Piezoelectric MEMS-based wideband energy harvesting systems using a frequency-up-conversion cantilever stopper

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ABSTRACT

Two MEMS-based piezoelectric energy harvesting (EH) systems with wideband operation frequency range and capability of converting random and low-frequency vibrations to high-frequency self-oscillations have been proposed. In the first EH system (EH-I), by incorporating a high-resonant-frequency (HRF) cantilever as a frequency-up-conversion (FUC) stopper, the vibration amplitude of a low-resonant-frequency (LRF) cantilever with a resonant frequency of 36 Hz is suppressed and the operation bandwidth is increased to 22 Hz at 0.8 g. The HRF cantilever is then triggered to vibrate at 618 Hz. In the second EH system (EH-II), by employing a straight cantilever as the FUC stopper, the operation frequency range of a meandered cantilever which responds to lower frequency vibration is further moved downward from 12 Hz to 26 Hz, and the voltage and power generation are significantly improved. The peak-power densities of the EH-II system are 61.5 μW/cm³ and 159.4 μW/cm³ operating at relatively lower operation frequencies of 20 Hz and 25 Hz at 0.8 g, respectively.

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1. Introduction

Thin film piezoelectric lead zirconate titanate (PZT) materials offer a number of advantages in microelectromechanical systems (MEMS) as such devices provide large motions with low hysteresis in applications such as actuating mirrors [1], and raster scanning mirrors [2]. They also provide good signal-to-noise ratio in a wide dynamic range [3–7]. The piezoelectric coefficient of PZT is more superior than other piezoelectric thin films, such as ZnO and AlN, due to the high energy density. Hence, PZT thin films are good transducer materials for MEMS based energy harvesters [8–10].

Vibration-based MEMS energy harvesters have received increasing attention as a potential power source for micro-electronics and wireless sensor nodes [11,12]. To date most energy harvesters based on piezoelectric, electromagnetic and electrostatic transduction mechanisms, particularly MEMS-based harvesters, operate at frequencies of more than 100 Hz [13–17]. Increasing compliant spring and bulk movable mass are required to achieve lower resonant frequency. It is a great challenge to realize small size and low resonant frequency at the same time due to the limitation of microfabrication processes and brittle properties of silicon material. The generated power

is theoretically proportional to the cube of the operation frequency and drops dramatically at low frequencies [18]. Thus energy harvesters with low resonant frequencies would result in reduced power output. However, harvesting energy from low frequency vibrations, such as human motions (<10 Hz), vehicle (<20 Hz) and machine vibrations (<50 Hz) [19–21] is desirable in applications such as implantable electronic devices and wireless sensor nodes. Thus FUC approach has been touted as a breakthrough to boost output power at low vibration frequencies [22].

Several researchers have developed FUC energy harvesters by utilizing magnetic forces [23,24]. In this approach, a magnet attached to a low-frequency or bulked diaphragm resonantly or non-resonantly catches and releases magnetic strips mounted on high-frequency oscillators, resulting in self-oscillations of the oscillators. These methods require additional magnets to generate current and are suitable for electromagnetic energy harvesters. Jung et al. [25] demonstrated a shock-based FUC approach using a buckled elastic beam integrated with high-frequency piezoelectric cantilevers. A sudden acceleration change introduced by the buckled beam would excite the self-oscillations of the piezoelectric cantilevers. However, this method requires large accelerations to drive the buckled beam. Renaud et al. [26] has reported a non-resonant impact-based energy harvester driven by a free ball moving in a guided channel where top and bottom piezoelectric benders are mounted in between. The method however does not benefit from the power enhancement of a resonant operation. A

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resonant impact-based energy harvesting prototype which utilizes a low-frequency resonator to directly impact two high-frequency PZT bimorphs in order to trigger their self-oscillations and generate power at high operation frequencies was also reported by Gu et al. [27]. The prototype suffered from large device size and has not been realized by MEMS technology. In fact, none of the aforementioned works use micro-scale approaches [25–26].

For a given acceleration, the vibration amplitude of an oscillator is inversely proportional to the square of the vibration frequency. A lower resonant frequency requires an increased displacement space and mechanical stoppers to prevent damage of the oscillator, thus reducing the generated power density of the device, though the mechanical stopper does broaden the frequency bandwidth [28,29]. In this work, instead of increasing the extra space to accommodate the displacement of the LRF oscillator, we incorporate a piezoelectric HRF cantilever which is excited into self-oscillation by the impact of the LRF cantilever and at the same time acts as an energy harvester. This will not only reduce the device space and protect the oscillator, but also realize a wide operation band and FUC behavior. As a result, additional significant power will be generated and power density of the system will be improved.

