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Piezoelectric energy harvester for rolling bearings with capability of self-powered condition monitoring

Liufeng Zhang, Feibin Zhang, Zhaoye Qin*, Qinkai Han, Tianyang Wang, Fulei Chu

State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing, China

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ABSTRACT

Rotational energy harvesting for powering low-power electronic devices and wireless sensors has attracted increasing attention in recent years. This paper proposes an energy harvester to scavenge rotational energy from rotating machines by installing an arc-shaped piezoelectric sheet between the outer race of rolling bearing and bearing pedestal. The proposed piezoelectric energy harvester cannot only supply power to sensors but also has the capability of bearing fault detection. The structural design and working principle are initially demonstrated, where an electromechanical coupling model is developed to explain the working principle of energy harvester. Then, a prototype of the energy harvester is fabricated and mounted on a rotor test rig, on which experiments are carried out to evaluate the output performance of energy harvester. The effects of rotating speed, rotor weight, shaft span and matched resistances on energy harvester performance are comprehensively evaluated. It is revealed that a single piezoelectric section of the energy harvester can generate RMS voltage of 25 V, and RMS power of 60–131 μW under the rotating speed range from 600 to 1200 r/min. Finally, the applications of the proposed energy harvester for bearing fault detection and self-powered wireless sensing are demonstrated to manifest its capability of bearing condition monitoring.

1. Introduction

Wireless sensor networks are becoming increasingly attractive in condition monitoring of rotating machines owing to the advantages such as low cost, simple installation, inherent intelligent-processing capability, flexible networking [1,2]. However, power supplies are a serious constraint for the development of wireless sensor networks due to the limited lifetime of batteries, the requirement of regular replacement or recharging, and the pollution to nature environment [3–6]. As an alternative to conventional batteries, energy harvesting from ambient energy, including wind energy, solar energy, thermal energy and vibration energy, to generate electricity has been found to be an effective solution in industrial production [7,8], agricultural production [9–11] and daily life [12,13]. To achieve self-powered wireless sensor networks for long-term condition monitoring in rotating environments, rotational energy harvesting has attracted sustainable research interest in recent years [14–18]. The dominant transduction mechanisms for rotational energy harvesting are piezoelectric [19–22], electromagnetic [23,24], and electrostatic [25,26] mechanisms. Their advantages and drawbacks were discussed in detail in Refs. [27,28]. Compared with the other two methods, piezoelectric conversion has received much attention owing to its simplicity in structure, high power density and high conversion efficiency.

Various types of piezoelectric energy harvesters scavenging rotational energy have been developed. Most of them utilize rotating motion of disks to generate electric energy via resonant cantilever beams excited either by inertial force or magnetic loads [29–34]. Although it is inspiring to find in recently published literature [35] that a piezoelectric energy harvester mounted on a rotating disk successfully supplied power to wireless sensors and realized real-time monitoring of rotating components, the commonly used beam-type piezoelectric energy harvesters are subjected to alternative bending stress, and work at resonant states to achieve high power outputs, which tend to cause fatigue failure of energy harvesters. Besides, beam-type piezoelectric energy

* Corresponding author.
E-mail address: qinzy@mail.tsinghua.edu.cn (Z. Qin).

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harvesters usually require proof masses to get high response amplitudes and low resonant frequencies. The proof masses attached to energy harvesting beams will bring imbalance to rotating machines, which is quite undesirable for high-performance rotating machines with high rotating speeds. Hence, there is still a long distance from practical application of such beam-type energy harvesters in rotating machines.

Apart from rotating disks and shafts, where energy harvesters are usually mounted, rolling bearings involving both rotating and non-rotating parts are another desired source for energy harvesting. Besides, as critical supporting components, the state of rolling bearings directly determines the health and remaining lifetime of rotating machines. Hence, condition monitoring of rolling bearings is highly demanded for rotating machines. However, compared with rotating disks and shafts, research on energy harvesting from rolling motion of rolling bearings are relatively little. Zhang et al. [36] proposed a circular Halbach electromagnetic energy harvester to collect rotational energy from rolling bearings, where magnets and coils were attached to the end cover and cage of bearing, respectively. By utilizing the mechanism of in-plane charge separation in rotation mode, self-powered triboelectric rolling bearings were also developed, which were capable of detecting variations of rotating speed [37–39]. The aforementioned studies are good attempts to harvest rotational energy from rolling bearings and develop self-powered condition monitoring systems. However, electromagnetic energy harvesters require large space to install both stationary and rotating parts, which is difficult to satisfy due to the compact layout of bearings. As for triboelectric rolling bearings, the rolling elements have to be non-metallic to generate electricity based on triboelectric effect and electrostatic induction. Those issues place severe constraints on the application of electromagnetic energy harvesters and triboelectric nanogenerators for harvesting rotational energy from rolling bearings.

In this paper, a piezoelectric energy harvester is proposed by installing an arc-shaped piezoelectric sheet between the outer race of rolling bearing and bearing pedestal. By cutting the electrode layer of the piezoelectric sheet into several conductive sections along the central line, the quasi-constant compressive load generated by rotating components is converted into fluctuating compressive loads on these conductive sections, which are then transduced into electrical energy, as the rolling elements roll along the raceway of out race during normal operation of rotating machines. To demonstrate the working principle of the proposed energy harvester, an electromechanical coupling model is developed. Then, experiments are conducted on a rotor test rig to investigate the output performance of the energy harvester under different rotating speeds, rotor weights, shaft spans and matched resistances. Defective rolling bearings are employed to replace the health one in the experiments to evaluate the fault detecting capability of the proposed energy harvester. Finally, a self-powered wireless sensor system is set up to acquire and transmit the vibration signals from rolling bearings.

In the proposed energy harvester, the piezoelectric sheet is always subjected to compressive load, which guarantees long lifespan of the energy harvester. Moreover, the installation of piezoelectric sheet has no effect on the assembling relations and working state of rolling bearing. Those features of the proposed energy harvester allow its application in long-term condition monitoring for rotating machines.

2. Concept, design and fabrication

2.1. Structural design

A rolling bearing consists of four basic parts: outer race, inner race, rolling elements and cage, where the inner race is fixed to and rotates with shaft, and the outer race is installed into bearing pedestal and remains stationary. Separated evenly by cage, rolling elements roll between the inner and outer races and transmit load from rotating shaft to pedestal. Considering weight-dominant case, the load transmitted to pedestal are mainly gravity force of rotating components and applied on the lower part of pedestal. Apart from gravity force, unbalance force is another loading source rotating about with the shaft, which affects the performance of energy harvester.

