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RESEARCH ARTICLE

Contact and Non-Contact Dual-Piezoelectric Energy Harvesting System Driven by Cantilever Vibration

LAIHU PENG[1], YUBAO QI[1], JIANTING LIU[2], YUAN SUN[1], HONGFEI ZU[1], AND XIN RU[1]
[1]Faculty of Mechanical Engineering and Automation, Zhejiang Sci-Tech University, Hangzhou 310018, China
[2]Research Institute of Zhejiang Sci-Tech University in Longgang, Wenzhou 325802, China

Corresponding author: Yubao Qi (202020601042@mails.zstu.edu.cn)

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ABSTRACT In this study, a dual-piezoelectric energy harvesting system with contact and non-contact characteristics was driven by a cantilever beam. The harvester performance of the multipoint energy harvesting system driven by cantilever-beam vibration was designed, detailed analysis and optimization strategies were developed, and its application in the security field was successfully demonstrated. Herein, we provide theoretical guidance for the design of the dual-piezoelectric energy harvesting. We designed and fabricated a prototype of the dual-piezoelectric energy harvesting. A test system was designed and constructed. The relationships among the distance and frequency of the two piezoelectric acquisition mechanisms and the open-circuit voltage were investigated. Additionally, the effects of different loads on the output power were examined. The peak power reached 10.12 mW under a gravitational acceleration of 1g. The analysis indicated that the dual-piezoelectric energy harvest device has a higher energy harvest efficiency than the single-piezoelectric energy harvest device. Owing to the multipoint harvest strategy, even if a generator suddenly deteriorates or fails, the entire system can maintain a certain power output, which is more commercially feasible. The results of this study indicate that the output of the piezoelectric energy harvesting is stable and reliable and that the output energy satisfies the requirements for a safety warning device.

INDEX TERMS Vibration, piezoelectric energy harvester, high performance, multipoint harvesting.

I. INTRODUCTION

Energy is important for human survival and development [1]. With the rapid industrialization in recent years, the problem of energy shortage has become increasingly severe. Recycling wasted energy in the use process to power the sensors of systems has become a research priority [2], [3]. In addition, the development of wireless sensors and the expectation of self-sustaining wireless sensors have promoted the investigation of various energy harvest technologies [4]. Current energy harvest methods can convert the heat energy [5], [6], human movement [7], [8], [9], and environmental vibration [10], [11], [12] generated during equipment operation into electrical energy, which plays an important role in the lightweight and self-possession of wireless sensors. Among the many energy- harvest methods, piezoelectric energy harvest devices have the characteristics of miniaturization, flexibility, low costs, and high energy densities [13], and the collected energy can be used in sensors [14], [15] and intelligent devices [16], [17]. Therefore, piezoelectric energy harvesting have become the focus of research for supplying power to wireless sensing equipment [18], [19], [20]. Piezoelectric energy based on environmental vibrations is an important method for harvesting waste energy [21], [22], [23]. This energy harvest method allows the sensor to work in harsh environments throughout the year without replacing the battery. Despite extensive research on materials, device design and application demonstrations, the average

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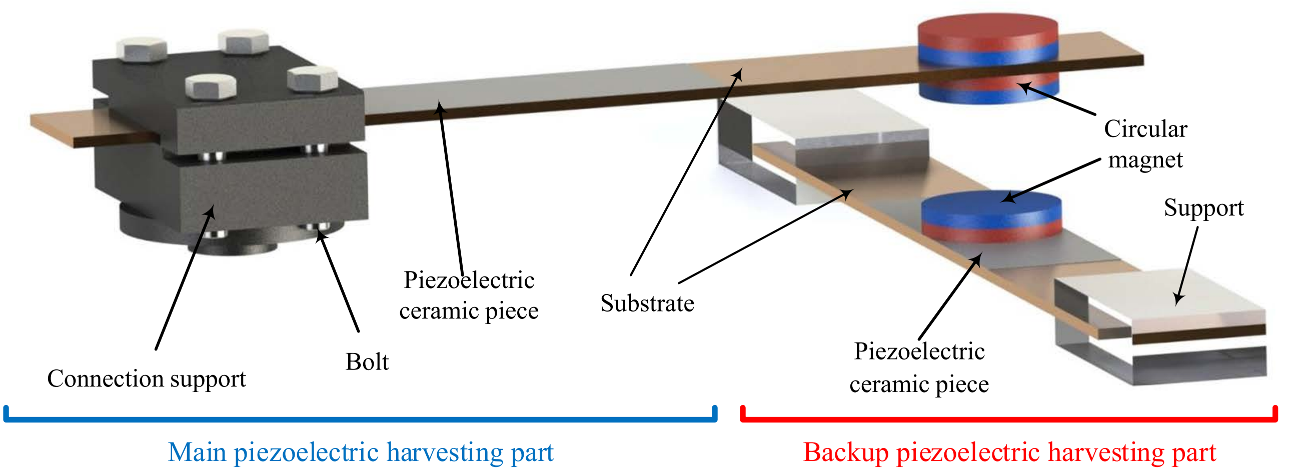


FIGURE 1. Schematic of the dual-piezoelectric energy harvester.

power of energy harvests is still severely limited in current practical applications and there is a lack of practical and effective optimization methods.

In view of the limited output power of energy harvest systems in different applications, researchers have made different types of exploration. Inki Jung, Jaehoon Choi et al. produced a system suitable for the Internet of Things (IoT) and provided an optimization strategy for the energy- harvest structure. After optimization, it achieved an average power output of 25.45 mW under vibration of 60 Hz and 0.5 g. Multimodule energy harvest ensures the basic function output even if a single module fails. This was demonstrated in a study where a hybrid energy harvest device provided power for a commercial IoT module [23]. Lipeng et al. and Da Zhao et al. designed a harvest device that can be used to collect the energy stored during idling of the inertial wheel. The energy harvest device adopts dual-module energy harvest. It consists of a beryllium bronze cantilever attached to a rectangular lead zirconate titanate (PZT) plate that directly contacts the inertia wheel to generate a power output. The circular PZT is coupled with the system under the action of magnetic repulsion to generate the power output. The peak output power can be 5.47mW and 0.05 mW, and the energy harvest efficiency can reach 18.27%. The generated energy can be supplied to an onboard sensor [24]. Bin Bao and Quan Wang designed a rainwater harvest device with a self-turning square container. When rainwater fills the water tank, the tank automatically releases rainwater and impacts the piezoelectric cantilever beam. The open-circuit voltage of the device can reach 160 V, and the researchers designed an energy harvest circuit. The multimodule energy harvest device can quickly charge a 100-μF capacitor after four working cycles to reach a saturation voltage of 3.3 V [25]. Piezoelectric energy harvest devices are suitable for various applications, such as piezoelectric windmills [26] and wearable piezoelectric systems. Machine operations, automobile driving, and human activities waste considerable amounts of energy. This energy can be collected to satisfy the requirements of sensors in machine systems [27], [28]. The energy generated without relying on an external power supply is suitable for providing backup energy for safety systems, e.g., hazard warning, self-detection, and self-protection in mechanical systems, and is also applicable to situations such as safe passage and railway transportation [29].

However, although the power output of these mechanisms has reached the MW level, the energy harvest efficiency of these vibration energy harvest devices is still low. There are three main reasons for this problem. First of all, these studies excessively pursue the harvest of energy by a certain part of the mechanism, ignoring the overall energy input of the mechanism; Secondly, there are many studies on energy harvest and optimization of coupling multiple mechanisms, but there is little research on how to collect energy and optimize energy harvest strategies for a single mechanism and multiple locations in the mechanism; Third, the research on the existence of only one generator in the device also leads to the low reliability of the energy harvest equipment. Once the generator fails, the entire equipment will be paralyzed, which is also an important reason why many energy harvest equipment do not have commercial value.

