Research Article

Energy Harvesting Using an Analog Circuit under Multimodal Vibration

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The efficiency of harvesting energy from a vibrating structure using a piezoelectric transducer and a simple analog circuit is investigated experimentally. This analog circuit was originally invented for a synchronized switch damping on inductor (SSDI) technique, which enhances the damping of mechanical vibration. In this study, the circuit is used to implement a synchronized switch harvesting on inductor (SSHI) technique. A multiple degree of freedom (MDOF) structure is excited by single sinusoidal forces at its resonant frequencies and by random forces. The piezoelectric transducer converts this mechanical energy into electrical energy which is harvested using a standard rectifier bridge circuit with and without our analog circuit. Experimental results show that our analog circuit makes it possible to harvest twice as much energy under both single sinusoidal and random vibration excitations.

1. Introduction

Energy harvesting techniques have been studied extensively in recent years. Energy harvesting is a process by which energy is captured and stored. Energy can be harvested from various power sources, including wind power, solar power, ocean tides, heart, magnetic fields, and structural vibrations. We focused on the vibration energy of a structure, using the piezoelectric effect to convert structural vibration energy into electrical energy. There is substantial research on this technique, as reviewed by Sodano et al. [1]. Lesieutre et al. [2] addressed the damping associated with energy harvesting from structural vibrations.

Badel et al. [3–5] proposed a synchronized switch harvesting on inductor (SSHI) technique to improve energy harvesting. SSHI is based on vibration suppression technique named synchronized switch damping on inductor (SSDI). Both SSHI and SSDI use a piezoelectric transducer attached to the structure and connected to an inductive circuit

having an on-off switch [6–10]. The switch in the circuit is flipped at each extremum of displacement of the structure. A displacement sensor and a controller are needed to synchronize the switching commands with the mechanical vibration. In a self-powered system, these sensors and controllers need to be driven using a fraction of the harvested energy.

We previously invented an analog circuit that automatically performs switching without an external energy source [11]. We describe in this paper how this analog circuit enhances the energy harvesting performance when used with SSHI.

Although many studies [12–14] have been conducted on SSHI, most of them are limited to the sinusoidal vibration of a single degree of freedom (SDOF) structure. This paper focuses on the energy harvesting performance of our analog vibration suppression system for a multiple degree of freedom (MDOF) structure under various excitations. First, we describe the SSDI mechanism. Next, we describe our analog self-powered device. Finally, we present the experimental

FIGURE 4: (a) SDOF energy harvester connected a piezoelectric transducer. (b) SDOF energy harvester connected a piezoelectric transducer with original SSDI.

turning the thyristor on is equivalent to flipping the switch in Figure 1 to point A. When the value of V_p reaches a minimum and starts to increase, PUT_2 is similarly turned on, and subsequently, SCR_2 is also turned on. This action is equivalent to flipping the switch in Figure 1 to point B.

In effect, this analog circuit flips the switch in Figure 1 to point A when V_p is approximately at a maximum and flips the switch to point B when V_p is approximately at a minimum. Therefore, this simple analog circuit performs the functions of a sensor, a controller, and a switch for SSDI.

2.3. Energy Harvesting with Original SSHI. An electric circuit consisting of a piezoelectric transducer connected to an energy harvester and a load resistance R_s is shown in Figure 4(a). The energy harvester is composed of four diodes and a capacitor C_s . This is a basic energy harvesting system with a piezoelectric transducer. A bridge circuit with four diodes rectifies the electrical energy from the piezoelectric transducer and stores it in capacitor C_s .

Figure 4(b) shows a typical system for energy harvesting with SSHI. As shown in this figure, a switchable inductive circuit is connected to the system shown in Figure 4(a). SSHI tunes the switch in Figure 4(b) just as SSDI does. Because this switching increases the absolute value of V_p , as mentioned, SSHI can effectively harvest energy. In Figure 2, the broken line shows the vibration in V_p when some energy is harvested by SSHI, whereas the solid line shows the variation in V_p when SSDI is used. The figure shows that when the absolute value of V_p reaches the voltage of C_s , the energy starts to flow into C_s . C_s has a large capacitance, causing V_p to plateau.

2.4. Energy Harvesting with Analog Self-Powered SSDI. The SSDI technique is implemented as shown in Figure 5, by replacing the switchable inductive shunt circuit shown in

Figure 1 with our analog circuit. Similarly, SSHI is implemented as shown in Figure 5 by replacing the switchable shunt circuit in Figure 4(b) by our analog circuit.

