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A WIDE-BAND PIEZOELECTRIC ENERGY-HARVESTER FOR HIGH-EFFICIENCY POWER GENERATION AT LOW FREQUENCIES

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ABSTRACT

This paper presents a miniaturized piezoelectric vibration energy harvester that can generate over 1.5μW of average power at the frequency range of 9Hz to 19Hz under sinusoidal input acceleration of 1g. The harvester employs non-contact frequency up-conversion technique to excite two stages of generators, achieving wide-band low-frequency generating capability with a small size. The fabricated harvester was mounted on a moving bus to test its performance in a real-life situation and generated up to 1.11V of peak voltage and 123nW of peak power.

KEYWORDS

Vibration energy harvester; frequency up-conversion;

INTRODUCTION

Vibration energy harvesting is increasingly exploited since it is a promising candidate of power supply for ubiquitous wireless microsystems [1]. Ambient vibration is usually distributed over a wide spectrum, may change in spectral density over time, and is dominant at very low frequencies [2], making harvesters based on linear oscillators inefficient. Methods such as oscillator arrays, multi-modal oscillators and frequency-tuning are explored to improve frequency adaptability [3-5]. Yet another issue is that transduction mechanisms e.g. piezoelectric coupling has power generating capability that increases with vibrating frequency of the transducer [6]. Frequency up-conversion became a promising solution to this dilemma. This technique converts ambient vibration of time-varying low frequency to vibration of transducers with a higher and definite resonant frequency [7]. However, harvesters employing this technique often involve mechanical impacts such as snapping or plucking [7-10]. Meanwhile, this technique usually relies on two-stage resonant structures, but only one stage is used for transduction [11-13]. Thus, Mechanical energy is not fully exploited for power generation.

To improve harvesting capability, we propose an energy harvester that generates electric power on both stages, utilizing highly endurable non-contact frequency up-conversion mechanism previously validated by our bench top prototype [14]. Using piezoelectric unimorphs that have different resonant frequencies interacting with magnetic repulsive force, the harvester shows considerable generating capability over a wide band of frequency.

DESIGN

Schematically shown in Fig. 1(a), the harvester consists of two cantilevers connected to a frame. Permanent magnets and additional masses are mounted on the tips of the cantilevers. For operation, the side of the frame with which the shorter cantilever attaches to is fixed on the vibration source. Therefore, the longer cantilever, together with the free part of the frame and the tip mass-magnet, acts as a low-frequency (~10Hz) primary resonator-generator, while the short cantilever with a tip magnet acts as a high-frequency (~10^2Hz) secondary resonator-generator. Fig. 1(b) shows simulated mode shapes and frequencies of the two stages of generator-generators. The highly compliant primary stage is prone to low-frequency ambient vibration.

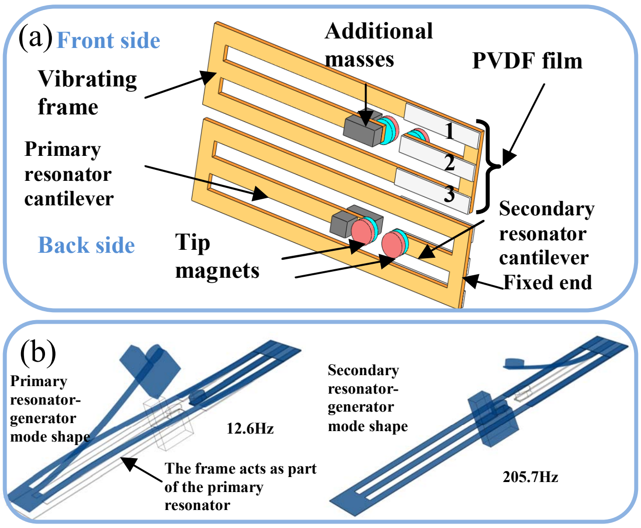

Figure 1: (a) Schematic view of the energy harvester. (b) Mode shapes and resonant frequencies of primary and secondary resonators.

