Polymer-Based Piezoelectric Energy Harvester for Low-Frequency Vibration Using Frequency Up-Conversion Driven by Collision with a Flexible Beam

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Abstract. This paper reports a polymer-based piezoelectric vibration energy harvester using mechanical frequency up-conversion driven by collision with a flexible beam, targeting for low-frequency vibration (under 10 Hz). By driving the flexible beam with low-frequency, the beam periodically hits against the underlying impact-driven piezoelectric component and excites the free oscillation, i.e. frequency up-conversion. We verified the validity of the proposed method by FEM analysis and the proposed vibration energy harvester showed 32 µW at 9 Hz of excitation frequency.

1. Introduction
In recent decades, a piezoelectric vibration energy harvester (VEH) have attracted much attention as a self-sustainable power source for low-power applications [1]. Typical VEHs usually utilize the resonance for efficient power generation [2]. However, if the ambient vibration frequency does not match with the device resonance frequency, the output power significantly decreases. Particularly, matching with the low-frequency ambient vibration is challenging for small-size VEHs because the resonance frequency increases with miniaturization of the device size. It is the major issue for realizing low-frequency VEH [3].

Here, methods to lower resonance frequency are classified as follows: 1) incorporate two-dimensional zigzag or spiral shape structures [4-5], 2) adopt three-dimensional flexible mesh structure as supportive layer [6], 3) attach a heavy mass to the tip, 4) utilize flexible piezoelectric polymer materials [7], 5) apply frequency up-conversion mechanism [8], etc. Among the above methods, the frequency up-conversion mechanism is a relatively easy way to realize low-frequency applications. In addition, the output electrical impedance is decreased by up-converted output voltage frequency. However, even with the frequency up-conversion method, there are few compact and wearable devices that works at low-frequency vibration of less than 10 Hz, such as human body movement and bridge/building vibration [9]. Moreover, since brittle ceramic piezoelectric materials are usually used in the conventional impact-driven up-conversion type VEHs, the device could be damaged by a sudden ambient impact.

Therefore, we propose a polymer-based piezoelectric vibration energy harvester (PVEH) using frequency up-conversion driven by collision with a flexible beam and a piezoelectric component. The
The purpose of this study is to harvest several tens of microwatt electric power in the low-frequency band that is less than 10 Hz, and simultaneously realize less brittle device.

2. Design of PVEH Using Frequency Up-conversion

2.1. Configuration of PVEH

The proposed PVEH consists of a flexible impact-driving beam and an impact-driven piezoelectric component. The impact-driving beam is designed to resonate with low-frequency vibration without attaching heavy tip mass by adopting silicone rubber with low Young's modulus as the beam’s material. The impact-driven piezoelectric component is a bimorph type cantilever, i.e. composed of two piezoelectric layers and an elastic middle layer. Polyvinylidene fluoride (PVDF) is used for piezoelectric layers, and flexible polymer polyimide is used for an elastic layer, respectively. The masses are attached to each tip of the beams. The schematic of the proposed PVEH is shown in Figure 1, and the dimensions and physical properties are shown in Table 1.

![Schematic of a proposed PVEH using mechanical frequency up-conversion driven by collision with a flexible impact-driving beam.](image)

**Figure 1.** Schematic of a proposed PVEH using mechanical frequency up-conversion driven by collision with a flexible impact-driving beam.

**Table 1.** Dimensions and physical properties of the proposed PVEH.

| Parameters                                              | Values          |
|---------------------------------------------------------|-----------------|
| Occupied volume of the device                          | 5200 [mm³]      |
| Gap between impact-driving flexible beam and           |                 |
| impact-driven piezoelectric component                  | 7 [mm]          |
| Thickness of elastic layer                             | 50 [μm]         |
| Thickness of piezoelectric layers                      | 80 [μm]         |
| Piezoelectric constant : \(d_{31}\)                   | 25 [pC/N]       |
| Piezoelectric constant : \(d_{33}\)                   | 35 [pC/N]       |
| Young's modulus of PVDF                                | 2.9 [GPa]       |
| Young’s modulus of Polyimide                           | 3.1 [GPa]       |
| Young’s modulus of silicone rubber                      | 0.1 [GPa]       |

2.2. FEM structural analysis of PVEH

We designed the size, weight, and frequency characteristics of the proposed PVEH by FEM analysis using COMSOL Multiphysics 5.3a. The analytical result is shown in Figure 2. According to the FEM modal analysis, the resonance frequency of impact-driving beam is 8.1 Hz and the impact-driven piezoelectric component is 42.6 Hz, respectively. This indicates that the impact-driving beam swings
largely in the low-frequency band of 10 Hz or less, and induces frequency up-conversion by the collision with the impact-driven piezoelectric component. In order to verify the validity of the FEM analysis, we fabricated and evaluated the proposed device.

