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Design and Analysis of a Mechanical Device to Harvest Energy From Human Footstep Motion

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Abstract: Portable electronics is usually powered by battery, which is not sustainable not only to the longtime outdoor use but also to our living environment. There is rich kinetic energy in footstep motion during walking, so it is ideal to harvest the kinetic energy from human footstep motion as power source for portable electronic devices. In this paper, a novel mechanism based on dual-oscillating mode is designed to harvest the kinetic energy from footstep motion. The harvester contains two oscillating sub-mechanisms: one is spring-mass oscillator to absorb the vibration from external excitation, *i.e.* the footstep motion, and the other is cantilever beam with tip mass for amplifying the vibration. Theoretic analysis shows that the dual-oscillating mechanism can be more effectively harness the foot step motion. The energy conversion sub-mechanism is based on the electromagnetic induction, where the wire coils fixed at the tip end of the cantilever beam serves as the slider and permanent magnets and yoke form the changing magnetic field. Simulation shows that the harvester, with total mass 70 g, can produce about 100 mW of electricity at the walking speed of 2 steps per second.

Key words: energy harvesting, dual-oscillating mechanism, human motion

1 Introduction

In recent years, humans have become increasingly dependent on electronic devices, such as mobile phones, PDAs, and etc. Especially for soldiers in remote area, they need to use electronic devices for communication or other necessary functions, such as the US Army Land Warrior system providing radio, navigation, computer for soldiers[1]. Nowadays, most of these mobile electronic devices are powered by batteries. Although substantial progresses have been made in reducing the power requirements of the electronic devices and increasing the power densities of batteries, the limited energy storage of battery and its considerable weight hinder the extensive use of electronic devices. For example, the above-mentioned Land Warrior system needs 5 kg of battery to reach the design goal, which is inconvenient for soldier application. Furthermore, discarded battery generates billions of wastes every year, resulting in negative environment impacts. Therefore, it is necessary to find alternative methods to solve the energy problem for portable electronic devices.

The human body is a tremendous resource of chemical energy, some of which is converted into kinetic energy to support human activities. The store chemical energy of an average person of 68kg with 15% body fat is approximately equivalent to 384 MJ [2]. Thus, if even a very small fraction of this stored energy could be extracted, a portable device would have a large and renewable resource to draw on. Some researchers have explored to extract energy from body heat[3, 4], breathing[5], typing[6], arm motion[7], and walking[8, 9]. Walking is a main energy consumption activity which also has mechanical power to be exploited. It has been calculated that up to 67 W of power are available from heel strike during normal walking for a 68 kg person with the walking frequency at 2 steps per second[2]. There are mainly two methods to harvest the heel strike energy during human walking. One is to use piezoelectric effect to convert the pressure generated when the foot strikes the ground to electricity, but the energy density of piezoelectric harvester is very low (on the scale of milliwatts)[10]. Another is to us electromagnetic induction to convert body motion into electricity. CHEN[11] and LAKIC[12] reported electromechanical generators to convert the footstep motion. However these designs are very complex with many parts, and can only harvest the press-down motion, which make these device is fragile, expensive and lower efficiency.

This paper is focused on how to harvest the kinetic energy from human footstep motion based on dual-oscillating mechanism and electromagnetic induction. In order to avoid the fragile contact between the transmission components, the design presented in this paper adopts a dual-oscillating mechanism to harvest footstep motion. Because the harvester only absorbs the acceleration

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from footstep motion and needn't transmit motion directly from heel strike, it is stronger and more reliable than other designs with similar functions. And what's more, the design is based on the mass-spring oscillating mechanism, so it can harness not only the heel strike motion, but also the acceleration during foot swing, which can contribute to higher energy efficiency. The rest of this paper is organized as follows. Section 2 illustrates the physical model of the harvester. Section 3 conducts the system analysis, including electromagnetic and kinematical analysis. Section 4 shows the system performance during normal walking. Section 5 contains the conclusions.

