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Power Harvesting In Shoes with Android Mobiles


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Abstract:

Abstract: Harvesting mechanical energy from human motion is an attractive approach for obtaining clean and sustainable electric energy to power wearable sensors, which are widely used for health monitoring, activity recognition, gait analysis and so on. This paper studies a piezoelectric energy harvester for the parasitic mechanical energy in shoes originated from human motion. The harvester is based on a specially designed sandwich structure with a thin thickness, which makes it readily compatible with a shoe. Besides, consideration is given to both high performance and excellent durability.The harvester provides an average output power of 1 mW during a walk at a frequency of roughly 1 Hz. Furthermore, a direct current (DC) power supply is built through integrating the harvester with a power management circuit. The DC power supply is tested by driving a simulated wireless transmitter, which can be activated once every 2–3 steps with an active period lasting 5 ms and a mean power of 50 mW. This work demonstrates the feasibility of applying piezoelectric energy harvesters to power wearable sensors.

Keywords:

Energy harvester; wearable sensors; power supply; wearable energy harvester.

1.Introduction:

Wearable sensors are becoming smaller and increasingly widely used, resulting in an increasing need for independent and compact power supplies. Electrochemical batteries, the most common power supplies for wearable sensors, cannot meet the need because of their limited energy storage capacity and potential environmental and health risks, emerging as a critical bottleneck for wearable sensors.

This has driven the development of wearable energy harvesters, which harvest the mechanical energy dissipated in human motion to provide renewable and clean energy. Several concepts of wearable energy harvesters based on different mechanisms have been studied, such as electromagnetic, electrostatic, thermoelectric, nano-triboelectric and piezoelectric. Piezoelectric energy harvesters and nano-triboelectric generators can convert mechanical energy into electric energy directly, thus their structures are more compact and simpler in comparison to those of other types. The materials for nano-triboelectric generators are generally not accessible in the market, hence this work focuses on piezoelectric energy harvesters. Lead zirconate titanate (PZT) and polyvinylidene difluoride (PVDF) are the two most important piezoelectric materials for energy harvesting, owing to their high piezoelectric performance. PZT is rigid, brittle, and heavy, bringing limitations in wearable applications where flexibility is necessary. PVDF has considerable flexibility, good stability, and is easy to handle and shape. Taking into account the human motion characteristics of high amplitude and low frequency, PVDF is more appropriate for wearable applications than PZT. PVDF has been used in wearable energy harvesters that are implemented in shoes , bags and clothing. Kymissis, et al. developed an insole made of eight-layer stacks of 28 μm PVDF sheets with a central 2 mm flexible plastic substrate. It harnessed the parasitic energy in shoes and the average power reached 1.1 mW at 1 Hz. Granstrom, et al. utilized PVDF straps as backpack shoulder straps to collect mechanical energy produced by the backpack, with an average power of 45.6 mW during a walking of 0.9–1.3 m/s. Yang and Yun fabricated a PVDF shell structure generating an output power of 0.87 mW at a folding angle of 80° and a folding-and-unfolding frequency of 3.3 Hz, which could be worn on the elbow joint to harvest energy from human motion. The mechanical energy dissipated in shoes can even power a computer, serving as an attractive energy source for wearable harvesters.

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This paper develops a shoe-embedded piezoelectric energy harvester, which can be integrated in a shoe readily for energy harvesting from human locomotion with little discomfort for the wearers. The harvester is based on a specially designed sandwich structure, resulting in a thin geometrical form, a high performance and an excellent durability. Two harvester prototypes are made and tested. The first one is made up of a multilayer PVDF film and a structure of engineering plastics, which is placed under the heel.

The second one is designed as an insole shape and used as a normal insole, consisting of a structure of flexible silicone rubber and two multilayer PVDF films. More power can be generated by the former prototype, while the other one has an advantage of remarkable comfort. In order to store the harvested energy and provide a constant DC output voltage, a power management circuit is designed. A series of experiments are performed to characterize the harvester prototypes, proving that the harvester can serve as a wearable power supply for low power wearable sensors and potentially provide a valuable alternative to the use of batteries.

2. Harvester Design:

The main structure of the harvester is a sandwich structure, where a multilayer PVDF film is sandwiched between two wavy surfaces of a movable upper plate and a lower plate, as shown in Figure 1a. The multilayer PVDF film (Figure 1b) is fixed on the lower plate, and composed of several PVDF layers which are wired in parallel for a high output current. When the upper plate is subject to a compressive force produced by foot, the upper plate moves down and the PVDF film is stretched along 1-axis simultaneously, as presented in Figure 1c. This leads to a piezoelectric field created inside every PVDF layer, driving the free electrons in the external circuit to accumulate on the upper and lower 3-axis surfaces (electrodes) of every PVDF layer to screen the piezo-potential.

