A mechanical solution of self-powered SSHI interface for piezoelectric energy harvesting systems

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ABSTRACT

The synchronized switch interface circuits, e.g., synchronized switch harvesting on inductor (SSHI), can significantly enhance the harvesting capability of piezoelectric energy harvesting (PEH) systems. In these power conditioning circuits, the piezoelectric voltage is flipped with respect to a bias voltage at the instants when the piezoelectric element is at maximum deforming positions. Voltage peak detection and in time switching action are required for implementing these functions. The state-of-the-art solutions are mostly realized by electronic methods, i.e., both functions are carried out by electronic comparators and electronic switches. However, the peak detectors usually introduce switching phase lag; while the electronic switches function only when the vibration magnitude is above a threshold level. When the vibration is lower than such threshold, the SSHI interface shows no improvement. In this paper, we propose a mechanical solution for constructing the self-powered SSHI interface for PEH systems. This technique is realized by installing a low cost vibration sensor switch (VSS) at the free end of a piezoelectric cantilever. It senses the maximum deflecting places of the cantilever and automatically carries out synchronized switching actions. Compared to the existing electronic solutions, this mechanical solution is compact and has relative low switching threshold. Therefore, with this self-powered solution, the advantage of SSHI interface circuit can be sufficiently released, in particular, at low level vibration. Experiment shows the feasibility of this mechanical solution. The advantages and limitations are also discussed in this paper.

Keywords: piezoelectric energy harvesting, synchronized switch interface circuits, self-powered SSHI, vibration sensor switch

1. INTRODUCTION

Piezoelectric energy harvesting (PEH) technology provides eco-friendly alternative power supplies for low-power wireless sensors [1-4]. Based on the capacitive nature of PEH elements, synchronized switch harvesting on inductor (SSHI)[5] and other switch interface circuits [6] were proposed. It was reported that the SSHI can enhance the harvesting capability by several hundred percent [5]. In SSHI, the synchronized switches should detect the instants when a piezoelectric element is at maximum deformation and simultaneously carry out voltage flipping action in time. The extreme voltage detection and switch action were delivered by a controller, which is powered by external power supply [3, 5], until the inventions of some self-powered schemes [7-8]. Compared the externally powered solutions in the early stage, the self-powered solutions can diminish the additional power demand and thus make SSHI more applicable in practice.

A self-powered SSHI circuit is composed of three functional blocks, i.e., voltage peak detector, comparator, and electronics switch. The non-ideal peak detector lowers the open circuit voltage of the piezoelectric cantilever; the non-ideal comparator introduces a switching delay; the non-ideal switch can properly work only when the open circuit voltage is above a threshold voltage. The voltage drop of diodes and transistors [9] is an important issue in self-powered circuits, it might introduce considerable energy losses [8, 10] and therefore undermine the improvement by using SSHI. Aiming to reduce the threshold voltage and diminish the energy losses in diodes and transistors, Liu et al. proposed a mechanical solution, in which the synchronized switches are realized by the mechanical contacts of a piezoelectric cantilever and two mechanical stoppers at each side of the cantilever [9, 11-12]. Yet, in their design, the vibration magnitude can be neither too small (cantilever cannot touch the stopper in small magnitude vibration) nor too large

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(strong collision might happen under large vibration). On the other hand, the stoppers confine the deflection of the cantilever, which makes this solution not very universal under variable vibration magnitude.

In this paper, we propose a better mechanical solution of self-powered SSHI interface for PEH systems. This technique is realized by making use of a low cost vibration sensor switch (VSS) at the free end of a piezoelectric cantilever. The VSS senses the maximum deflecting instants of a cantilever and automatically carries out synchronized switching actions. Referring to the commonly used single degree-of-freedom (1DOF) model [2, 13-14] for PEH system, the PEH system with a VSS is modeled as a two DOF (2DOF) system. Design guidelines are made based on the theoretical derivation. The working principle is further studied with numerical simulation. Experiments show the feasibility of this technique.