2 Physical Model of the Harvester

The bottom rear part of a shoe, i.e. the heel, is designed to support the heel of the foot, which is usually higher than the shoe sole. Therefore it is ideal to employ the room of the shoe heel to set up a harvester to harness the footstep motion. Fig. 1 shows the appearance of the harvester, which is a box container where the harvester is fixed. The container is made of non-magnetic mental to endure human body weight and the impulsive force from heel strike. There are two helical springs on the harvester: one is attached to the bottom base of the container, and the other is attached to the upper cover of the container. And the container cover is fixed via screws to the container body.

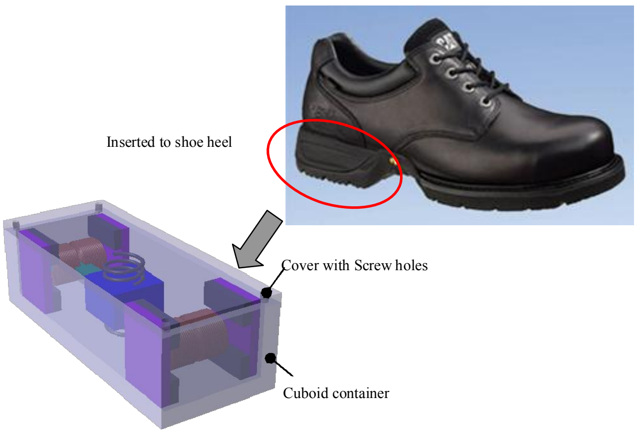

Fig. 1. The overview of the dual-oscillating harvester

The harvester is symmetric, and there are independent magnetic fields in the harvester. As shown in Fig.2, there are two sets of components to produce magnetic field arranged at the two ends of container body. Each set is composed of two pairs of NdFeB permanent magnets arranged in opposite magnetization direction and yoke made of electric steel. Permanent magnets are attached to yoke, which forms a magnetic circuit with the counterpart.

The oscillating mechanism is used to produce vibration from external excitation, as shown in Fig. 3. There are a proof mass, called oscillating weight, and two helical springs attached to the oscillating weight, which forms the first tier of oscillating mechanism to absorb the external excitation. Two identical cantilever beams attached to the oscillating weight, and the weight at its tip end, make up of the second tier of oscillating mechanism to amplify the vibration from the oscillating weight. The wire coils are wound at the tip end of the cantilever beam as the proof mass for the second tier of the oscillating mechanism. With the magnetic field produced by permanent magnets, the vibration from the two tiers of oscillating mechanism makes the wire coils generate induction voltage.