In this paper, a kind of contact and non-contact piezoelectric energy harvest driven by cantilever vibration, which is suitable for most occasions, is studied. The structure of the paper is as follows. In Section 2, we designed and optimized the structure of the dual piezoelectric energy harvest mechanism, including the protection of piezoelectric elements, the maximization of the energy harvest effect of the equipment, the optimization of the magnetic repulsion force, and the derivation of the conversion efficiency of the energy capture device. In section 3, an experimental platform and a test system are built to investigate the multipoint harvest performance of the piezoelectric energy harvest device driven by the cantilever vibration. The typical application in security field is given. Section 4 summarizes the conclusions.

After optimization, the efficiency of the energy harvest mechanism is 64.73% higher than that of the previous single point harvest mechanism. This research shows that the output of this dual piezoelectric energy harvest is stable and reliable, and the output energy meets the power requirements of some sensors.

II. MODEL OF DUAL-PIEZOELECTRIC ENERGY HARVESTER AND ENHANCEMENT STRATEGY

A. WORKING PRINCIPLE AND DESIGN REQUIREMENTS

Figure. 1 shows a schematic of the dual-piezoelectric energy harvester. The device consists of rectangular cantilever piezoelectric plate harvesting part and simple supported beam piezoelectric plate harvesting part. The cantilever piezoelectric plate vibrates after being impacted by external forces, generating an output voltage for the piezoelectric elements attached to the cantilever beam. The circular magnet attached to the cantilever beam continuously impacts the piezoelectric plates up and down in vibration, which deforms the piezoelectric plates under the action of the magnet's gravity and repulsion force and generates a voltage output. Details regarding the experimental device used in this study are presented in Table 1, including the sizes of the key parts. The base plate of the main cantilever beam was fixed on the outer support using four M5 bolts, the auxiliary beam was fixed on the outer support by clamping at both ends, and the round magnet was fixed on the cantilever beam by magnetic attraction. All the other parts were fabricated via 3D printing.

For the structural design, we mainly need to complete two basic criteria. The first is to ensure that the piezoelectric components of the structure will not be damaged during operation, and the second is that the whole system should be in the maximum energy harvest state during operation.

In order to prevent the piezoelectric element from breaking due to excessive amplitude during vibration, we check the allowable stress to protect the piezoelectric element. When the analytical model is obtained by simplifying the structural design model, the cantilever piezoelectric plate collects a partial structure, as shown in Figure. 2. By simplifying the structure, we can obtain its deflection equation as follows:

$$w_{\max} = |w| = \frac{Fl^3}{3EI} \tag{1}$$

TABLE 1. Geometry and material properties of the prototypes.

Description	Material Properties	Value
Substrate	Dimensions (mm^3)	200×25×0.5
	Dimensions (mm^3)	200×25×0.5
	Density (kg/m^3)	8300
	Young's modulus (GPa)	128
Proof mass	Dimensions (mm)	7500
	Total mass (g)	16.3
Piezoelectric element	Density (kg/m^3)	7800
	Piezoelectric constant d_{31} (10^{-12}m/V)	-190
	Young's modulus (GPa)	74
	Dimensions (mm)	72.4×25×0.1

where F represents the external impact force of the rectangular piezoelectric plate, which mainly originates from the impact caused by vibrations in the environment; w represents the deflection under the impact; l represents the distance between the impact force and the fixed end; E represents the elastic modulus; and I represents the moment of inertia.

The deflection equation of the center of the sub-voltage plate is:

$$w_{\max} = -\frac{Fb\sqrt{\left(l^2 - b^2\right)^3}}{9\sqrt{3}\, EIl} \tag{2}$$

where F represents the external impact force, which is primarily generated by the magnetic force (because the circular piezoelectric plate is a non-contact power-generation system, the friction force can be neglected); w represents the deflection at the midpoint of the circular piezoelectric plate; b represents the distance between the magnetic point of action and the fixed end; l represents the span of the auxiliary beam; E represents the elastic modulus; and I represents the moment of inertia.

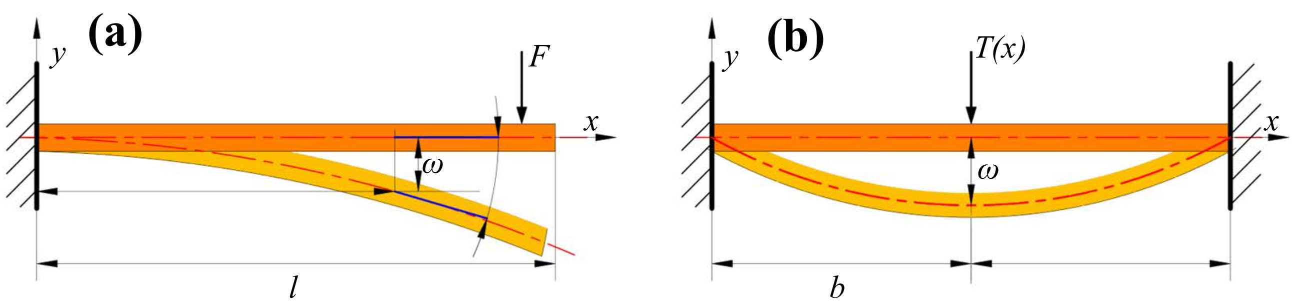


FIGURE 2. Analytical models of piezoelectric plates: (a) Main piezoelectric plate. (b) Backup piezoelectric plate.

The bending stress of the piezoelectric element on the main piezoelectric cantilever beam is given as:

$$\sigma_{\max} = \frac{M_{\max}}{W_z} = \frac{6F_s l}{bh^2} = \frac{6F_1 l}{bh^2} \tag{3}$$

where b represents the width of the cantilever beam, h represents the height of the cantilever beam, and the remaining parameters are identical to those in the deflection equation. For the overall energy harvest system, a larger deformation of the piezoelectric element corresponds to a higher output voltage and output power. To protect the piezoelectric element from damage caused by excessive deformation, it is necessary to ensure that the deformation of the piezoelectric plate is less than the yield strength of the piezoelectric element. However, the true deformation of the piezoelectric plate should be far smaller than the theoretical value owing to magnetic attraction and repulsion.

When the mechanism is in resonance state, the overall shape variable of the structure is the largest, which is most beneficial to energy harvest. The structure we designed has two generating elements, which are stuck on two beams. If two generator blades reach the resonance position at the same time, accurate design is required and high requirements for installation are required, which is very unrealistic in commercial applications. So we make the cantilever resonate, and its end hits the simply supported beam to achieve the goal of harvesting energy at two places of one mechanism. The cantilever beam is subjected to damping force, elastic force and coupling force due to piezoelectric effect in the working process of dual piezoelectric energy harvest. The dynamic equation of the mechanism can be obtained according to Newton's second law, and the circuit equation can be obtained according to Kirchhoff's first law. The motion equation of the cantilever beam is [30]:

$$\begin{cases} P(t) + \theta V_m(t) + T(x)\sin\overline{\omega}t \\ \qquad = M_m \ddot{Z}_m(\mathrm{t}) + \eta_m \dot{Z}_m(t) + K_m Z_m(t) \\ \theta \dot{Z}_m(t) = \frac{C_{mp}\dot{V}_m(t)}{2} + \frac{V_m(\mathrm{t})}{R_{Lm}} \end{cases} \tag{4}$$

where $Z_m(t)$ represents the displacement of the piezoelectric plate; $P(t)$ represents the external vibration source, To analyze the system output response, we input a sinusoidal signal to the system $P(t) = A\sin(\overline{\omega}t)$. θ represents the electromechanical coupling coefficient of PZT, and $\theta V_m(t)$ represents the coupling force generated by the piezoelectric effect; C_{mp} represents the capacitance of PZT; $T(x)$ represents the magnetic repulsive force, and M_m represents the equivalent mass of the piezoelectric plate and magnet:

$$M_m = m + \frac{33M}{140} \tag{5}$$

M represents the mass of the cantilever beam, and m represents the mass of the cantilever beam.