Fig. 1 shows the schematic diagram of the proposed piezoelectric energy harvester, where the cage is neglected for simplicity. It is composed of rolling bearing, pedestal, arc-shaped piezoelectric sheet, and insulation layer. Considering the load distribution on pedestal in weight-dominant case, only one piece of arc-shaped piezoelectric sheet is installed on the lower part of pedestal, where reliable fits among the outer race of bearing, piezoelectric sheet with insulation layer, and lower part of pedestal are required to guarantee that the installation of piezoelectric sheet has no effect on the performance of rolling bearing. During normal operation of rotating machines, a distributed load of approximately constant

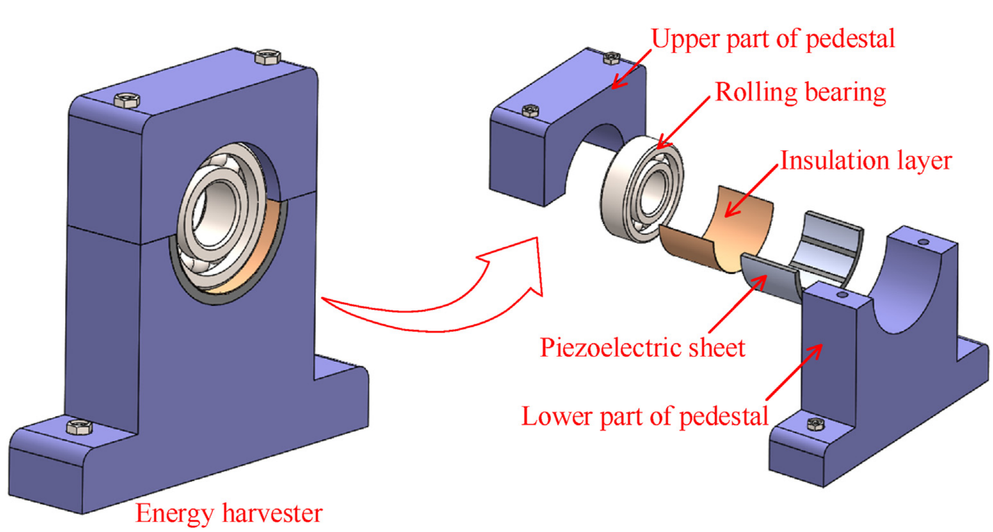

Fig. 1. Structural design of the proposed energy harvester.

value caused by gravity force of rotating components is applied to the piezoelectric sheet, which will lead to very little or even no output power. To overcome this issue and achieve desired output performance of the energy harvester, the electrode layer of piezoelectric sheet is cut into several conductive sections along the central line. Then, the constant compressive load applied onto the whole piezoelectric sheet is converted into fluctuating compressive loads acting on each conductive section by ingeniously utilizing the rolling motion of rolling elements. Each conductive section is capable of transducing rotational energy into electric energy.

2.2. Working principle

Taking one rolling element and a single conductive section as an example, the working principle of the proposed energy harvester is explained in detail. The process of a rolling element passing by the conductive section is illustrated in Fig. 2. Assuming a distributed constant load is applied to the inner race of rolling bearing. The load is transmitted to the outer race by rolling elements, which, in turn, is applied to the conductive section. Initially, the rolling element is out of the region of conductive section as shown in Fig. 2 (a). In this case, the compressive load acting on the section increases gradually as the rolling element rolls close. When the rolling element enters the region of conductive section, the compressive load increase significantly, which leads to an obvious peak of output voltage as illustrated in Fig. 2 (b). The compressive load together with output voltage of the conductive section decreases to relatively low state as the rolling element leaves the section region. The aforementioned variations of load and output voltage repeat as different rolling elements pass by the section, which results in stable output of the energy harvester. Following this working principle, the kinetic energy scavenged by the proposed energy harvester is generated by rolling motion of rolling elements, which is completely wasted energy for rotating machines.

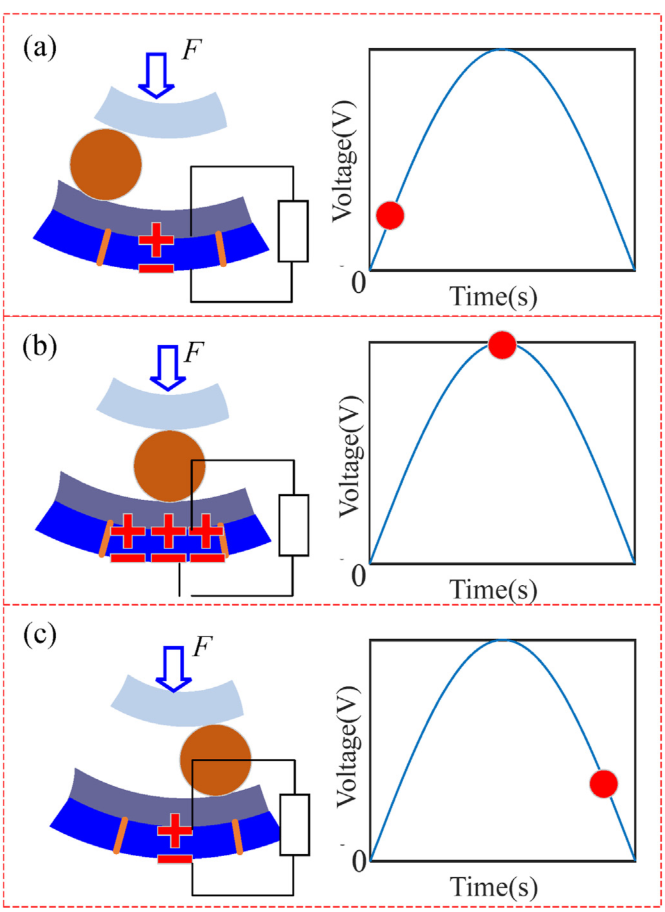

Fig. 2. Schematic working principle of the proposed energy harvester.

It is worth noting that as rolling elements roll along the raceway of out race, the magnitude of normal contact force between rolling elements and outer race generated by gravity force of rotating components varies in accordance with the angular location of rolling elements. The maximum loading condition occurs when the rolling elements locate exactly below the central axis of rotating shaft. Correspondingly, the piezoelectric section symmetric about the central axis generates the maximum output voltage, and the output voltage decreases for those piezoelectric sections away from the point below the central axis. In the following studies, the conductive piezoelectric section exactly below the central axis is investigated.

For better understanding the working principle and design optimization of the proposed energy harvester, an electromechanical coupling model is established. The maximum normal contact force Q between a single rolling element and the outer race resulting from gravity force F_g of rotating components can be expressed as [40].

$$Q = \frac{5}{z} F_g \tag{1}$$

where z is the number of rolling elements.