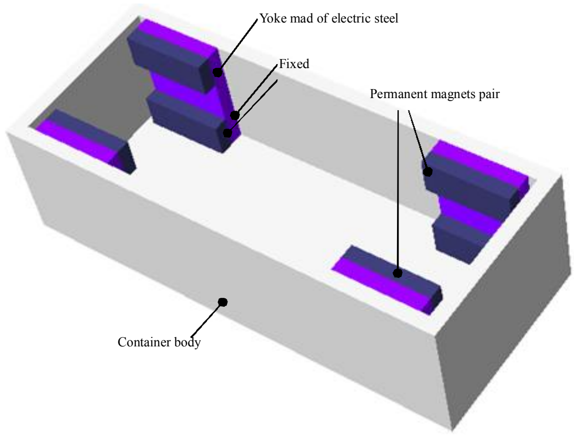

Fig. 2. Structure for producing magnetic field

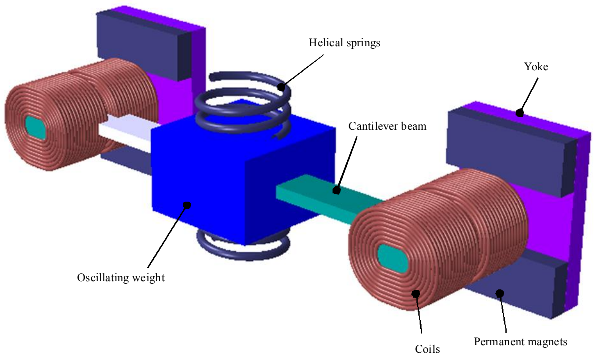

Fig. 3. Structure of the oscillating mechanism

Abstracted from the physical model, Fig. 4 shows the schematic diagram of the harvester, which can be divided into three functional parts: vibration absorber, vibration amplifier and harvesting mechanism. The vibration absorber, consisting of an oscillating weight and two helical springs attached to the oscillating weight and the container base, transmits vibration from external excitation to the oscillating weight. The vibration amplifier consists of a cantilever beam and a tip mass composed of the wire coils and their iron core, which is similar to spring-mass system, to amplify the vibration from the oscillating weight. The harvesting mechanism mainly consists of permanent magnet pairs and coils. The magnets are arranged to produce changing magnetic field, from which the moving coils can produce induced voltage due to the electromagnetic induction effect.

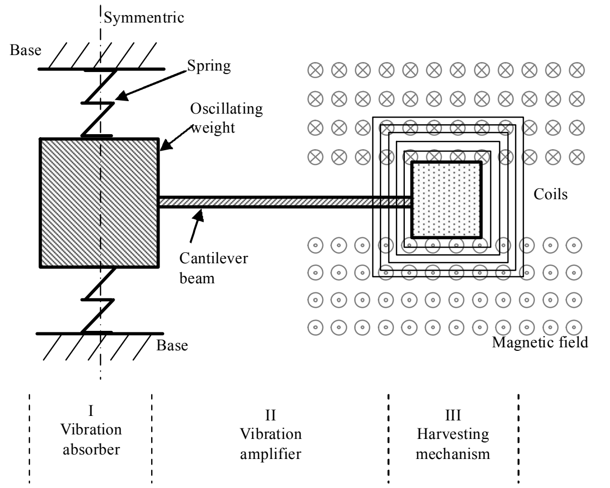

Fig. 4. Schematic diagram of the dual-oscillating harvester

3 System Analysis

The energy conversion, from kinetic energy to electricity, is based on electromagnetic induction. The schematic diagram of magnetic structure and magnetic flux path are shown in Fig. 5. There are two pairs of permanent magnets separated by plastic spacers, arranged with different magnetization direction to produce different flux directions. All permanent magnets are attached to yoke made of electric steel. Yoke and permanent magnets constitute the magnetic flux path, shown as dash lines in Fig. 5. In this harvester, the magnets, yokes and spacers are all symmetric, so the coordinate is created at the symmetric center where *Z* direction is perpendicular to the ground and *X* direction is the magnetization direction of the permanents. When the harvester is excited by external motion, the coils will vibrate on the *YOZ* plane where the magnetic flux is at its maximum.

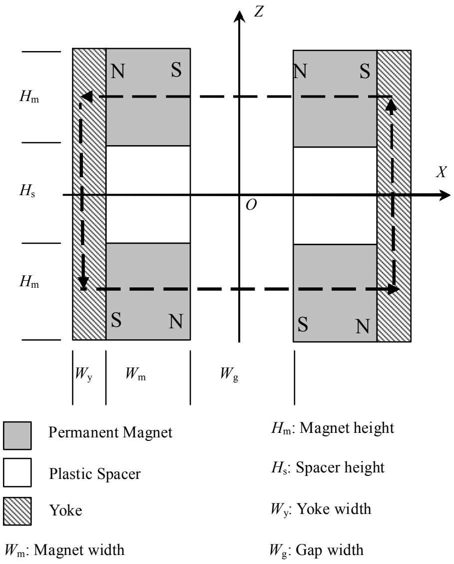

Fig. 5. Schematic diagram of magnetic structure and the flux paths

FEA models were built in Ansys® to investigate the magnetic field. The structures related to magnetic field are simplified as Fig. 6, where the areas with different material properties are displayed in different color. There are four types of material areas: permanent magnets magnetized from left to right (in red), permanent magnets magnetized from right to left (in deep blue), the electric steels (in pink) and the air area (in light blue).

