# Harvest human kinetic energy to power portable electronics [†]

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## Abstract

It is known that the human body contains rich chemical energy, part of which is converted to mechanical energy of up to 200W when in motion. Therefore, it is ideal to harvest human body kinetic energy to power mobile electronic devices. This paper presents an energy harvester to unintentionally extract human kinetic energy and directly convert it to electricity, which can serve as a power source for portable electronics. The proposed harvester mainly consists of an eccentric rotor made of permanent magnet, electric steel and coils as stator. The eccentric rotor, as a simple pendulum, acts as the kinetic energy harvester, which can absorb the motion from the human body during walking. With the permanent magnets on the rotor, the moving rotor can produce a changing magnetic field, where electric coils can induce electricity. A torsion spring is also added onto the rotor such that the harvester works even when placed on a horizontal plane where the gravitational acceleration fails. The electromagnetic and kinematical model is built to analyze the performance. Numerical analysis and system optimization are also conducted. Simulation shows that the harvester with 40mm diameter and 50g weight, worn on the wrist, can produce dozens of milliwatts of electricity during normal walking.

*Keywords*: Energy harvesting; Human motion; Pendulum; Electromagnetic induction

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## 1. Introduction

In modern life, humans have become dependent on portable electronics, such as cell phones, most of which are powered by batteries. Although the performance of batteries is continuously being improved, their limited energy storage constrains the lasting use of these mobile electronics. Therefore, it is necessary to find alternative or supplementary methods to solve the energy shortage for portable electronics. According to the literature, there are a number of methods to power mobile electronic devices. One way to overcome the power limitations is to extract energy from the environment, such as vibration [1, 2], light [3, 4], either to recharge a battery or to directly power the electronic devices. The other way is to harvest the energy from the human body [5, 6]. As we know, there is a huge amount of kinetic energy generated when the human body is in motion, which can be up to 200W [7]. Thus, we propose to scavenge a couple watts of energy from the human body to power portable electronics, in a way that will not put an onerous load on the user.

In order to efficiently produce power for portable electronics with reasonable weight, a novel harvester is proposed which is based on electromagnetic induction. This device mainly consists of an eccentric permanent magnet as the rotor and wire coils wound on the shell made of electric steel as the stator. A torsion spring is added into the device so that it can work even when the rotor is placed on the horizontal plane. Compared with the existing designs discussed above, the proposed design needn't any gear sets nor auxiliary mechanisms, and can harvest the motion when placed on any plane. The rest of this paper is organized as follows. Section 2 introduces the physical model of the harvester. Section 3 gives the theoretical analysis of the system. Section 4 contains simulation. Section 5 makes the conclusions.

## 2. The architecture of the harvester

The harvesting device presented in this paper is based on electromagnetic induction, which needs a stator and rotor pair to produce changing magnetic field and induce electricity in the wire coils. As shown in Fig. 1, the harvesting device mainly consists of the rotor, stator and torsion spring. The eccentric rotor, made of permanent magnet and rotating around the central shaft, serves as the oscillating weight to absorb human motion during walking. Due to the rotor motion, the permanent magnets produce changing magnetic field. The coils, wound on the iron core made of electric steel, serves as the stator, which can produce induction electricity in this chang-
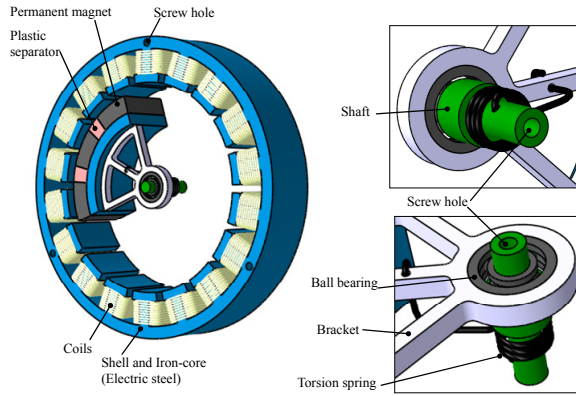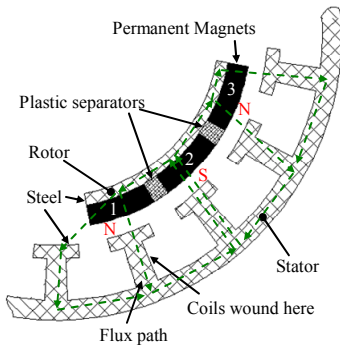
Fig. 1. The architecture of the harvester.



Fig. 2. Topology of the rotor and stator.

ing electricity. Human motion is not always on the vertical plane, even in normal walking. Thus, the device adds a torsion spring, one end of which is fixed on the bracket of the rotor, the other fixed on the shaft, so the device can work even if human motion is on the horizontal plane.

