Boosting the efficiency of a footstep piezoelectric-stack energy harvester using the synchronized switch technology

Haili Liu¹, Rui Hua², Yang Lu³, Ya Wang², Emre Salman³ and Junrui Liang⁴

Abstract
In this article, the self-supported power conditioning circuits are studied for a footstep energy harvester, which consists of a monolithic multilayer piezoelectric stack with a force amplification frame to extract electricity from human walking locomotion. Based on the synchronized switch harvesting on inductance (SSHI) technology, the power conditioning circuits are designed to optimize the power flow from the piezoelectric stack to the energy storage device under real-time human walking excitation instead of a simple sine waveform input, as reported in most literatures. The unique properties of human walking locomotion and multilayer piezoelectric stack both impose complications for circuit design. Three common interface circuits, for example, standard energy harvesting circuit, series-SSHI, and parallel-SSHI, are compared in terms of their output power to find the best candidate for the real-time-footstep energy harvester. Experimental results show that the use of parallel-SSHI circuit interface produces 74% more power than the standard energy harvesting counterpart, while the use of series-SSHI circuit demonstrates a similar performance in comparison to the standard energy harvesting interface. The reasons for such a huge efficiency improvement using the parallel-SSHI interface are detailed in this article.

Keywords
piezoelectric energy harvesting, synchronized switch energy harvesting on inductance, human walking locomotion, self-powered, piezoelectric stack

1. Introduction
Power demands are increasing everyday with increasing purchase and usage of mobile electronics. Although the great progress in large-scale integrated circuit has decreased the power requirement of the mobile electronics, the stagnancy of modern battery technologies creates the need for the alternative methods to meet the power demands from the large number of the mobile electronics (Paradiso and Starner, 2005). Human footsteps are a great source of power, and previous studies have revealed the forces generated from human footsteps (Giakas and Baltzopoulos, 1997) along with their potential to generate power (Starner and Paradiso, 2004). A healthy person is expected to walk 10,000 steps a day and thus can output considerable power if harvested efficiently. This power can be stored and used to charge a mobile phone afterward or directly power the wireless sensors, such as a geo-positioning sensor and temperature sensor, without using a battery.

Electromagnet systems have much higher efficiency in the mechanical-to-electrical energy transfer, while it usually involves coils and magnets (Cho et al., 2016; Ylli et al., 2015), which means a complicated and bulky mechanism is unavoidable. Piezoelectric materials can directly produce charge when stress is applied on it, and thus, piezoelectric energy harvesting (PEH) is

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widely studied (Xie and Cai, 2014) for some integrated working circumstances. In particular, a miniature piezoelectric-stack energy-harvesting device is one of the best replacements for battery, and it can be installed inside the insole to directly convert human walking and running motion into usable electrical form (Ylli et al., 2015). Among existing piezoelectric materials, lead zirconate titanate (PZT) is one of the most efficient and cost-acceptable materials. Its piezoelectric coefficient $d_{33}$ is usually two times of $d_{31}$ and thus can output more power in $d_{33}$ mode when exposed to the same stress or strain. The stand-alone piezoelectric multilayer stack working at $d_{33}$ mode is widely researched (Lee et al., 2014; Zhao and Erturk, 2014). However, it has relatively low conversion efficiency. Thus, force amplification frames are designed to improve the efficiency performance. There are two different mechanisms of the amplification frame: concave (Feenstra et al., 2008) and convex (Liu et al., 2014a) shape. In addition, a multilayer piezoelectric stack (Wang et al., 2016) with a flexure-free convex force amplification frame is used by our group to further improve the conversion efficiency. Besides the force amplification, semi-active vibration damping methods such as synchronized switch damping techniques (Ji et al., 2010, 2012) are developed to improve the conversion efficiency with advanced control strategies.

