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Folded Spring and Mechanically Switching SSHI for High Performance Miniature Piezoelectric Vibration Energy Harvester

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Folded Spring and Mechanically Switching SSHI for High Performance Miniature Piezoelectric Vibration Energy Harvester

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Abstract. To downsize the clamp area and increase the output power of the harvester, we developed a miniature piezoelectric vibration energy harvester with combining a Z-shaped folded spring and a mechanically-switching SSHI (synchronized switch harvesting on inductor). The overall harvester size is 4×2×3 cm^3. The FEM analysis revealed that the output power increases and the value of the 1st and 2nd resonance frequencies move closer as the angle of the Z-shaped spring decreases, therefore, the smaller angle would be more promising. The experimental results showed that the maximum output power of our harvester for the 1st (20.2 Hz) and 2nd (53.0 Hz) resonance frequencies at the applied acceleration of 4.9 m/s^2 are 0.088 and 0.98 mW, respectively. The reason for a marked enhancement of the output power for the 2nd resonance frequency is attributed to the vertical movement of the 2nd vibrational mode which applies larger mechanical stress to the piezo ceramic and achieves better electrical contact between the tip of the Z-shaped spring and the spring plunger.

1. Introduction

A piezoelectric vibration energy harvester (P-VEH), which typically consists of a piezoelectric material, beam, and additional mass, represents one promising power source for internet of things (IoT) modules because of the high output power density. However, in most cases, volume for clamping the beam accounts for a large portion of the harvester, which leads to decrease in the actual power density. In addition, we need to further increase the output power of P-VEHs to shorten the sensing period of the wireless sensor module.

Recently, SSHI (synchronized switch harvesting on inductor) interface incorporating mechanical switch was developed to increase the output power and simplify the complexity of the circuit [1, 2]. However, the clamp jig for their clamped-free beam structure increase the harvester's volume. To downsize the clamp volume and increase the output power, we propose a miniature P-VEH with combining a folded spring and a mechanically-switching SSHI.

2. Harvester Structure and Interface Schematic

Figure 1 shows a photograph and interface schematic of the proposed harvester. The overall harvester size is 4×2×3 cm^3 and the clamp area of the bottom base is 1.7×2 cm^2. We employed a fine-grained stainless steel (Nippon Steel & Sumitomo Metal, SUS304 H-SR3, 67×20×0.15 mm^3) to ensure mechanical reliability [3, 4], and formed the Z-shaped spring by folding the steel thin film. As shown in Figure 1(a), the screwed ball spring plunger was employed to achieve soft contact with the tip of the Z-shaped spring, as well as to adjust the gap between the tip and the plunger. The gap distance between the upper and lower plunger was set to 4.2 mm. The piezo ceramic (Fuji Ceramics, C-6, 12×20×0.2 mm^3) and the copper mass (26.7 gram) are attached on the Z-shaped spring. As shown in Figure 1(b), the lower electrode of the piezo ceramic is electrically connected with the conductive Z-shaped spring. When the tip of the Z-shaped spring contacts with the plunger under large enough acceleration, the mechanical switch closes and thus the SSHI works.

Firstly, we used the FEM analysis (Comsol Multiphysics) to investigate the dependence of the output power on the angles of the Z-shaped spring. The applied acceleration and the resistive load are 4.9 m/s^2 and 270 kΩ, respectively. In this FEM analysis, the output power is evaluated when the piezo ceramic is only connected to the load. Figure 2 shows output power P_{out} vs frequency with different five angles of the Z-shaped spring and vibrational mode. The analysis revealed that the output power increases and the value of the 1st and 2nd resonance frequencies move closer with reducing the angle. Therefore, the smaller angle would be more promising. However, for a technical difficulty attaching the piezo ceramic onto the Z-shape spring with the angle of 15º, the angle of 30º was chosen in the experiment.

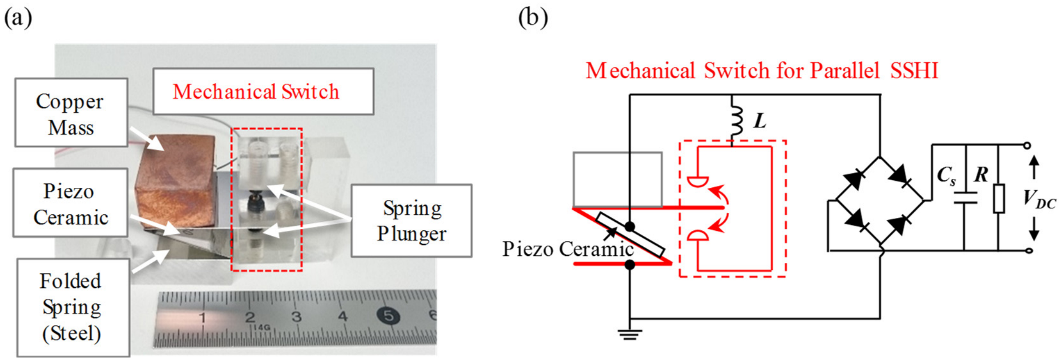

Figure 1. (a) Photograph and (b) interface schematic of the proposed harvester. The overall harvester size is 4×2×3 cm^3.