Fig. 2 shows the topology of the rotor and part of the stator, which are comprised of a magnetic circuit. There are three permanent magnets arranged in alternating orientation facing the stator poles, numbered as 1,2,3, and separated by two plastic separators. Magnets and separators are all fixed to an armature made of electrical steel, which is attached to the bracket made of aluminum and can rotate around the shaft. The stator, made of electrical steel, has 18 poles, around which copper coils are wound. Two neighboring magnets, the armature and two poles will form a magnetic flux path (dash lines in Fig. 2), which will change periodically when the rotor is rotating; therefore, the magnetic flux through each wire coil will change and then induce electricity.

The torsion spring is a helix with two ends in special shape. The lower end is bended and drills through the hole in the shaft, which is fixed on the cover via screws. The higher end is bent through the hole in the bracket. The bracket connects to the shaft through a ball bearing. Besides the first oscillating system comprising the rotor and the gravity, the rotor and the torsion spring make up the second oscillating system, allowing the harvester to work on any plane.
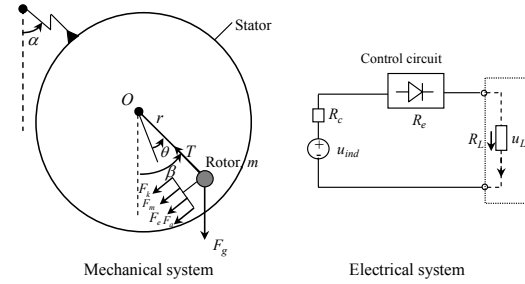


Fig. 3. Lumped parameter model of the harvester.

## 3. Theoretical investigation

Based on the above topology of the harvesting device, the mathematical model was deduced in this section to obtain the relation between human motion as system input and the electricity output. The electromagnetic analysis was conducted firstly to obtain the electrical damping force and other characteristics of the magnetic field. Then the kinematic performance of the system was explored, and finally the coupled analysis of the mechanical and electromagnetic subsystem was carried out to find the power output.

Fig. 3 shows the lumped parameter model of the harvester for analyzing the kinetic performance, where the left part is the mechanical subsystem and the right one is the electrical model of the whole system. In the mechanical model, the rotor is simplified as a point particle with four forces acting upon it, with the effective distance $r$ from the rotating center. Besides the inertia force on the tangential direction, there are three forces, namely, the torsion spring force $F_k$, the electrical damping force $F_e$ and the mechanical damping force $F_m$. There is also gravity $F_g$ and tension $T$ acting on the rotor. $\alpha$, $\beta$ and $\theta$ are the angular displacement of the harvesting device from human motion, the absolute angular displacement, relative to the world coordinates, and the relative angular displacement respectively, and they have the relationship $\beta = \alpha + \theta$.

According to Newton's Law, the following governing equation on the tangential direction of the rotor trajectory can be obtained:

$$k \cdot \theta + mg \sin\gamma \sin(\alpha + \theta) + C_e \dot{\theta} + m \cdot r(\ddot{\alpha} + \ddot{\theta}) = 0 \ . \tag{1}$$

In the above equation, the angular displacement of the device, $\alpha$, is the input variable, and the relative angular displacement of the rotor, $\theta$, is the output of the mechanical subsystem and its derivative is the input of the electrical subsystem which can be used to calculate the power output. $C_e$ is electrical damping coefficient, which can be expressed as the following:

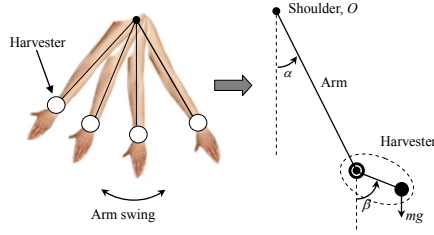$$C_e = \frac{16(n_e N \Phi)^2}{9\phi_m^2 (R_c + R_e + R_L)r} \tag{2}$$

Fig. 4. The working model of the harvesting device.



Fig. 5. Power output performance versus the sector angle of each magnet, in which curve there is the same outer radius of the permanent magnet $r_m$.

where $R_c$, $R_e$, and $R_L$ are the resistance of the coils, the resistance in the control circuit and the load resistance, respectively; $\phi_m$ is the angle of the magnet sector; $\Phi$ is the total magnetic flux; and $n_e$ is the number of poles which has effective magnetic flux.

If the external excitation, i.e. human motion such as the human arm swing, is defined as $\alpha = f(t)$, then the kinematical performance $\theta$ and $\dot{\theta}$ can be obtained by solving Eq. (1). Noted that the term $(\alpha + \theta)$ is not a small value, Eq. (1) can't be solved analytically but can be solved numerically using Matlab®.