Besides the energy harvesting structure, a typical PEH device also needs a power conditioning circuit to convert the alternate current (AC) power from the piezoelectric element to directive current (DC) power for electronics. A full-bridge rectifier is the most commonly used power conditioning circuit, and it is regarded as the standard energy harvesting (SEH) circuit (Li et al., 2016). Yet, using SEH, there is a phase difference between the voltage and current, and thus, they produce negative power, which means that some energy flows back to the mechanical part of the system (Nechibvute et al., 2014). In order to avoid this phase difference and boost the output power, synchronous electric charge extraction (SECE; Lefeuvre et al., 2005) and synchronized switch harvesting on inductor (SSHI; Guyomar et al., 2005; Li and You, 2015; Wu et al., 2017) are developed as two efficient circuit interfaces.

It was proven that such interface circuits can increase the energy harvesting capability by several hundred percent. SECE was first addressed by Lefeuvre et al. (2005), and several optimized synchronous electric charge extraction (OSECE; Wu et al., 2012; Xia et al., 2018) methods have been proposed to reduce power loss and achieve self-powered switches (Liu et al., 2018a, 2018b) or reduce components with the design of mechanical switches (Liu et al., 2014b; Wu et al., 2014). SECE has been proved to be better applicable for low-coupling piezoelectric harvesters, which is not applicable for strong-coupling piezoelectric stacks. Compared to SECE, SSHI is suitable for all piezoelectric harvesters, but sensitive to loads. In SSHI, we need to sense the maximum deforming instants of a piezoelectric transducer and simultaneously form an inductive shortcut for the charge stored in the piezoelectric element, such that the voltage across the piezoelectric element can be inverted after half of a resistance–inductance–capacitance (RLC) cycle. For the stand-alone application of SSHI, the sensing, synchronization, and switching functions are better to be self-contained without using any external sensor, power supply, and controller. Given these requirements, several self-powered SSHI circuits have been invented (Cheng et al., 2016; Lallart and Guyomar, 2008; Liang and Liao, 2012), which consist of the voltage peak detector, comparator, and electronic switch. Recently, some mechanical self-powered SSHI solutions (Hua et al., 2018; Liu et al., 2015) are proposed to eliminate some electronic components used in the electronic self-powered SSHI as well as reduce the voltage drop, phase lag, and energy consumption caused by these electronic components. These mechanical switches were designed for base-excited cantilever beams or specific mechanisms and therefore cannot be applied directly since the footstep piezoelectric-stack harvester works in a different way.

So far, the SSHI technologies are not applied on the piezoelectric stacks, which have strong coupling coefficient and much higher impedance than piezoelectric patches, and most of the studies (Guyomar and Lallart, 2011; Qiu et al., 2009; Yang et al., 2015) are based on harmonic vibrations, and multiple-frequency excitations are seldom explored. On the contrary, in previous footstep energy harvester study (Xie and Cai, 2014), the piezoelectric stack outputs the AC power directly to a linear resistor. Due to the complexity of human walking pattern, most of the footstep energy harvesting devices in the literature still use a SEH interface (Liang and Liao, 2012), which has relatively low AC–DC energy conversion efficiency.

In this article, a monolithic multilayer piezoelectric stack is used as a transducer, and multi-frequency waveforms are used to simulate real-time human walking motion. Section 2 introduces the model of multiple frequency excitations as the input force and the electromechanical coupling equations of the piezoelectric-stack harvester. In section 3, the circuit topology and working principle of SEH and both self-powered series-SSHI (S-SSHI) and self-powered parallel-SSHI (P-SSHI) are introduced. Section 4 includes experimental procedures, results, and analyses. Conclusions and future work are discussed in section 5.

Experiments show that the parallel-SSHI circuit outperforms the series-SSHI and the SEH interface, in particular, for the stack configuration. However, the parallel-SSHI does not show this obvious advantage over the series-SSHI for the single-layer-piezoelectric-patch configuration, which is commonly used in the
literature (Nechibvute et al., 2014; Qiu et al., 2009; Wu et al., 2017). The reasons are detailed throughout the article.