2. THEORY

The configuration of an SSHI based PEH system is shown in Figure 1(a). The SSHI circuit consists of a switch, an inductor and a bridge rectifier. The synchronized switch *sw* should be turned on for enabling a voltage flipping once the piezoelectric voltage reach its extremes. The VSS provides a low cost solution for vibration detection. A commonly used VSS is shown in Figure 1(b). It is composed of a soft spring and a rigid pin as its two poles. The on/off state of the two poles varies when the VSS is subjected to a certain level of vibration. The basic idea of this research is to make use of the low cost VSS for detecting the maximum deflecting instants and simultaneously carry out switching actions for SSHI interface circuits. To realize this idea, the VSS is mounted at the free end of a piezoelectric cantilever, where vibration magnitude is usually the largest. How to properly generate the synchronized switching actions is crucial towards the realization of this proposal.

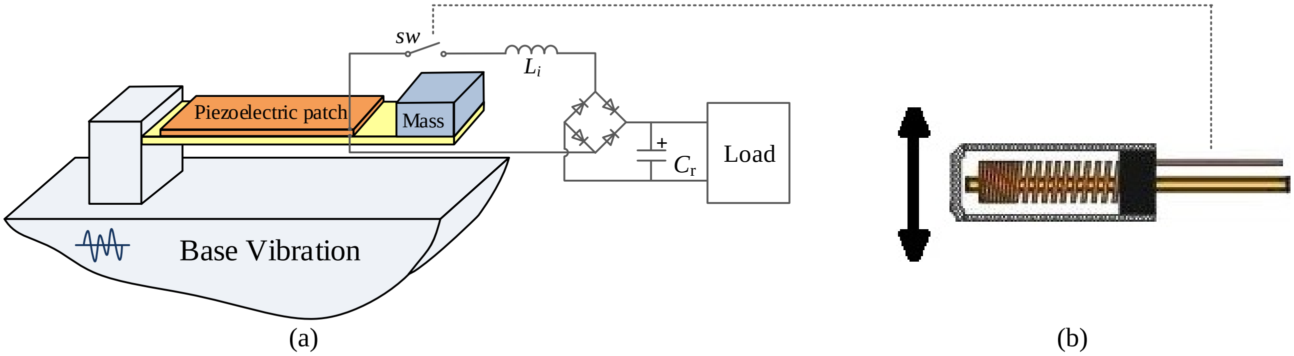


Figure 1. Basic idea of self-powered SSHI interface using VSS. (a) PEH system with SSHI interface circuit. (b) Configuration of VSS.

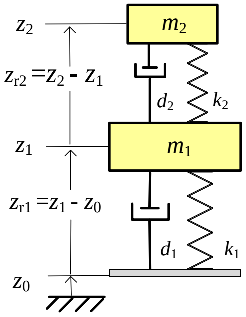


Figure 2. 2DOF model of a PEH system whose free end mounts a VSS.

In order to analyze the dynamic behavior of the whole system, the piezoelectric cantilever is modeled as a 1DOF vibrator, which works under its first flexural mode [13]; on the other hand, the VSS is assumed to be operating in a linear way and therefore can be modeled as an additional 1DOF vibrator, which is attached on the equivalent mass of the piezoelectric cantilever. Therefore the whole system combining with piezoelectric cantilever and VSS can be regarded as a 2DOF system, as illustrated in Figure 2 (the coupling effect is not considered at this stage). In Figure 2, m_1, d_1,and $k_1$are the equivalent mass, damping, and stiffness of the piezoelectric cantilever; m_2, d_2, and k_2 are the equivalent mass, damping and stiffness of the VSS; z_0 is the displacement of the vibrating base; z_1 and z_2 are the absolute displacements of m_1 and m_2, respectively; z_{r1} is the relative displacement of m_1 with respect to the base, and z_{r2} is that of $m_2$with respect to m_1. The relation between these two relative displacements are important, because z_{r1} is related to the deflection of the piezoelectric cantilever, while z_{r2}indicates whether the VSS is conducted or not.