As mentioned above, the normal contact force between rolling elements and outer race varies as rolling elements roll along the raceway of out race. Assuming that the contact force caused by gravity force of rotating components is a cosine function of the angular position of rolling elements, the normal contact force on a rolling element caused by gravity force of rotating components can be expressed as [41].

$$F_1 = Q\cos(\omega_1 t) \tag{2}$$

where ω_1 is the pass frequency of outer race. Note that only gravity force is considered when demonstrating the working principle of energy harvester. However, mass unbalance is inevitable in real rotating machines. The contact force due to unbalance force is given by

$$F_2 = F_e\cos(\omega_2 t) \tag{3}$$

where ω_2 is the rotating angular frequency of shaft, F_e is the amplitude of unbalance force. Apart from F_1 and F_2, there is another component of contact force F_r acting on rolling elements resulting from the preload applied to the rolling bearing when assembled with the pedestal. Hence, the total normal contact force between a single rolling element and the outer race is

$$F = F_r + F_1 + F_2 \tag{4}$$

Here it is assumed that the normal load applied by a single rolling element on the conductive piezoelectric section is equal to the contact force F between the rolling element and the outer ring.

In the proposed energy harvester, the piezoelectric sheet works in D33 model, and its simplified direct piezoelectric effect equations can be expressed as:

$$\begin{aligned} S_3(t) &= s_{33}^D T_3(t) + g_{33} D_3(t) \\ E_3(t) &= -g_{33}(t) T_3(t) + \beta_{33}^T D_3(t) \end{aligned} \tag{5}$$

$$g_{33} = d_{33} \Big/ \varepsilon_{33}^{T} \tag{6}$$

$$\beta_{33}^{T} = 1 \Big/ \varepsilon_{33}^{T} \tag{7}$$

where, S_3 is strain, g_{33} is voltage constant, ε_{33}^T is dielectric constant, s_{33}^D is elastic compliance coefficient, β_{33}^T is dielectric induction coefficient, E_3 is electric field intensity, $T_3(t)$ is stress and D_3 is the electric displacement vector. Combining Eqs. (4)–(6), the output voltage u_o is obtained as

$$u_o = E_3(t)h = -g_{33}(t)h\frac{F}{A} + \beta_{33}^{T} h D_3(t) \tag{8}$$

where

$$\beta_{33}^{T} h D_3(t) = \frac{h}{\varepsilon_{33}^{T} A} A D_3(t) = \frac{F(t)}{C_p} \tag{9}$$

According to Electric displacement vector Gauss theorem, we get

$$D_3(t) = \frac{F(t)}{A} = \frac{1}{A}\int i_o dt = \frac{1}{A}\int \frac{u_o}{R} dt \tag{10}$$

Substituting Eq. (10) into Eq. (8) yields

$$u_o = E_3(t)h = -g_{33}(t)\frac{hF}{A} + \beta_{33}^{T}\frac{h}{A}\int \frac{u_o}{R} dt \tag{11}$$

By solving Eq. (11), the output voltage of one conductive section of the proposed energy harvester can be achieved as

$$u_o = \frac{Q g_{33} h \omega_1 R}{\sqrt{(A\omega_1 R)^2 + \left(\beta_{33}^{T} h\right)^2}} \cos(\omega_1 t + \phi_1) + \frac{F_e g_{33} h \omega_2 R}{\sqrt{(A\omega_2 R)^2 + \left(\beta_{33}^{T} h\right)^2}} \cos(\omega_2 t + \phi_2) \tag{12}$$

Adopting the electromechanical coupling model given in Eq. (12), the output voltage of a single conductive section of energy harvester is illustrated in Fig. 3. It can be observed that the output voltage contains two frequency components caused by rolling element pass with angular frequency of ω_1 and unbalanced force with rotating angular frequency of ω_2, respectively. The first peak in Fig. 3(b) corresponds to the rotating frequency of shaft, and the second one the pass frequency of rolling elements. As for the peak values, they depend on the magnitude of gravity force and unbalance force. In the case of weight dominance as assumed in this study, the peak resulting from rolling element pass is higher than that excited by unbalance force as shown in Fig. 3(b). However, the response amplitude due to unbalance force will be amplified along with the increase of rotating frequency; whereas, that caused by gravity force of rotating components remain constant for different rotating frequency. It is worth noting that beside the two main frequency components, more components will appear in the output signals measured from rotor experiments due to environmental noise and disturbance.

2.3. Experimental setup

The prototype of the proposed energy harvester is fabricated and mounted on the machinery fault simulator shown in Fig. 4, where the rotor involves one disc with the diameter of 152 mm and thickness of 16 mm mounted at the mid span of a shaft with the span of 455 mm and diameter of 16 mm, and the shaft is supported by two 6204 rolling bearings. The right pedestal is replaced by the energy harvester to harvest rotational motion energy through supported rolling bearing. Correspondingly, the dimensions of arc-shaped piezoelectric sheet in this prototype of energy harvester are determined according to the size of the rolling bearing and pedestal. To be specific, an arc-shaped piezoelectric sheet made by PZT-5H with the inner and outer diameters, height and subtended angle of 47 mm, 50.2 mm, 10 mm, and 90°, respectively, is used here. The piezoelectric sheet is equally cut into three conductive sections, namely sections I, II and III, and placed between rolling bearing and lower part of pedestal and exactly below the central axis of shaft. With this symmetric arrangement, section II in the middle generate the highest output power, and sections I and III have equal outputs, which are lower than that of section II. In the experiments, the outputs of section II measured by an electrometer are analyzed. The picture of experimental setup is illustrated in Fig. 5.

Note that the weight-dominant case is considered in this study. To minimize the effect of unbalance force, the rotating speed of machinery fault simulator is set to be far away from its critical speeds. The 1st critical speed of machinery fault simulator is 3486 r/min, that is, 58.1 Hz. Therefore, during the experiments, the rotating frequency ranges from 5 Hz to 25 Hz, with 15 Hz chosen as the baseline value of rotating frequency.

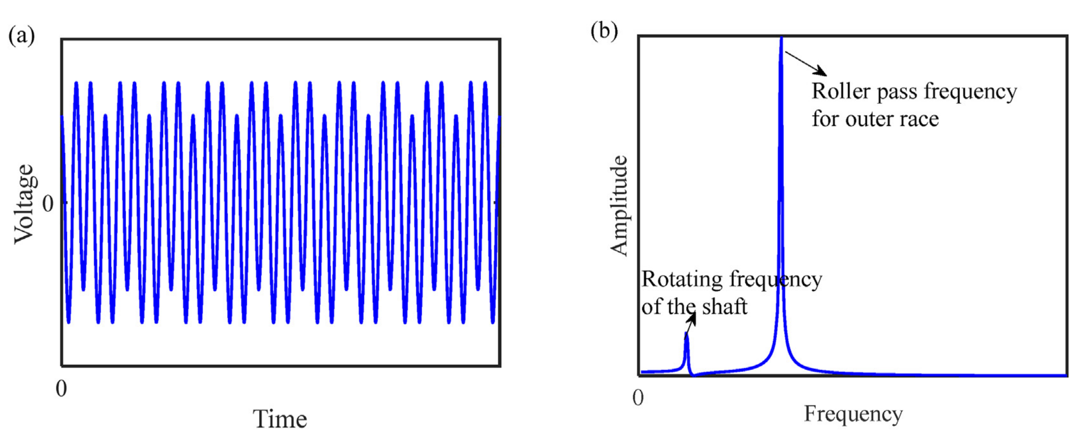

Fig. 3. Schematic of output voltage of energy harvester in (a) time domain and (b) frequency domain.