2. Work principles of the mechanical part

2.1. Force amplification frame

The piezoelectric stack in $d_{33}$ configuration has a larger piezoelectric coefficient and a higher efficiency while it is with greater stiffness and limited strain. The force amplification frame can be used to multiply the input force from human walking. As shown in Figure 1, the piezoelectric stack is surrounded by the force amplification frame. The $F_{in}$ indicates the input force from walking in the vertical direction, and the $F_{out}$ indicates the output force in the horizontal direction. The detailed force analysis has been done in our previous publications (Chen et al., 2016; Wang et al., 2016).

2.2. Input force from the foot strike

Walking introduces a repetitive impact force, which is exerted on the ground. Although the force of walking has anteroposterior and medial–lateral components, the dominant part is the vertical component—often termed as the vertical ground reaction force (VGRF), which is the easiest to be utilized and quantified (Keller et al., 1996). Studies have also revealed that the VGRF varies with the gait speed and the body weight. Tongen and Wunderlich (2010) had used a force plate to measure the magnitude of VGRFs during walking of a male subject weighing 77.51 kg. A continuous equation can be derived using curve-fitting method through the experimental data of human locomotion with the body weight about 70 kg (Chen et al., 2016; Masani et al., 2002) and formulated as

\[
y = M_b \times [10.53 \sin(3.921x + 0.1854) \\
+ 1.9 \sin(16.5x - 1.1114)]
\]

(1)

where $M_b$ is the body weight of a person in kilograms. This means there are two peaks on the input force curves, as shown in Figure 2, which is different from the harmonic vibration excitation and its corresponding high-efficiency interface circuit is not well studied.

2.3. Modeling

In this article, the piezoelectric-stack energy harvester is simply equivalent to single degree of freedom (SDOF; Lee et al., 2014). According to the detailed modeling in our previous paper (Wang et al., 2016), the governing equations can be expressed as

\[
\ddot{u} + \omega_n^2 u - n \omega_n^2 d_{33} v = \frac{F_{in}}{M_{eff}} 
\]

(2)

\[
\dot{V} + \frac{1}{R_L C_p} V + \frac{n d_{33} M_{eff} \omega_n^2}{C_p} \dot{u} = 0
\]

(3)

where $u$ is the axial displacement, $n$ is the number of piezoelectric layers in one stack, $M_{eff}$ is the effective mass of piezoelectric stack, $d_{33}$ is the piezoelectric constant, $F_{in}$ is the input force on the stack, $v$ is the output voltage, $R_L$ is the external load, and $\omega_n$ is the natural frequency, which is defined as

\[
\omega_n = \sqrt{\frac{k_{eff}}{M_{eff}}}
\]

(4)

where $k_{eff}$ is the effective stiffness of the piezoelectric stack, and $C_p$ is the internal capacitance, which is defined as

\[
C_p = \frac{n e_{T33} A}{h}
\]

(5)

where $e_{T33}$ is the dielectric permittivity constant, $A$ is the cross-sectional area of each piezoelectric layer, and $h$ is the thickness of each piezoelectric layer.

3. Work principle of the conditioning circuits

3.1. Conditioning circuits

The AC power generated by the piezoelectric stack cannot be directly used by many electric devices. Therefore, an AC–DC energy conditioning circuit between the
piezoelectric electrical generator and the energy storage is necessary. In order to reach higher energy conversion efficiency, there are many different schemes of electric interfaces. In this work, three interfaces including SEH, series-SSHI, and parallel-SSHI are studied.