Defining $\tilde{m} = m_2/m_1$ as the mass ratio; $\omega_j = \sqrt{k_j/m_j}, (j = 1,2)$ as the resonant frequency; $\zeta_j = d_j/(2m_j\omega_j)$ as the damping ratio, the equation of motion of the two masses can be expressed as follows

$$\ddot{z}_{r1}(t) + 2\omega_1\zeta_1\dot{z}_{r1}(t) + \omega_1^2 z_{r1}(t) - \tilde{m}\left[2\omega_2\zeta_2\dot{z}_{r2}(t) + \omega_2^2 z_{r2}(t)\right] = -\ddot{z}_0(t), \tag{1}$$

$$\ddot{z}_{r2}(t) + 2\omega_2\zeta_2\dot{z}_{r2}(t) + \omega_2^2 z_{r2}(t) = -\ddot{z}_1(t). \tag{2}$$

From equations (1) and (2), the relation of z_{r1} and z_{r2} can be analytically derived in the frequency domain as follows

$$\frac{Z_{r2}}{Z_{r1}} = \frac{2\zeta_1\omega_1 s + \omega_1^2}{\left(s^2 + 2\zeta_2\omega_2 s + \omega_2^2\right) + \tilde{m}\left(2\zeta_2\omega_2 s + \omega_2^2\right)} \tag{3}$$

where $s = j\omega$. When the system vibrates under the resonant frequency ω_1, i.e., $\omega = \omega_1$, (3) can be simplified as follows

$$\frac{Z_{r2}}{Z_{r1}} = \frac{1 + j2\zeta_1}{(1+\tilde{m})\tilde{\omega}(\tilde{\omega} + j2\zeta_2) - 1} \tag{4}$$

where the frequency ratio $\tilde{\omega} = \omega_2/\omega_1$. In addition, if $\tilde{\omega} \ll 1$, $\tilde{m} \ll 1$, $\zeta_1 \ll 1$, and $\zeta_2 \ll 1$, (4) can be further simplified into

$$\frac{Z_{r2}}{Z_{r1}} = -1 \tag{5}$$

Equation (3) to (5) indicates that if all those conditions are satisfied, the movements of the piezoelectric cantilever and the unbound VSS are out of phase. In general, we obtained five design guidelines for the self-powered SSHI using VSS as follows

1. $\tilde{\omega} \ll 1$, the resonant frequency of the VSS should be designed to be much lower than the piezoelectric cantilever, or even the moving part of the VSS is free from mechanical connection;
2. $\tilde{m} \ll 1$, the moving mass of the VSS should be designed to be much smaller than the equivalent mass of the cantilever, so that the installation of the VSS can hardly affect the original dynamics of the cantilever;
3. $\zeta_1 \ll 1$, the piezoelectric cantilever should be a low loss cantilever. This condition is also the preference for the cantilevers used for energy harvesting purpose;
4. $\zeta_2 \ll 1$, the VSS moving part should has low loss. This can be achieved through the design process;
5. $\omega = \omega_1$, the whole system vibrates near the resonant frequency of the original piezoelectric cantilever.

Figure 3 shows the conceptual displacement waveforms of the PEH cantilever with VSS when the aforementioned five criterions are satisfied. The relative movement of the cantilever z_{r1}(black dashed) and that of the designed VSSz_{r2}(solid) are out of phase under linear assumption. On the other hand, since the VSS changes its on/off state by hitting its boundaries on either sides (gray dashed), we assumed that, in the constrained scenario, z_{r2} leaves from either of the constraints after the linear z_{r2}attains its extremes (also the extremes of z_{r1}). Therefore, we can imagine the movement z_{r2} under constrained condition as that given by the dot line in Figure 3. Comparing the waveforms of z_{r1} and z_{r2} with constraints, there is approximately 90 degree of phase difference, which means that the VSS change states when

z_{r1} attains its extremes, i.e., the piezoelectric cantilever has maximum deflection. So the VSS can be used to detect the maximum deflection of the cantilever and then take switching actions with the mechanical contacts between its moving part and either of the boundaries.

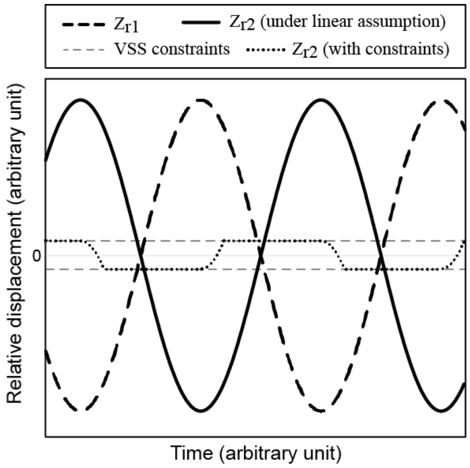


Figure 3. Conceptual displacement waveforms of the PEH cantilever with VSS.