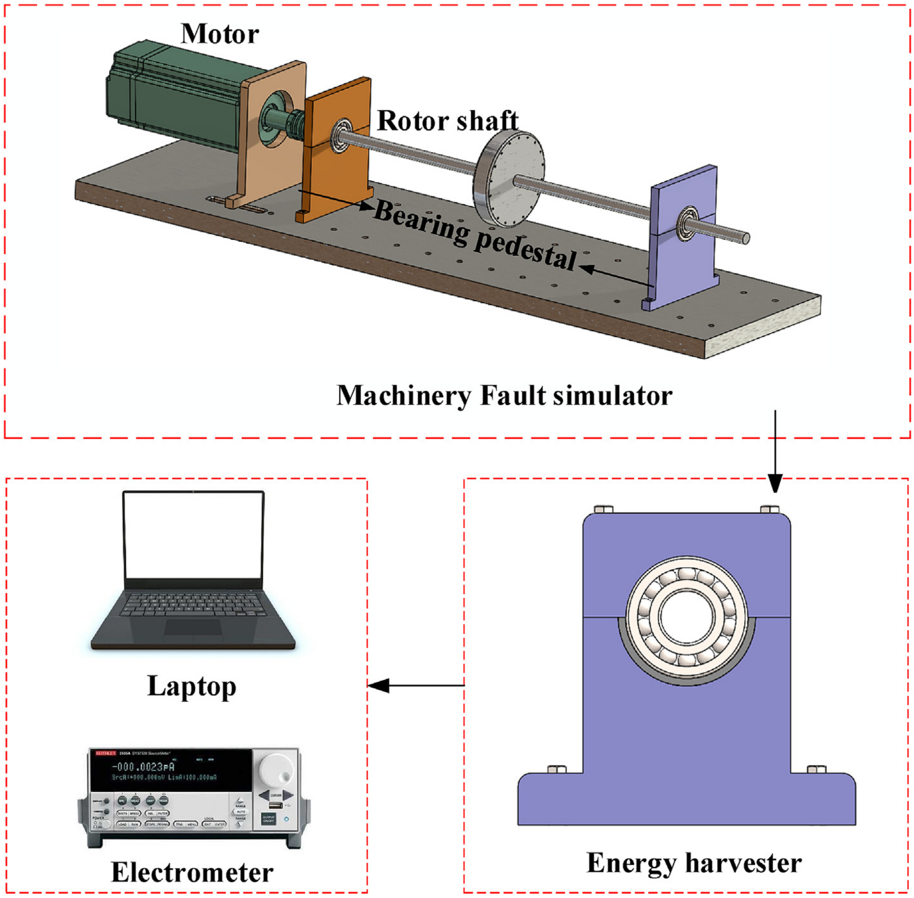

Fig. 4. Schematic diagram of the experimental device.

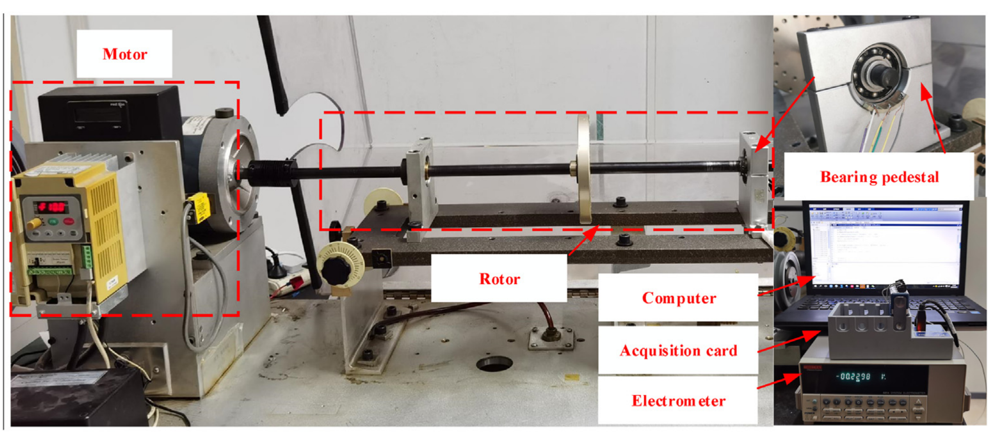

Fig. 5. Experimental setup.

3. Results and discussion

A series of experiments are carried out to evaluate the performance of the proposed energy harvester, where the effects of rotating frequency, rotor weight, shaft span and external resistance are evaluated. With the baseline values of dimension parameters given in Section 2.2, the output voltage of energy harvester in time domain is shown in Fig. 6, where it can be seen that the peak-to-peak output voltage of a single conductive section of energy harvester can reach 100 V. Fig. 7 illustrates the output voltage in frequency domain, where the highest peak is associated with the rolling element pass frequency of outer race caused by rolling elements passing through section II. Apart from the main peak, another relatively small but obvious peak at the shaft rotating frequency of 15 Hz is also observed. As pointed out in Section 2.2, this peak results from mass unbalance on the rotating shaft and disc. There are also some other peaks in the spectrum in Fig. 7, which are multiples and modulations of rotating frequency. Compared with the one caused by pass of rolling elements, those peaks are quite small. It is worth noting that the rolling element

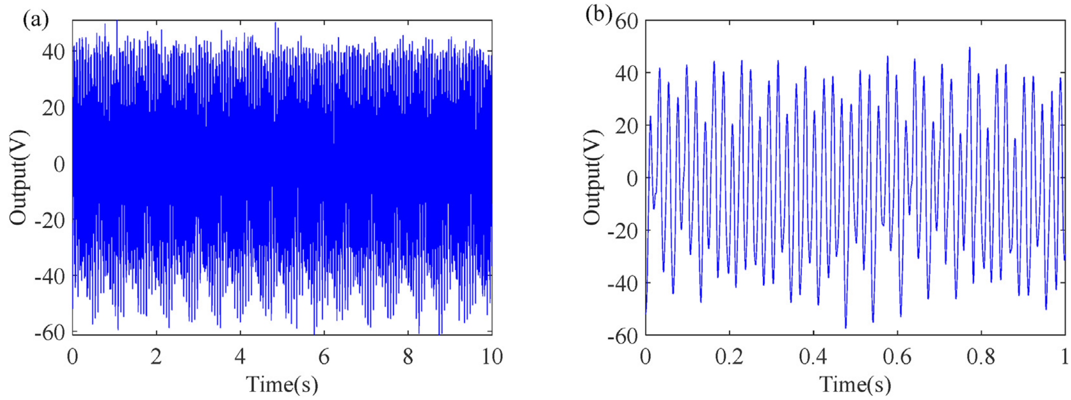

Fig. 6. Time domain output voltage of energy harvester under rotating frequency of 15 Hz: (a) original signal, (b) zoomed view.