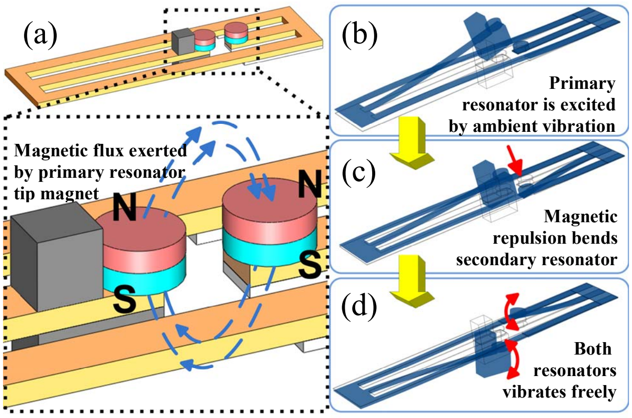

Figure 2: Principle of operation: (a) The identical poling direction of tip magnets results in repulsion. (b)-(d) Three instances of time during one stroke of the primary resonator: (b) Primary resonator is excited. (c) Secondary resonator bends until the restoring force exceeds magnetic

repulsive force. (d) Both resonators are “released” to vibrate freely. Red arrows denote displacements.

Fig. 2 illustrates the principle of frequency up-conversion. When low-frequency ambient vibration is present, the primary resonator starts to vibrate. When its mass-magnet moves towards the tip magnet of the secondary resonator-generator, the magnetic repulsive force causes the secondary cantilever to bend. Once the restoring force exceeds the repulsive force, the secondary resonator is “released” and starts free vibration at its resonant frequency. Meanwhile, the counteraction on the primary resonator makes it vibrate in a bi-stable manner, which also introduces higher frequencies. Thereby, frequency up-conversion on both stages is realized. Calculated tip displacements of both resonators during normal operation are shown in Fig. 3.

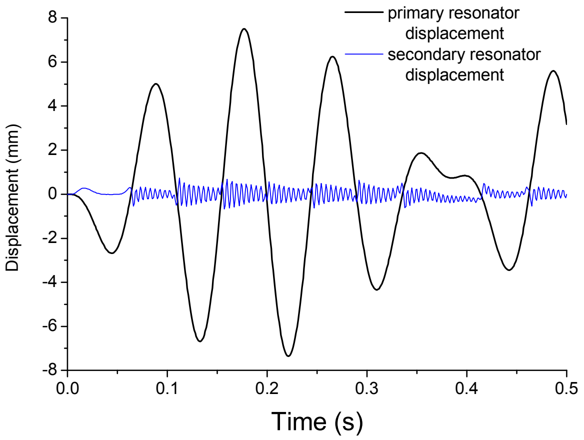

Figure 3: Calculated tip displacements of primary and secondary resonators.

FABRICATION

Fig. 4 shows the fabricated harvesters. The cantilever structures and the frame are defined on a 50μm-thick beryllium bronze sheet by photolithography and wet etched using ammonium persulfate. Three pieces of 30μm -thick piezoelectric polyvinylidene fluoride (PVDF) film (provided by Jinzhou KeXin Electronic Materials Co. Ltd) pre-coated with aluminum electrode layers are adhered to the structure using cyanoacrylate. NdFeB magnets for repulsive interaction are mounted on the tips of both cantilevers. Finally, additional lead masses are attached to the primary cantilever to lower its resonant frequency.

Table 1: Parameters of two types of harvester.

Parameter	**Type A**	**Type B**
Frame length (mm)	29.5	28.5
Primary cantilever length (mm)	15.5	14.5
Secondary cantilever length (mm)	9.5	9.5
Primary resonator tip mass (g)	0.14	0.08
Secondary resonator tip mass (g)	0.0057	0.0057
Centric distance between magnets (mm)	2	2.5

For different ambient vibration levels we fabricated two types of harvesters: Type A with larger proof mass and smaller gap between magnets, suitable for high level excitation, and Type B on the contrary, aimed at low-level vibrations, as shown in Table 1.

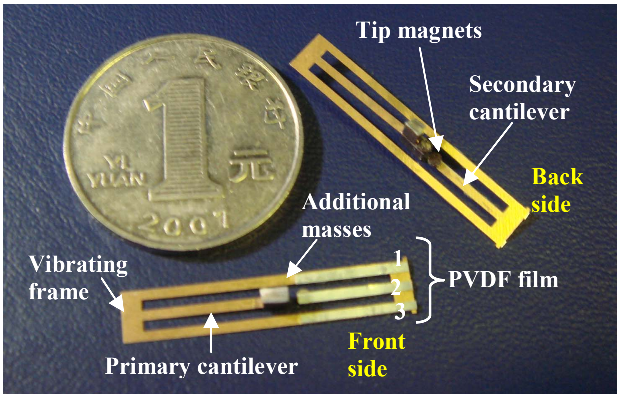

Figure 4: Fabricated harvesters in size comparison with a CNY 1 Yuan coin.