K_m represents the equivalent stiffness. The equivalent stiffness of the rectangular and circular piezoelectric plates can be calculated as follows:

$$K_m = \frac{F}{w} = \frac{l^3}{3EI} \tag{6}$$

$$\text{Order } \omega_m = \sqrt{\frac{K_m}{M_m}}, \quad \beta = \frac{\overline{\omega}}{\omega_m} \tag{7}$$

η represents equivalent damping:

$$\eta_m = 2M_m \xi_r \omega_m \tag{8}$$

The displacement of the solution is

$$Z_m(t) = \frac{\frac{P(t)}{K_m} + \theta V_m(t) + T(x)\sin\overline{\omega}t}{(1-\beta^2)^2 + (2\xi_r\beta)^2} \begin{bmatrix} (1-\beta^2)\sin\overline{\omega}t \\ +2\xi_r\beta\cos\overline{\omega}t \end{bmatrix} \tag{9}$$

When $\beta = 1$, that is, $\overline{\omega} = \omega_r$, the ambient vibration frequency and system resonance frequency are equal, and resonance occurs, at which time the maximum amplitude appears. In addition to changing the amplitude of the vibration induced by the external environment, reducing the damping ratio can increase the amplitude of the system and reduce the energy loss. Generally, there are two damping mechanisms: viscous air damping caused by the movement of gas molecules on the beam and strain-rate damping caused by energy dissipation inside the beam. The beam width can be reduced to improve the structural damping of the energy harvester for increasing the output power.

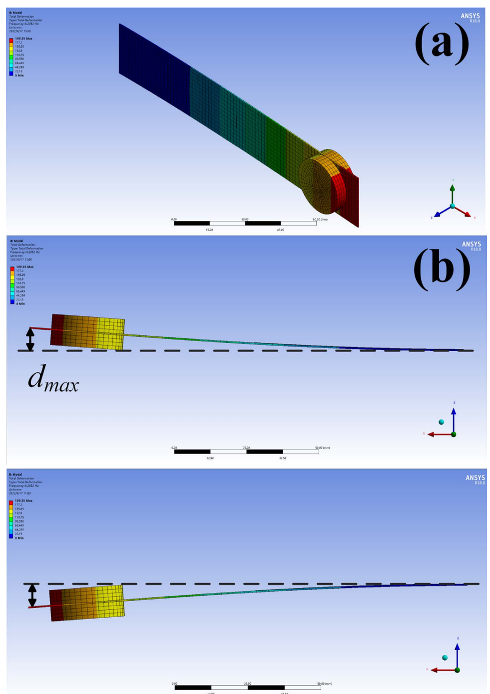


FIGURE 3. Finite element analysis results: (a) Modal analysis; (b) End displacement in first-order mode.

The energy source of the entire energy harvest mechanism mainly depends on the vibration of the main cantilever beam. The effective vibration of the main cantilever beam is the key to energy harvest. The larger the vibration, the more energy we can get. Figure 3(a) shows the shape of the first order model with the basic resonant frequency at about 8.85Hz obtained through finite element analysis, and Figure 3(b) shows that the maximum displacement of the end of the cantilever beam from the central axis reaches 43.2mm when it is in the first order mode. Therefore, in order to obtain a larger output voltage and output power, it will be easier to find this resonance point in the experiment.

B. OPTIMIZATION STRATEGY OF MAGNETIC REPULSION FORCE

There are two main points to consider when considering the magnetic repulsion force as the coupling force between two piezoelectric elements. First, the magnet can be used as the end mass to effectively reduce the resonance frequency of the cantilever beam and increase the amplitude of the vibration. Secondly, adding this non-linear force to the system can widen the working bandwidth of the structure for energy harvest.

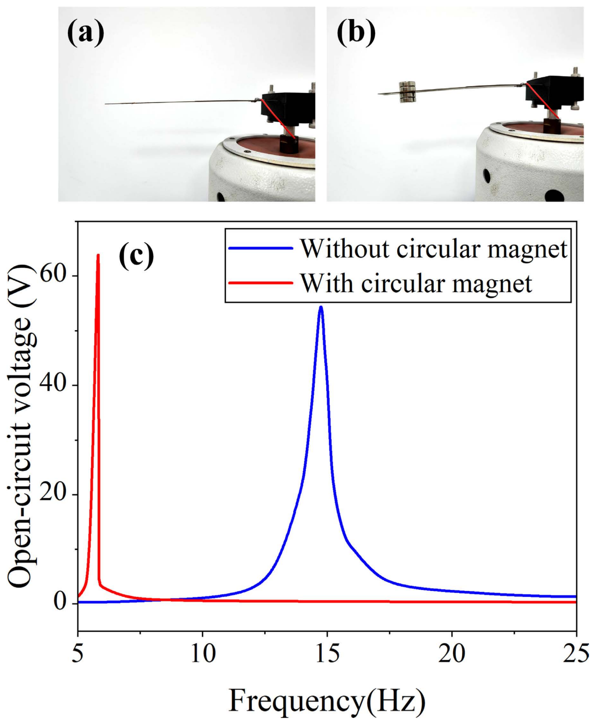


FIGURE 4. (a, b) Optical images of the oval-shaped energy harvester with and without magnetic springs. (c) Open-circuit voltages (V_{OC}) of the energy harvester with respect to the input vibration frequency.

To evaluate the effect of the magnet on the voltage generated by the vibration of the cantilever beam, as shown in Figure.4. (a) and (b), we designed two groups of experiments: 1) without magnets and 2) with magnets arranged at the end of the cantilever beam. Figure.4. (c) shows the results of open-circuit voltage measurements at a constant acceleration of 1g. The amplitude changed with respect to the input frequency. After introducing magnets at the end of the cantilever beam, we observed that the resonant frequency of the cantilever beam decreased significantly from 14.8 to 5.82 Hz, while the maximum output voltage increased from 54.8 to 64 V. The experimental results indicated that the introduction of a circular magnet structure reduces the resonance frequency of the cantilever mechanism and increases its vibration amplitude, increasing the stress on the piezoelectric layer and the open-circuit output voltage. Hereinafter, the cantilever-beam harvester without magnets is referred to as the ''single-piezoelectric harvester'' to distinguish it from the dual-piezoelectric harvester.

In the structure we designed, the coupling of the two piezoelectric harvests depends on the magnetic repulsion force, so the magnitude of the magnetic repulsion force affects the energy harvest performance of the structure. According to the Gilbert model, the forces between two cylindrical magnets of radius R and length L can be approximated as follows [31]:

$$T(x) \approx \frac{\pi \mu_0}{4} M^2 R^4 [\frac{1}{x^2} + \frac{1}{(x+2L)^2} + \frac{2}{(x+L)^2}] \quad (10)$$

where μ_0 represents the vacuum permeability, M represents the magnetization, x represents the distance between the two magnets, and R represents the magnet radius. As shown in Figure.5, a shorter distance corresponds to a stronger interaction force between the springs; therefore, a circular magnet can generate sufficient pressure to press on the piezoelectric element to produce an output. The graph indicates that the magnetic repulsion force varies nonlinearly with respect to the distance, and a shorter distance between the two magnets corresponds to a larger absolute value of the first derivative of the distance–force relationship line, i.e., a stronger force between them. However, in this energy harvest mechanism, a distance that is too short leads to a reduction in the amplitude of the main cantilever-beam vibration, reducing the output power.