When the force is lifted, the upper plate moves up and the PVDF film is relaxed, therefore the piezo-potential diminishes, resulting in releasing the accumulated electrons. A dynamic force Ffoot applied by foot on the upper plate drives the electrons in the external circuit to flow back and forth with an alternating current (AC) output. The sandwich structure is characterized by the inner wavy surfaces, where arc-shaped grooves and arc-shaped ribs exist.

3. Fabrication:

Two prototypes of the harvester are fabricated for two different purposes. Prototype 1 is made up of a multilayer PVDF film and a structure of rigid engineering plastics, for a high output power. Prototype 2 is designed as an insole shape, consisting of a structure of flexible silicone rubber and two multilayer PVDF films, with an advantage of excellent comfort. The multilayer PVDF film is composed of a stack of several PVDF layers connected in parallel. The properties of the PVDF layers are listed in Table 2. In order to provide a DC source for electronics, a power management circuit is utilized.

3.1. Fabrication of Prototype 1:

Prototype 1 is designed to exploit the high pressure exerted in heel strikes. The schematic of Prototype 1 is shown in Figure 3a. The upper plate and the lower plate are made of engineering plastics whose stiffness is far greater than that of the PVDF film. The multilayer PVDF film is bolted to the lower plate, as presented in Figure 3b. According to Table 2, the elastic region of the PVDF layer is about 0%–2%. Hence, the normal strain $\varepsilon 1$ should be no more than 2%. The dynamic foot pressure distribution is studied in reference, showing that the peak force of a heel strike is about 400 N.Thus the resistive force F3 is better no more than 400 N. The total thicknesses TS is set to not exceed 3 mm. Equation (6) indicates that α reaches the maximum value of 19.7° when $\varepsilon 1$ equals to 2%. The value ranges of N, L and α are defined in Equation (7). Besides, the PVDF film length l is 80 mm and the width w is 50 mm for a normal heel size. The harvester is designed by using optimization method. In conjunction with Matlab built-in optimization routines, several solutions are obtained. Among them, it is found that the solution of L = 10 mm, N = 8 as well as α = 19.7° is the optimal solution, which is selected for Prototype 1:

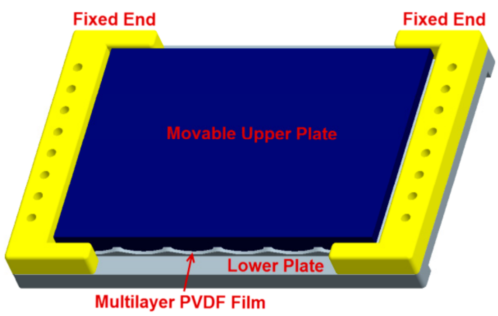
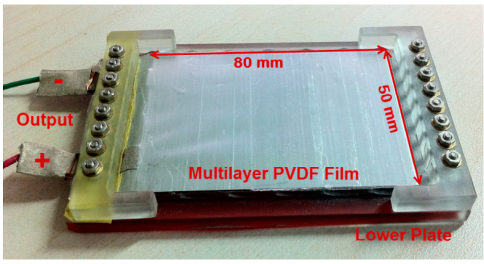


Figure 3. (a) The schematic of Prototype 1



(b) Prototype 1 without the movable upper plate.

3.2. Fabrication of Prototype 2:

Prototype 2 is designed as an insole shape, as illustrated in Figure 4a, which can be divided into three parts. Part 1 and Part 2 are the sandwich structures for harvesting energy with two 8-layer PVDF films. Similar to the rigid energy harvester, Part 1 is applied to harness the energy from heel strikes. Part 2 is used to tap the energy dissipated in bending of the shoe. Part 3 is under foot arch where foot pressure is low, which is a chamber offering vacant space to accommodate circuits and energy storage devices. The upper plate and the lower plate are made of silicone rubber (by injecting modeling process) whose stiffness is far less than that of the engineering plastics used in Prototype 1. Therefore, the practical PVDF film deformation is lower than the theoretical maximum value calculated by Equation (3). In order to reduce this adverse influence caused by the flexible material, the angle α is increased to 27.7°, resulting in a theoretical maximum normal strain $\varepsilon 1$ of 4%. The chord length L is assigned 10 mm. The upper plate, the lower plate and two multilayer PVDF films are fixed together by bolts, and the finished Prototype 2 is shown in Figure 4b.

