Applied Physics Letters

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Cite as: Appl. Phys. Lett. **116**, 053902 (2020); https://doi.org/10.1063/1.5142575
Submitted: 14 December 2019 . Accepted: 19 January 2020 . Published Online: 04 February 2020

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ABSTRACT

A rotational electromagnetic energy harvester is designed to collect the mechanical energy of human motion at a low frequency. Linear motion can be converted to high speed rotation with an inertial system, which is mainly composed of a twist driving structure and a ratchet-clutch structure. When the twist rod is compressed by a footstep, the ratchet can keep rotating for about 20 s inertially, and an overall energy of 85.2 mJ can be harvested. The peak power output can reach 32.2 mW and a root mean square power of 7.7 mW is achieved. The maximum speed of the ratchet would be as high as 3700 revolutions per minute. When driven by the human footstep at a frequency of 1 Hz, an electronic hygrothermograph and 70 light-emitting diodes (LEDs) could be easily powered, which demonstrates the promising application of self-powered microelectronic devices.

Recently, kinetic energy harvesting has been proved to be a sustainable method for low-power electronic devices,[1–3] as it can achieve self-power supply without replacement of expired batteries. Traditionally, vibrational energy harvesters are designed and fabricated based on resonant structures based on piezoelectric,[4,5] electrostatic,[6–8] and electromagnetic[9,10] transduction mechanisms. However, the resonant frequency (∼100 Hz) is usually higher than the frequency of human motions (<5 Hz).[11,12] The mismatch between the resonant frequency of the device and the external vibration sources may cause a poor efficiency of energy conversion.

Frequency upconversion structures[13–17] and rotational structures[18–25] have been reported for energy harvesting at an ultra-low frequency. Kuang has invented a knee-joint energy harvester (KEH) that uses a mechanical plucking technique to provide a frequency upconversion from a few Hz to the resonant frequency of the KEH.[13] Li has developed a wearable piezoelectric energy harvester to generate electricity from the movement of human joints based on a magnetic interaction structure, which can harvest vibrations at a frequency from 0.5 to 5 Hz.[14] Hou has presented a non-resonant rotational electromagnetic energy harvester for scavenging low-frequency and irregular human motion.[19] Maharjan has demonstrated an electromagnetic energy harvester to harvest energy from low frequency swing vibrations based on a cycloid structure.[20] Tcho has fabricated a disk-based triboelectric nanogenerator operated by rotational force converted from linear force by a gear system, which could collect mechanical energy from a human footstep.[21] Recently, Fan has also proposed a twisting-vibration based energy harvesting approach to generate electricity from ultra-low frequency excitations.[22]

In this paper, we have developed a compact non-resonant structure for rotational electromagnetic energy harvesting from human motion at an ultra-low frequency. Based on a twist driving system and a ratchet clutch system, our device can transfer linear motion at ultra-low frequency into rotation at high-speed, which could keep rotating inertially even when the driven motion is released. This inertial structure can greatly improve the mechanical energy conversion efficiency, and generate high output power. The design and application of this device will be described below in detail.

The 3D schematic diagram of the device is illustrated in Fig. 1, and the structure parameters are listed in supplementary Table S1, and the materials for fabricating the harvester are also listed in supplementary Table S2. Figure 1(a) shows the overall device and Fig. 1(b) shows the core component of the device which converts mechanical energy into electrical energy. The overall size of the device is approximately $4.2 \times 4.2 \times 5.5\,\mathrm{cm}^3$, which is mainly composed of a twist driving