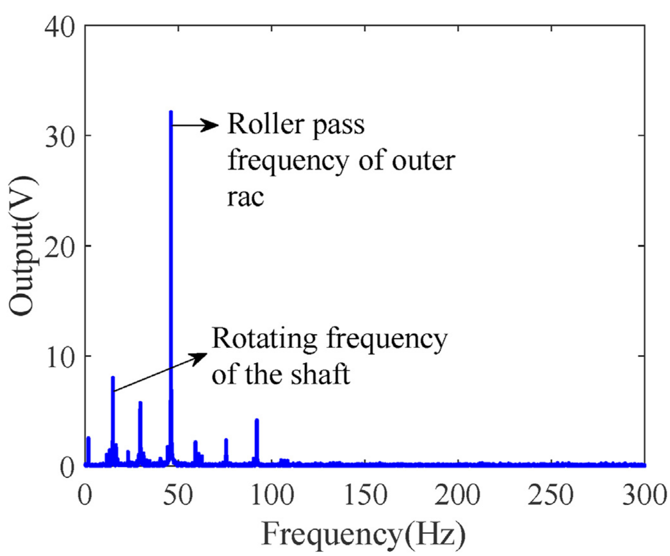

Fig. 7. Frequency domain output voltage of energy harvester under rotating frequency of 15 Hz.

pass frequency of outer race is approximately three times higher than the shaft rotating frequency in this paper. The relation between these two frequencies is determined by the structural parameters of rolling bearing studied here.

3.1. Effect of rotating frequency

Fig. 8 shows the open circuit voltage and short circuit current of the energy harvester at different rotating frequencies. It can be found that the voltage amplitude changes little as the rotating frequency increases. This is because that the output voltage of energy harvester is mainly generated by gravity load of rotating shaft and disc and transmitted by rolling element passing over the piezoelectric section. The magnitude of gravity remains constant with varying rotating frequencies. It is worth noting that there exists inevitably unbalance force from rotating shaft and disc, which is amplified with the increase of rotating frequency and contributes to the output voltage of energy harvester. However, as mentioned before, only weight-dominant case is studied in this paper, where the effect of unbalance force is relatively weak especially under low rotating frequency. Hence, the amplitude of output voltage remains constant approximately as rotating frequency increases from 5 to 25 Hz.

The amplitude of short circuit current generated by section II of energy harvester is increased along with the increment of rotating frequency in an approximately linear manner as shown in Fig. 8(b). The conductive section of piezoelectric sheet can be treated as a parallel connection of a voltage source and a capacitor. As the rotating frequency gets higher, the frequency of its output current will increase, which benefits reducing the impedance of the capacitor. Hence, increasing the rotating frequency of shaft leads to higher amplitude of short circuit current of the energy harvester.

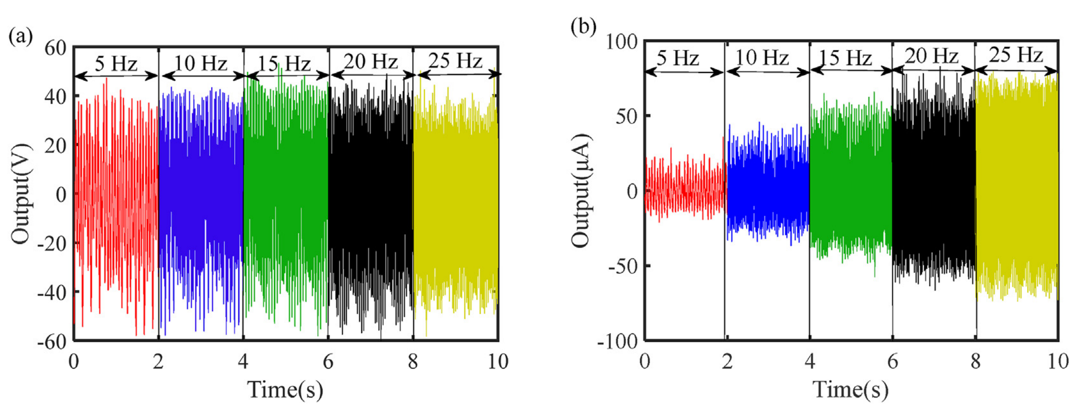

Fig. 8. The outputs of energy harvester under different rotating frequencies: (a) open circuit voltage, (b) short circuit current.

3.2. Effect of rotor weight

By mounting another disc of identical dimension at the middle of shaft, the output voltage and current with different rotor weights are measured under the rotating frequency of 15 Hz. The measured results are illustrated in Fig. 9, where it can be seen that the amplitudes of output voltage and current with double discs are approximately twice higher than those of single disc. Considering that the disc is much heavier than the shaft, the rotor weight is nearly doubled by adding another disc. Hence, it can be concluded that the output voltage and current get higher linearly along with the increase of rotor weight. As can be predicted, a large amount of electricity power can be generated when installing the proposed energy harvester into heavy duty rotating machinery.

3.3. Effect of shaft span

Maintaining a single disc at the mid span of shaft and 15 Hz rotating frequency, the effect of shaft span on the outputs of energy harvester is also evaluated by moving the right pedestal with piezoelectric sheet to increase the shaft span. As can be seen in Fig. 10, along with the extension of shaft span, the amplitudes of output voltage and current get larger slightly. When the shaft span is extended, the rotor stiffness decreases obviously, which leads to more severe deformation of rotor and fluctuation of loads applied to the piezoelectric sheet. This is believed the main reason for the slight enlargement of output voltage and current of the energy harvester.

3.4. Effect of load resistance

Different resistances are connected to section II to measure the RMS output voltage and RMS output power of energy harvester as shown in Fig. 11. It can be seen that with the increase of rotating frequency, the matched resistance of the energy harvester decreases and the output power under matched resistance becomes higher. When the rotating frequency is 20 Hz, section II of the energy harvester can generate 131 μW electrical power with the matched resistance, which is enough to realize the self-power supply for low-power sensors.

The arc-shaped piezoelectric sheet is cut into three conductive sections to harvest rotational energy here. Only the output performance of section II symmetric about the central axis of shaft is investigated above. To better understand the output performance of energy harvester, the outputs of section I is also measured with different resistances. Comparisons of the output voltage and power of sections I and II are illustrated in Fig. 12, where it can be observed that the matched resistance of the two sections are identical, and the output voltage and power of section II in the middle are higher than those of sections I. Considering the symmetric arrangement of piezoelectric sections, the total output power of energy harvester with the three conductive sections can reach 286 μW.

