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Towards Self-Powered Wearables via Wrist-Worn Energy Harvesters

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ABSTRACT

Wearable electronics are demonstrating great potential in many areas, but finite capacity of chemical batteries become a bottleneck of their applications. We develop three kinds of wrist-worn energy harvesters that have different power enhancement mechanisms to address this issue. A compact energy harvester with magnetic frequency-up converter is developed to increase energy conversion capacity while a tiny repulsive magnetic spring is introduced to enhance response motion. Besides, a proof-massless energy harvester is investigated to improve motion capture capacity of wrist-worn energy harvester. A general model is constructed to predict the performances of these energy harvesters. The experimental results show that these energy harvesters achieve significant power improvement and their power output and power density can reach ten times that of the counterparts.

Keywords: self-powered wearables, energy harvesting, arm swing, wrist-worn, electromagnetic transducer

1. INTRODUCTION

Wearable electronics, such as smart watches and wristbands, are prevailing in daily life because of their versatility in health monitoring, communication, living assistance, etc. However, due to critical size constraints, the applications of the wearables are significantly hindered by finite energy capacity of chemical batteries. To improve user experience and extend working time of the wearables, it calls for developing alternative energy supplies that can sustainably power the wearable electronics. Since biomechanical energy of human motion is nearly sustainable, scavenging kinetic energy of human arm swinging renders a promising solution to realize self-powered wearables [1]. To this end, a great amount of wrist-worn energy harvesters have been developed based on linear and rotational inertial devices. Compared with linear wrist-worn energy harvester, the rotational devices have advantages of compact structure and improved power generation performance. For wrist-worn energy harvesters, there are great challenges that constrain power generation performance [2]: low-frequency excitation of human motion and critical size requirement of the wearables. Various mechanisms have been investigated to tackle these challenges. For example, mechanical gears were used to increase the excitation frequency of the transducers [3]. Such frequency-up conversion effect could also be achieved by increasing the poles of electret transducer [4]. Other than this approach, some researchers used mechanical spring to extend the bandwidth of wrist-worn energy harvesters [5]. Considering that the proof mass of wrist-worn energy harvester is bulky and occupies considerable space, asymmetric structure was introduced to excite the transducer [6].

This work carries out systematic investigation of wrist-worn energy harvesters to boost power generation performance. Starting from the fundamental structure of wrist-worn energy harvesters, we will propose three mechanisms that can improve power output from different perspectives. Design, modeling and experiments of the proposed energy harvesters will be introduced in this paper.

2. PRINCIPLES AND DESIGN

As shown in Fig. 1 (a), a rotational wrist-worn energy harvester generally utilizes a proof mass to capture the kinetic energy when human arm swings. The captured energy is then converted into electrical energy via the transducer. To enhance the response motion of the proof mass, a spring may be introduced to the energy harvesting system. Based on this structure, we propose three approaches to boost the power output of wrist-worn energy harvesters. As shown in Fig. 1 (b), we first

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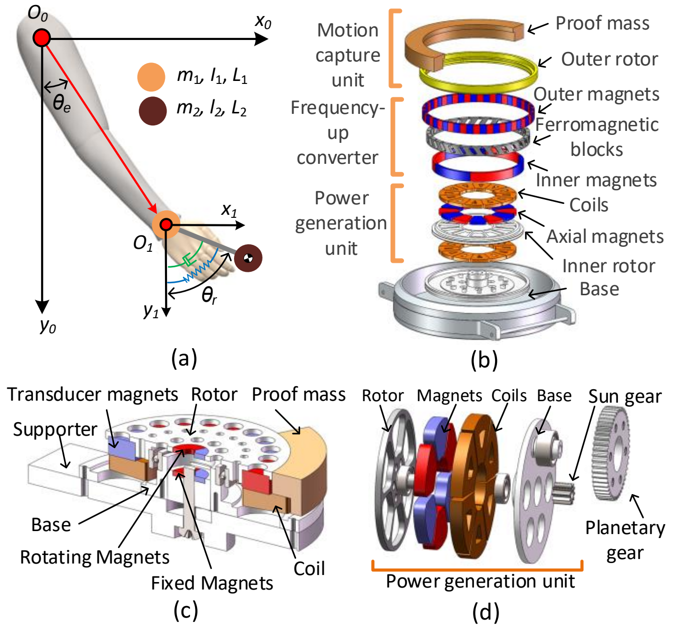
develop a coaxial energy harvester (MFEH) with magnetic frequency-up converter to improve the equivalent energy conversion capacity of the transducer. The kinetic energy of arm swing can be captured by the motion capture unit, and the captured motion is then accelerated by the magnetic frequency-up converter. With accelerated motion, the power generation unit is excited to efficiently generate electricity for the wearables. Thanks to the magnetic frequency-up converter, the energy harvester obtains highly compact structure and significantly increases energy conversion capacity to improve the performance [7].



