energy harvester at 5 Hz. Figure 13a represents the instantaneous voltage waveforms generated by the EVEH. The maximum peak-to-peak voltage is 36.87 V. While Fig. 13b shows the instantaneous voltage waveforms generated by the PVEH. The maximum peak-to-peak voltage is 40.39 V. As can be seen that the harvested peak-to-peak voltage for these configurations has little difference, but the density of generated voltage for PVEH is higher than that for EVEH. This is because the cantilever beam of PVEH produces high-frequency vibration after release, but the excitation frequency is 5 Hz.

The HVEH generates maximum power when the internal resistance matched the load resistance. In order to characterize the output power characteristics and measure the optimum load resistance of the energy harvester, the theoretical and experimental results of the output voltage and power for the energy harvester varying the load resistance are obtained. Figure 14 shows the theoretical and experiment root mean square (RMS) voltage and average power of the EVEH in the proposed HVEH as a function of load resistance under excitation of 5 Hz. It can be seen from the Fig. 12 that the RMS voltage increased with the increase of the load resistance, and then gradually kept stable. However, as the resistance value increased, the power increased first and then decreased. The average power generated by EVEH was calculated by V_{RMS}^2/R_c , where the R_c is the load resistance. The experimental results show that the average power reached to 2.173 mW, when load resistance was 3.2 k Ω . The RMS voltage

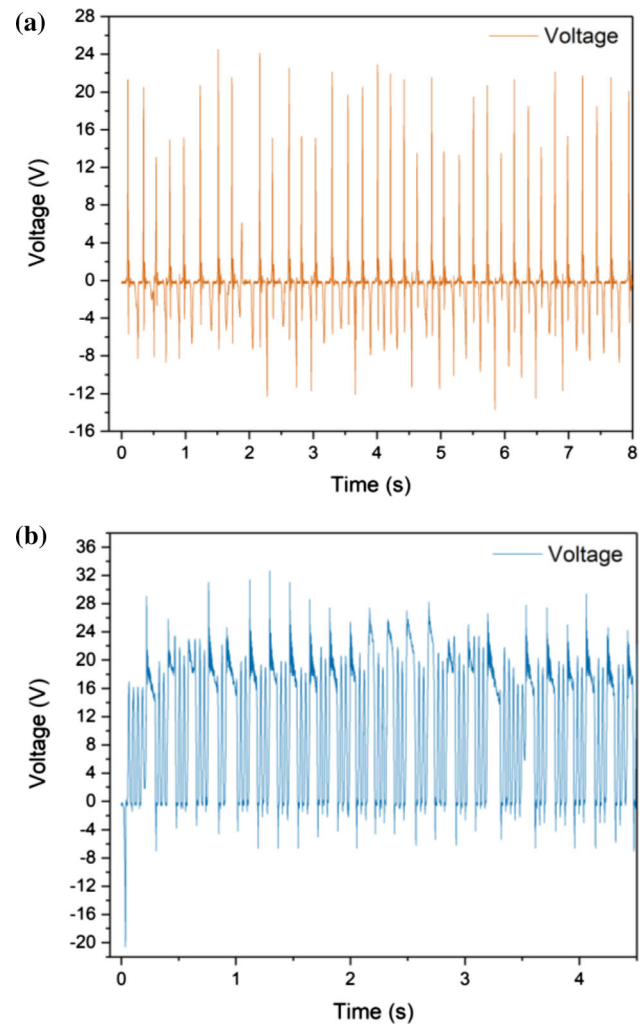


Fig. 13 Open-circuit voltage waveforms of **a** the EVEH and **b** the PVEH under excitation of 5 Hz

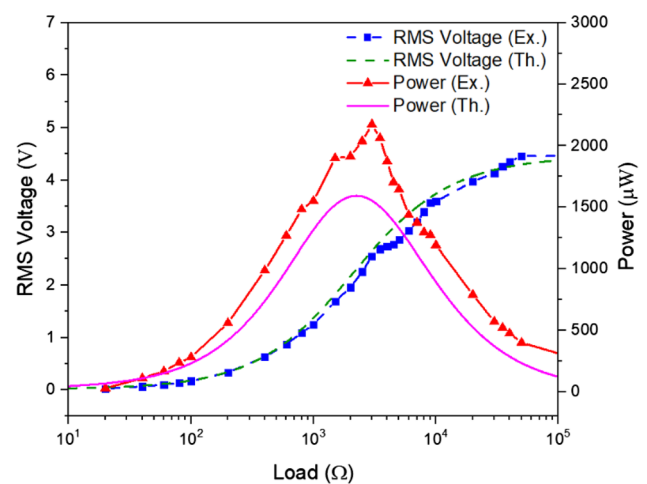


Fig. 14 Theoretical and experiment performances of the EVEH in the proposed HVEH as function of load resistance under excitation of 5 Hz

