A LOW-FREQUENCY THREE-DIMENSIONAL HYBRID ENERGY HARVESTER

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Abstract. This paper reports a new design of a three-dimensional vibration energy harvester with high energy output and low working frequency. In a three-dimensional vibrating environment, this electromagnet harvesting structure will have voltage outputs from any directions under a low driving frequency. The volume is about 30mm*30mm*27mm. For an excitation acceleration of 1g, the peak voltage and power output of the electromagnetic part under the vertical vibration can reach to 1.3 V and 0.31mW/cm$^3$, respectively. When the excitation comes from horizontal direction, the peak voltage and power output of electromagnetic part can reach to 361 mV and 0.88mW at 30 Hz. The maximum output of triboelectric part under the vertical vibration can reach to 20V and 17.32μW/cm$^2$ at the excitation frequency of 35 Hz.

1. Introduction

Energy harvesting has become an active field of research in past few years and has showed tremendous applications in many areas [1-2]. Vibration based energy harvesting is an alternative to solar and thermoelectric energy harvesting for scenarios where sun and thermal gradients are not readily present [3]. Many vibration energy harvesting devices based on different conversion mechanisms have been proposed [4-5]. Research shows that the vibration in ambient environment are usually below 200 Hz and directionless, while the existing harvesters with high energy output always work at high frequency and single direction [6-8]. Wang’s group [9-10] has developed a variety of triboelectric nanogenerators based on vertical contact-separation model, sliding model, and single-electrode model. The highest energy density is up to 45mW/cm$^3$. Liu et al [11] also proposed a hybrid generator with triboelectric and electromagnetic mechanisms based on vertical contact-separation model. The peak power density of triboelectric part and electromagnetic part can reach to 31μW/cm$^2$ and 28μW/cm$^2$ at a low operating frequency of 23.5 Hz.

In this study, we demonstrated a three-dimensional vibration energy harvester with high energy output and low working frequency. In a three-dimensional vibrating environment, the electromagnetic part and triboelectric part will both have electric voltage outputs.

2. Device and working principle

The schematic diagram of the fabricated harvesting device is shown in Fig. 1. The volume is about 30mm*30mm*27mm. It consists of top winding coil, bottom winding coil, permanent magnet, spring structure beam, sponge gasket, FEP (Fluoro-Ethylene Polymer) and two pieces of copper
electrode. The permanent magnets are attached on the bottom of the spring structure beam and the sponge gasket with one piece of copper electrode and FEP is on the bottom of the magnet (Fig. 1(a)). In order to save space, top winding coil of 0.2 mm in diameter and 500 turns is cohered into a hollow cylinder. A bottom winding coil consists of varnished wire with 0.2 mm in diameter assembled to the pedestal. On the surface of the bottom winding coil, the copper electrode of triboelectric part is attached on it (Fig. 1(c)).

**Figure 1.** Schematic drawing of the hybrid energy harvester

The principle for electromagnetic and triboelectric parts are based on Faraday’s law of electromagnetic induction and coupling effect of triboelectrification and electrostatic induction, respectively. As shown in Fig. 2(a), as the harvesting device is driven by an external excitation, the spring structure will drive the permanent magnet to vibrate, which will change the magnetic flux across the winding coil. Hence, two parts of the electric voltage across the coil are generated from the electromagnetic part. At the same time, the periodic movement of the permanent magnet causes the periodic contact and separation between the copper foil and FEP.