EXPERIMENTAL RESULTS

The harvesters are tested with sinusoidal excitation on a shaker, as shown in Fig. 5. A custom made fixture is used to ensure mechanical clamping and electric lead-out. Load resistors are connected to the harvester, 10MΩ, 20MΩ and 10MΩ for PVDF film 1, 2 and 3, respectively. The left column of Fig. 6 and 7 illustrate the output voltages of PVDF film 2 and 1 of type A harvester excited by acceleration of 1g, 10Hz. Their normalized amplitude in frequency domain are also shown in the figures. It can be clearly seen that the secondary resonator vibrates at almost solely its resonant frequency i.e. 120Hz (PVDF film 2) with hardly any 10Hz component. It deviates from the simulated result due to fabrication imprecision. This indicates that the behavior of the secondary resonator is hardly affected by the frequency of ambient vibration. Meanwhile, in the spectrum of the primary resonator (PVDF film 1 and 3), peaks at 21Hz, 30Hz and 50 Hz can be observed other than the 10Hz maximum peak resulting from the excitation. Therefore, both primary and secondary resonators generate voltages with frequencies higher than driving frequency, validating frequency up-conversion mechanism for both stages.

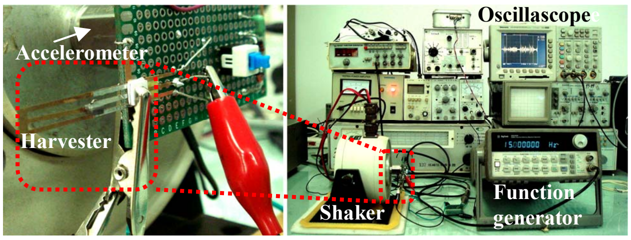

Figure 5: Test setup of fabricated harvesters. The vibration direction is horizontal in order to rule out the affect of gravity.

Fig. 8 shows the average output power of both types against frequency. As can be seen from the figure, under 1g acceleration, type A generates nearly 2μW over the frequency range of 9 to 19Hz, much higher than type B due to larger magnetic repulsive force, which results from a smaller gap between magnets of primary and secondary resonators. Both types operate properly over a considerable bandwidth.

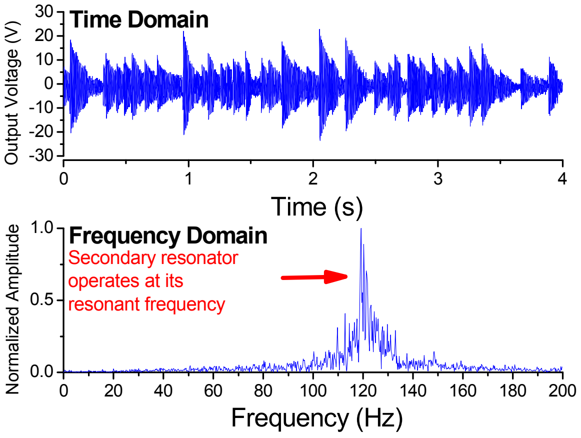

Figure 6: Output voltage and its Fourier transform of PVDF film 2 of Type A harvester at 1g, 10Hz.

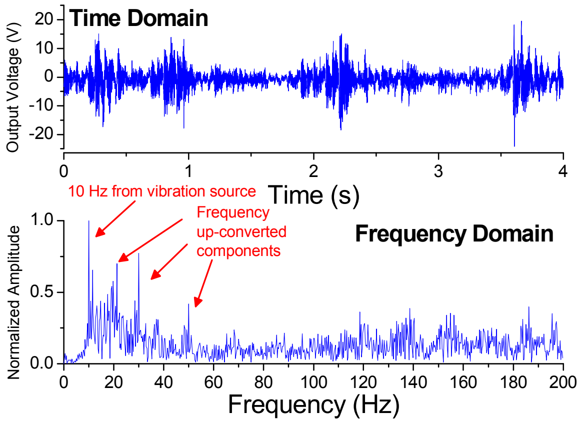

Figure 7: Output voltage and its Fourier transform of PVDF film 1 of Type A harvester at 1g, 10Hz. It can be seen from the frequency spectrum that there are frequency components higher than 10Hz, indicating that frequency up-conversion mechanism is effective on the primary resonator.

As can be seen in Fig. 8, the output power reaches its largest when the input acceleration is at the resonant frequencies of primary resonators, when the probability of successful push-through is at maximum. The frequencies at which peaks of type B appear vary with input acceleration. This might result from the inherit nonlinearity of the harvester architecture.

