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Numerical Investigation of Mechanically and Electrically Switching SSHI in Highly Coupled Piezoelectric Vibration Energy Harvester

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Numerical Investigation of Mechanically and Electrically Switching SSHI in Highly Coupled Piezoelectric Vibration Energy Harvester

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Abstract. In aiming to increase output power for piezoelectric vibration energy harvesters, a self-powered synchronized switch harvesting on inductor (SSHI) using an electrical or mechanical switch has considerable attention. However, the advantages and disadvantages of the two switching technique for the self-powered SSHIs remains unclear. In addition, for a harvester with a high electromechanical coupling coefficient *k*, the piezoelectric damping force, which enhances by the SSHI's voltage increase, is likely to reduce the harvester's displacement and thus lower the output power. We developed simulation technique, and numerically investigated the performance for the electrical switch SSHI (ESS) and for the mechanical switch SSHI (MSS) harvester, considering the feedback of the piezoelectric damping force. The numerical investigation revealed that, for the ESS, the piezoelectric damping force reduces the displacement every switching on at the maximum/minimum displacement, and thus lowers the output power. In contrast, the MSS, in which the switch turns on only when the displacement exceeds the gap distance, achieved a higher output power, and exhibited intriguing phenomena that the output power continues to increase, whereas the displacement is held constant. Therefore, for a harvester with high *k*, the MSS can outweigh the ESS.

1. Introduction

To increase the output power for a piezoelectric VEH, Guyomar *et al* [1] developed a synchronized switch harvesting on inductor (SSHI) technique. The SSHI employs an additional set component of an active switch and an inductor, which are connected in parallel or series with the standard AC-DC circuit. When the switch turns on at every maximum/minimum of the harvester's displacement, the piezoelectric voltage was inversed by the *LC* electrical oscillation caused between the inductor and the capacitance of the piezoelectric material, thereby increasing the output voltage and thus the output power. However, the switch used in the early stage SSHI was controlled by an external power source.

Subsequently, a self-powered SSHI using an electrical or mechanical switch that requires no external power source was developed. The electrical switch, which consists of the envelope detector, the comparator, and the digital switch, successfully controlled on/off by consuming a small portion of the harvested energy [2,3]. The mechanical switch was designed by utilizing a main beam of the harvester [4,5]. The self-powered SSHI using the electrical and mechanical switches showed excellent performance, however, the advantages and disadvantages for the two switching technique are still not clear. In addition, for a harvester with a high electromechanical coupling coefficient *k*, the piezoelectric damping force, which enhances the SSHI voltage increase, suppresses vibration of the harvester and thus lowers output power [6].

This study investigates the performance of the electrical and mechanical switch SSHI numerically, considering the feedback of the piezoelectric damping force from.

2. Harvester Structure and Circuits

Figure 1 shows the harvester for the electrically-switching SSHI (ESS) and for the mechanically-switching SSHI (MSS). This study employs a cantilever-type VEH consisting of a stainless steel beam, copper mass, and piezoelectric bimorph connected in parallel. The squared electromechanical coupling coefficient k^2 is 0.038, which is several times higher than that for the previous studies [1].

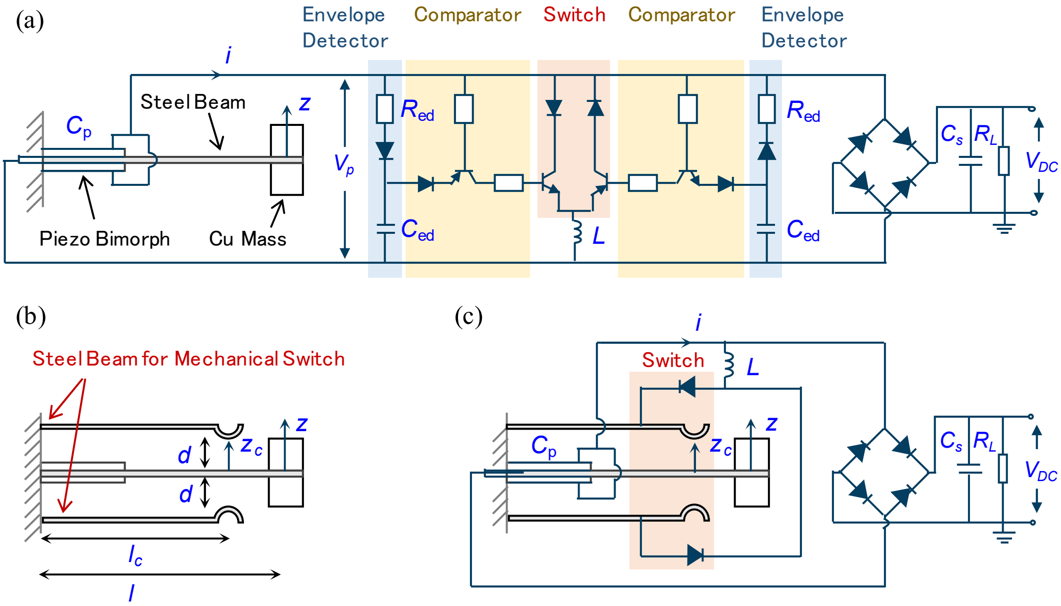

Figure 1. (a) ESS harvester, (b) structure of mechanical switch and (c) MSS harvester.