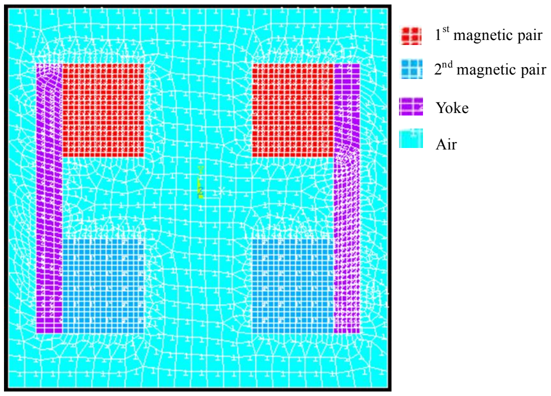

Fig. 6. FEA model and its mesh in Ansys®

The density of 2D flux lines, shown in Fig. 7, also indicates that the flux density is concentrated around the magnetic circuit. It also shows the flux distribution of the magnetic field, from which the flux density at the center of pole pitch is higher than that at the fringes.

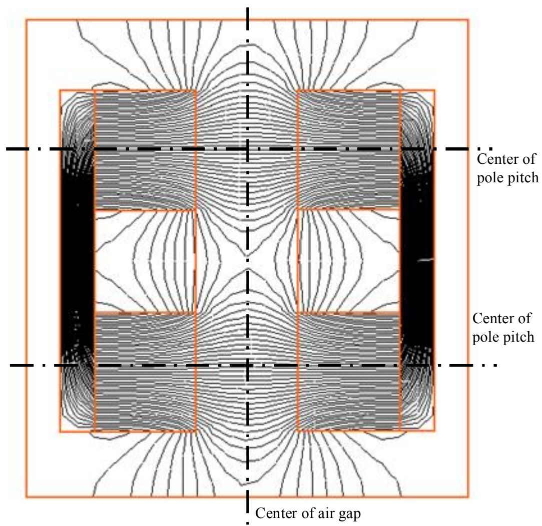

Fig. 7. 2D Flux distribution of the magnetic field

For a single coil lying on the *YOZ* plane at the position $x = x_0$, the density of magnetic flux through the coil is changing along *Z* direction, so the total flux through the coil should be calculated by integral by the following equation, where $B(x_0, z)$ is the flux density at point (x_0, z) and there is the assumption of equal distribution of flux density along *Y* direction:

$$\Phi_c = \int_{z-\frac{H_c}{2}}^{z+\frac{H_c}{2}} B(x_0, \hat{z}) \cdot D \cdot d\hat{z} \quad . \tag{1}$$

Where D is the thickness of the permanent magnet, and H_c is the height of the coil. Based on the Faraday's Law, the induction voltage of a single coil is

$$\varepsilon=\frac{\mathrm{d}\Phi_c}{\mathrm{d}t}=\frac{\mathrm{d}\Phi_c}{\mathrm{d}z}\frac{\mathrm{d}z}{\mathrm{d}t}=\frac{\mathrm{d}}{\mathrm{d}z}\left(\int_{z-\frac{H_c}{2}}^{z+\frac{H_c}{2}}B(x_0,\hat{z})\cdot D\cdot \mathrm{d}\hat{z}\right)\cdot\dot{z}\ . \quad (2)$$

For simplification, the height of winding coils can be equivalent to the height of the middle layer H_{cm}, and assumed that there are N coils, so the total induction voltage at one end of cantilever beam is

$$\begin{aligned}V&=N\frac{\mathrm{d}\Phi_c}{\mathrm{d}t}=N\frac{\mathrm{d}\Phi_c}{\mathrm{d}z}\frac{\mathrm{d}z}{\mathrm{d}t}\\&=N\frac{\mathrm{d}}{\mathrm{d}z}\left(\int_{z-\frac{H_{cm}}{2}}^{z+\frac{H_{cm}}{2}}B(x_0,\hat{z})\cdot D\cdot \mathrm{d}\hat{z}\right)\cdot\dot{z}\end{aligned}\ . \quad (3)$$