With the relative angular velocity $\dot{\theta}$, the conversion energy from mechanical motion to electricity can be calculated by the integral of the electrical damping force $F_e$, as follows, where $T$ is the time for integral.

$$\overline{P_{con}} = -\frac{1}{T}\int_0^T F_e \cdot r\dot{\theta} \cdot dt = \frac{1}{T}\int_0^T C_e \cdot r\dot{\theta}^2 \cdot dt \qquad (3)$$

## 4. Numerical analysis

This section will study the harvesting device to extract energy from the arm swing of the human body. The common motion pattern of the human upper limb during normal walking is out-of-phase swing, which can be modeled as a single simple pendulum with mass concentrated at its center of mass [8], as shown in Fig. 4. Therefore, during normal walking, the trajectory of the arm swing can be expressed as $\alpha = \alpha_0 \sin(\omega \cdot t) \, [rad]$, i.e. the harvester is imposed the excitation defined by a sine displacement. For healthy adults, the swing frequency during normal walking is 0.8~1.1 Hz (or 5~7 rad/s) for different stride speeds [9]. Fig. 7 shows the simulation results with a sine wave, $\alpha = (\pi/6)\sin(5 \cdot t) \, [rad]$, as the external motion input. The relative angular displacement $(\beta - \alpha)$ between the upper pendulum (the arm) and lower pendulum (the rotor) is a sine function with amplitude attenuation. During daily working, human motion usually is discontinuous, such as impulse or step motion when user suddenly raises his hand. Fig. 8 shows the simulation results with a step function, where the angular displacement of the lower pendulum (the rotor) is a damped sine function.

According to the conservation of energy, the kinetic energy of the rotor converts to electricity and other energy loss. Based on the definition of kinetic energy, $K = (1/2)J \cdot \dot{\theta}^2$, the ro-
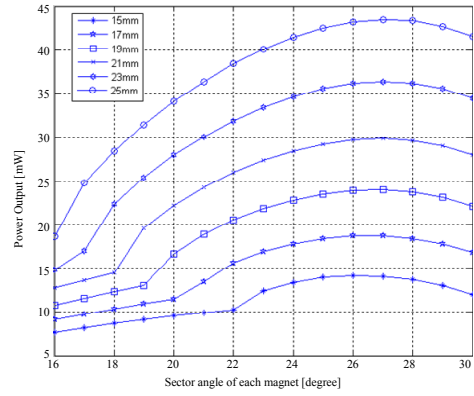
tor's topology should be taken into account to achieve maximum moment of inertia, $J$, so as to harvest maximum energy. To get optimal moment of inertia, $J = mr^2$, the total mass of the rotor $m$ and the effective radius $r$ should be maximized.

In the case that the harvester topology is unchanged, the structural arrangement of the rotor affects the power output. Given constant outer radius of the permanent magnet $r_m$ and its initial thickness, the change of the sector angle of each magnet $\phi_m$ will affect the power output. Fig. 5 shows the power output performance with respect to the magnet sector, where $r_m$ changes in each curve from 15 mm to 25 mm with intervals of 2 mm. It is shown that a larger outer radius of the magnet results in more power output. In other words, the bigger the rotor is, there will be more power output, and that the optimal sector angle increases slightly with the increase in the outer radius of the magnet.

Since the gravitational acceleration is constant and the effective radius of the rotor is usually small (on centimeter scale), the natural resonance frequency is more than dozens of radians per second, which is far greater than that of human motion. Therefore, the harvester can't achieve resonance during normal walking even if the stiffness of the torsion spring can be tuned. The function of the torsion spring is to make the harvester work even when it is placed on the horizontal plane where gravity fails. In other words, the torsion spring replaces gravity, so the value of the torsion spring stiffness can be calculated by $k = mg$. Simulation also shows that the torsion spring stiffness has a tiny effect on the power output. Since the power level of the harvester is low and in AC voltage, ranging from several to hundreds of milliwatts, and the loads usually require steady DC bus for their operation, a direct AC/DC converter developed by Dwari [10] is used to rectify and boost the voltage.

## 5. Conclusions

Based on the discussion above, the following conclusions

can be drawn:

(1) A novel harvester for harvesting human kinetic energy is presented. The harvester is based on both the oscillating principle and electromagnetic induction, as it uses an eccentric rotor made of permanent magnet and coils as stator. With a torsion spring, the harvester works even when placed on the horizontal plane.

(2) Theoretical investigation and numerical analysis is made, showing that total mass and effective radius of the rotor, the arm swing frequency and amplitude are critical to the power output. The structural topology of the rotor also has obvious impact on the power output.

(3) The harvester can be served as the middleware to portable electronics, such as cell phones and photoelectric mouse. This energy harvesting principle can also be applied to extract kinetic energy from other kinds of movement.

## Acknowledgment

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