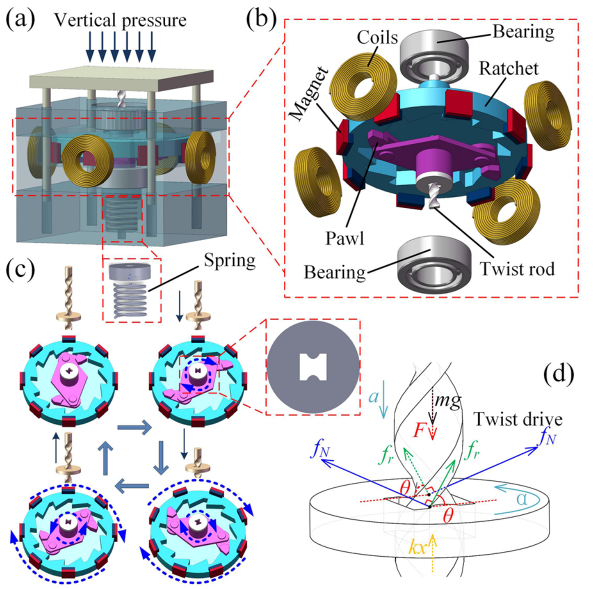

FIG. 1. (a) The 3D structure of the rotational electromagnetic energy harvester; (b) the main part that converts mechanical energy into electrical energy; (c) the conversion between linear motion and rotational motion; and (d) the force analysis diagram of the twist rod in the twist driving system.

system and a ratchet clutch system. In the twist driving system, a rod with a double-helix structured surface, penetrates through a circular disk with a dumbbell-shaped hole as shown in Fig. 1(c), and four guide rails made are applied to constraint the movement direction of the rod. When the twist rod is driven down perpendicular to the disk, the disk will rotate with the pawl due to the interaction between the twist rod and the hyperboloid hole. Therefore, the linear motion can be converted into the ratchet rotational motion. In addition, a spring is used to restore the initial position of the twist rod.

The ratchet clutch system mainly consists of a ratchet and two pawls. Four, six, or eight magnets (Nd-Fe-B-N35) are evenly distributed on the circumference of the ratchet. Two unidirectional pawls are symmetrically mounted on a chuck to push the ratchet in a fixed direction. Figure 1(c) shows the working mechanism of the ratchet clutch system. With the twist driving system, external linear motion is converted to the rotation of the circular disk, which further drives the pawls via the chuck. The two pawls will interact with the ratchet and accelerate it to a high speed rotation. During the interaction between the pawls and ratchet, the pawls can swing flexibly without obstructing the rotation of the ratchet; therefore, the ratchet can keep rotating thanks to inertia as shown in supplementary videos 1.

As shown in Fig. 1(d), the force analysis of the twist rod can be expressed as

$$F + mg - kx - 2f_r \sin\theta - 2f_N \cos\theta = ma, \quad (1)$$

where m and a are the mass and acceleration of the rod, respectively; θ is the thread angle; x is the driven displacement; k is the spring stiffness; F is the driven force from the external vibration; f_N is the normal force on the thread grooves; and f_r is the sliding friction force between the thread and the convex, which can also be expressed as μf_N with a friction coefficient of μ.

During the rod driving process, the rotation of the circular disk can be described as

$$I\alpha = (2f_N \sin\theta - 2f_r \cos\theta - f_{damp})r, \quad (2)$$

where I is the effective moment of inertia for the entire rotational structures; α is the angular acceleration; f_{damp} represents the mechanical damping force including the air damping and other mechanical friction; and r is the radius of the rod. The relationship between a and α can be expressed as

$$\tan\theta = \frac{a}{\alpha r}. \quad (3)$$

Based on Eqs. (1)–(3), the angular acceleration of the small disk during the acceleration of the twist rod can be expressed as

$$\alpha = \frac{r(F + mg - kx)(\tan\theta - \mu) - rf_{damp}(\mu\tan\theta + 1)}{I(1 + \mu\tan\theta) + mr^2\tan\theta(\tan\theta - \mu)}. \quad (4)$$

In this device, the magnets are aligned along the radial direction of the disk, and evenly distributed on the ratchet. Four sets of coils are made of a 0.12 mm copper wire with different turns and attached on the frame structure. These coils are connected in series with internal resistances of 30 Ω and 70 Ω for coil turns of 200 and 400, respectively. Based on the principle of electromagnetic induction, when the magnets rotate with the ratchet, current can be generated in the coils due to the change of magnetic flux. The induced electromotive force (EMF) across each coil E, could be expressed as

$$\mathcal{E} = -N\frac{d}{dt}(BS\cos\omega t) = NBS\omega\sin\omega t, \quad (5)$$

where N is the number of coil turns; B shows the magnetic field density; S represents the area of the coils; and ω demonstrates the angular velocity of the ratchet.