The electrical damping force converts the kinetic energy to electricity, so the power done by the electrical damping force should be equal to the one done by electricity, that is:

$$F_e\cdot\dot{z}=-\frac{V^2}{R_c+R_e+R_L}\ . \quad (4)$$

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. Inserting Eq. (3) into Eq. (4), then the electrical damping force is

$$F_e=-\frac{\left[N\cdot D\cdot\frac{\mathrm{d}}{\mathrm{d}z}\left(\int_{z-\frac{H_{cm}}{2}}^{z+\frac{H_{cm}}{2}}B(x_0,\hat{z})\cdot \mathrm{d}\hat{z}\right)\right]^2}{R_c+R_e+R_L}\cdot\dot{z}\ . \quad (5)$$

Define the electrical damping coefficient C_e as

$$C_e=\frac{\left[N\cdot D\cdot\frac{\mathrm{d}}{\mathrm{d}z}\left(\int_{z-\frac{H_{cm}}{2}}^{z+\frac{H_{cm}}{2}}B(x_0,\hat{z})\cdot \mathrm{d}\hat{z}\right)\right]^2}{R_c+R_e+R_L}\ . \quad (6)$$

There are two coupled sub-oscillating mechanism in this harvesting system: the vibration absorber and the vibration amplifier. The vibration amplifier is a rectangular cantilever beam with a tip mass m_2 which made up of a non-magnetic material core and the wire coils wound around the core. For analysis convenient, the cantilever beam can be equivalent to a spring with the spring constant $k_2=Ebh^3/(4L^3)$, where b, h and L are the width, thickness and the length of the beam, respectively; and E is the Young's module of the beam. Since the mass of the beam is much less than the tip mass, its mass is neglected for analysis convenience. The vibration amplifier is subject to both the mechanical damping force C_{m_2} and the electrical damping force C_e which represents the energy converted into electricity.

For the vibration absorber, there are two helical springs attached to the oscillating weight m_1, which can be combined together and has a combined spring constant k_1, calculated by $k_1=[k_{11}+k_{12}]$, where k_{11} and k_{12} are the spring constant of the upper and lower spring respectively. The vibration absorber is also subject to mechanical damping force C_{m_1}.

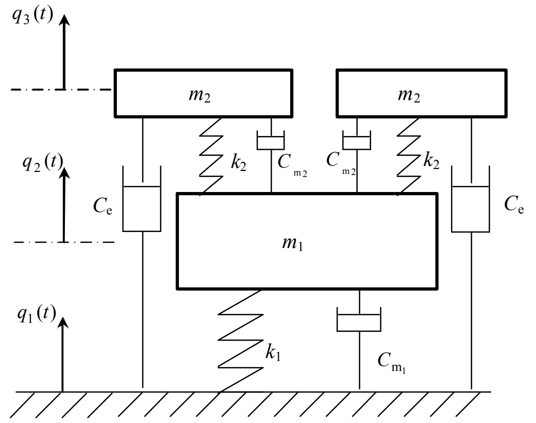

Fig. 8.　Schematic model of the oscillating mechanism

Fig. 8 shows the coupled schematic model of the oscillating mechanism, where base excitation is $q_1(t)$, and the displacements of the oscillating weight of the vibration absorber and tip mass of the vibration amplifier are $q_2(t)$ and $q_3(t)$ respectively, then the kinetic energy, potential energy and Rayleigh potential can be obtained as following. With the lagrangian method and let $z=q_3-q_1$, $y=q_2-q_1$ and $x=q_1$, the governing equation of the harvester can be expressed as