Figure 3(a) shows the schematic diagram of SEH, which includes a full-bridge rectifier, a filter capacitor $C_L$, and a resistive load $R_L$. Since footstep energy harvester usually works at low-frequency range (around 1.5–2.3 Hz) and this working frequency is far from the resonance of the stack, the piezoelectric element can be modeled as an equivalent current source in parallel with a capacitor $C_p$ and the internal leakage resistance $R_p$. The rectifier is in a blocked state when piezoelectric output voltage is lower than the voltage across the capacitor, and when the piezoelectric output voltage is larger than the voltage across the capacitor, the current will flow through the diodes and power the load. The shortage of SEH circuit is that the output voltage and current cannot keep the same phase and would produce some negative power, which means the harvested energy may return to the mechanical part, losing some of the harvested power (Liang and Liao, 2009).

Figure 3(b) and (c) illustrates the schematic diagram of the parallel-SSHI and the series-SSHI, respectively. The SSHI overcomes the energy return issue by adding a switch path, which contains a switch $S_1$ and an inductor $L_1$. The switch $S_1$ turns on at the short instant when output voltage reaches a maximum or minimum, which ensures the output voltage and current have the same phase and thus prevents the harvested power from turning back. The only difference between the parallel-SSHI and series-SSHI is whether the switch path is connected in parallel with the rectifier or it is connected in series with the rectifier. Both of these SSHI interfaces can increase the output voltage from the piezoelectric stack due to a voltage inversion process (Lallart and Guyomar, 2008).

3.2. Self-powered SSHI circuit

In SSHI circuits, the switch $S_1$ needs to turn on/off at the desired time instant, which involves sensing the voltage extreme point, switching on/off, and inverting the voltage across the piezoelectric elements. Electronic breaker can sense the voltage extreme point and thus can form a self-powered SSHI interface (Lallart and Guyomar, 2008). Without the requirement of any external power supply, it can automatically perform switching actions once the output voltage from the piezoelectric stack reaches its extremum. Figure 4 shows the schematic of self-powered series-SSHII, and Table 1 demonstrates related component models and values. One breaker can only allow the current flow in one direction, and therefore, each SSHI circuit employs two such breakers.

In the self-powered series-SSHI, the current comes from the piezoelectric transducer. When the output voltage across the piezoelectric stack increases, $C_2$ will be charged, while $T_1$ and $T_2$ are blocked; when the output voltage reaches an extreme point, and starts decreasing, a voltage difference appears between the emitter and the base of $T_1$. When this difference is greater than the threshold voltage of $T_1$, $T_1$ will conduct. At the same time, $C_2$ provides the base voltage for $T_2$ because $D_1$ is blocked. The conduction of these two transistors $T_1$ and $T_2$ initiates the inductance–capacitance (LC) resonant circuit, so that $C_p$ will be quickly discharged through $D_3$, $T_2$, $R_L$, $D_{12}$, and $L_1$. With the presence of inductor $L_1$, the voltage across $C_p$ will be inverted. On the other hand, when the voltage reaches the negative extremum, similarly, it will also be inverted due to symmetrical circuit topology.

The schematic of self-powered parallel-SSHI is shown in Figure 5. The self-powered series-SSHII has a

![Image](https://example.com/image.png)

**Figure 3.** Schematic diagram of (a) the standard energy harvesting circuit, (b) the parallel-SSHI circuit, and (c) the series-SSHI circuit.

**Table 1.** Components for the self-powered series-SSHII and parallel-SSHII.

<table>
<thead>
<tr>
<th>Component</th>
<th>Model/value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_x$</td>
<td>IN4004</td>
</tr>
<tr>
<td>$T_1$ and $T_3$</td>
<td>TIP32C</td>
</tr>
<tr>
<td>$T_2$ and $T_4$</td>
<td>TIP31C</td>
</tr>
<tr>
<td>$L_1$</td>
<td>120 mH 97 Ω</td>
</tr>
<tr>
<td>$C_2$ and $C_4$</td>
<td>23 nF</td>
</tr>
<tr>
<td>$C_L$</td>
<td>47 μF</td>
</tr>
</tbody>
</table>
similar working principle as the self-powered parallel-SSHl. One minor difference is that in the parallel-SSHl, when $C_p$ is discharging, the current only passes $D_3$, $T_2$, and $L_1$ (or $D_6$, $T_3$, and $L_1$), which means that $R_L$ does not influence the performance of the voltage inverting process.