(a) (b) (c) (d)

Fig. 1. Fundamental structures and designs of wrist-worn energy harvesters. (a) Fundamental structure of wrist-worn energy harvester. (b) Design of coaxial energy harvester with magnetic frequency-up converter. (c) Design of magnetic spring enhanced energy harvester. (d) Design of proof-massless energy harvester.

The second approach to enhance power output is realized by introducing a tiny repulsive magnetic spring to the energy harvester (MSEH), as shown in Fig. 1 (c). The magnetic spring comprises two pairs of magnets that exert repulsive torque on each other. One pair of magnets is fixed on the base while the other one is installed on the rotor to oscillate with the proof mass. Due to repulsive torque, the magnets act like a negative spring to lower potential energy well depth, thereby increasing response amplitude of the proof mass under the same excitation [8]. With increased motion amplitude, the transducer can produce more electricity for the wearables.

Fig. 1 (d) shows the design a proof-massless wrist-worn energy harvester (PMEH), which employs the transducer as inertial weight to improve motion capture capacity. Excited by human arm swinging, the power generation unit oscillates such that the rotor and magnets are driven by the planetary gear via the sun gear to convert the captured kinetic energy. Therefore, without additional proof mass, the energy harvester can obtain sufficient inertial weight to capture kinetic energy of arm swing [9]. Due to high density of electromagnetic transducer, the motion capture capacity of the energy harvester is significantly enhanced to boost the power output.

In summary, the proposed energy harvesters are targeted at improving different chains of the energy harvesting system. The proof-massless design can enhance the capacity of captured energy while the magnetic frequency-up converter improves the capacity of energy conversion. As a parallel element of the transducer, the magnetic spring enhances the response motion, which intrinsically changes the system dynamics. Thanks to these approaches, the generated power of the energy harvester can be remarkably enhanced.

3. GENERAL MODEL

3.1 *Power generation model*

The transducers of the energy harvesters comprise a set of axially magnetized permanent magnets and copper coils. Therefore, the flux linkage of the coils at a certain angular displacement of the proof mass ϑ_r can be obtained by integrating the magnetic vector potential along the copper wires:

$$\varphi(\theta_r)=\sum_{n=1}^{N}\oint_{L(n)} A \tag{1}$$

where N and A are the turns of copper wires and magnetic vector potential, respectively. $L(n)$ denotes the integral path of the n^{th} turn of wires. The magnetic vector potential can be analytically derived [10]. Note that the flux linkage is the function of ϑ_r. With flux linkage, the induced electromagnetic force is expressed as:

$$E(t)=\frac{d\varphi(\theta_r)}{dt}=\frac{d\varphi(\theta_r)}{d\theta_r}\dot{\theta}_r \tag{2}$$

Assume a resistor is used as load, the average output power of the energy harvester can be calculated as:

$$P_{avr}=\frac{1}{\Delta t}\int_{t}^{t+\Delta t}\frac{E^2R_L}{(R_i+R_L)^2}dt \tag{3}$$

where R_i and R_L are the internal and the load resistors, respectively.

