An Innovative Controller to Increase Harvested Energy

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Abstract. This paper proposes an innovative energy-harvesting controller to increase energy harvested from vibrations. Energy harvesting is a process that removes mechanical energy from a vibrating structure, which necessarily results in damping. The damping associated with piezoelectric energy harvesting suppresses the amplitude of mechanical vibration and reduces the harvested energy. To address this critical problem, we devise an energy-harvesting controller that maintains the vibration amplitude as high as possible to increase the harvested energy. Our proposed switching controller is designed to intentionally stop the switching action intermittently. We experimentally demonstrate that the proposed control scheme successfully increases the harvested energy. The piezoelectric voltage with the proposed controller is larger than that with the original synchronized switching harvesting on inductor (SSHI) technique, which increases the harvested energy. The stored energy with our controller is up to 5.7 times greater than that with the conventional SSHI control scheme.

1. Introduction

Interest in energy-harvesting technology has been growing in recent years. Energy harvesting refers to any process that scavenges useful energy for later use from a wide variety of sources, such as wind energy, solar energy, tidal energy, piezoelectricity, thermoelectricity, and kinematic energy. Vibration-based energy harvesters convert mechanical vibration energy into electrical energy by utilizing electromagnetic materials [1], piezoelectric materials including lead zirconate titanate (PZT), macro fiber composites (MFCs), polyvinylidene difluoride (PVDF) [2, 3], and magnetostrictive materials [4]. Of these substances, here we explore the use of piezoelectric materials for energy-harvesting devices. The conventional method of energy harvesting, which uses only a diode bridge, is a simple AC-to-DC power conversion scheme [5, 6] that is commonly known as a standard rectifier. Numerous experimental and theoretical studies have been conducted with vibration-based energy harvesters that exploit piezoelectric materials. To increase the output power relative to standard energy-harvesting circuits, Guyomar et al. [7] proposed the technique of synchronized switch harvesting on an inductor (SSHI), in which a nonlinear electric element is appended to the conventional harvesting circuit. Specifically, their SSHI technique utilized a circuit composed of on-off switches to provide two electric states: one in which electric current flows and another in which it does not. Many proposals have been advanced and studies conducted to improve the SSHI scheme [8-10]. Badel et al. [8] achieved a four-fold increase in harvested energy over the standard circuit by using the SSHI circuit. Makihara et al. [9] used a selector switch to make the SSHI circuit more compact and more sophisticated, and enhanced harvesting performance by reducing unnecessary energy consumption. Qiu et al. [10] compared four different SSHI
conditioning circuits and their output power equations. They proposed a simple source-less circuit to implement SSHI scheme based on the trigger circuitry design.

2. Objectives statement

Energy harvesting deprives a vibrating structure of mechanical energy, and necessarily results in damping of vibration [11]. The damping associated with piezoelectric energy harvesting suppresses the amplitude of mechanical vibration, which in turn reduces subsequently harvested energy. The reduction in harvested energy becomes clear, especially if the structural inertia or excited force is small relative to the harvesting force. From the viewpoint of vibration suppression, the reduced amplitude of the vibration is beneficial. However, in terms of energy harvesting, the reduced vibration is quite harmful because the resultant energy is also reduced. To date, energy-harvesting technologies that incorporate measures to counter the reduction of stored energy have yet to be proposed. To address this critical issue, we devise an energy-harvesting controller based on the SSHI scheme to increase the harvested energy. The SSHI scheme utilizes switching control in cases where the harvesting circuit has electric switches; the switches are controlled in synchronization with the structural vibration phase to increase the piezoelectric voltage, which eventually increases the harvested voltage. To avoid the decrease in vibration amplitude, here we manipulate the timing of switching actions for electric switches to maintain the vibration amplitude as high as possible.

3. Fabrication of energy harvester

We experimentally demonstrate that our proposed controller successfully increases the harvested energy. We fabricate a concise energy harvester comprising the following three parts: a cantilevered beam with a piezoelectric PZT patch, a switching circuit to increase PZT voltage, and a controller to govern the switching action. The cantilevered beam is made of a brass plate (38 × 8 × 0.25 mm) and a tip mass (10.3 g), as shown in figure 1. The PZT patch is attached onto the beam. The natural frequency of the beam is 18.05 Hz, with a constant-charge state.

![Figure 1. Energy-harvesting device.](image1)

![Figure 2. Experimental setup for harvesting.](image2)

Figure 2 shows the experimental setup of the concise energy harvester. The cantilevered beam is mounted on the base of a vibration exciter and is clamped with a fixation device. A function generator sends a sinusoidal wave signal for exciting the beam vibration to a vibration exciter, which moves up and down according to the signal. The motion of the exciter causes the beam to vibrate. An accelerometer is also mounted on the base to measure the vibration acceleration. It measures the base acceleration to feed it back to the function generator so that the base acceleration can be maintained at 10 mG (0.098 N/m²). A laser displacement sensor measures the displacement of tip mass of the cantilevered beam. The motion of the base is negligible compared to that of the tip. The switching circuit shown in figure 3 is created to implement the SSHI scheme [7]. The circuit has a storage capacitor and two on-
off switches (SW1 and SW2) to control the current direction. The circuit branch composed of the switches and the inductor boosts the value of the piezoelectric voltage with the appropriate switching action. A diode bridge comprising four diodes rectifies the boosted voltage by providing rectified current to the storage capacitor, which is connected in parallel.

![Switching control circuit for SSHI.](image)

Figure 3. Switching control circuit for SSHI.

![Concept of switching and pause durations for switching action.](image)

Figure 4. Concept of switching and pause durations for switching action.