Based on the single degree of freedom (SDOF) model, the electromechanical equation for the piezoelectric vibration energy harvester are expressed as follows [1]:

$$M_{eff}\ddot{z} + D\dot{z} + K_{sc}z = F - \alpha V_p \tag{1}$$

$$i = \alpha\dot{z} - C_p\dot{V}_p, \tag{2}$$

where F is the external force, M_{eff} (9.4 gram) is the effective mass, D (0.036 Ns/m) is the mechanical damping coefficient, K_{sc} (344 N/m) is the short-circuited stiffness, z is the tip displacement of the harvester, α (7.73×10^{-4} N/V) is the force factor, V_p is the piezoelectric voltage, i is the outgoing current, C_p (44 nF) is the capacitance of the piezo bimorph, respectively. We stress that, unlike the SPICE-based simulation [3], our numerical model incorporates the feedback of the piezoelectric damping force αV_p from the electrical to the mechanical domain, which is enhanced by the SSHI's voltage increase. We used Matlab/Simulink and Simscape/Simeletronics to simulate the harvester's performance. R_{ed} and C_{ed} in the ESS are 300 kΩ and 2.2 nF, respectively.

As shown in figure 1(b) and (c), for the MSS harvester, the equation about mechanical vibration is changed as follows:

$$z_c = sz = \frac{3}{2}\left(\frac{l_c}{l}\right)^2\left(1-\frac{l_c}{3l}\right)z \tag{3}$$

$$M_{eff}\ddot{z} + D\dot{z} + K_{sc}z + F_{MS} = F - \alpha V_p \tag{4}$$

$$F_{MS} = \begin{cases} K_{MS}(z_c - d) + D_{MS}\dot{z}_c = sK_{MS}(z - d/s) + sD_{MS}\dot{z} & z_c > d \\ 0 & |z_c| \le d \\ K_{MS}(z_c + d) + D_{MS}\dot{z}_c = sK_{MS}(z + d/s) + sD_{MS}\dot{z} & z_c < -d \end{cases}, \tag{5}$$

where z_c is the displacement at the contact position l_c, d (0.41 mm) is the gap distance, F_{MS}, K_{MS} (66.3 N/m), and D_{MS} (0.3 Ns/m) are the total reaction force, the stiffness, and the mechanical damping coefficient of the mechanical switch, respectively. l and l_c in figure 1(b) are set to 53 and 30 mm. The impedance-matched R_L for the ESS and MSS are 150 and 180 kΩ, C_s is 10 μF, and the inductance L is 100 mH, respectively. All parameters used in the simulation are empirically attainable.