3. SIMULATION

Simulation is carried out by using SimMechanics, a toolbox in Matlab, for studying the dynamic behavior of a cantilever with a linkage-free VSS connected to its free end. The block diagram is shown in Figure 4. The simulation result presented in animation are automatically generated by SimMechanics. The six key phases in each vibration cycle are illustrated in Figure 5. From Figure 5(a) and (d), we can observe that the moving part of the VSS hits either wall of the VSS framework, which is mounted at the free end of a cantilever, at right instants, when the beam deflection is maximized. These mechanical contact variations are further utilized for manufacturing a prototype of self-powered SSHI.

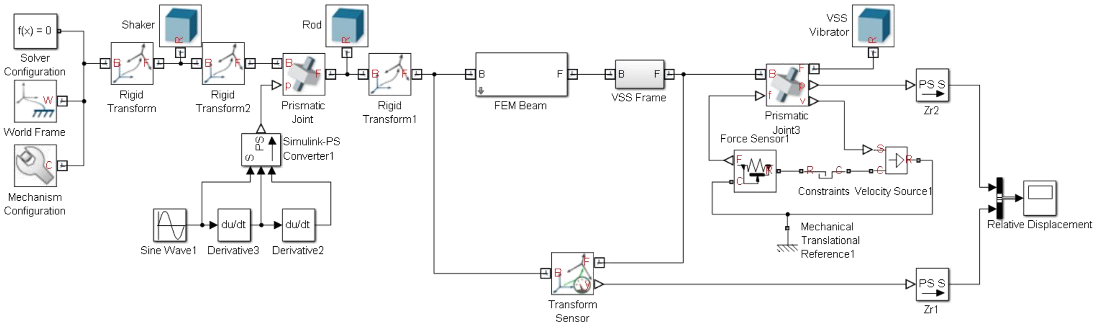


Figure 4.Block diagram in the simulation.