4. Applications in bearing condition monitoring

4.1. Output voltage signals for fault detecting

As illustrated in Fig. 7, the output voltage signals of energy harvester contain rich frequency information, which inspires us to use the proposed piezoelectric energy harvester as a sensor to directly detect rolling bearing faults. To explore the fault detecting capability of energy harvester, the healthy rolling bearing used in aforementioned studies is replaced by defective rolling bearings with inner and outer race defects, respectively, as shown in Fig. 13. The output voltages of section II of the energy harvester are measured for these two defective rolling bearings.

Figs. 14 and 15 show the output voltage of energy harvester when rolling bearings with defects are installed. As rolling elements pass through the defect, they experience sudden contact losses and gains, which results in periodic impact on the outer race and the conductive section. The periodic impact causes sudden changes in the output voltage of energy harvester as shown in Figs. 14 and 15. Compared with the output signals of energy harvester with healthy bearing in Fig. 7, obvious fault characteristic frequency component and its multiples can be observed in the frequency spectrums shown in Figs. 14 and 15.

By comparing the output signals of energy harvester with healthy and defective rolling bearings, it can be concluded that the proposed energy harvester has the capability of sensing rolling bearing defects, which is desirable for condition monitoring of rolling bearings.

4.2. Output power for wireless sensor system

To demonstrate the power generation capability of the proposed energy harvester, a self-powered wireless sensor system is developed, which is constructed by an energy harvester prototype, a sensor, a power management circuit (DB107, LTC3588-1), a wireless data transmitter (STM32L151C8T6, nRF24L01) and a wireless data receiver (STM32L151C8T6, nRF24L01), as illustrated in Fig. 16(a). In this work, a single conductive section of piezoelectric sheet is employed as the sensor, which can be replaced by other sensors according to measuring requirements. Signals acquired by the sensor are received approximately every 50 s from the wireless data

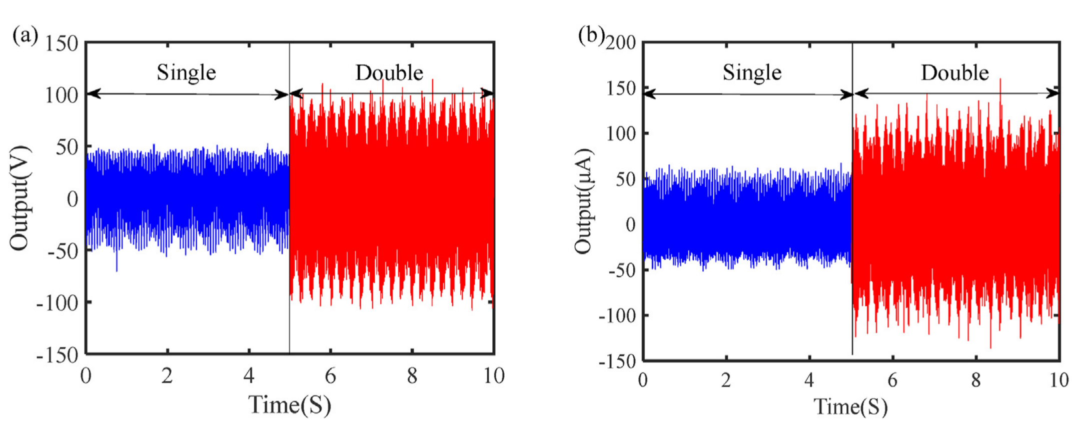

Fig. 9. The outputs of energy harvester with different rotor weights: (a) open circuit voltage, (b) short circuit current.

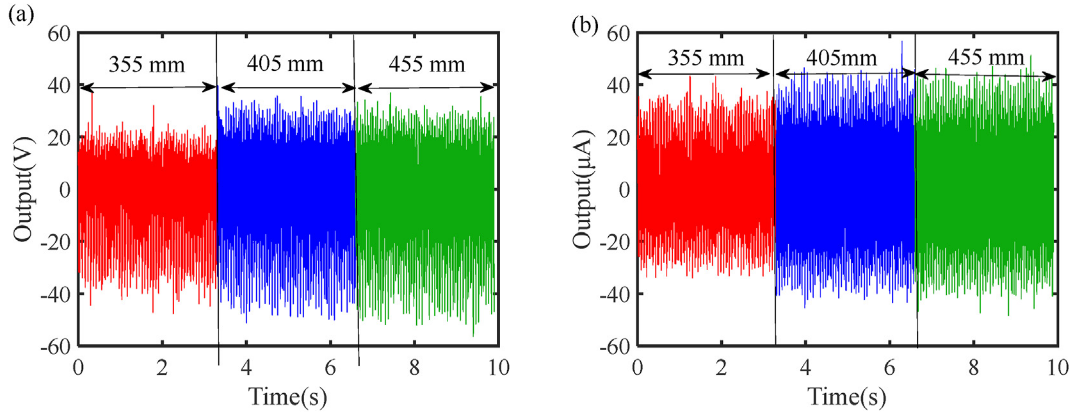

Fig. 10. The outputs of energy harvester with different shaft span: (a) open circuit voltage, (b) short circuit current.

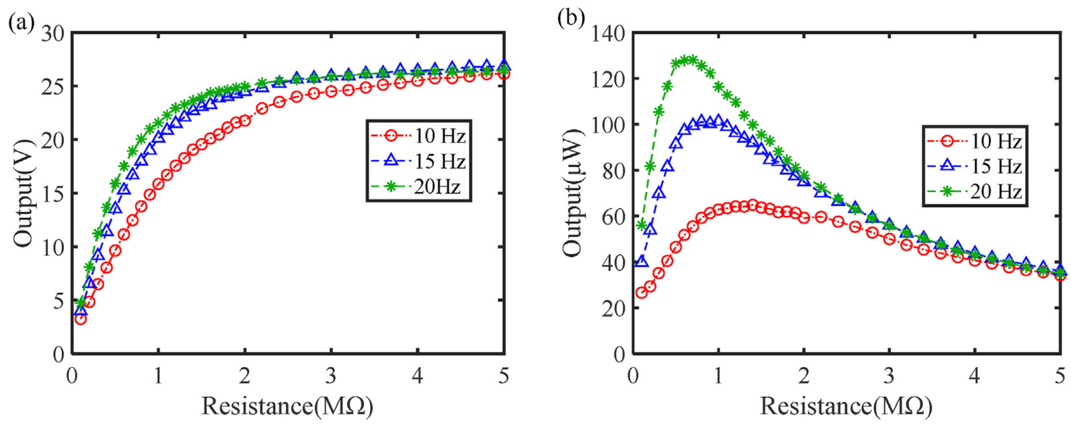

Fig. 11. Effect of resistance on the outputs of energy harvester under different rotating frequencies: (a) RMS voltage, (b) RMS power.