As shown in Fig. 2, our device is installed between an oscillator and a fixed box in for device characterization. The sinusoidal vibration signal is loaded on the shaker, which can push the twist rod in a linear motion with a given vibration frequency from 0.5 Hz to 5 Hz during the test. As shown in Fig. 2(a), the red line and blue line show the movement condition during the test for the vibrator and the device, respectively. The oscillator is controlled to speed up from the lowest position Fig. 2(b) to the initial position Fig. 2(c), so that the twist rod

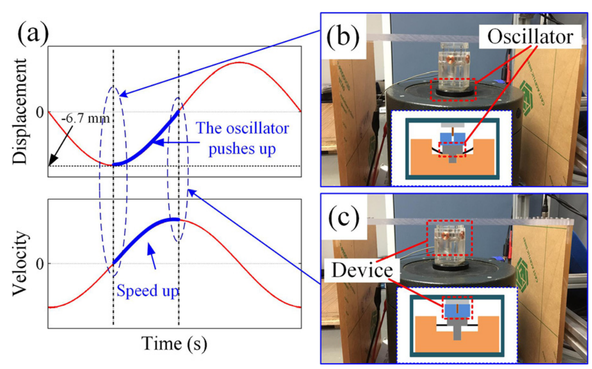

FIG. 2. The experimental setup. Based on the (a) sinusoidal vibration signal, the oscillator can push the device from (b) the lowest position to (c) the initial position.

can also speed up at the same time. Limited by the vibrator, the maximum displacement of the rod is 6.7 mm.

Figure 3(a) shows the output performance of the device on an external load of 30 Ω with different number of magnets. Herein, we have used a copper coil of 200 turns. It is observed that the peak voltages of the generators with 4 and 8 magnets are almost the same, while the average output powers are different. There is a short period of flat waveform for the voltage of the device with 4 magnets, which is due to the weak change of magnetic flux when the magnet rotates between two coils. This magnetic flux in the coils would change more frequently by utilizing 8 magnets, which has filled up the flat waveform between two peaks of the output voltage; therefore, the overall output power is increased. A root mean squared (RMS) power of 3.2 mW is achieved when an external vibration is applied with an amplitude of 6.7 mm at 5 Hz.

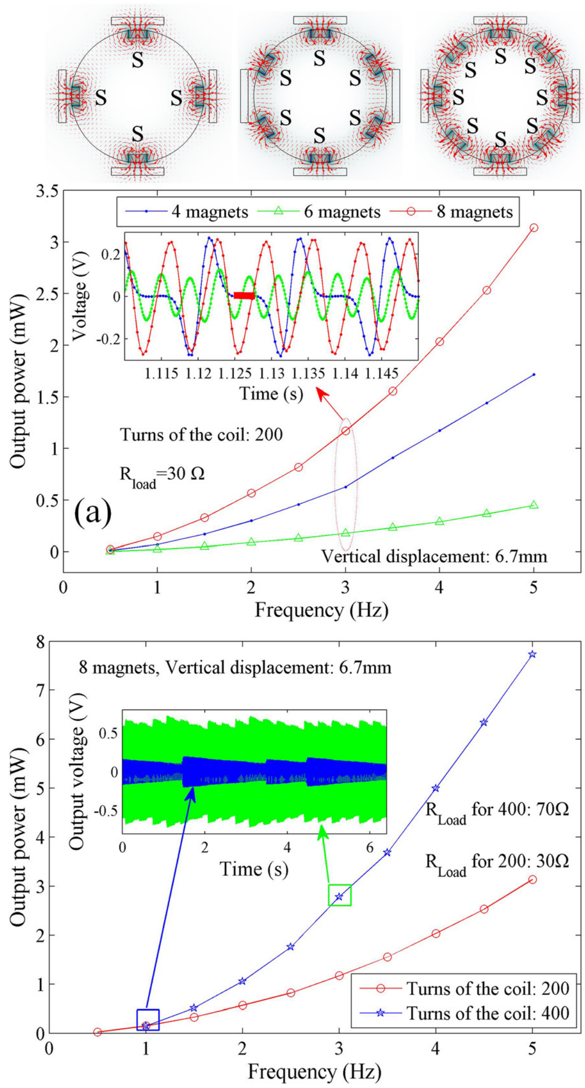

FIG. 3. (a) The output power vs driving frequency under different magnet arrangements. (b) The output power vs driving frequency under different turns of the coil.