2. Working principle

Fig. 1(a) and (b) shows the architecture and schematic model of a vibration-based wideband EH system assembled with FUC stopper. The system contains an excitation oscillator with stiffness k_0, damping coefficient c_0, and proof mass m_0. Another oscillator which acts as a FUC stopper is placed at a distance of x_0 above the excitation oscillator, with stiffness k_1, damping coefficient c_1 and proof mass m_1. The resonant frequency and the spring stiffness of the FUC oscillator are larger while the proof mass is smaller than that of the excitation oscillator. The operation mechanism is outlined in Fig. 1(c). The differential equation of the motion of the wideband EH system with cantilever stopper engaged can be written as

$$\begin{cases} (m_0+m_1)\ddot{z} + (c_0+c_1)\dot{z} + (k_0+k_1)z - k_1 x_0 = -(m_0+m_1)\ddot{y} & (z \geq x_0) \\ m_0\ddot{z} + c_0\dot{z} + k_0 z = -m_0\ddot{y} & (z < x_0) \end{cases} \tag{1}$$

When the vibration amplitude of the excitation oscillator is less than x_0, the stiffness of the oscillator remains as k_0. When the vibration amplitude exceeds x_0, the excitation oscillator would engage the FUC oscillator, resulting in a sudden change in the effective stiffness (from k_0 to k_0+k_1) and the effective mass (from m_0 to m_0+m_1). Since $m_1 \leq m_0$ and $k_1 \geq k_0$, the effective resonant frequency is increased accordingly. Such increment enables the resonance of the excitation oscillator to broaden over a wider frequency range [30]. When the excitation oscillator moves away from the FUC oscillator, the FUC oscillator would vibrate at its own resonant frequency, which is much higher than the excitation frequency. Thus broadening of the frequency wideband and FUC behavior are achieved simultaneously.

The analytical model of a wideband energy harvester using stopper has been built and analyzed by Soliman et al. [31,32] and Liu et al. [29], which is applicable to our proposed EH systems. Based on the analytical model, it is found that the key parameters affected on the frequency wideband behavior include input acceleration, damping coefficient, effective stiffness and gap distance. The frequency wideband behavior of the system is strengthened by an increase in the effective stiffness and a decrease in the damping coefficient. However, the practical situation is that higher stiffness will also induce higher damping coefficient of the structure. Normally it is impossible to increase the effective stiffness of the system and decrease the damping of the FUC stopper at the same time.

According to our experiments, if the resonant frequency of the excitation oscillator is below 50 Hz, the resonant frequency of the FUC stopper should be around 5–10 times higher. In addition, a high acceleration is also preferred to realize a better performance (wider operating bandwidth and higher power output). There is a trade-off for the gap distance, since it affects the frequency bandwidth and output voltage with opposite trend.

3. Device configurations

3.1. EH-I system

As shown in Fig. 2(a), the proposed wideband EH-I system contains a low-resonant-frequency energy harvesting cantilever (denoted as LRF cantilever) and a high-resonant-frequency energy harvesting cantilever (denoted as HRF cantilever). The LRF cantilever as shown in Fig. 2(b) comprises of a silicon supporting beam (3 mm × 5 mm × 5 μm) deposited with a PZT layer and silicon inertial mass (5 mm × 5 mm × 0.4 mm). The PZT layer consists of 10 PZT stripes electrically isolated from one another. The HRF cantilever (Fig. 2(c)) has similar dimensions and configuration with that of the LRF cantilever, but without an inertial mass. The resonant frequencies of the LRF and HRF cantilevers are 36 Hz and 618 Hz, respectively. Figs. 2(d) and (e) illustrate the vibration behavior of the wideband EH-I system. The LRF and HRF cantilevers are assembled with a pre-determined stop-spacing of 1 mm. The vibration amplitude of the LRF cantilever is larger than the stop-spacing and it is able to respond to ambient vibrations nearby its resonant frequency and further extend over a wider frequency bandwidth by the HRF cantilever which acts as a FUC stopper. In the meantime, the HRF cantilever is triggered by the inertial mass of the LRF cantilever into a high frequency self-oscillation. Due to the piezoelectric effect, the electric current is generated once the PZT layer on both LRF and HRF cantilevers deform.

The advantages in employing the HRF cantilever as a FUC stopper are that it protects the excitation oscillator from damage during vibration and broadens the operation range. The system also converts ambient low frequency vibration to a high frequency self-oscillation. Using MEMS technology, the proposed system is applied to a piezoelectric-based EH system by the use of cantilever beams deposited with piezoelectric PZT material. To further improve the effectiveness of the FUC stopper, as well as reduce the device size and operation frequency, a wideband EH-II system is developed.

3.2. EH-II system

As illustrated in Fig. 3(a), the LRF cantilever used in wideband EH-I system is replaced by a meandered cantilever with a smaller chip size (5.2 mm × 4.2 mm) in the proposed EH-II system. The HRF cantilever is replaced by a straight cantilever of the same size. A cross-sectional view of the EH-II system is shown in Fig. 3(b). The meandered cantilever as shown in Fig. 3(c) consists of a double-S-shaped silicon beam coated with PZT thin film layer and a silicon mass (2 mm × 1.65 mm × 0.4 mm) at its end. It is not only smaller in size but also has a lower resonant frequency of 20 Hz as well. The straight cantilever which has a relatively higher resonant frequency of 127 Hz has a rectangular silicon beam and a mass at its end and a PZT layer is also coated on the silicon beam. The PZT layer deposited on the meandered cantilever is limited and the operation frequency is low, hence the power generated by the meandered cantilever would be extremely small. However, due to the low stiffness of the beam, its vibration amplitude is relatively large. Hence, with the large vibration amplitude, the meandered cantilever is able to convert its low-frequency vibration into a high-frequency oscillation of the straight cantilever after impact and increase the total output power significantly.