3.2 Magnetic spring model

As mentioned, the magnetic spring can be introduced to improve the performance of the energy harvester. The magnetic torque of the magnetic spring can be written as

$$T=\int_{s}\boldsymbol{\rho}\times\left[\boldsymbol{j}_{\boldsymbol{M}}\times\boldsymbol{B}_{z}\right]d\boldsymbol{S} \tag{4}$$

where j_M and B_z are the equivalent surface current of the rotating magnets and axial component of the flux density contributed by the fixed magnets. The equivalent surface current and axial component of the flux density can also be analytically derived [10]. In addition, ρ represents the unit radial vector and S denotes all the surfaces of the rotating magnets.

3.3 System dynamics model

As shown in Fig. 1 (a), the proposed energy harvesters mainly consist of two masses: a) combined mass of the components that are directly fixed with the transducer's rotor. The weight, moment of inertia, and eccentric length are m_1, I_1, and L_1, respectively. b) combined mass of the components that are directly fixed with the proof mass. The weight, moment of inertia, and eccentric length are m_2, I_2, and L_2, respectively. Note that L_1 is not equal to zero only if the energy harvester has proof-massless design since the rotation axis of the transducer is not coincident with that of the proof mass. Now it is sufficient to obtain the system's equation of motion using Lagrangian approach:

$$\begin{aligned}\ddot{\theta}_r=&-\Big[\left(m_1L_1+m_2L_2\right)\left(\ddot{X}\cos\theta_r-\ddot{Y}\sin\theta_r\right)+c\dot{\theta}_r-T\\&+\left(m_1L_1^2+iI_1+m_2L_2^2+I_2\right)\ddot{\theta}_e\Big]\Big/\left(m_1L_1^2+i^2I_1+m_2L_2^2+I_2\right)\end{aligned} \tag{5}$$

where $\ddot{X}$ and $\ddot{Y}$ are the excitation accelerations expressed in coordinate frame O_1. The magnetic spring torque T should be zero for the energy harvesters without magnetic spring. Furthermore, c and i are the linear damping coefficient and transmission ratio, respectively. Note that the transmission ratio equals to 1 if the rotor of the transducer and the proof mass are synchronous. After numerically solving this equation, the states of ϑ_r can be substituting into Eq. (1) ~ (3) to calculate the average output power.

4. EXPERIMENTAL VALIDATION

4.1 Prototypes and experimental setup

As shown in Fig. 2 (a)~(c), miniature prototypes of different energy harvesters were fabricated. The volumes of MFEH, MSEH, and PMEH are 5.01 cm^3, 6.46 cm^3, and 3.21 cm^3, respectively. These prototypes were tested using an experimental setup shown in Fig. 2 (d). In this experimental setup, a pendulum is used to simulate human arm while driven by a stepper motor. A resistor with optimal resistance (equal to the internal resistance) served as load and its voltage was recorded by the oscilloscope to measure the output power. In the testing, the output power under different excitation frequencies was measured.

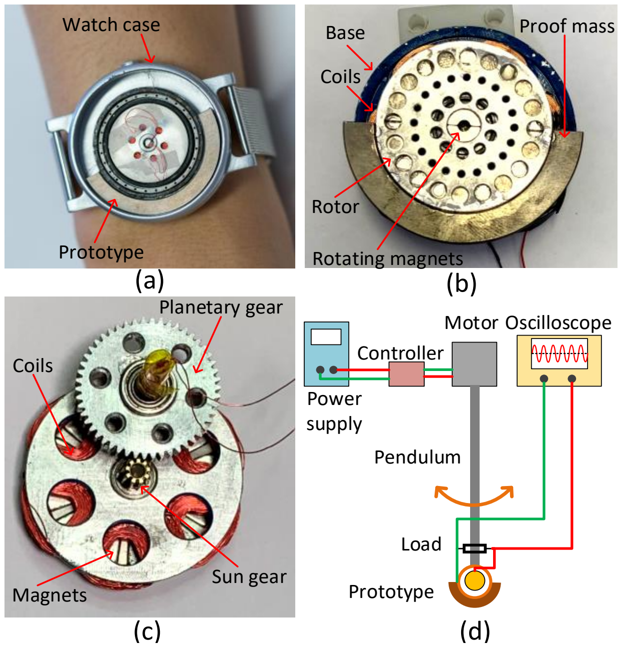


Fig. 2. Prototypes and experimental setup. (a) Prototype of MFEH. (B) Prototype of MSEH. (c) Prototype of PMEH. (d) Schematic illustration of the experimental setup