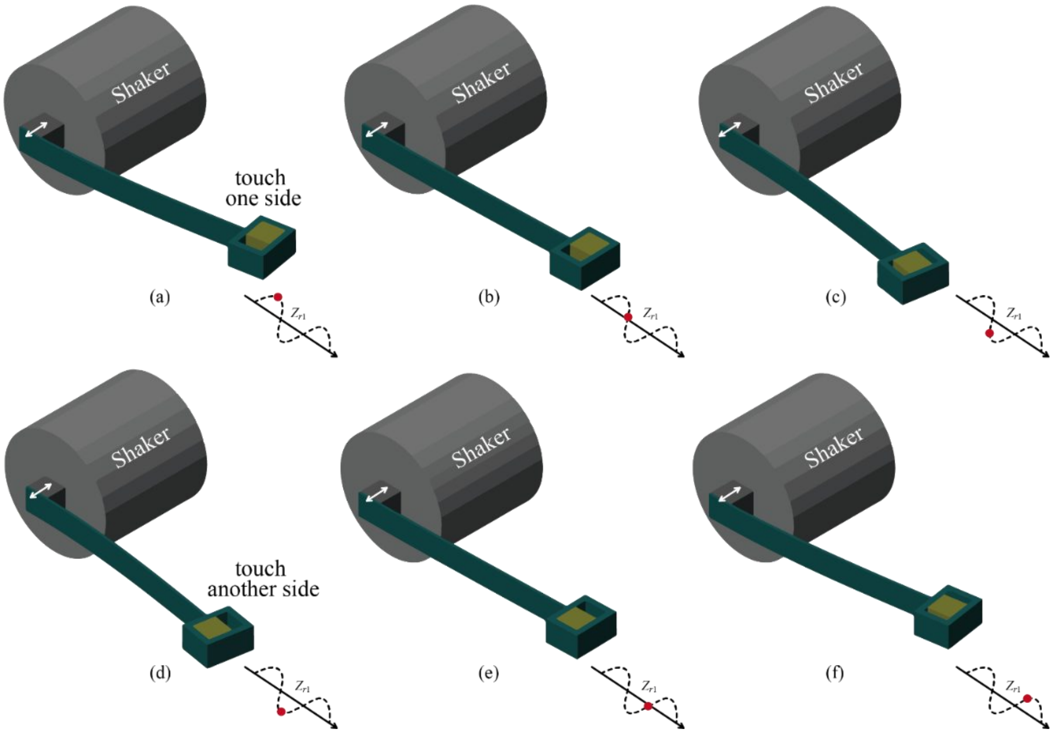


Figure 5. Operation of a linkage-free VSS in simulation. The phase sequences are (a)-(b)-(c)-(d)-(e)-(f)-(a)-(b)…

4. EXPERIMENTS

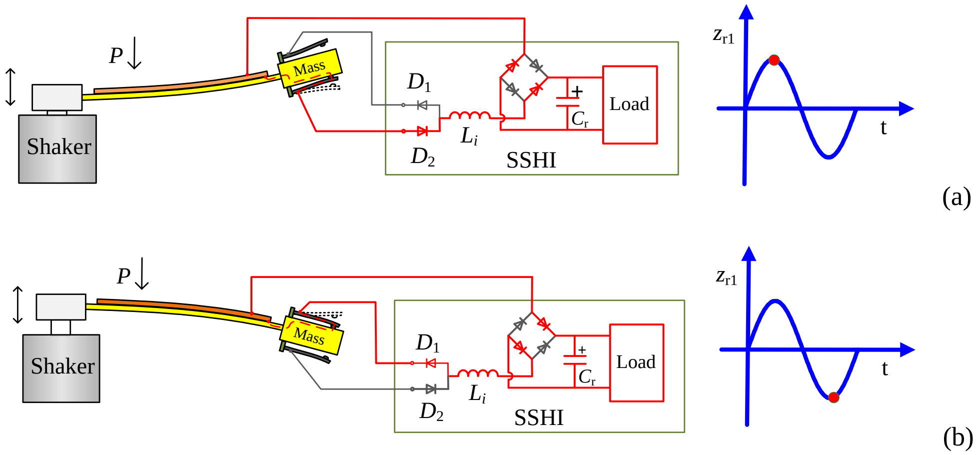


Figure 6. Schematic of the experimental setup.

Given that the double-wall VSS might introduce multiple strikes at one synchronized instant, the final prototype is manufactured with two single-wall VSSs. The experimental setup is illustrated in Figure 6. Its mechanical parameters and electrical components are listed in Table 1 and Table 2, respectively. The piezoelectric cantilever is made of a piezoelectric bimorph attached on a copper substrate. One of the piezoelectric patch is used for energy harvesting purpose, while the other is used as the reference for the vibration condition (it is not shown in the figure). The resonant frequency of the system was measured at 16.1 Hz, and thus the shaker output the excitation at this frequency. The electrical connection as well as the conductions at two displacement extremes are also shown in Figure 6. At each of the synchronized instants, the current flow through the corresponding red path.

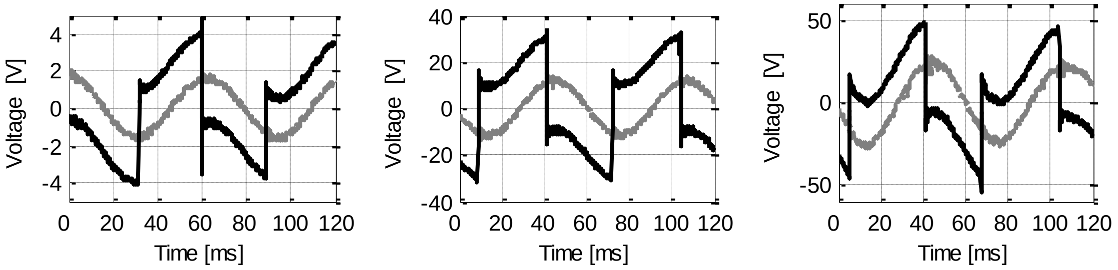
Table 1. Mechanical parameters.