4. **Proposed energy-harvesting controller to increase harvested energy**

According to the original SSHI scheme [7], the on-off switches are turned on every time the tip mass displacement reaches its peak value. Theoretically, the switching action at every peak of displacement results in the most efficient harvesting only when the structural inertia or excited force is large enough compared with the harvesting force. However, because the inertia of small and concise harvesters is usually small, switching at every peak suppresses the vibration and accordingly reduces the harvested energy, contrary to expectation. In other words, the switching action simultaneously imparts two effects on vibrating structures: vibration suppression and energy harvesting. Improved energy harvesting requires a new switching controller that boosts the harvesting effect and negates the suppression effect.

Our proposed switching controller is designed to intentionally stop the switching action intermittently; that is, pause durations are added to the switching durations. An example is shown in figure 4, in which the pause and switching durations are designated as three vibration periods and one vibration period, respectively. Numerous combinations of these two durations can be selected and designed. The amplitude of the vibration, which is reduced by switching, is expected to recover to its original value during the pause. This recovery of mechanical energy compensates for the vibration-suppression effect that reduces the mechanical energy. Note that our switching controller is designed so that the harvesting effect dominates the suppression effect. We have already submitted patent applications for this switching controller to contribute to the creation and development of industry [12].

5. **Experimental results and discussions**

We carried out experiments with the fabricated harvester to implement the proposed control scheme and investigated whether the scheme could successfully increase the piezoelectric voltage. The PZT voltage shows complex behavior caused by interference between the PZT and the storage capacitor. Therefore, the storage capacitor in the harvesting circuit was initially inactivated to focus on the behavior of the PZT voltage. Figure 5 compares the displacement of the tip mass for two switching controllers (with and without a three-period pause). The original displacement amplitude (without a pause) was 80 μm and the maximum displacement with a three-period pause was 260 μm. The displacement with the three-period pause was larger than that without a pause. The sloped lines in figure 5 are added to easily identify the recovery of displacement during the pauses. Figure 6 shows the piezoelectric voltage history.
for the two switching controllers. During the switching duration, the voltage reversed from negative to positive and vice versa. This voltage inversion partly reflects the electrical vibration induced by the inductor and the capacitance element of the PZT. The piezoelectric voltage with the three-period pause was larger than that without the pause (the original SSHI scheme). This increase is consistent with our prediction that the new switching controller should promote recovery of the vibration amplitude. Accordingly, the voltage of the storage capacitor also increases, which increases the harvested energy.

![Figure 5. Tip displacement history with and without three-period pauses.](image1)

![Figure 6. Piezoelectric voltage history with and without three-period pauses.](image2)

Second, by inserting a storage capacitor in the harvesting circuit as shown in figure 3, we carried out an energy-harvesting experiment to verify the proficiency of the proposed switching controller. The storage capacitance was set to 47 μF and four types of switching controllers (no switching, no pause, one-period pause, and three-period pause) were implemented. Figure 7 compares the stored energy with the four switching controllers. The stored energy with a three-period pause was up to 2.8 times greater than that without a pause (original SSHI).

Third, we carried out extensive experiments for energy harvesting. The stored energy was normalized with respect to that of switching without a pause (original SSHI) and evaluated as a function of the number of pause periods. Figure 8 shows the normalized stored energy as a function of the number of pause periods. The controller without pause periods (number of pause periods = 0) is equivalent to the original SSHI controller proposed by Guyomar et al. [7], in which the switching action is activated at every peak of structural displacement. As described next, figure 8 also clearly indicates the relation between the energy-harvesting and vibration-suppression effects. Between 0 and 4 pause periods, the normalized stored energy increases as the number increases; that is, the energy-harvesting effect becomes more dominant than the suppression effect. Beyond 5 pause periods, the normalized energy decreases as the number increases; that is, the energy-harvesting mechanism of the SSHI scheme does not work well with over 5 pause periods. If the controller skips too many periods, the voltage inversion rarely occurs and the harvested energy becomes that of the standard harvester.

For our concise energy harvester, a four-period pause provides the best harvesting performance, as shown in figure 8. The stored energy with a four-period pause is up to 5.7 times larger than that without a pause (original SSHI). A factor of 5.7 is noteworthy for the future development of energy harvesters. The energy without switching (i.e., standard harvesting) is indicated by the horizontal line for reference. The optimal number of pause periods for proficient harvesting may depend on the characteristics of energy harvesters, such as their mass, size, natural frequency, and PZT volume. Theoretical prediction
of the optimal number will require consideration of unsteady vibrations, as seen in the sloped lines in figure 5. investigation of this intriguing phenomenon, although promising for future work, is beyond the scope of this paper.

![Figure 7. Stored energy history for various switching controls (Storage capacitance = 47 \mu F).](image1)

![Figure 8. Normalized stored energy vs. number of pause periods.](image2)

6. Conclusions
An innovative energy-harvesting controller was proposed to increase the harvested energy from vibration. The proposed switching controller improves the original SSHI controller by intentionally stopping the switching action intermittently. Although the aim of the original SSHI scheme was to increase the harvested energy, the scheme actually suppresses the vibration amplitude and reduces the harvested output. The aim of the proposed controller was to restore the original amplitude of the vibration during the pauses. This recovery of mechanical energy was expected to boost the energy-harvesting effect and negate the vibration-suppression effect. Subsequently, we experimentally demonstrated that the proposed controller could successfully increase the harvested energy. The piezoelectric voltage with the proposed controller was greater than that with the original SSHI controller. This resulted in an increase in harvested energy. The stored energy was up to 5.7 times greater than that with the original scheme. The control principle that we proposed here can be applied to various MEMS harvesters with low voltage and power.

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