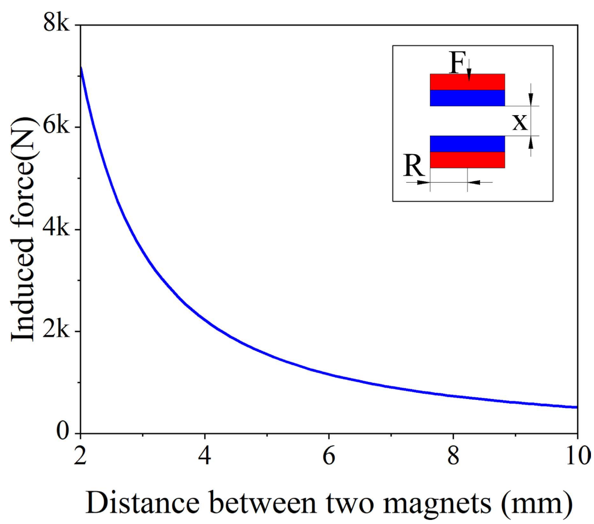


FIGURE 5. Magnetic interaction force between two cylindrical magnets according to the distance.

C. ENERGY CONVERSION EFFICIENCY

In the whole energy harvest system, the external impact on the main piezoelectric cantilever is the only source of external energy for the system. The shocks received are stored in the system in the form of potential energy. In this process, the potential energy stored in the place of maximum deformation of the cantilever beam is equal to the energy input into the system:

$$E_{in} = W(w_{\max}) \tag{11}$$

The energy obtained by the piezoelectric cantilever beam is affected by three potential forces during its motion: repulsion force F, elastic recovery force Kz (t), and gravity M. When z=0 is taken, the total potential energy of the piezoelectric cantilever equals zero, then when a=1, the total potential energy of the piezoelectric cantilever is:

$$\begin{aligned} W\left(w_{\max}\right) &= \int_0^{w_{\max}} K_m w dw + \int_0^{w_{\max}} M_m g dw - \int_0^{w_{\max}} T dw \\ &= \frac{1}{2} K_{eq} w_{\max}^2 + M_m g w_{\max} - T w_{\max} \end{aligned} \tag{12}$$

For the energy obtained, we get by formula 1:

$$E_{out} = \int_0^{t} (P_1 + P_2) dt \tag{13}$$

P1 is the power of the main piezoelectric plate and P2 is the power of the simply supported beam. The output expressions of P1 and P2 can be obtained by numerical fitting after the experiment. The expression of output efficiency is:

$$\gamma = \frac{E_{out}}{E_{in}} \tag{14}$$

The output efficiency of the structure is calculated. This is an important basis for us to verify whether the energy harvest equipment has been improved.

III. RESULTS AND DISCUSSION

Contact and non-contact dual-piezoelectric energy harvester driven by cantilever-beam vibration were tested under the driving conditions shown in Figure.7. (a) and (b). In the experiment, the energy harvester were tested at different frequencies to determine the voltage and output power. Figure.6. shows the experimental setup for a dual-piezoelectric harvester with contact and non-contact dual-piezoelectric energy harvester driven by cantilever-beam vibration. The experimental system mainly included a piezoelectric energy harvester, an oscilloscope (Keysight MSO9404A), a vibration exciter (TV51120-M), a signal transmitter (VICTOR 2015H), a power amplifier (BAA 500), and a PC terminal. The output voltage and output power of a single-cantilever beam energy harvester were also evaluated for comparison, to identify the advantages and disadvantages of the multipoint piezoelectric energy harvester.

A. OUTPUT ENERGY CHARACTERISTICS OF ENERGY-HARVEST SYSTEM

Figure.7. (c) and (d) show the relationship between the main and auxiliary piezoelectric plates and the open-circuit voltage at different frequencies and distances. The peak output voltages of the main and auxiliary piezoelectric plates indicate that the maximum open-circuit voltage of the piezoelectric system increased nonlinearly with a reduction in the distance between the two plates in the dual-piezoelectric system. At each distance, the open-circuit voltage increased steadily and then decreased rapidly after reaching the resonance frequency. The piezoelectric system exhibited the peak output voltage at a distance of 40 mm and a frequency of 8.5 Hz. The peak voltage of the main piezoelectric plate was 43.67 V, and that of the secondary piezoelectric plate was 17.27 V. As shown in Figure.7, before the peak voltage was reached, the deformation of the piezoelectric plate increased with the frequency. After the peak voltage was reached, the deformation of the piezoelectric plate decreased owing to the increase in the vibration frequency. Therefore, the optimal distance of the piezoelectric element was 40 mm, and the optimal response frequency was 8.5 Hz.

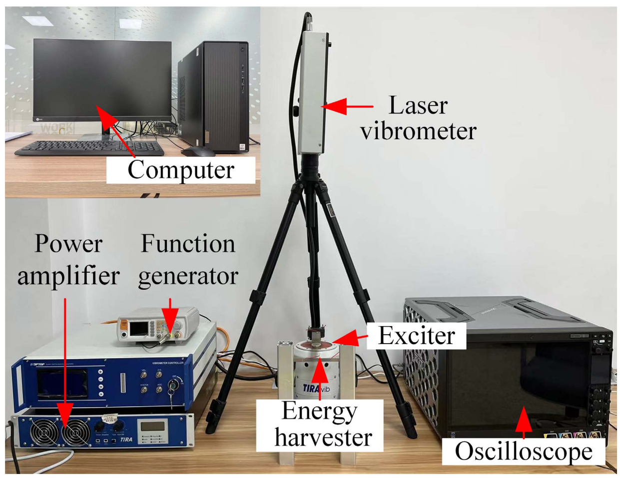


FIGURE 6. Experimental setup used to determine the open-circuit voltage of the energy harvester.

The experimental results indicated that a piezoelectric vibration frequency closer to the natural frequency corresponded to a higher output voltage of the piezoelectric energy harvester. The piezoelectric energy harvester exhibited the highest output efficiency at a test frequency of 8.5 Hz and a distance of 40 mm. Therefore, at a distance of 40 mm, the frequency of 8.5 Hz was close to the natural frequency of the piezoelectric element, and the input frequency matched the piezoelectric energy harvester.

Both types of piezoelectric plates exhibited large peaks. Generally, Their output voltage all went up first and then down. According to the model analysis, the deformation of the main piezoelectric plate was the largest when the driving frequency was close to the natural frequency. Under the combined action of resonance and gravity, the secondary