Parameters	Substrate	Piezoelectric patches	Switch beam
Length (mm)	59.9	49.9	32.0
Width (mm)	53.3	49.9	6.3
Thickness (mm)	0.2	0.25	0.1
Proof mass (g)	42.0	--	0.85

Table 2. Electrical components.

Components	Parameters/model
C_p(nF)	218
C_r(uF)	100
L_i (mH)	47
Bridge rectifier	DB107
D_1, D_2(Ω)	1N4004

In the first experiment, we test the synchronized switching function of the VSS in the PEH system. In order to focus on the switch action, the filter capacitor and load are not connected in this part. Figure 6 (a) and (b) show the two switching instants in each cycle. In Figure 6 (a), the proof mass reaches its maximum displacement and begin to go back; at this time, due to the inertial, the VSS electrode below the proof mass hit the proof mass and the upper electrode leave from the proof mass; thus the circuit branch below the proof mass is turned on. Once the circuit is turned on, an LC resonant circuit is formed, and thus the voltage across the piezoelectric patch can be inverted. In the circuit, the diode D_1 and D_2 are used to block the reverse current. Therefore, once the voltage is inverted, it does not rewind. Figure 7 shows the voltage waveforms across the piezoelectric patches at different vibration levels, where the corresponding open-circuit reference voltage is 1.6 V, 13 V and 26 V in (a), (b) and (c), respectively. It can be observed from the figures that the VSS can sense the extreme points at a wide range of excitation amplitude and perform very good synchronized switching actions. The switching threshold is only two diode voltage drops, which is much lower than that in the electrical self-powered solutions. On the other hand, its effective range of vibration amplitude is much wider compared to the solution based on mechanical stopper. There is some phase lead for the switching action when the vibration amplitude gets larger, as observed from Figure 7(c). This phenomenon needs further investigation in future studies.



(a) (b) (c)

Figure 7. Voltage waveforms across the piezoelectric patches at different vibration levels: (a) Open-circuit reference voltage is 1.6 V; (b) Open-circuit reference voltage is 13 V;(c) Open-circuit reference voltage is 26 V. ▬ Open-circuit; ▬ SSHI.

In the second experiment, we compare the harvesting performances between the standard energy harvesting (SEH) interface (bridge rectifier) and VSS based self-powered SSHI, when the vibration generates an open-circuit voltage of 16.2 V. The measurement results are shown in Figure 8. From the results, the self-powered SSHI outperforms the SEH. The optimal load of the SSHI and SEH is about 30 kΩ and 70 kΩ, respectively. In these case, the maximum output power of SSHI and SEH are 0.341 mW and 0.248 mW, respectively, which means that the output power improvement by using VSS based self-powered SSHI is about 37.5%.

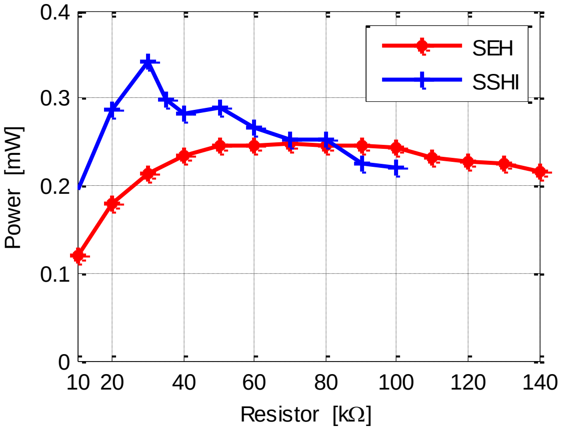


Figure 8. Output power in SEH and VSS based self-powered SSHI.

5. CONCLUSIONS

Inspired by the low cost vibration sensor switch (VSS), this paper has proposed a mechanical solution for self-powered synchronized switch harvesting on inductor (SSHI) in piezoelectric energy harvesting (PEH) systems. Through analytical modeling and numerical simulation, the working principle of the VSS in self-powered SSHI was explained in detail. Five design guidelines are derived for the constructing the VSS based self-powered SSHI system. Experimental results show that the VSS has very low voltage switching threshold (about two diode voltage drops) and it can normally operate over a wide range of vibration amplitude. Future work will focus on better design on the collision interface between the moving part and walls of the VSS and also the delicate manufacturing of a compact and stable VSS based self-powered SSHI.

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