**Figure 2.** Illustration of the operating principle of the hybrid energy harvester

The contact materials Cu and FEP have large differences in the ability to attract and retain electrons according to triboelectric series. In Fig. 2(b), as the Cu and FEP layers get in contact with each other by a pressure force, the positive and negative charges will be gathered on the contact surfaces of Cu and FEP layers, respectively, due to triboelectrification effect. But there is no electric potential difference (EPD) between the two contact materials, because the charges with opposite signs
coincide at almost the same plan. When the Cu and FEP are separated, the top and bottom electrodes are connected. The established EPD drives the electrons to flow from the top electrode to the bottom electrode. As a result, the positive triboelectric charges on the top electrode will be gradually neutralized until the gap distance reaches to the maximum. Thus the current is generated from the triboelectric part during the releasing process. After that, the gap distance starts to decrease due to the periodic vibration. The top electrode gets close to the FEP layer gathering with negative charges, the electrons will flow back from the top electrode to the bottom electrode because of the electrostatic induction and thus the positive charges on the top electrode surface will increase again. Finally, as the two contact materials get in contact, the charge distribution is returned to the initial state again.

3. Experiment and results

The assembled device is tested by a vibration control system. The experimental results in Fig.3 shows the output performance of the top winding coil under vertical vibration in frequency domain and time domain. For an excitation acceleration of 1g, the peak voltage output across the top winding coil can reach to 369 mV at resonant frequency of 32.7 Hz. Fig.4 shows the output performance of the total winding coil in frequency domain and time domain. For an excitation acceleration of 1g, the peak voltage output across the total winding coil can reach 1.32V at resonant frequency of 32.7 Hz.

![Figure 3](image1.png)  
**Figure 3.** The voltage output of the top winding coil in frequency and time domain at 1g

![Figure 4](image2.png)  
**Figure 4.** The voltage output of the total winding coil in frequency and time domain at 1g

![Figure 5](image3.png)  
**Figure 5.** The voltage output of the bottom winding coil in frequency and time domain at 1g

![Figure 6](image4.png)  
**Figure 6.** The voltage output of the triboelectric part in frequency and time domain at 1g

When the excitation comes from horizontal direction, the bottom winding coil’s peak voltage output can reach to 361 mV at 30 Hz. Fig.5 shows the voltage waveform of the bottom winding coil in frequency domain and time domain at 30Hz. The output performance of the triboelectric part in
frequency domain and time domain is shown in Fig.6. The maximum output voltage can reach to 20V at the excitation frequency of 35 Hz. For an excitation acceleration of 1g, the power output of the triboelectric part under vertical vibration at 35Hz is shown in Fig.7. When the top and bottom winding coil are connected into the total winding coil, the total power output under vertical vibration and the bottom winding coil under horizontal vibration is shown in Fig.8 at 32.7Hz.

4. Conclusion
In this paper, we proposed a three-dimensional hybrid vibration energy harvester, which can achieve high output performance from any directions under low excitation frequency. For an excitation acceleration of 1g, the power output under vertical and horizontal vibration can reach to 5.87mW at load resistance of 62Ω and 0.88mW at load resistance of 82Ω at 32.7Hz, respectively.

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References
[1] Beeby S P, Tudor M J and White N M, 2006, Meas. Sci. Technol. 17 R175-R195.
[2] Chen T, Xia Y, Liu H, 2016, J. Journal of Microelectromechanical Systems, 25 845-847.
[3] Wang X, Niu S, Fang Y, 2017, J. Acs Nano. 11 1728.
[4] Khaligh A, Zeng P, and Zheng C, 2010, IEEE Trans. Ind. Electron. 57 850-860.
[5] Zhang X, Han M, Wang R, Zhu F, Li Z, and Zhang H. 2013, Nano Lett. 13 1168-72.
[6] Roundy S, Wright P K, and Rabaey, 2003, J. Comput. Commun. 26 1131-44.
[7] Sari I, Balkan T, Külah H, 2010, J. Journal of Microelectromechanical Systems, 19 14-27.
[8] L. Dhakar, F. Tay, C. Lee, 2015, J. Microelectromech.S., 24 91-99.
[9] Bai P, Zhu G, Zhou Y S, W S, Ma J, Zhang G and Wang Z L, 2014, Nano Res. 7 990-997.
[10] Tang W, Zhang C, Han C B and Wang Z L, 2014, Adv. Funct. Mater. 24 6684-90.
[11] Liu H, Xia Y, Chen T, 2017, J. IEEE Sensors Journal, 99 pp.1-1.