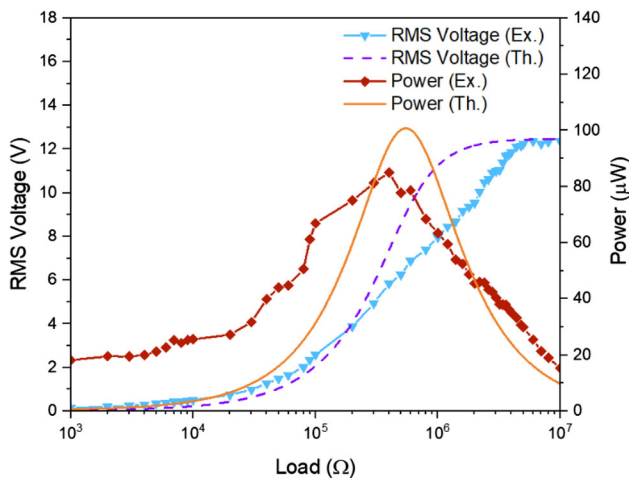


Fig. 15 Theoretical and experiment performances of the PVEH in the proposed HVEH as function of load resistance under excitation of 5 Hz

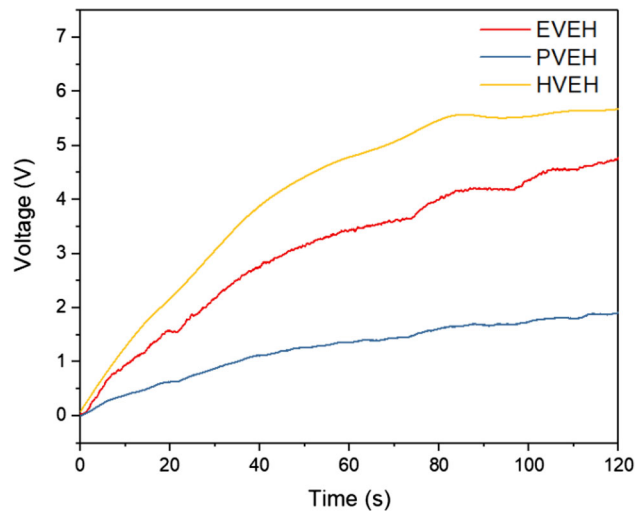


Fig. 16 The charging characteristics of EVEH, PVEH and HVEH across a 3300 µF capacitor

generated at this optimum load resistance was 2.55 V. The peak average power of theoretical results was 1.592 mW at 2.24 kΩ, and the voltage was 2.305 V. It is observed that the experimentally obtained results are basically consistent with the results predicted by simulation.

Figure 15 shows the theoretical and experimental results of the PVEH as a function of load resistance under excitation of 5 Hz. It is observed that the experimental maximum average power of 87.9 µW was approximately at the point of 398.7 kΩ. The RMS voltage was 5.92 V at this point. While the theoretical maximum average power was 100.7 µW at 547 kΩ, the corresponding RMS voltage was 9.03 V. It can be seen that the maximum average power of the theoretical simulation was larger than the maximum

average power of the experimental test. The reason for this error is the deviation in the force applied by hands and some minor factors that the model ignores, such as the influence of the magnet. After all, the results of experimental tests truly meet the expectations.

The cycle experiments of charging were conducted at 5 Hz. The AC voltage generated by the harvester was transformed to DC voltage through a full-wave rectifier. A 3300 µF capacitor was connected to the rectifier. Then the DC voltage was stored in the capacitor until the capacitance was filled up. Figure 16 shows the charging characteristics of EVEH, PVEH and HVEH across a 3300 µF capacitor. As seen that the voltage growth of the EVEH was faster than that of the PVEH in the same time. The voltage growth of the HVEH was faster than either of them, but slightly less than sum of them.

6 Conclusions

In this paper, a piezoelectric-electromagnetic hybrid vibration energy harvester operating under ultra-low frequency excitation was designed, fabricated, and tested. The proposed energy harvester had a PVEH and an EVEH in a system, and it was shown that the energy harvested by the HVEH was improved over individual energy harvester. A pair of magnets with opposite polarities realized the frequency up-conversion of the cantilever beam, enabling the energy harvester to work in an ultra-low frequency environment, and the movement of the magnets increased the magnetic flux rate in the coil, thereby increasing the output energy. The results of the single press experiments show that the PVEH generated a peak open-circuit voltage of 23.4 V during clamping and a peak voltage of 20.57 V during release. While, as the magnets moves back and forth, the EVEH generated a positive peak voltage of 26.7 V and a negative peak voltage of 11.3 V, respectively. By connecting different resistance loads, the voltage and power values were obtained from PVEH and EVEH. In the cycle experiments, the output power value of the EVEH was 2.173 mW across the resistance load of 3.2 kΩ at 5 Hz. The PVEH produced a power of 87.9 µW at the point of 398.7 kΩ. In addition, the charging characteristics of EVEH, PVEH, and HVEH across a 3300 µF capacitor show that the voltage growth of the HVEH was faster than PVEH and EVEH. It is shown that the HVEH can generate higher energy levels than that of them. The proposed energy harvester can work in an ultra-low frequency environment and can get better harvesting performance, so it has great potential applications.

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