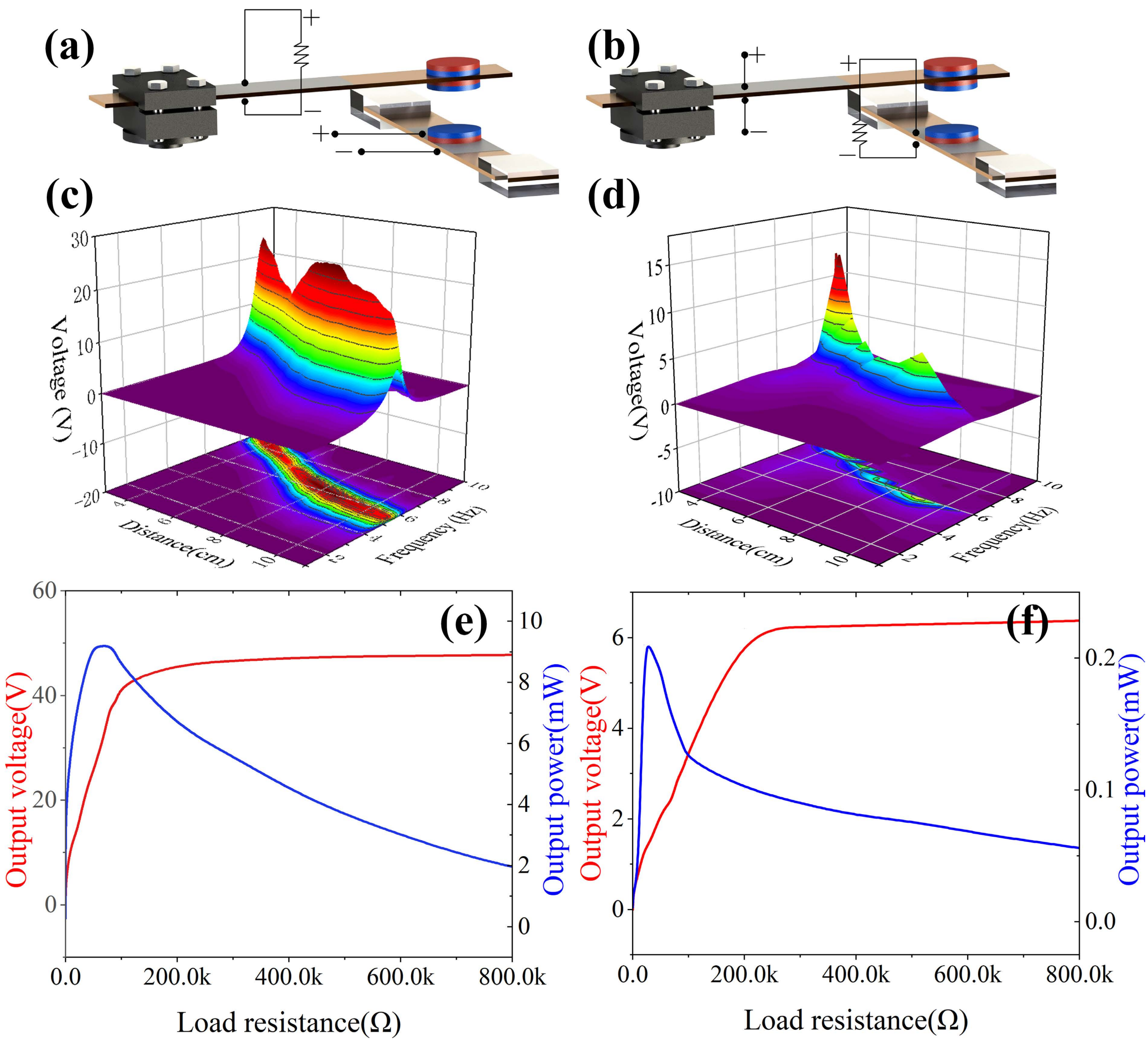


FIGURE 7. (a, b) Circuit configurations employed for measuring the electrical outputs of individual energy harvester. (c) Output voltage of the main cantilever energy harvest mechanism at different frequencies and distances under circuit configuration (a). (d) Output voltage of auxiliary cantilever energy harvest mechanism at different frequencies and distances under circuit configuration (b). (e) Output voltage and power of the main cantilever with respect to the load resistance. (f) Output voltage and power of the auxiliary cantilever with respect to the load resistance.

piezoelectric plate was affected by the magnetic repulsion force generated by the magnet when vibration occurred.

Thus, the electricity generation rapidly increased. In this piezoelectric energy harvester, the output voltage of the main piezoelectric plate was higher than that of the secondary piezoelectric plate at different frequencies. The reasons for this are as follows. First, the effective PZT area of the main voltage layer was 1800 mm^2, and that of the secondary voltage layer was 1500 mm^2. Second, the energy of the energy harvester was affected by the manner in which the piezoelectric plates are fixed. The power generated by the cantilever-fixed mode exceeds that generated by the two-end support mode. Third, the impact force provided by the magnetic force was in indirect contact, whereas the main piezoelectric plate was in direct contact, and the conversion efficiency was higher than that of the secondary piezoelectric plate. To maximize the output frequency, we connected a single-cantilever beam and hybrid dual-piezoelectric system to the load to investigate the output characteristics of the energy harvest system. Figure.7. (e) and (f) show the dual-piezoelectric system, at a constant frequency of 8.5 Hz, the RMS voltages of the main and secondary voltage plates gradually increased with the increasing load resistance. The maximum RMS voltages of the main and secondary plates were 47.67 and 6.42 V, respectively, and the optimal load resistances were 70 and 30 kΩ, respectively. The voltage of the load resistor was measured, and the effective voltage increased as the resistance voltage increased. The power was calculated from the available voltage using the formula P=U^2/R. The RMS power increased to a high value. For the dual piezoelectric system, the peak values of the RMS power were 9.19 and 0.21 mW, were reached at 70 and 30 kΩ, respectively.

B. SINGLE- AND DUAL-PIEZOELECTRIC SENSORS

In practical applications, the amplitudes of the vibration and acceleration of energy harvest devices are often limited. We limited the amplitude of the energy harvest devices and reduced the acceleration to 0.5g. The aforementioned methods were used to perform experiments and compare the output power levels of the single- and double-piezoelectric energy harvest systems. We found that the dual-piezoelectric energy harvest system did not cause a simple increase in the single-energy output point (Figure.8.). When the single-cantilever beam and dual-piezoelectric systems operated, the energy harvester generated an average power of 2.22 and 3.64 mW, respectively, under fixed input conditions. However, under the respective matching impedance, the total output power of the cantilever beam in the dual-piezoelectric system increased to 3.65 mW, and the total output power of the sub-piezoelectric system was 0.19 and 3.46 mW. The energy harvest enhancement rate of the dual-piezoelectric system compared with the single-cantilever beam system was 64.73%, clearly indicating the benefits of the optimized dual-piezoelectric system. The foregoing results indicate that two different energy harvest points in the same system can optimize the load impedance and that there is a ''coupling effect'' between the two energy harvest points, similar to the coupling observed in energy harvest via different mechanisms.

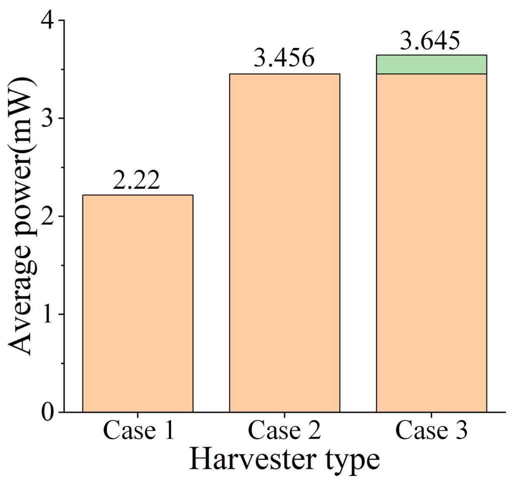


FIGURE 8. Output-power comparison. Case 1: Output power of single piezoelectric energy harvest system. Case 2: Output power of main cantilever in dual piezoelectric energy harvest system. Case 3: Output power of dual piezoelectric energy harvest system.

As shown in Figure 9, the relationship between the power and time of the energy harvest system, we use the numerical fitting method to obtain the expression of the power output of the single piezoelectric system in Figure 9 (a):

$$P_0 = 2.07 - \frac{1.064}{1 + e^{\frac{t-10.41}{0.34}}} \tag{15}$$

Fig. 9 (b) Expression of power output of dual piezoelectric system:

$$P = 3.37 - \frac{2.39}{1 + e^{\frac{t-11.6}{0.87}}} \tag{16}$$

By introducing Equations (15) and (16) into Equation (14), it is found that the efficiency of the traditional harvest mechanism is 14.8%, while the efficiency of the dual piezoelectric energy harvest equipment is 18.9%. It is much higher than the traditional energy harvest mechanism. From the perspective of energy conversion, the energy contained in environmental vibration is stored in the form of potential energy by the beam structure. Piezoelectric elements are attached to the beam to convert the bending deformation of the beam into electrical energy.

