Energy Harvesting from Human Motion Using Footstep-Induced Airflow

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Energy Harvesting from Human Motion Using Footstep-Induced Airflow

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Abstract. This paper presents an unobtrusive in-shoe energy harvester converting foot-strike energy into electricity to power wearable or portable devices. An air-pumped turbine system is developed to address the issues of the limited vertical deformation of shoes and the low frequency of human motion that impede harvesting energy from this source. The air pump is employed to convert the vertical foot-strike motion into airflow. The generated airflow passes through the miniaturized wind turbine whose transduction is realized by an electromagnetic generator. Energy is extracted from the generator with a higher frequency than that of footsteps, boosting the output power of the device. The turbine casing is specifically designed to enable the device to operate continuously with airflow in both directions. A prototype was fabricated and then tested under different situations. A 6 mW peak power output was obtained with a 4.9 Ω load. The achievable power from this design was estimated theoretically for understanding and further improvement.

1. Introduction

Wearable or portable devices are becoming increasingly popular in our daily lives, including smart watches, health monitors, radio frequency identification tags and emergency locators [1, 2]. However, they are generally powered by batteries that have a limited lifetime. Replacement or recharging is needed regularly, which is inconvenient in some situations. Harvesting wasted energy from human motion to power these devices is a potential alternative to conventional batteries, enabling the devices to be autonomous and fit-and-forget [3].

Extracting energy from foot strike has drawn significant interest [4-6], as the energy from foot-strike during walking is a plentiful and readily tapped wasted energy source [4]. However, it is always in a low frequency range and the deformation of shoe heel is quite limited, which exposes power limits for foot-strike energy harvesting. One interesting development to address these issues is a rotary arm converting the vertical linear motion of footsteps into rotation with a gearbox employed to magnify the rotational speed [5]. However, the rotary arm affects the shoe's comfort, and the gear train increases the manufacturing complexity and system unreliability. Moro *et al*. proposed a piezoelectric shoe energy harvester [6]. Although the structure of the device is simpler, its performance is limited due to the low operating frequency and the restricted volume of piezoelectric material. In this paper, a flexible air pump is employed to convert the vertical footstep motion into airflow, and a miniature wind generator is developed to generate electricity from the airflow at high frequencies. This design

overcomes the difficulties in foot-strike energy harvesting mentioned above with a simpler structure and an enhanced power output.

2. Design and Operating Principle

The schematic of the device is presented in Figure 1. It consists of an air bulb pump and a miniature wind turbine. The pump converts the vertical distortion of shoes into airflow, and the turbine generates electrical energy from the passing airflow. The pump cover is constructed from latex rubber, and a wave spring is adopted to restore the shape of the pump after each strike. In order to enhance the speed and pressure of the airflow, an amplification mechanism is achieved by designing a shrunken outlet on the pump. Its sectional area is 500 times smaller than that of the pump, which means the airflow velocity is magnified up to 500 times on entry to the plastic tube. The airflow then passes through the wind turbine and energy is collected from a miniature DC motor as a generator attached to the turbine impeller. This design allows the turbine rotor to operate at a higher frequency than that of human motion. Thus, frequency up-conversion is achieved by the air pump-wind turbine system, addressing the issue of low frequency of footstep and boosting the power output.

The device is installed in the shoe heel, as shown in Figure 2. Due to the miniaturized size, the harvester can be embedded in a shoe heel unobtrusively. The support provided by the wave spring is stiff enough to ensure the wearer's comfort. When a footstep is applied to the air cushion, the pump is deformed and air in the pump is pushed forward to the turbine. When the force is removed, the pump shape is restored by the spring force, and a reversed airflow is generated in the device, further activating the turbine.
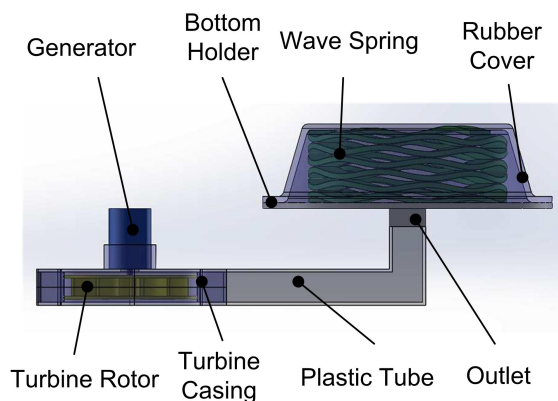