4. Experiments and analyses

Figure 6 shows the experiment setup used to measure the output voltage and output power from the piezoelectric stack. The monolithic multilayer piezoelectric stack is SP505 manufactured by Smart Material. It consists of 300 layers of piezoelectric patches, and each layer is 0.1 mm in thickness. Its dimension is 7 mm $\times$ 7 mm $\times$ 32 mm, and the internal capacitance $C_p$ is 2.1 $\mu$F. As shown in Figure 6(b), the piezoelectric stack is placed in the amplification frame. The simulated input force signal is sent to NI DAQ and amplified by power amplifier to drive the shaker (APS 420). The shaker is used to provide excitations to the amplification frame on one side through its moving armature, and the other side of the frame is fixed. A force transducer is placed between the amplification frame and the shaker to measure the input force. Another force transducer is placed between the interface of the piezoelectric-stack harvester and the amplification frame to measure the amplified force. Both force transducers connect to a charge amplifier to send amplified signals to NI DAQ. When different interface circuits connect to the harvester, the output voltage from the circuit is measured with the oscilloscope. By alternating the load (resistance value), we can test the output power for further analysis.

In order to simulate the force excitation of human locomotion, the input force adopts the curve-fitted function in equation (1), where $M_b$ is the body weight of a person in kilograms. Considering the shaker
cannot output the same level of excitations as human locomotion, the amplitude of the input force is set to around 114 N, so that the maximum output force of the shaker is used in the testing. Figure 7 shows the waveforms of one cycle of the input force applied on the force amplification frame and input force applied on the piezoelectric stack. These data are measured by a force transducer with a charge amplifier. From the figure, we can see that the force applied on the frame is about 114 N, and the amplified force on the stack is about 846 N; thus, the amplification ratio calculated from one cycle is about 7.4.

With the amplified force transferred to the piezoelectric stack, the voltage will be generated across the stack. In the experiments, the stack is connected to a SEH circuit, a self-powered series-SSHI circuit, or a self-powered parallel-SSHI circuit, respectively, using a series of load resistance $R_L$. Figure 8 shows the output voltage across piezoelectric stack under different load resistance. From the waveforms, we can see that for the self-powered series-SSHI circuit, when the value of load resistance increases, the voltage amplitude decreases, and the performance of voltage inversion process becomes worse; for the self-powered parallel-SSHI circuit, when the value of load resistance increases, the voltage amplitude increases, and the value of load resistance $R_L$ does not affect its voltage inversion process.

The output power can be calculated by measuring the voltage $U$ across the different load resistance $R_L$.

$$P = \frac{U^2}{R_L}$$ (6)
Figure 9 compares the output power of the three interface circuits at different load resistances. Figure 9(a) uses the resistance as $x$ axis, named as resistance–power curve, and can directly indicate the optimum resistance; Figure 9(b) uses the voltage across the load resistance as $x$ axis, named as voltage–power curve, and can be used to verify the optimum power being correctly selected. Figure 9 shows that the SEH and the series-SSHI have the similar performance, while parallel-SSHI is the best under different load resistances. The values of the optimal power output of the three interface circuits are compared in Table 2. In particular, the SEH circuit provides the optimal power output 1.35 mW at $R_L = 50 \, k\Omega$, which is similar to the series-SSHI circuit (1.33 mW at $R_L = 60 \, k\Omega$). However, the parallel-SSHI circuit outputs the power of 2.35 mW at $R_L = 80 \, k\Omega$, and thus, the harvesting efficiency increases by 74%, in comparison to that of the SEH circuit.

Also, Figure 10 shows the output voltage waveforms of the two interface circuits with the optimal load. At the resistive load of 80 k$\Omega$, the parallel-SSHI has the optimal output power, while at the resistive load of 60 k$\Omega$, the series-SSHI has the optimal output power.