However, it is not always beneficial to use more magnets since the phase of the outputs from each coil should be synchronized. The device with 6 magnets, for instance, achieves a lower power output than the device with 4 magnets. As shown in Fig. 3(a), only two of the magnets overlap with the coil while the other four magnets deviate from the center of the coils. Therefore, the overall power output is quite low despite the increased frequency.

Moreover, we can also notice that the output power rises with the increase in the driving frequency, as the EMF increases with the rotation speed. Two devices with 200 and 400 turns of coil (both with 8 magnets) have been tested, as shown in Fig. 3(b). The resistances of the two coils are about 30 Ω and 70 Ω, respectively. Therefore, the optimal power output should be achieved when the external load resistance is equal to the coil resistance. It is obvious that the device with more turns of coils can generate a higher output power at the same frequency. This result agrees well with the principle of electromagnetic induction in Eq. (5). A maximum RMS output power of 7.7 mW can be harvested at a frequency of 5 Hz for the device with a 400-turns coil. The inset in Fig. 3(b) shows the voltage curve of the device with 400-turns of the coil at frequencies of 1 Hz and 3 Hz, respectively. The output voltage rises rapidly to the maximum value during each drive of the vibrator, then decreases gradually until the next interaction occurs.

We have applied this energy harvester to collect energy from human motions. As demonstrated in Fig.4, a device with 400 turns of coil and 8 magnets was installed on the wood floor. Regular compression at a low frequency was applied on this device by the footstep. The maximum rotation speed of the ratchet can reach 3700 rpm as estimated from the voltage waveform and, the rotation from single compression would last for more than 20 s thanks to the excellent inertial system. During rotation, the overall energy harvested by the device is about 85.2 mJ. In the first 0.1 seconds of the rotation, the average power output of the device can be as high as 32.2 mW.

To demonstrate the potential applications of the rotational electromagnetic energy harvester, a capacitor, an electronic hygrothermograph, and dozens of LEDs have been powered by the harvester, respectively. In all demonstrations, the device was driven by a human

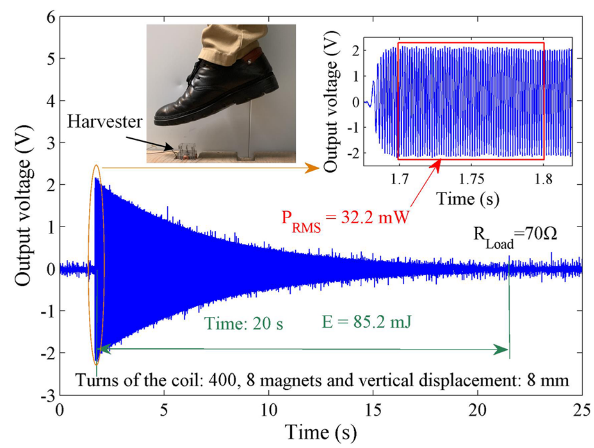

FIG. 4. The output voltage on an external load of 70 Ω with 400 turns of the coil after compression by a footstep.