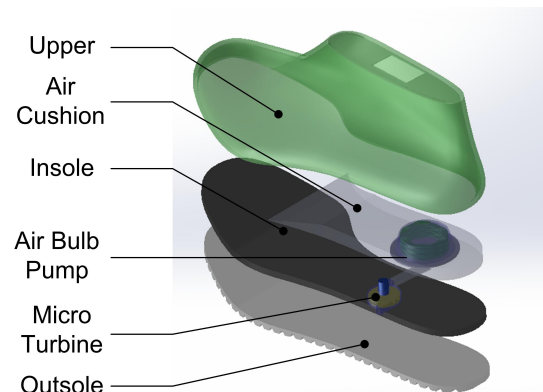Figure 1. Schematic of the shoe energy harvester.

Figure 2. Installation and composition of the harvester in a shoe.

The inlet and outlet of the turbine is designed specially to ensure the airflow direction to be the same during and after each foot strike (Figure 3). The rotational direction of the turbine rotor, therefore, remains uniform during the entire motion cycle, which enables the continuous operation of the device during human motion.

3. Prototype and Experimental Set-up

A prototype of the harvester was built, as illustrated in Figure 4. An air pump was mounted on a sheet of stainless steel with the dimension of 120 mm × 60 mm × 13 mm. It is smaller than the foot heel of a shoe of size 9 (UK). A miniaturized wind turbine was fabricated using rapid prototyping with ABS materials. These two parts were connected by a plastic tube whose cross-sectional area (~Ø4 mm) was 500 times smaller than that of the pump. The overall dimension of the turbine was Ø12 mm × 6 mm, and its transduction was achieved by a DC motor with the dimension of Ø7 mm × 15 mm. The air pump was actuated by normal footsteps from a person weighing 65 kg.
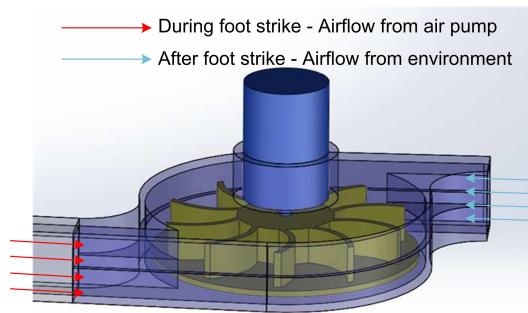
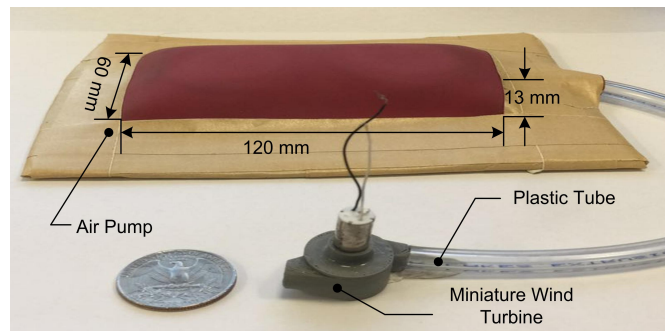Figure 3. Design of the wind turbine with two generation cycles per foot strike.

Figure 4. Experimental set-up with a 25¢ US coin as reference.