$$\begin{aligned}&\begin{bmatrix}m_1&0\\0&2m_2\end{bmatrix}\begin{bmatrix}\ddot{y}\\\ddot{z}\end{bmatrix}+\begin{bmatrix}C_{m_1}+2C_{m_2}&-2C_{m_2}\\-2C_{m_2}&2(C_{m_2}+C_e)\end{bmatrix}\begin{bmatrix}\dot{y}\\\dot{z}\end{bmatrix}+\\&\begin{bmatrix}k_1+2k_2&-2k_2\\-2k_2&2k_2\end{bmatrix}\begin{bmatrix}y\\z\end{bmatrix}=\begin{bmatrix}-m_1\ddot{x}-m_1g\\-2m_2\ddot{x}-2m_2g\end{bmatrix}\end{aligned}\ . \quad (7)$$

4 System Performance

This dual-oscillating harvester is used to harvest the vertical acceleration of human footstep motion not only during the foot swinging process but also when the foot heel strike the ground. Therefore there are two major components of the footstep acceleration: one is from the foot stride along with the body trunk, which is equal to the vertical acceleration of the body center; the other is from heel strike against the ground during walking, which can be expressed as a step function. Since the body center can be modeled as an inverted pendulum, therefore the vertical acceleration of body center can be expressed as a sine wave function as $x = a_0 \sin(\omega t)$, where a_0 can be obtained from experiment and is related to body weight, foot stride and frequency. Then the foot acceleration on the vertical direction can be expressed as by combining a sine function with a step function. Fig. 9 shows the sine acceleration from foot swing, step acceleration from foot strike and their combination.

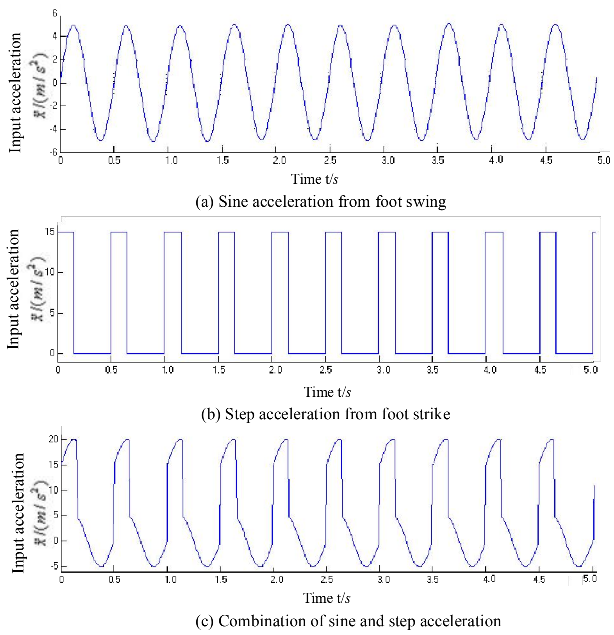

Fig. 9. Acceleration performance during foot swinging

First of all, the system kinematical performance is studied at the condition of open circuit, that is, there is no power output. The system parameters for obtaining the kinematical performance and simulation are shown in Table 1.

Fig. 10 shows the relative velocity of oscillating weight and coils in terms of time (upper figure) with the external input of sine function (lower figure) from the footstep acceleration during normal walking (2 steps per second). From the figure, the vibration amplifier can obviously speed up the vibration from oscillating weight, which can contribute to higher power output.