Figure 2. Results of FEM modal analysis. An impact-driving beam resonates at 8.1 Hz and an impact-driven piezoelectric component resonates at 42.6 Hz. Around 8.1 Hz, the displacement of the driving beam is large and the beam collides with underlying piezoelectric component.

3. Experiments

3.1. Fabrication of PVEH
The impact-driven piezoelectric component of the proposed PVEH is fabricated by adhering a piezoelectric PVDF film (KF piezo film: Kureha Corporation) onto both sides of a polyimide film (Kapton: Toray Du Pont Co.). The size of the piezoelectric PVDF film is 20 mm×20 mm×40 μm. The impact-driven piezoelectric component is fixed to jig and attached a mass (0.4 g) to the tip. Then, a silicone rubber sheet with 3 mm thickness is cut into 16 mm×20 mm and attached tip mass (1.2 g) that is designed by FEM analysis. The silicon rubber beam is set as the impact-driving beam at the distance of 7 mm above the impact-driven piezoelectric component.

3.2. Sweep-Frequency Vibration Experiment
We evaluated the performance of the proposed PVEH by sweep-frequency vibration experiment. The setup of the vibration experiment is shown in Figure 3. The PVEH is fixed to a jig and set on an excitation shaker. An accelerometer monitors the vibration acceleration during the excitation. The acceleration is adjusted to be constant at 1G (9.8 m/s²). The input excitation frequency was swept from 5 Hz to 60 Hz. A load resistance of 1 MΩ, that is close to the optimum load value, is connected to the PVEH. We calculated the output power from the measured output voltage on the oscilloscope and the value of load resistance.
Figure 3. Setup for vibration excitation experiment. The excitation acceleration of a shaker is monitored by a wireless acceleration sensor and kept at 1 G.

4. Results and Discussion

Figure 4 shows output voltage waveform of the piezoelectric component at the resonance condition of the impact-driving flexible beam. The impact-driving beam periodically collides with the impact-driven piezoelectric component under the resonance frequency of 9 Hz, and the piezoelectric component starts free oscillation at the natural frequency of 47 Hz by frequency up-conversion. Approximate 5.6 V of the output voltage is measured at 1 MΩ load resistance that is close to the optimum resistance value of the piezoelectric component. Figure 5 shows the output power at sweep-frequency vibration experiment. The output powers of 32 μW and 60 μW were observed at each resonance frequency of the driving beam (9 Hz) and the piezoelectric component (47 Hz). The powers indicates more than 10 μW that is the minimum power required for low-power consumption electronic devices. Further study for optimization of the constituent materials and device configuration would expand the possibility to use the proposed PVEH as a power supply for self-sustainable Internet of Things (IoT) devices.

Furthermore, regardless of the device constituent materials such as inorganic ceramics or piezoelectric polymer, the proposed method can be applied to the many cantilever-type PVEHs reported in the past [10]. Also, by arraying the impact-driving beams, wideband PVEH can be achieved without incurring complication of a management circuit, which is one of the drawbacks of the arrayed cantilever-type PVEHs [3].

Figure 4. Output voltage at resonance frequency of impact-driving flexible beam. The output voltage shows up-converted waveform, i.e. the sinusoidal input (9 Hz) is converted to the higher output frequency that is the natural frequency of the impact-driven piezoelectric component.

Figure 5. Output power at sweep-frequency (from 5 Hz to 60 Hz) vibration experiment. The proposed PVEH shows 2 peaks. First peak is driven by collision with impact-driving beam and the other one is 1st resonance mode of piezoelectric component.
5. Conclusion
In this paper, we proposed a polymer-based PVEH using frequency up-conversion driven by collision with a flexible beam, targeting for low-frequency vibration of less than 10 Hz. By exciting the impact-driving flexible beam at low-frequencies, the beam hits against the impact-driven piezoelectric component and excites the free oscillation, i.e. frequency up-conversion. The proposed device generates 32 μW at the excitation frequency of 9 Hz. Further study for optimization of the constituent materials and device configuration would be expected for improvement of output power and wideband application.

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