3. Experiment

3.1. Experimental Setup. Figures 6 and 7 show a view of the experimental system, which consists of two masses, a pantograph-type displacement-magnification mechanism, a piezoelectric transducer (PSt 1000/10/200-VS18, Piezomechanik GmbH), two cantilevered beams, a spring, a vibration shaker, and a platform. The displacement-magnification mechanism is attached to the upper beam, and upper side of the platform is used to accommodate the small elongation of the piezoelectric transducer in response to the large amplitude of vibration. The natural frequencies of the first and second vibration modes at a constant electric charge are 20.3 and 36.6 Hz, respectively [16].

The experiment is performed under three types of vibration excitations: a sinusoidal vibration excitation at the first mode resonant frequency, a sinusoidal vibration excitation at the second mode resonant frequency, and a random vibration excitation. We investigated the performance in harvesting energy using our system shown in Figure 5 for various values of load resistance R_s .

3.2. Experimental Results with Sinusoidal Excitation. Figure 8(a) shows the steady-state variations in displacement of the upper mass 1, the voltage of the piezoelectric transducer V_p , and the harvested voltage V_s under a sinusoidal excitation at the first mode resonant frequency. In this case, the value of R_s is very large. At each extremum of displacement, the polarity of voltage V_p reverses. This voltage behavior is a typical feature of SSHI. Figure 8(b) shows a magnified view of Figure 8(a). When the absolute value of V_p is increased

FIGURE 5: SDOF energy harvester with our analog self-powered circuit.

FIGURE 6: Mechanical part in 2-DOF system.

FIGURE 7: Mechanical experimental configuration in 2-DOF system.

to a certain value, energy starts flowing into capacitor C_s , and as a result, V_p stays almost constant, making a plateau in the waveform. The difference between the plateau voltage and voltage V_s is attributed to the forward voltage of the diodes in the rectifier circuit. Figure 8(b) shows that the difference

is 1.2 V, which is consistent with the forward voltage of 0.6 V for each diode.

Figure 9(a) shows a comparison of the normalized harvested energy for various values of load resistance under a sinusoidal excitation at the first and second mode resonant frequencies. The energy dissipated by the load resistance is influenced by the value of resistance R_s . To optimize the harvested power, we apply various load resistances in the electric circuit. The horizontal axis represents the load resistance, and the vertical axis represents the harvested power divided by the mean square of displacement of mass 1, with and without our analog circuit. These figures indicate that our system significantly increases the energy harvested from the MDOF structure under sinusoidal vibrations. Although the amount of energy harvested depends on the value of the electric load R_s , the amount is drastically increased using our circuit under vibration excitation at both the first and the second mode resonant frequencies.

3.3. Experimental Results with Random Excitation. We also carried out experiments using random excitation. The vibration shaker connected the upper cantilever through the load cell. A function generator creates an input voltage wave and sends it to vibration shaker. The PSD of the random excitation force is constant over the frequency range from 10 Hz to 50 Hz.

Figure 9(b) shows the normalized harvested energy for various values of load resistances under random excitation. The horizontal axis is the load resistance, and the vertical axis is the harvested power divided by the mean square of displacement of mass 1, with and without our analog circuit. This figure indicates that our system significantly increases the energy harvested from the MDOF structure under random vibrations. Although the amount of energy harvested depends on the value of the electric load R_s , the amount is drastically increased using our circuit under random excitation.

The harvested energy can be increased by a factor of at least 2.3 using our simple analog circuit not only under sinusoidal vibration excitation but also under random vibration excitation.

FIGURE 8: (a) Time history of the piezoelectric voltage, harvested voltage, and displacement of mass 1 under first mode sinusoidal vibration excitation ($C_S = 47 \text{ mF}$, $R_S = \infty \Omega$). (b) Magnified view of (a).

FIGURE 9: (a) Comparison of normalized harvest power for various load resistances under sinusoidal vibration excitations. (b) Comparison of normalized harvest power for various load resistances under random vibration excitations.

4. Conclusion

We proposed a simple analog circuit to implement SSHI for harvesting energy from structural vibrations using piezoelectric transducers, and we investigated the resulting performance. Experiments were performed using an MDOF structure under sinusoidal vibration excitation at resonance frequencies and under random vibration excitation. Experimental results show that connecting our simple analog circuit to the standard circuit more than doubles the amount of energy harvested under both single sinusoidal vibration excitation and random vibration excitation.

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