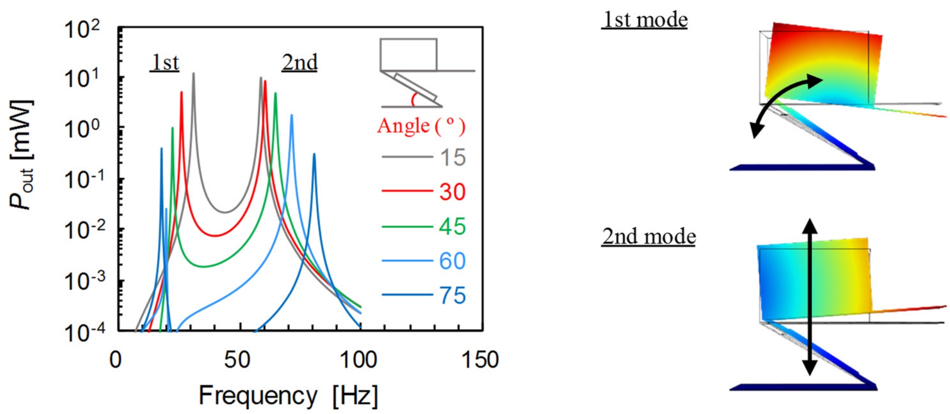

Figure 2. Output power P_{out} vs frequency with different five angles of the Z-shaped spring.

3. Experimental

Figure 3 shows frequency sweep of the output power P_{out} and of the peak-to-peak tip displacement $Disp._{p\text{-}p}$ of the Z-shaped spring for the mechanically-switching SSHI (MSS) and the standard circuit. $Disp._{p\text{-}p}$ was measured by a laser displacement meter (Keyence LC-2450 and LC2400). The standard circuit is equal to the MSS circuit shown in Figure 1(b) without the inductor L. The output power is calculated from V_{DC}^2/R. The applied acceleration a, load R, inductor L, capacitor C_s, are 4.9 m/s^2, 270 kΩ, 100 mH, and 47 μF, respectively. The harvester for the MSS circuit showed 1.2-fold increase in the power at the 1st resonance frequency (20.2 Hz) and 2.1-fold increase at the 2nd resonance frequency (53.0 Hz) over the standard circuit. The maximum output power for the MSS at 1st and 2nd resonance frequencies are 0.088 and 0.98 mW, respectively. The reason why the output power for the 2nd resonance frequency was much higher than that for the 1st one is attributed to the vertical movement of the 2nd mode which applies larger mechanical stress to the piezo ceramic and achieves better electrical contact between the tip and the plunger. For the standard circuit removing the mechanical switch structure shown in Figure 1(a), the maximum output power for the 2nd resonance frequency was 0.72 mw, however, the piezo ceramic was broken during the measurement due to the large displacement. Therefore, the mechanical switch also works as a stopper for improving mechanical reliability.