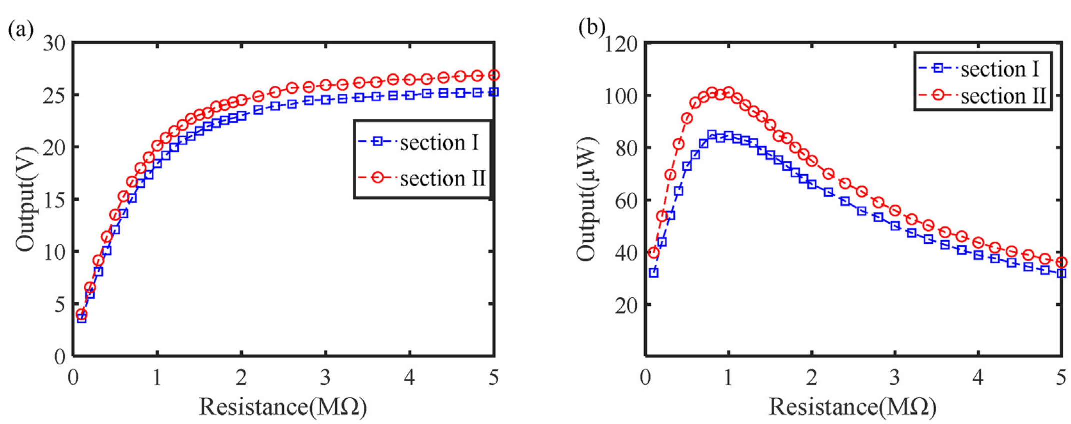

Fig. 12. Output Comparison between different conductive sections of energy harvester: (a) RMS voltage, (b) RMS power.

transmitter over 10 m as shown in Fig. 16(b) and (c). More details are demonstrated in Movie S1.

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2021.121770.

It is worth noting that the rotor shaft and disk employed in this study are light weight with low rotating speed. The output power of the proposed energy harvester is approximately proportional to the weight of rotor, and also increase along with the increment of rotating speed. Hence, considerable volume of electricity power can be generated when installing the proposed energy harvester into heavy duty rotating machinery. It is trustworthy that the self-powered wireless sensor system has strong potential for

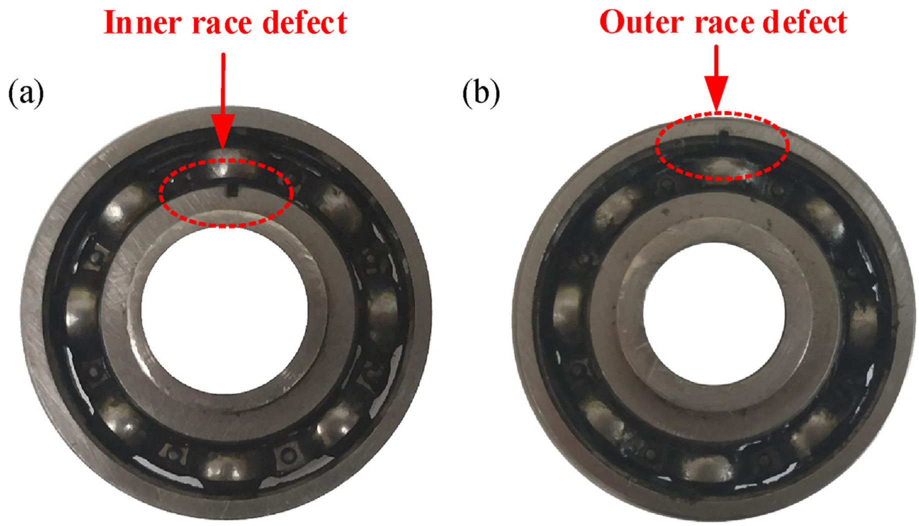

Fig. 13. Defective rolling bearings with (a) Inner race defect, and (b) Outer race defect.

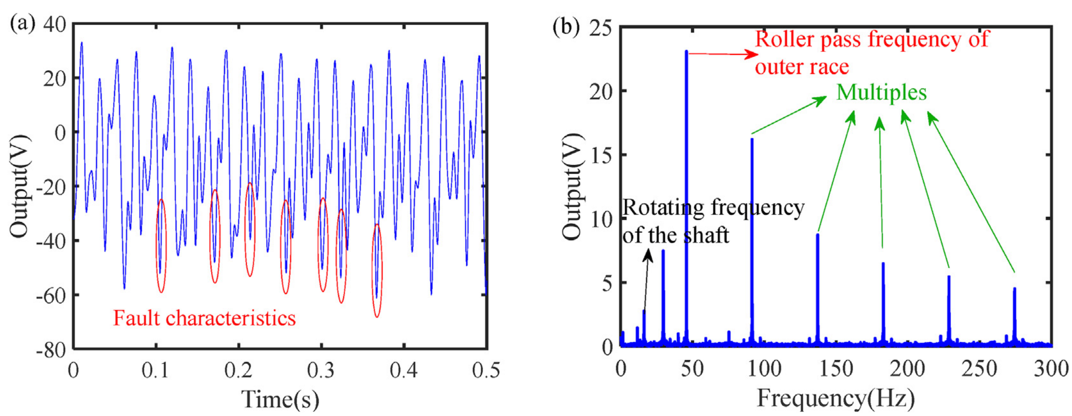

Fig. 14. Output voltage with rolling bearing involving outer race defect: (a) time domain, (b)frequency domain.

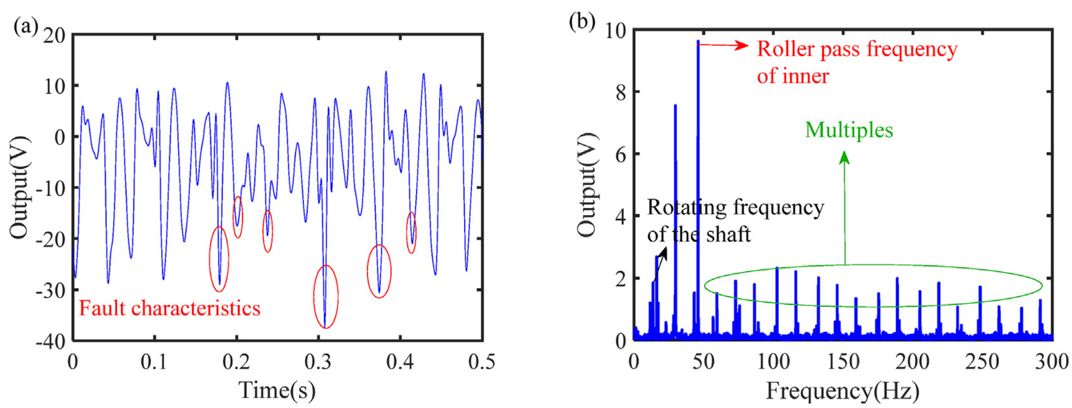

Fig. 15. Output voltage with rolling bearing involving inner race defect: (a) time domain, (b)frequency domain.

applications in remote condition monitoring of rotating machinery.