According to the piezoelectric formula, the deformation of piezoelectric elements is the main reason for generating electric charges. In traditional single piezoelectric systems, the input energy is only stored in a cantilever beam, and these systems have only one degree of freedom and simple structure. The dual piezoelectric structure proposed in this paper stores the input energy in two sets of subsystems. The high degree of freedom of storage can collect the energy that is difficult to store, greatly improving the conversion efficiency of effective energy.

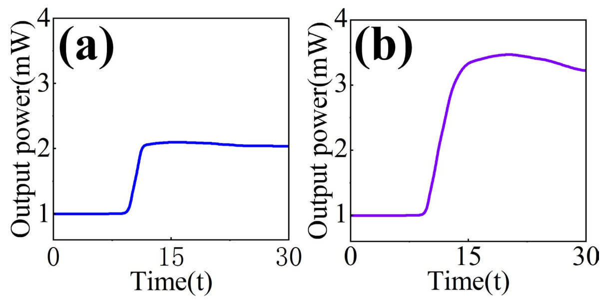


FIGURE 9. (a) Relationship between power output and time of single piezoelectric system. (b) Relationship between power output and time of dual piezoelectric system.

C. APPLICATION OF ENERGY HARVESTER FOR SAFETY WARNING

The frequency range of vibration in rail transit engineering is 0.5–25 Hz. The proposed energy harvest device has a good power harvest effect at 8.5 Hz and can be used to collect the energy generated by rail transit vibration. As shown in Figure.10.(a), the vibration generated during high-speed railway driving provides the basic input for the energy- harvest device, which converts the vibration energy into electrical energy to supply energy for the safety warning device. A standard harvest circuit was used for rectification and energy storage. The circuit in Figure.10.(b) shows that the piezoelectric energy harvester can be approximately modeled as a current source with an instantaneous current and parallel internal capacitance. When the PZT is bent, the generated instantaneous current charges the internal load and potential

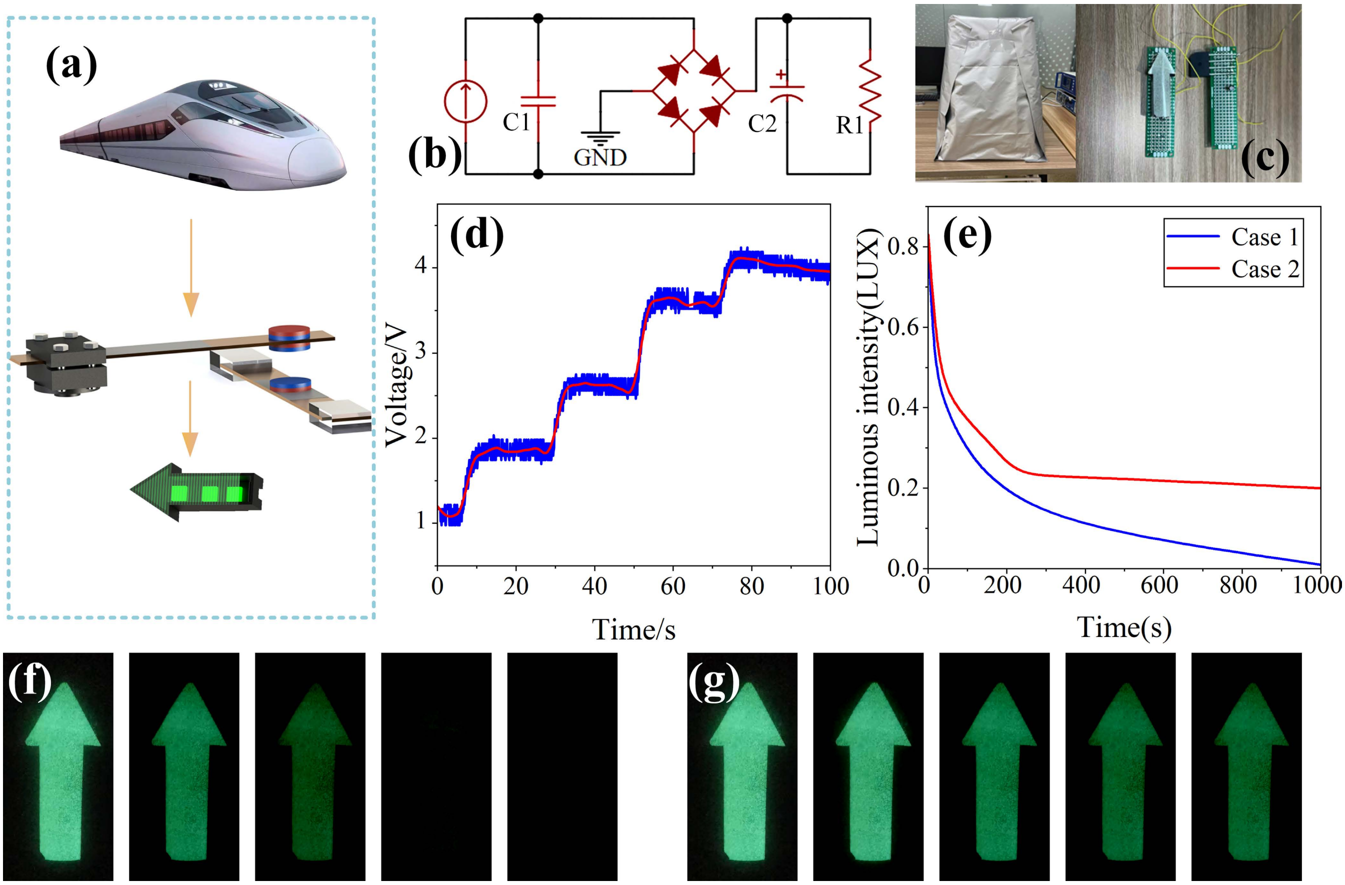


FIGURE 10. (a) Excite the excitation cantilever beam to supply energy to the safety warning device. (b) Standard energy-harvesting circuit. (c) Darkroom used for the experiment (left); experimental circuit and safety sign (right). (d) Open-circuit voltage signal generated by toggling four times. (e) Safety-sign brightness change curve. Case 1: The process of the safety indicator light going out naturally (f) Darkness variation of the non-energy harvest system. (g) Darkness variation of the energy harvest system.

external load, generates voltage at the output end, is connected to the harvest circuit for rectification, and is connected to the load through a filter capacitor. To better fit the environmental vibration and emulate random vibration generated by human activities, it was demonstrated that the input vibration and acceleration due to finger flicking could supply power to commercial light-emitting diodes (LEDs). As shown in Figure.10.(d), each flick of the finger increased the voltage at both ends of the capacitor by 0.74 V; the output voltage waveform increased in a stepwise manner, and the LED tube emitted light stably during the vibration process. The light emitted by the LED was stored by a phosphor light-storage mechanism to obtain visible light with longer luminous time. To provide long-term vibration, we demonstrated that the power supply for the safety channel led to identification under an input vibration of 8.5 Hz and an acceleration of 0.5g.

The safety channel module was successfully operated. Figure.10.(c) shows the energy harvest and load circuit used to test the sensor, the self-built safety channel warning signs, and the black box used in the experiment. The experimental setup also included an energy harvest module and a light meter.