To verify the power generating capability in realistic situations, we mounted the harvesters on a bus, as is shown in Fig. 9. Buses as well as other vehicles are highly potential application fields of wireless Microsystems [15]. Meanwhile, the vibration induced by vehicles in motion is a good power source for energy harvesters. Two spots, namely, a chair back in the middle of the bus and a side board at the rear were chosen to mount the device. The output voltage charges a 1μF capacitor through a rectifier bridge. As the voltage across the capacitor varies slowly with time, it is monitored by a portable multimeter. At the bus rear where the vibration is strong due to engine and suspension, type A can charge the capacitor to a peak voltage of 1.11V. Considering the multimeter's input resistance, which is 10MΩ, the instantaneous power is about 123nW. In the middle of the bus where vibration amplitude is smaller, type A fails to operate. However, type B maintains frequency up-conversion mechanism and charges the capacitor to at most 0.3V, corresponding to an instantaneous power of 9nW. In order to practically supply power for microsystems, the harvester needs to be further optimized and possibly arrayed.

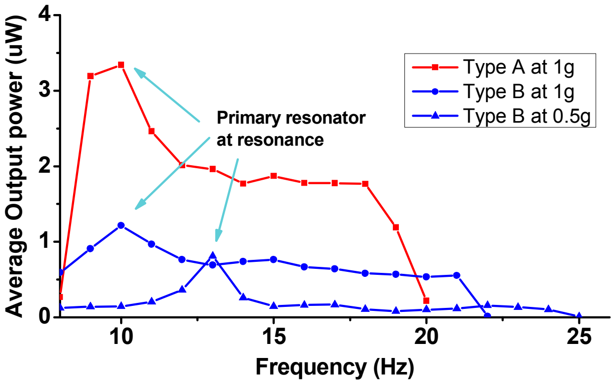

Figure 8: Frequency response of Type A and Type B harvesters. Frequency up-conversion fails on Type A under 0.5g acceleration due to its stronger magnetic coupling.

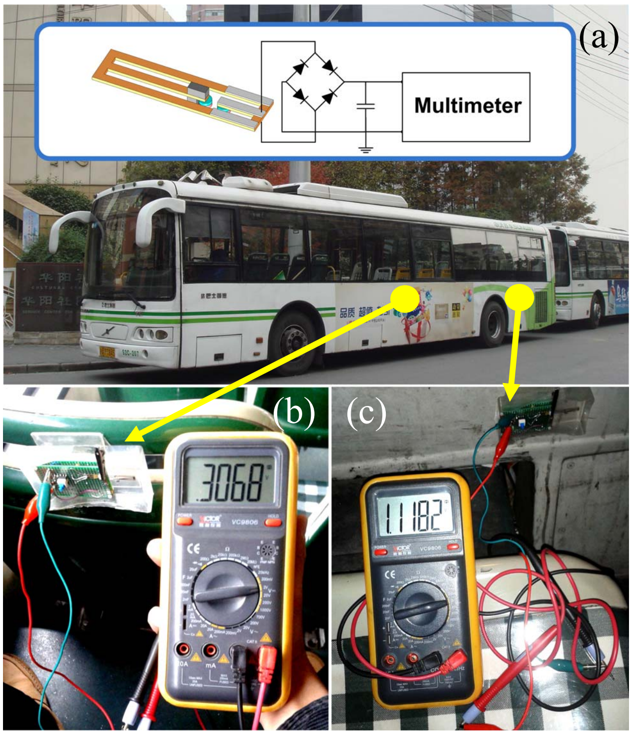

Figure 9: A preliminary test on a moving bus. (a) The harvester is mounted on 2 locations inside of the bus. (b) In the middle of the bus, Type B reaches a peak voltage of about 0.3V. (c) At the rear of the bus, Type A reaches a peak voltage of about 1.12V.

CONCLUSION

This paper describes a wideband piezoelectric energy harvester that can generate over 1.5μW of power under input acceleration of 1g over the frequency range of 9 to 19Hz. Using copper-PVDF composite beam structure and magnetic repulsive force, frequency up-conversion mechanism is realized on two stages of resonator-generators with different resonant frequencies.

The harvester was mounted on a moving bus to test its performance in a realistic situation. Frequency up-conversion mechanism prevails when excited by interior vibration of the bus. The harvester can charge a capacitor of 1 μF to 1.11V, yielding 123nW of power.

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