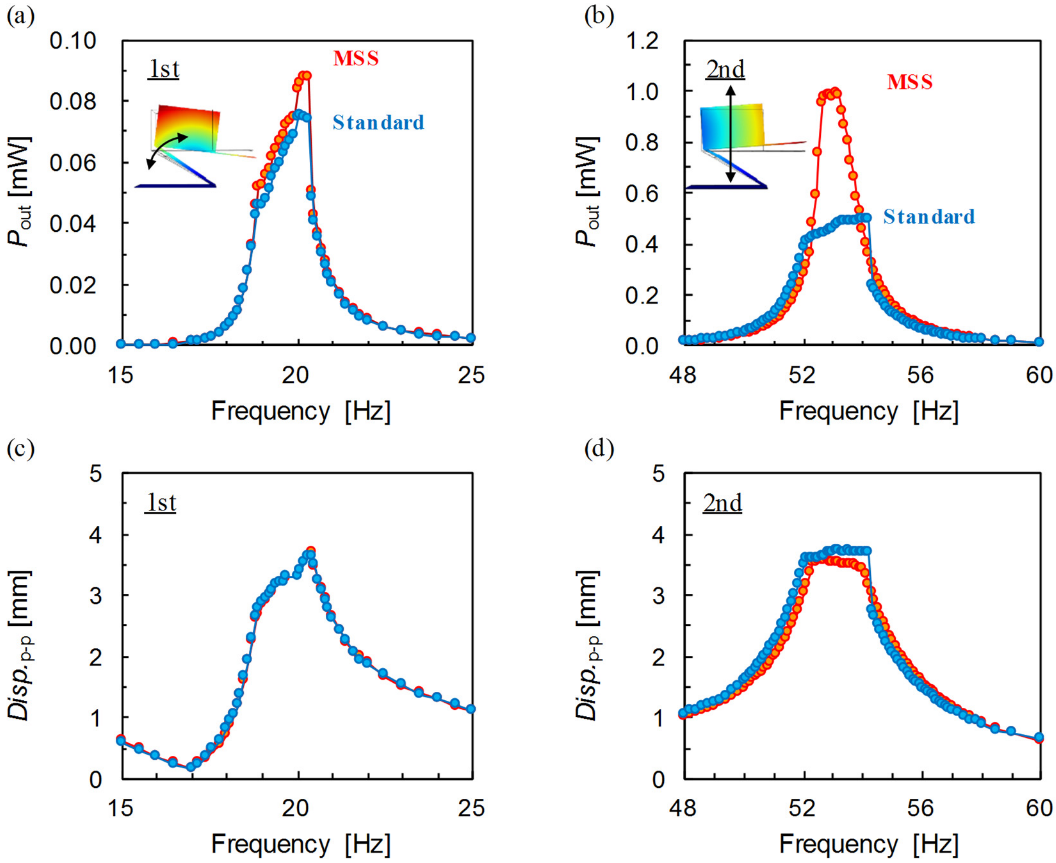

Figure 3. Frequency sweep of the output power P_{out} and of the peak-to-peak tip displacement $Disp._{p\text{-}p}$ of the Z-shaped spring for the mechanically-switching SSHI (MSS) and the standard circuit at the applied acceleration a of 4.9 m/s^2.

Figure 4 shows the output power P_{out} vs the acceleration a at (a) the 1st and (b) 2nd resonance frequencies. For the 2nd mode, after the tip of the Z-shaped spring start contacting the plunger under large enough acceleration, the output power for the MSS continues to increase, while the power for the standard circuit showed saturation. The increase in power may be attributed to longer contact duration. The too long contact duration at the acceleration greater than 5 m/s^2 may lead to the decrease in the power for the MSS.

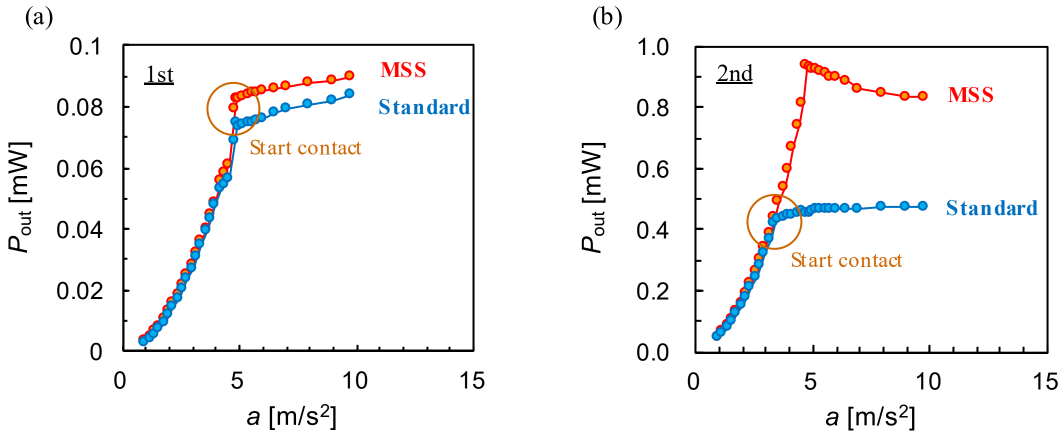

Figure 4. Output power P_{out} vs acceleration a at (a) 1st and (b) 2nd resonance frequencies.

4. Conclusion

We developed a miniature piezoelectric vibration energy harvester with combining a Z-shaped folded spring and a mechanically-switching SSHI (synchronized switch harvesting on inductor). The FEM analysis revealed that the output power increases and the value of the 1st and 2nd resonance frequencies move closer as the angle of the Z-shaped spring decreases, therefore, the smaller angle would be more promising. Under the applied acceleration of 4.9 m/s^2, the proposed harvester with the size of 4×2×3 cm^3 exhibited the maximum output power of 0.088 mW at the 1st resonance frequency and of 0.98 mW at the 2nd resonance frequency. The reason for a marked enhancement of the output power for the 2nd resonance frequency is attributed to the vertical movement of the 2nd vibrational mode which applies larger mechanical stress to the piezo ceramic and achieves better electrical contact between the tip of the Z-shaped spring and the spring plunger.

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