To demonstrate the process of reducing the luminous intensity of a safe passage from 0.83 to 0.23 LUX and maintaining it under vibration, the phosphor was placed under light conditions to fully absorb light and placed in a darkroom. As shown in Figure.10.(e), the light intensity of the phosphor decreased rapidly in the early stage, and the decrease gradually slowed in the later stage. Overall, it exhibited the trend of an inverse proportional function. For the safety sign made of phosphor, after it absorbed light for a period of time under the condition of 862 LUX, the light intensity reached the peak value of 0.83 LUX and quickly decreased to 0 within 10 min. The safety mark of the energy- harvest device was 0.83 LUX at the beginning. The light-intensity degradation rate was obviously reduced, and the light intensity remained at approximately 0.23 LUX. If there is a large impact, the light intensity can be immediately restored to 0.8 LUX. As shown in Figure.10.(f) and (g), the light-storage module matched with the energy harvest device always maintained the visible level of the human eye, indicating its effectiveness for safety warning. The vibration of the main cantilever beam provided most of the energy required for LED lighting, and the auxiliary cantilever beam also contributed a small part of the supply as backup energy. Owing to the rational use of phosphor light-storage mechanisms in the structural design, there is no need to worry about overcharging or not charging for a long time. These faint lights undoubtedly provide a good indication to people in complete darkness. The successful operation of the sensor module indicates that the piezoelectric energy-harvest device with a sufficient power output and optimized design can supply power to safety equipment and reduce the use of batteries (or even eliminate the need for batteries). For applications requiring fluorescent identification, the energy-harvest device can theoretically extend its luminous time indefinitely to operate continuously for several years.

IV. CONCLUSION

We designed and demonstrated contact and non-contact dual-piezoelectric energy harvesters driven by cantilever vibration. Our work mainly has the following contributions:

(1) We used the spring–mass–damper model to theoretically design the system and provided design guidance for multipoint energy harvester in mechanical structures. Optimizing the energy harvester includes finding the best resonance point and optimizing the matching impedance to achieve the best power output and potentially improve the durability.

(2) Compared with the traditional energy harvest mechanism, the efficiency of the energy harvest device proposed by us is increased by 64.73% and the energy conversion rate is 18.9%. When multiple power-generation locations exist in the system, multiple power-generation mechanisms can provide a better energy harvest effect than a single mechanism.

(3) The model and design guidelines established in this study are general and applicable to multiple energy harvest systems. The peak power of the dual-energy harvest device can reach 10.05 mW under a gravitational acceleration of 1g at a frequency of 8.5 Hz.

The results of this study indicated that the output of the piezoelectric energy harvester is stable and reliable and that the output energy satisfies the power requirements of some sensors. We demonstrated the process of using a dual-piezoelectric energy harvest mechanism to supply power to commercial LEDs and create safety signs. Even after the rectifier and AC/DC conversion circuit, we could effectively improve the brightness of the fluorescent safety signs; 350 s after the beginning of the experiment, the brightness was enhanced by $>130\%$. The proposed energy harvester is expected to be applied in next-generation security equipment, provide a self-sustainable power supply for some equipment, and play a vital role in unattended and hostile environments.

REFERENCES

[1] J. Han, J. Hu, Y. Yang, Z. Wang, S. X. Wang, and J. He, "A nonintrusive power supply design for self-powered sensor networks in the smart grid by scavenging energy from AC power line," *IEEE Trans. Ind. Electron.*, vol. 62, no. 7, pp. 4398–4407, Jul. 2015, doi: 10.1109/TIE.2014.2383992.

[2] J. Y. Cho, J. Kim, K.-B. Kim, C. H. Ryu, W. Hwang, T. H. Lee, and T. H. Sung, "Significant power enhancement method of magneto-piezoelectric energy harvester through directional optimization of magnetization for autonomous IIoT platform," *Appl. Energy*, vol. 254, Nov. 2019, Art. no. 113710, doi: 10.1016/j.apenergy.2019.113710.

[3] I. Jung, J. Choi, H.-J. Park, T.-G. Lee, S. Nahm, H.-C. Song, S. Kim, and C.-Y. Kang, "Design principles for coupled piezoelectric and electromagnetic hybrid energy harvesters for autonomous sensor systems," *Nano Energy*, vol. 75, Sep. 2020, Art. no. 104921, doi: 10.1016/j.nanoen.2020.104921.

[4] K. Fan, S. Liu, H. Liu, Y. Zhu, W. Wang, and D. Zhang, "Scavenging energy from ultra-low frequency mechanical excitations through a bi-directional hybrid energy harvester," *Appl. Energy*, vol. 216, pp. 8–20, Apr. 2018.

[5] A. Nammari, L. Caskey, J. Negrete, and H. Bardaweel, "Fabrication and characterization of non-resonant magneto-mechanical low-frequency vibration energy harvester," *Mech. Syst. Signal Process.*, vol. 102, pp. 298–311, Mar. 2018, doi: 10.1016/j.ymssp.2017.09.036.

[6] J. Boughaleb, A. Arnaud, P. J. Cottinet, S. Monfray, P. Gelenne, P. Kermel, S. Quenard, F. Boeuf, D. Guyomar, and T. Skotnicki, "Thermal modeling and optimization of a thermally matched energy harvester," *Smart Mater. Struct.*, vol. 24, no. 8, Aug. 2015, Art. no. 085025, doi: 10.1088/0964-1726/24/8/085025.

[7] M. Pozzi, "Magnetic plucking of piezoelectric bimorphs for a wearable energy harvester," *Smart Mater. Struct.*, vol. 25, no. 4, Mar. 2016, Art. no. 045008, doi: 10.1088/0964-1726/25/4/045008.

[8] M. B. Khan, D. H. Kim, J. H. Han, H. Saif, H. Lee, Y. Lee, M. Kim, E. Jang, S. K. Hong, D. J. Joe, T.-I. Lee, T.-S. Kim, K. J. Lee, and Y. Lee, "Performance improvement of flexible piezoelectric energy harvester for irregular human motion with energy extraction enhancement circuit," *Nano Energy*, vol. 58, pp. 211–219, Apr. 2019, doi: 10.1016/j.nanoen.2019.01.049.

[9] Y. Bai, P. Tofel, Z. Hadas, J. Smilek, P. Losak, P. Skarvada, and R. Macku, "Investigation of a cantilever structured piezoelectric energy harvester used for wearable devices with random vibration input," *Mech. Syst. Signal Process.*, vol. 106, pp. 303–318, Jun. 2018, doi: 10.1016/j.ymssp.2018.01.006.

[10] W. Hwang, K.-B. Kim, J. Y. Cho, C. H. Yang, J. H. Kim, G. J. Song, Y. Song, D. H. Jeon, J. H. Ahn, S. Do Hong, J. Kim, T. H. Lee, J. Y. Choi, H. Cheong, and T. H. Sung, "Watts-level road-compatible piezoelectric energy harvester for a self-powered temperature monitoring system on an actual roadway," *Appl. Energy*, vol. 243, pp. 313–320, Jun. 2019, doi: 10.1016/j.apenergy.2019.03.122.

[11] Y.-H. Shin, I. Jung, M.-S. Noh, J. H. Kim, J.-Y. Choi, S. Kim, and C.-Y. Kang, "Piezoelectric polymer-based roadway energy harvesting via displacement amplification module," *Appl. Energy*, vol. 216, pp. 741–750, Apr. 2018, doi: 10.1016/j.apenergy.2018.02.074.

[12] I. Jung, Y.-H. Shin, S. Kim, J.-Y. Choi, and C.-Y. Kang, "Flexible piezoelectric polymer-based energy harvesting system for roadway applications," *Appl. Energy*, vol. 197, pp. 222–229, Jul. 2017, doi: 10.1016/j.apenergy.2017.04.020.

[13] K. A. Cook-Chennault, N. Thambi, and A. M. Sastry, "Powering MEMS portable devices—A review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems," *Smart Mater. Struct.*, vol. 17, no. 4, Aug. 2008, Art. no. 043001, doi: 10.1088/0964-1726/17/4/043001.