4. Results

The device was tested under different situations. Figure 5 shows the open-circuit output voltage during walking and running. In walking situations (1 Hz), the turbine rotates intermittently, whereas it can rotate continuously during running (4 Hz). The continuous motion also proves the successful implementation of the inlet and outlet design (Figure 3) for the uniform rotational direction of the turbine during and after each foot strike.
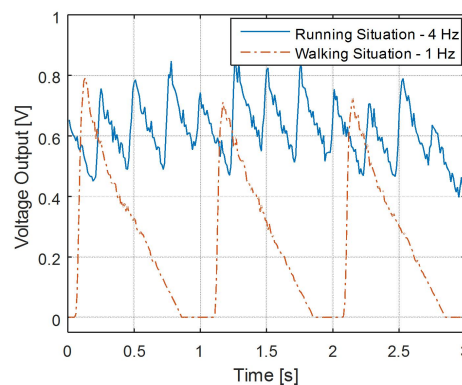

Figure 5. Open-circuit voltage output for different motion situations.
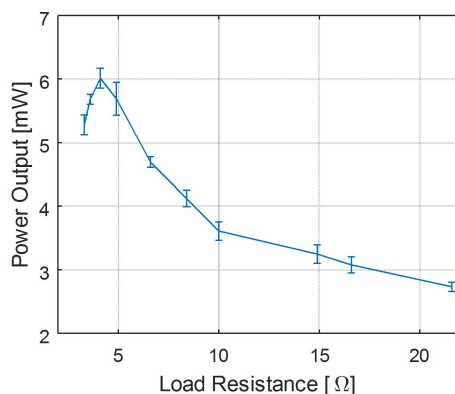

Figure 6. Measured peak power output for a single footstep versus different load resistances.
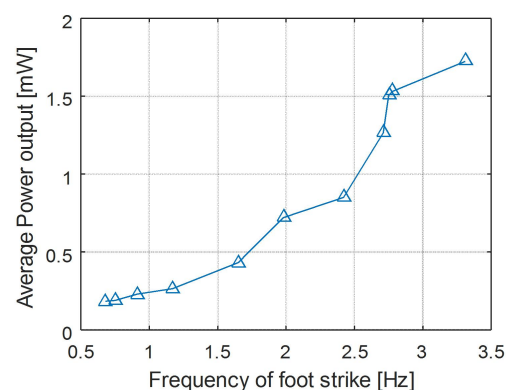

Figure 7. Average power output with different footstep frequencies.

Figure 6 illustrates the measured peak power output for a single footstep with varying load resistances. A 6 mW power output was obtained with a 4.9 Ω load which is identical to the motor's internal resistance. Figure 7 depicts the power output against footstep frequency. The average power output is on the mW scale, which is enough to power certain wireless sensors monitoring the condition of a human body. The device was finally embedded into a running shoe as shown in Figure 8. More tests will be carried out on a treadmill in future work.
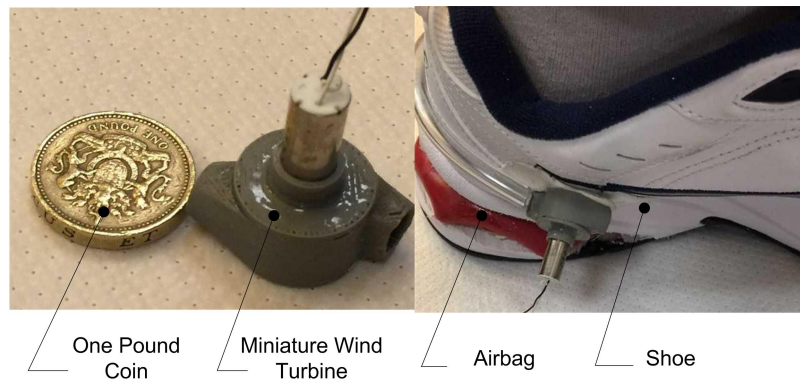
Figure 8. An integrated shoe energy harvester.

5. Achievable Energy in Theory

In order to understand the potential achievable power from this mechanism, the upper limit and the theoretically achievable power of using this specific method are estimated analytically, showing the potential improvement of the power output and the unimpeded nature of the harvester to human motion due to the marginal energy extracted.