4.2 Results and discussions

As shown in Fig. 3 (a), MFEH generates a maximum power of 1.74±0.12 mW at an excitation frequency of 0.65 Hz. Given the total volume of 5.01 cm^3, the maximum power density achieves 346.61 $\mu W/cm^3$. For MSEH, it can be found from Fig. 3 (b) that the magnetic spring has significant effect on boosting the output power for all the testing frequencies. Compared with the case without magnetic spring, the energy harvester with magnetic spring increases the average power output by 17%~425%, which highlights the advantages of the repulsive magnetic spring as power booster. The average power output of PMEH with respective to excitation frequency is presented in Fig. 3 (c). It is observed that the maximum power achieves 1.46±0.06 mW, corresponding to the maximum power density of 452.82 $\mu W/cm^3$. Furthermore, the simulated data generated by the constructed model can match the measured results in general. For performance comparison, the average power and power density of MFEH, PMEH, and the counterparts are given in Fig. 3 (d). It is clear that our energy harvesters significantly overperform the counterparts in terms of average power and power density. Specifically, the average power and power density of MFEH and PMEH are over ten times that of the counterparts.

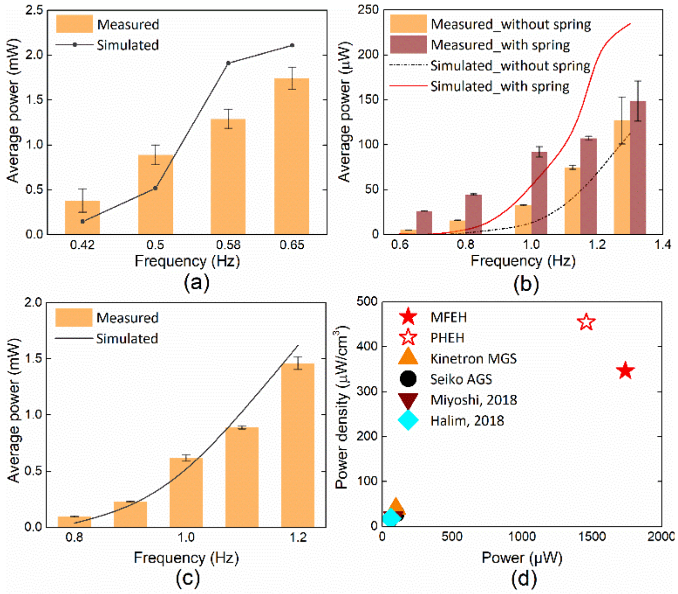


Fig. 3. Experimental results. (a) Measured and simulated power of MFEH. (b) Measured and simulated power of MSEH with and without magnetic spring. (c) Measured and simulated power of PMEH (d) Performance comparison between our energy harvesters and the counterparts.

For a smart watch or wristband that is equipped with a micro-controller unit, multiple sensors (temperature sensor, heartrate sensor, and pedometer), and communication module (Bluetooth), the power requirement is estimated to be around 300 μW. Therefore, our energy harvesters are sufficient to realize self-powered function of these devices or even competent for more sophisticated wearables.

5. CONCLUSIONS

It can be concluded that three energy harvesters are designed to boost the power output of wrist-worn energy harvesters from different perspectives. The magnetic frequency-up converter can effectively improve energy conversion capacity and the magnetic spring can enhance the response motion of the proof mass. In addition, due to proof-massless design, the wrist-worn energy harvester can achieve high power output without additional proof mass. In the experiments, the energy harvesters demonstrate significant improvement in power output and remarkably overperform the counterparts. With high performance, the proposed energy harvesters can realize self-powered function of the wearables.

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