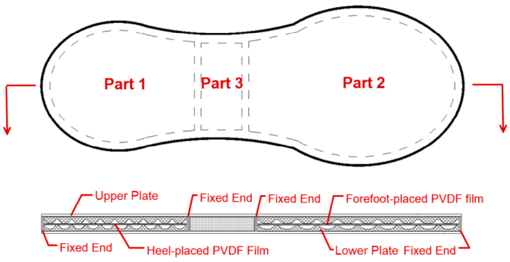
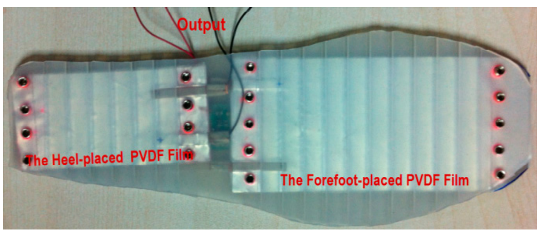


Figure 4. (a) The schematic of flexible energy harvester



(b) The finished Prototype 2.

3.3. Power Circuit:

The PVDF film generates AC power with high voltage and low current, which cannot meet the need of commercial electronics that are practically driven by a uniform DC power. Furthermore, if wearable sensors are not in operation, the harvested energy needs storing in a storage device. Based on the above the two considerations, a power management circuit is designed, as diagrammed in Figure 5, mainly consisting of two full bridge rectifiers, a buck converter, two button batteries (optional) and some capacitors.

The buck converter and one rectifier are contained in the chip LTC 3588-1. Two rectifiers can simultaneously rectify two AC currents of different phases respectively, which is useful for Prototype 2. The harvested energy accumulates on the input capacitor Cin, and then transferred by the buck converter to the output capacitor Cout. The target value of the output voltage Vout (the voltage across output capacitor Cout) is set to 3.6 V.

When Vout reaches the target value, a logic high is produced on the PGOOG pin. If the load shuts off or the input power is more than the output power, there exists unused energy, which will be stored in the batteries. On the contrary, if the harvester cannot generate enough power to meet the load demand, the batteries will be discharged to offer supplemental power.

4. Experiments and Results:

Prototype 1 and Prototype 2 were implemented in shoes to harness the parasitic energy during walking, as shown in Figure 6. A series of experiments were carried out to evaluate the performance of the prototypes. In the first experiment, the prototype was terminated with a matched resistor(s), hence yielded maximum power transfer. In the second experiment, the quantities of the charge produced by the prototypes during one step (QS) were measured.

In the third and fourth experiment, the prototypes were connected with the power management circuit (without using batteries) to form DC power supply systems. The start-up time of the systems were measured. Besides, the power supply systems were tested to power a simulated transmitter load.

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Figure 6. (a) Prototype 1 with an 8-layer PVDF film was mounted on the inner sole and gathered energy under the heel.

(b) Prototype 2 with two 8-layer PVDF films was used as a normal insole in a shoe.

5. Discussion:

Compared with other reported shoe-embedded PVDF energy harvesters, the harvester proposed here has advantages of a thin geometrical form, high performance and an excellent durability, benefitting from its specially designed sandwich structure. The deformation of the multilayer PVDF film is kept elastic and the maximum deformation is close to PVDF elastic limit, thus there is a tradeoff between performance and durability. The average power of the harvester is up to 1 mW (at 1 Hz), which approximates the power of 1.1 mW (at 1 Hz) of the PVDF insole in reference . While more comfort and durability can be provided by our design. By combining the merits of Prototype 1 and Prototype 2, a better harvester can be developed in the future work. The arc-shaped grooves and ribs on the wavy surfaces will be made of some harder material, polyurethane for example, to improve the PVDF film deformation for more energy produced, and the other parts of the plates are made of flexible material to keep users comfortable. In addition, increasing the number of PVDF layers serves as another approach to improving generating performance.

6. Conclusions:

A shoe-embedded piezoelectric energy harvester is developed in this paper, and it can be integrated in a shoe readily for energy harvesting from human locomotion. Two prototypes with different characteristics are fabricated and tested. One prototype produces more energy, while the other one is more comfortable without creating any inconvenience or discomfort for wearers. The DC power supply system, including the harvester and a power management circuit, is used to collect the mechanical energy dissipated in shoes and power some low-power wearable sensors, such as activity trackers. Even though the harvester is unlikely to replace completely the batteries in all wearable sensors, it is a significant role in reducing the problems related to the use of batteries. The work presents a successful attempt in harnessing the parasitic energy expended during person's everyday actions to produce power for wearable sensors.

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