5.1. Upper Limit of Power Output

The upper limit is estimated without considering the specific operating mechanism. It is defined as the work done on an enclosed air pump during a foot strike. Assuming it is an isotropic process and the temperature, T, is constant, the energy needed to compress the air by a ratio of λ can be calculated using the following equation.

$$W = \int p\,dv = nRT \int dv/v = nRT \ln(\lambda) \tag{1}$$

where p is the air pressure, v is the volume of the air, n is the number of moles of gas present and R is the ideal gas constant.

Assuming that the striking happens in a gradual process, the momentum of human motion can be neglected. Therefore, for a person weighing m, the compressing ratio can be calculated using

$$\lambda = v/v_0 = p_0/p = \frac{p_0}{mg/A_a + p_0} = \frac{1\times10^5}{637 \big/ \left(7.2\times10^{-3}\right) + 1\times10^5} = \frac{1}{1.87} \tag{2}$$

where m is the mass of a person, g is the gravitational acceleration, A_a is the sectional area of the air pump and p_0 is the initial pressure of the air in the air pump.

In the test, the weight of the person was 65 kg. The maximum power that can be obtained from each foot strike by the air pump for a compressing and releasing process is

$$W = nRT \ln\left(\frac{mg/A_a + p_0}{p_0}\right) = \frac{0.1}{22.4}\times8.31\times293.2\times\ln\left(\frac{1}{1.87}\right) = -6.55\ \text{J} \tag{3}$$

where the negative sign means the work done on the air.

For a walking frequency of 1 Hz, the maximum power obtained by the air pump is

$$P = W/T = 6.55\times1 = 6.55\ \text{W} \tag{4}$$

The estimated upper limit of power output using this transduction is similar to the estimation in [7].

5.2. Theoretical Achievable Energy of This Mechanism

For this specific design, the compressed and accelerated airflow in the pump is used to drive an electromagnetic turbine. Assuming the airflow exiting the wind turbine at an increased speed with a

modest pressure, the energy collected from the foot strike can be calculated from the kinetic energy of the airflow which is

$$E = \frac{1}{2} m_a v_a^2 \tag{5}$$

where m_a is the mass of the air and v_a is the velocity of the airflow exiting the turbine. In practice, wind turbines has a theoretical maximum power coefficient C_p of 0.593 [8]. According to the result from Figure 5, the working duration of each footstep on the air pump is around 0.1 s and the displacement of the air pump is about 10 mm. Hence, the velocity of the airflow entering the turbine can be up to 50 m/s considering the amplification factor (δ=500).

The energy obtained from each foot strike on the specific air pump mentioned above is

$$E = \frac{1}{2} C_p \cdot m_a \cdot (\delta \cdot v_0)^2 = \frac{1}{2} \cdot 0.593 \cdot (0.12 \times 0.06 \times 0.013 \times 1.29) \cdot (500 \cdot 0.1)^2 = 0.0895 \text{ J} \tag{6}$$

The theoretically achievable power from 1 Hz foot strikes is 89.5 mW. Therefore, the efficiency of the current design at 1 Hz is ~0.28% (0.25/89.5). It indicates that the comfort or feel of shoes is not affected due to the marginal energy extracted, and that the power output can be increased by an order of magnitude or more with appropriate design. Apparently, the theoretically achievable power highly depends on the amplification factor that is adjustable in the design process. Further investigation will be conducted to optimize the structure.

6. Conclusions

In this paper, an in-shoe energy harvester is developed to harness foot-strike energy. An air-pumped turbine system is designed to solve the difficulties of harvesting energy from foot strike, including the limited vertical distortion and the low motion frequency. An amplification mechanism for airflow speed is achieved by designing the air pump and turbine inlet with different cross-section areas. The turbine is activated by airflow and operates with a high frequency, enabling the foot-strike energy to be harvested with a higher frequency. The turbine casing is designed specifically to enable the device to operate continuously with airflow from both directions.

A prototype was fabricated and then tested under different situations. A 6 mW peak power output was obtained with a 4.9 Ω load. The achievable power from this design was estimated theoretically, showing the marginal energy extracted from human motion and the potential improvement of the power output. Future work will be on improving the efficiency of the system and exploring potential applications.

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