[14] G.-T. Hwang, Y. Kim, J.-H. Lee, S. Oh, C. K. Jeong, D. Y. Park, J. Ryu, H. Kwon, S.-G. Lee, B. Joung, D. Kim, and K. J. Lee, "Self-powered deep brain stimulation via a flexible PIMNT energy harvester," *Energy Environ. Sci.*, vol. 8, no. 9, pp. 2677–2684, 2015, doi: 10.1039/c5ee01593f.

[15] Z. Li, J. Luo, S. Xie, L. Xin, H. Guo, H. Pu, P. Yin, Z. Xu, D. Zhang, Y. Peng, Z. Yang, and H. Naguib, "Instantaneous peak 2.1 W-level hybrid energy harvesting from human motions for self-charging battery-powered electronics," *Nano Energy*, vol. 81, Mar. 2021, Art. no. 105629, doi: 10.1016/j.nanoen.2020.105629.

[16] Z. Yang, S. Zhou, J. Zu, and D. Inman, "High-performance piezoelectric energy harvesters and their applications," *Joule*, vol. 2, no. 4, pp. 642–697, 2018, doi: 10.1016/j.joule.2018.03.011.

[17] S. D. Hong, K.-B. Kim, W. Hwang, Y. S. Song, J. Y. Cho, S. Y. Jeong, J. H. Ahn, G.-H. Kim, H. Cheong, and T. H. Sung, "Enhanced energy-generation performance of a landfilled road-capable piezoelectric harvester to scavenge energy from passing vehicles," *Energy Convers. Manage.*, vol. 215, Jul. 2020, Art. no. 112900, doi: 10.1016/j.enconman.2020.112900.

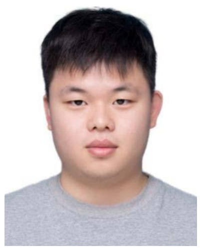
[18] E. Dechant, F. Fedulov, D. V. Chashin, L. Y. Fetisov, Y. K. Fetisov, and M. Shamonin, "Low-frequency, broadband vibration energy harvester using coupled oscillators and frequency up-conversion by mechanical stoppers," *Smart Mater. Struct.*, vol. 26, no. 6, May 2017, Art. no. 065021, doi: 10.1088/1361-665X/aa6e92.
[19] K. Fan, D. Wei, Y. Zhang, P. Wang, K. Tao, and R. Yang, "A whirligig-inspired intermittent-contact triboelectric nanogenerator for efficient low-frequency vibration energy harvesting," *Nano Energy*, vol. 90, Dec. 2021, Art. no. 106576, doi: 10.1016/j.nanoen.2021.106576.
[20] K. Fan, J. Chang, W. Pedrycz, Z. Liu, and Y. Zhu, "A nonlinear piezoelectric energy harvester for various mechanical motions," *Appl. Phys. Lett.*, vol. 106, no. 22, Jun. 2015, Art. no. 223902, doi: 10.1063/1.4922212.
[21] M. A. Halim, S. Khym, and J. Y. Park, "Frequency up-converted wide bandwidth piezoelectric energy harvester using mechanical impact," *J. Appl. Phys.*, vol. 114, no. 4, Jul. 2013, Art. no. 044902, doi: 10.1063/1.4816249.
[22] L. Xiong, L. Tang, and B. R. Mace, "Internal resonance with commensurability induced by an auxiliary oscillator for broadband energy harvesting," *Appl. Phys. Lett.*, vol. 108, no. 20, May 2016, Art. no. 203901, doi: 10.1063/1.4949557.
[23] R. M. Toyabur, M. Salauddin, H. Cho, and J. Y. Park, "A multimodal hybrid energy harvester based on piezoelectric-electromagnetic mechanisms for low-frequency ambient vibrations," *Energy Convers. Manage.*, vol. 168, pp. 454–466, Jul. 2018, doi: 10.1016/j.enconman.2018.05.018.
[24] L. He, D. Zhao, W. Li, X. Wu, and G. Cheng, "A dual piezoelectric energy harvester with contact and non-contact driven by inertial wheel," *Mech. Syst. Signal Process.*, vol. 146, Jan. 2021, Art. no. 106994, doi: 10.1016/j.ymssp.2020.106994.
[25] B. Bao and Q. Wang, "A rain energy harvester using a self-release tank," *Mech. Syst. Signal Process.*, vol. 147, Jan. 2021, Art. no. 107099, doi: 10.1016/j.ymssp.2020.107099.
[26] H. T. Luong and N. S. Goo, "Use of a magnetic force exciter to vibrate a piezocomposite generating element in a small-scale windmill," *Smart Mater. Struct.*, vol. 21, no. 2, Feb. 2012, Art. no. 025017, doi: 10.1088/0964-1726/21/2/025017.
[27] P. Pillatsch, E. M. Yeatman, and A. S. Holmes, "Magnetic plucking of piezoelectric beams for frequency up-converting energy harvesters," *Smart Mater. Struct.*, vol. 23, no. 2, Feb. 2014, Art. no. 025009, doi: 10.1088/0964-1726/23/2/025009.
[28] R. Ramezanpour, H. Nahvi, and S. Ziaei-Rad, "Electromechanical behavior of a pendulum-based piezoelectric frequency up-converting energy harvester," *J. Sound Vib.*, vol. 370, pp. 280–305, May 2016, doi: 10.1016/j.jsv.2016.01.052.
[29] T. Xue and S. Roundy, "On magnetic plucking configurations for frequency up-converting mechanical energy harvesters," *Sens. Actuators A, Phys.*, vol. 253, pp. 101–111, Jan. 2017, doi: 10.1016/j.sna.2016.11.030.
[30] H. Liu, D. Chen, L. Li, and B. Li, "Vibration response and research of energy harvesting of the piezoelectric cantilever," in *Proc. 2nd Int. Conf.*, Colombo, Sri Lanka, Jan. 2016, pp. 695–701, doi: 10.1007/978-3-319-31854-7_65.
[31] D. Vokoun, M. Beleggia, L. Heller, and P. Šittner, "Magnetostatic interactions and forces between cylindrical permanent magnets," *J. Magnetism Magn. Mater.*, vol. 321, no. 22, pp. 3758–3763, Nov. 2009, doi: 10.1016/j.jmmm.2009.07.030.

LAIHU PENG received the B.E., M.E., and Ph.D. degrees from Zhejiang Sci-Tech University, China, in 2005, 2008, and 2018, respectively, all in mechanical engineering.

Since 2008, he has been an Associate Professor with the Modern Textile Equipment Research and Development Center, College of Mechanical and Automatic Control, Zhejiang Sci-Tech University. His research interests include intelligent knitting equipment control, intelligent manufacturing and industrial Internet standardization, and intelligent instruments and meters.

YUBAO QI received the B.E. degree in mechanical engineering from Zhejiang Sci-Tech University, China, in 2020. His research interests include material and mechatronics.

JIANTING LIU received the B.E. degree in mechanical engineering from Zhejiang Sci-Tech University, China, in 2020. His research interests include material and mechatronics.



YUAN SUN received the B.E. degree in mechanical engineering from Zhejiang Sci-Tech University, China, in 2021. His research interests include material and mechatronics.

HONGFEI ZU received the B.E. and M.E. degrees in telecom from Xi 'an Jiaotong University, China, and the Ph.D. degree in mechanical engineering from the University of Pittsburgh, USA. His research interests include robot performance detection and calibration, piezoelectric sensors, and intelligent detection.

XIN RU received the B.E. degree in automation and the Ph.D. degree in mechanical engineering from Zhejiang Sci-Tech University, China, in 2012 and 2018, respectively.

Since 2018, she has been a Lecturer with the College of Mechanical and Automatic Control, Zhejiang Sci-Tech University. Her research interests include textile digitization, and intelligent and intelligent textile manufacturing.