### 5. Discussion

According to many previous studies (Niazi and Goudarzi, 2015; Pang et al., 2016), series-SSHI and parallel-SSHI should both bring a significant improvement and the performance is almost the same. Why the series-SSHI circuit does not work well in this footstep piezoelectric-stack energy harvester? Some factors may cause this result: first, the optimum load resistance for the two SSHI interfaces is around 50–70 k$\Omega$ (given in Table 2), which is determined by the piezoelectric stack and its working condition; from Figure 8, we can see that the voltage is not inverted well for series-SSHI at this range of $R_L$, which undermines the performance of the SSHI technique, while parallel-SSHI can invert the voltage well at high load resistance and thus shows better performance. In series-SSHI circuit, $R_L$ is located within the discharge loop. Thus, when the value of the load resistance $R_L$ increases, the discharging speed decreases, which degrades the voltage inversion.

![Figure 8. Output voltage across piezoelectric stack with (a) series-SSHI circuit and (b) parallel-SSHI circuit under different load resistance: 0 $\Omega$, 10 k$\Omega$, 100 k$\Omega$, and 1 M$\Omega$.](image)

![Figure 9. Comparison of the output power of the three interface circuits at different load resistance: (a) resistance–power curve and (b) voltage–power curve.](image)
process. Second, the input force from human locomotion is not a simple harmonic wave, as usually studied. The experimental results show that the series-SSHI cannot invert the voltage at some small peaks of the voltage waves, as shown in Figure 8, which means some negative power would be produced and thus undermine the performance of the SSHI, decreasing the efficiency to around the SEH counterpart. Another test was carried out to rule out the input dependence on the performance superiority of the parallel-SSHI in comparison with its series-SSHI counterpart. Results are shown in Figure 11, indicating the power output of the three interface circuits at their respective optimal load resistance, under a harmonic excitation. Their waveforms show that the parallel-SSHI still performs better than the series-SSHI under a harmonic excitation.

6. Conclusion

Aiming to take advantage of the great energy source of human locomotion, the high-efficiency energy harvesting circuits, that is, self-powered series-SSHI and self-powered parallel-SSHI, are discussed and experimentally tested for the footstep piezoelectric-stack energy harvester. According to the unique characteristics of the footstep piezoelectric-stack energy harvester, including low frequency, multiple frequency, strong coupling, with a high internal resistance, and a large capacitance, the parameters of the self-powered SSHI are redesigned. Contrary to the most studied piezoelectric patch energy harvester under a base excitation, experiments show that the self-powered parallel-SSHI performs much better than the self-powered series-SSHI. Both of them are compared with the SEH circuit in terms of harvested energy. The results show that the parallel one can increase the harvested power by a factor of 174%, while the series one outputs almost the same power as the SEH circuit. This big difference is due to the unique characteristics of the footstep piezoelectric-stack energy harvester. These results are meaningful for the harvesting circuit selection and the further real-life applications of the footstep piezoelectric-stack energy harvester.

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<table>
<thead>
<tr>
<th>Circuit type</th>
<th>Optimal load resistance (kΩ)</th>
<th>Voltage across the storage capacitor (V)</th>
<th>Optimized power output (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEH</td>
<td>50</td>
<td>8.22</td>
<td>1.35</td>
</tr>
<tr>
<td>Series-SSHI</td>
<td>60</td>
<td>8.92</td>
<td>1.33</td>
</tr>
<tr>
<td>Parallel-SSHI</td>
<td>80</td>
<td>13.7</td>
<td>2.35</td>
</tr>
</tbody>
</table>

SEH: standard energy harvesting.

Table 2. Output power using different interface circuits.

Figure 10. Voltage output of two interface circuits at their respective optimal resistive loads: parallel-SSHI at 80 kΩ and series-SSHI at 60 kΩ.

Figure 11. The power output of three interface circuits under a harmonic excitation.
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