5. Conclusions

This paper proposed a piezoelectric energy harvester capable of harvesting electrical energy from rotating machines via rolling element bearings. In the energy harvester, an arc-shaped piezoelectric sheet was cut into conductive sections and installed between rolling bearings and lower part of pedestal. An electromechanical coupling model was proposed to demonstrate the working principle of the proposed energy harvester. A series of experiments were then conducted to explore the output

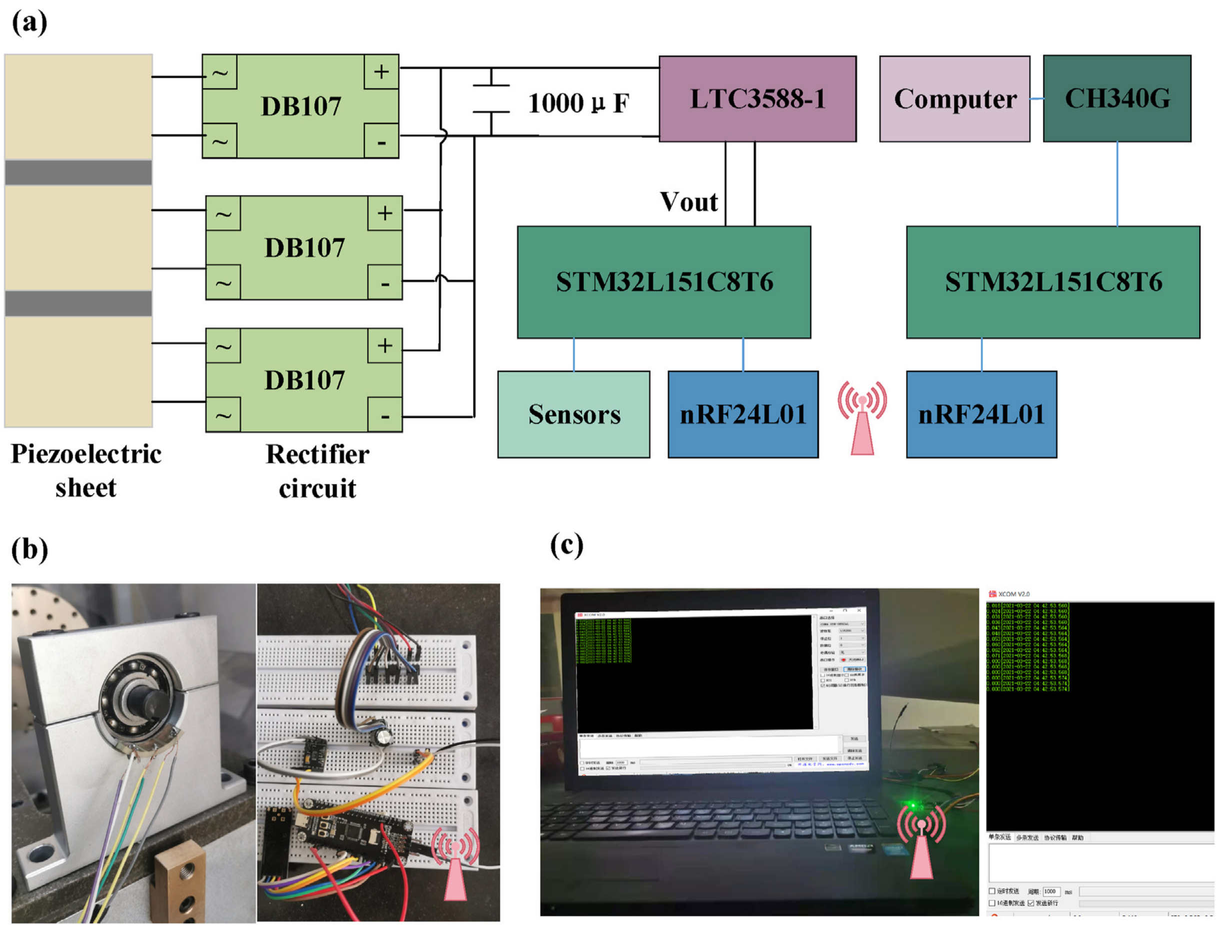

Fig. 16. Demonstrations of self-powered wireless sensor system. (a) self-powered wireless sensor system. (b) Sending signals. (c) Receiving signals.

performance of energy harvester, where comprehensive parameter studies were conducted to evaluate the effects of working conditions on energy harvester outputs. The proposed energy harvester was then employed to detect rolling bearing faults experimentally. A self-powered wireless sensor system was also developed based on the proposed energy harvester to sense the vibrations of bearing. Some critical conclusions are listed below:

(1) Increasing rotating frequency leads to decreased impedance of piezoelectric sheet, which results in large output current and power, but has little effect on the amplitude of output voltage in weight dominant case. Both the output voltage and current increase linearly with the increment of rotor weight. The extension of shaft span can also enlarge the output voltage and current slightly;
(2) By employing three conductive sections with subtended angle of 30°, the output electricity power generated by the one single conductive section of energy harvester mounted on a small rotor test rig can reach 131 μW with matched resistance under the rotating frequency of 20 Hz;
(3) The proposed energy harvester is capable of detecting rolling bearing faults, of which the output voltage signals contain the fault characteristic frequencies.
(4) The self-powered wireless sensor system is capable of measuring and transmitting vibration signals approximately every 50 s under the rotating frequency of 15 Hz.

The advantages of the proposed energy harvester are concluded as below: the installation of energy harvester has no effect on assembling relations and working state of rolling bearings; the piezoelectric sheet in the energy harvester works in D33 mode and is only subjected to compressive loads, which guarantees long lifespan of the energy harvester; the kinetic energy scavenged by the proposed energy harvester is completely wasted energy in rotating machines; the electricity generated by proposed energy harvester can effectively drive wireless sensor system. Those aforementioned advantages show great prospect of the proposed energy harvester for applications in long-term condition monitoring for rotating machines.

Statement of author contribution

Liufeng Zhang: Conceptualization, Methodology, Writing – original draft, **Feibin Zhang:** Methodology, Investigation, **Zhaoye Qin:** Conceptualization, Methodology, Writing – review & editing, Supervision, **Qinkai Han:** Methodology, Validation, **Tianyang Wang:** Investigation, Fulei Chu: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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