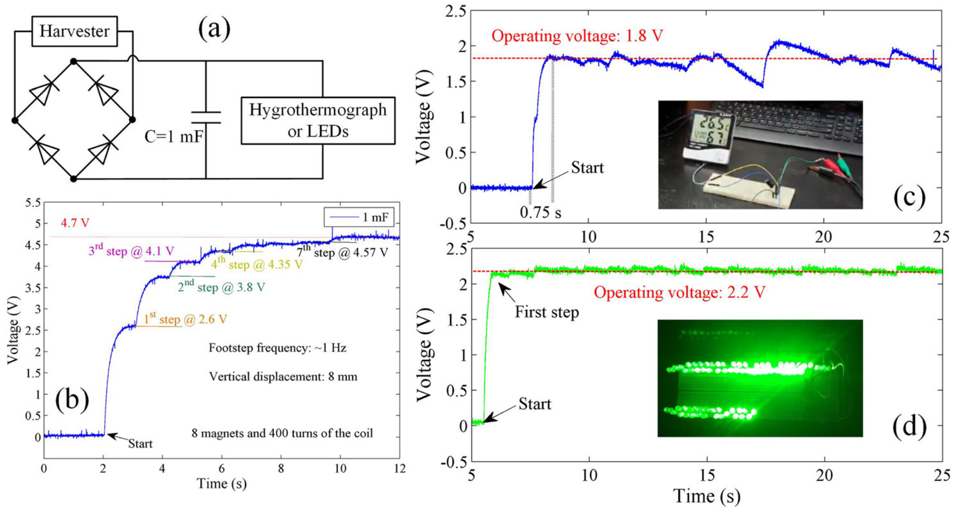

FIG. 5. (a) Rectifying circuit for the energy harvester, together with the storage capacitor and external application for sensors and LEDs; (b) the voltage across a capacitor of 1 mF charged by rotational energy harvesting from a human footstep; (c) a hygrothermograph and (d) 70 LEDs have also been powered by the harvested energy from footstep motion.

footstep at a frequency of about 1 Hz, and the vertical driving amplitude is about 8 mm. The output of the device was first rectified by a diode bridge then stored in a storage capacitor, as shown in Fig. 5(a). As Fig. 5(b) depicts, the voltage of the 1 mF capacitor without the external load can be charged up to 4.7 V when the device is compressed by human motion for 8 s. Furthermore, a hygrothermograph and 70 LEDs are connected in parallel with the capacitor, respectively. As shown in Fig. 5(c) and supplementary video 2, the voltage of the capacitor reaches 1.8 V within 0.75 s when the footstep is loaded on the device, which is enough to activate the electronic hygrothermograph. Afterwards, the hygrothermograph is able to work continuously under the footstep frequency of 1 Hz. Similarly, up to 70 green LEDs are also lit up simultaneously in another demonstration as shown in Fig. 5(d) and supplementary video 3. A stable voltage of 2.2 V is detected across the capacitor during the test. The power consumption of each LED is about 0.1 mW. Therefore, the overall output power from the 1 Hz footstep can be estimated to be 7 mW. Since the harvested power of the electromagnetic energy harvester is generally proportional to the square of the driving frequency, we have defined a figure of merit as P/f^2. Our device in this work has achieved the highest figure of merit, compared with the reported electromagnetic harvesters, as listed in Table I. Based on these demonstrations, we have proved that the rotational electromagnetic energy harvester converts the mechanical energy from human motion at an ultra-low frequency into electrical energy, which shows promising application in self-powered electronic devices.

TABLE I. Performance comparison of the reported electromagnetic energy harvesters.

References	Frequency (Hz)	Volume (cm^3)	Power (mW)	Figure of merit:P/f^2
Liu *et al.*[18]	8	33.1	10.4	1.625×10^{-4}
Fan *et al.*[22]	3	67.3	5.4	6×10^{-4}
Halim *et al.*[23]	0.91	20	0.0613	7.4×10^{-5}
Smilek *et al.*[24]	3.45	50	1.4	1.18×10^{-4}
Saha *et al.*[25]	2	12.5	0.3	7.5×10^{-5}
This work	1	97	7	7×10^{-3}

In summary, this paper proposed a rotational electromagnetic energy harvester with an inertial structure. The device is mainly comprised of a twist driving system and a ratchet clutch system. Linear motion at a low frequency can be converted to inertial rotation at a high speed. The output performance of the device has been investigated on a standard linear oscillator first, and then the device was applied to harvest energy from human motion. According to the experimental results, this energy harvester can convert ultra-low frequency mechanical energy into electrical energy, and a maximum power of 32.2 mW and an RMS power of 7.7 mW have been harvested. An electronic hygrothermograph and 70 LEDs have been easily powered by the device with a human footstep at 1 Hz, which proves the promising application of low-power electronic devices as a sustainable energy source.

See the supplementary material for the video demos and two tables with information of the device parameters and materials.

AUTHOR'S CONTRIBUTION

Y.Z. and A.L. contributed equally to this work.

We would like to acknowledge the technical support from the Materials Characterization and Preparation Center, Southern University of Science and Technology. This work was supported in part by the Shenzhen Science and Technology Innovation Committee under Grant No. JCYJ20170412154426330 and in part by the Guangdong Natural Science Funds under Grant Nos. 2016A030306042 and 2018A050506001.

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