3. Results and discussion

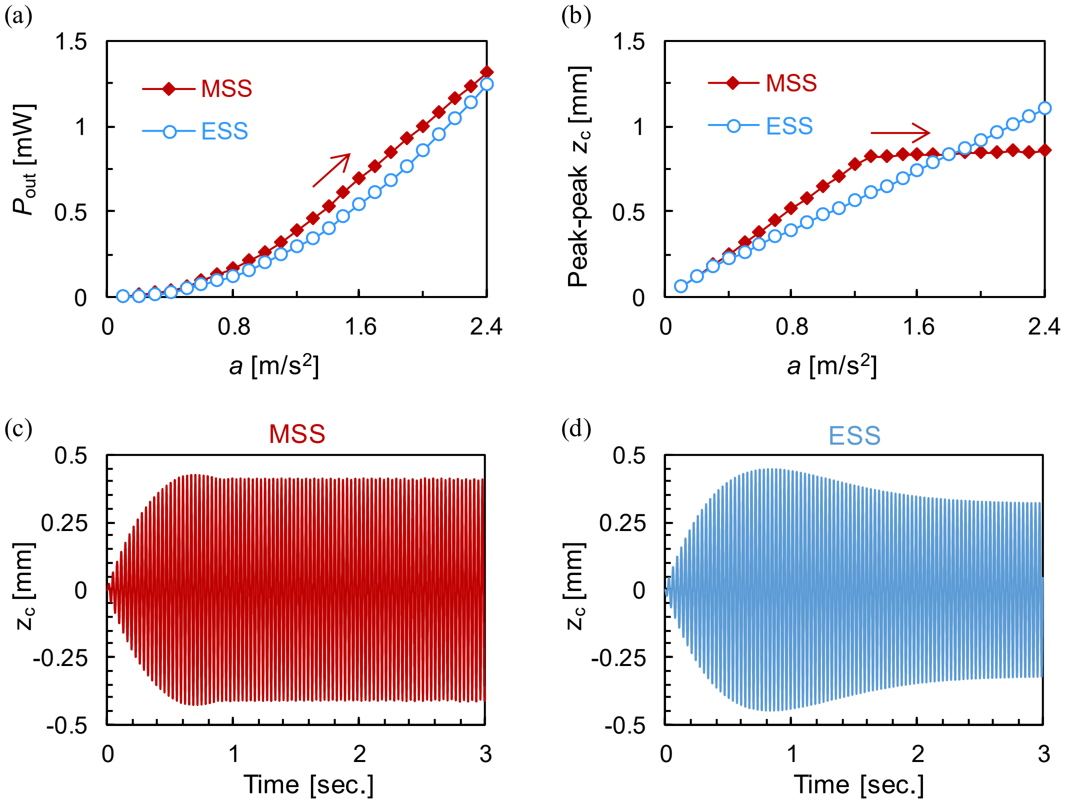

Figure 2. (a) Output power P_{out} and (b) peak-peak displacement z_c at the contact position l_c vs applied acceleration a, and transient response of z_c (c) for MSS and (d) for ESS.

Figure 2 shows output power P_{out} vs applied acceleration a at the resonance frequencies (30.4-30.8 Hz), and transient response of z_c for three seconds. For the ESS harvester, the piezoelectric damping force enhanced by the SSHI reduces the displacement and thus the resulting output power. Thus, for the harvester with high k, the ESS which turns on at every maximum/minimum displacement is not effective. In contrast, the MSS, which turns on only when z_c exceeds d, showed excellent performance. Intriguingly, the output power for the MSS continues to increase, whereas the displacement remains constant. The reason is explained as follows.

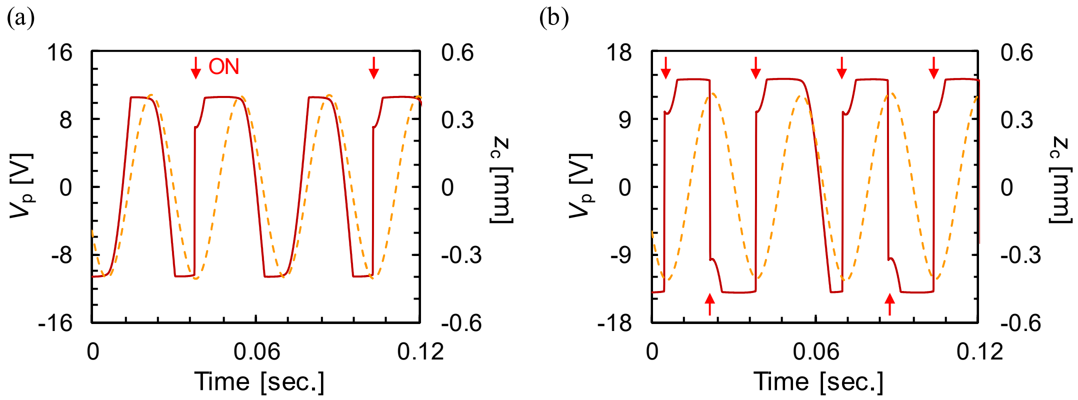

Figure 3. MSS's waveforms of the piezoelectric voltage V_p and of the displacement z_c at the contact position at acceleration of (a) 1.4 m/s^2 and (b) of 2.0 m/s^2.

Figure 3 shows waveforms of the piezoelectric voltage V_p and the displacement z_c at the contact position for the MSS at a of 1.4 and 2.0 m/s^2. As shown in figure 3(a), when the MSS turns on, the piezoelectric damping force reduces the displacement and skips the next switching on. However, the displacement gradually grows and MSS turns on again. Under higher excitation, the number of switching on increases, which leads to the increase in output power under the constant displacement.

4. Conclusion

We numerically investigated the performance of the ESS and the MSS harvester, considering the piezoelectric damping force enhanced by the SSHI's voltage increase in a harvester with high k. The displacement of the ESS decreases every switching on at the maximum/minimum displacement, which lowers the output power. In contrast, the MSS, which turns on only when the displacement exceeds the gap distance, showed the intriguing result that the output power continues to increase, whereas the displacement remains constant. Thus, for a harvester with high k, the MSS can outweigh the ESS.

Acknowledgements

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