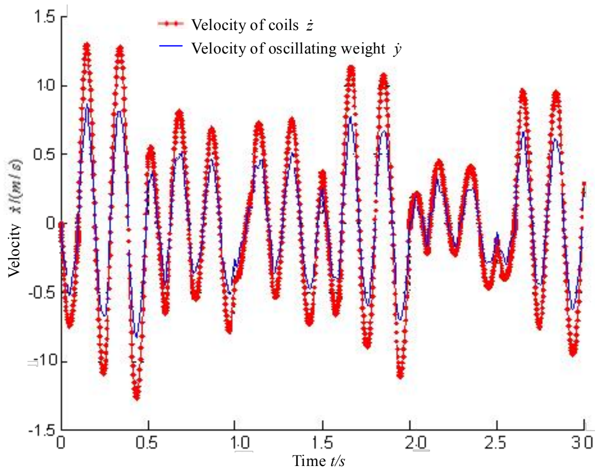

Fig. 10. Velocity response from footstep acceleration

Table 1. System parameters for simulation

Parameter	Value
Rigidity modulus of the helical spring G/GPa	80
Wire diameter of the helical spring d/mm	1
The Mean diameter of the spring D/mm	8
No. of active coils of the spring n	5
The spring constant k_1	$k_1 = G \cdot d^4 / 8n \cdot D^3$
Young's module of cantilever beam E/GPa	71
Width of the cantilever beam b/mm	1.5
Height of the cantilever beam h/mm	0.5
Length of the cantilever beam L/mm	15
Equivalent constant of the cantilever beam k_2	$k_2 = Ebh^3 / 4L^3$
The mass of oscillating weight m_1/g	10
The mass of tip mass at cantilever beam m_2/g	20
Damping coef. of the oscillating weight C_{m_1}	$C_{m_1} = 2\xi\sqrt{k_1(m_1 + 2m_2)}$
Damping coef. of the cantilever beam C_{m_2}	$C_{m_2} = 2\xi\sqrt{k_1 \cdot m_2}$

With the relative velocity of the coils and the electrical damping coefficient C_e, the transient power output can be calculated by $p = C_e \cdot \dot{z}^2$. Fig. 11 shows the transient power output of the harvester from the footstep acceleration. Since the acceleration from heel strike is bigger than that from the foot swing, the power output performance also shows that there is higher power output at the time of heel strike.

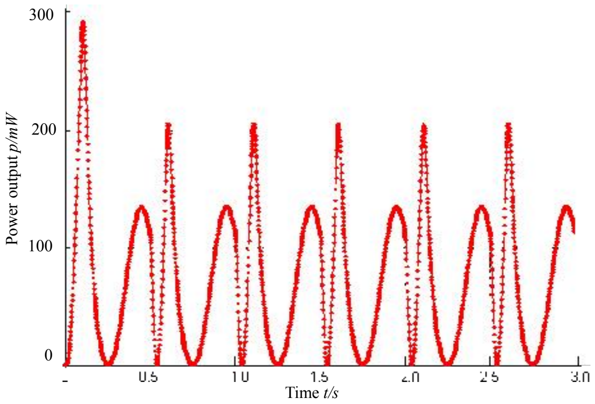

Fig. 11.　Transient power output

Since the power output is fluctuant and the charge for electronics usually requires steady DC power supplier, a direct AC/DC converter developed by DWARI[13] is used to rectify and boost the voltage. Neglecting the energy loss in the power rectifier, the average power output can be calculated by the integral of the electrical damping force and the relative velocity. The average power output from Fig. 11 is about 100 mW at the walking speed of 2 steps per second.

5　Conclusions

(1) A novel mechanism for energy harvesting from human footstep motion is presented. It adopts the dual-oscillating mode to harness acceleration from footstep, including the mass-spring oscillating sub-mechanism absorb external excitation and the cantilever beam with tip mass to amplify the vibration, and the electromagnetic induction to convert kinetic energy to electricity.

(2) Electromagnetic and kinematical analyses are conducted to study the harvester's performance. Analysis shows that the dual-oscillating mechanism can more effectively amplify the vibration which contributes to higher power output.

(3) The dual-oscillating mechanism does not transmit motion and not directly contact with the input component, so it is stronger and more reliable than other designs of similar function.

(4) The harvester is designed to insert into shoe heel as power supplier for portable electronics, especially for the use in wild area. This energy harvesting principle can also be applied to extract kinetic energy from other kind of movement.

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