Vibro-Impact Type Triboelectric Energy Harvester for Large Amplitude and Wideband Applications

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Abstract. This paper reports the design, fabrication and testing of a novel vibro-impact type triboelectric energy harvester. The dynamics of vibro-impact converts external vibration to large contact force for triboelectric power generation. Strong nonlinearities are measured for this vibro-impact system, and wideband frequency response under diverse structural parameters are analyzed. The proposed device is applied in two large amplitude scenarios, and generates maximal peak-to-peak voltage of 18V in foot swinging condition @2Hz 30cm, and maximal peak-to-peak voltage of 45V in arm swinging condition during running @5Hz 40cm.

1. Introduction
Energy harvesters such as piezoelectric, electromagnetic and electrostatic harvesters have been extensively explored in recent years [1-3]. The output power of energy harvesters is typically around the order of 1~100μW, which is still stringent for most sensor applications. It is necessary to further boost output power of energy harvesters.

Triboelectric energy harvesters are brought forward by Wang Z L et al. [4], and are able to generate high output voltage (up to the order of 100V) and power (up to the order of 10mW) [5]. The basic principle of triboelectric energy harvesters is that when two materials contact each other, electrons transfer through external load between the materials due to different electronegativity. So far, triboelectric energy harvesters have been utilized in lightening 100 LEDs [6], fabric of clothes [7], mobile phone battery charger [8], and etc. The high output voltage and power of triboelectric energy harvesters are usually achieved under pressing, rubbing, and bending conditions [9], which requires large contact force. But in real environment such as bridge vibration and human body movement, contact force is small while vibrations are abundant. To utilize triboelectric energy harvester in these scenarios, it is necessary to convert vibration to large contact force.

This paper presents a novel vibro-impact type triboelectric energy harvester to generate high output voltage and power under small contact force environment. The dynamics of vibro-impact introduce strong non-linearity into device performance over a wide range of frequency. The proposed device is more suitable for large amplitude vibrations, and can be utilized in human body wearable applications.

2. Concept
The vibro-impact type triboelectric energy harvester consists of two facing electrodes with frictional surface and one inner rotor. The inner rotor is springless, and is capable of free movement between electrodes. When horizontal vibration occurs, the inner rotor collides with the frictional surface of one electrode. The impact generates large contact force between rotor and frictional surface, and the
difference in electronegativity generates transferring electrons through external load in the process of
contact and separation. As horizontal vibration continues, the inner rotor collides with the other
electrode, and triboelectric power is produced in a similar way.

3. Device Fabrication
The frictional surface of the device is PDMS pyramid arrays, the fabrication process of which is
shown in Figure 2. 1000Å thermal SiO$_2$ is first grown on 4 inch silicon wafer, and then 1000Å Si$_3$N$_4$
is deposited using LPCVD on both sides. After spin coating and patterning 1μm photoresist, the
Si$_3$N$_4$/SiO$_2$ double layer on one side is dry etched, so that etching windows with the dimension of
300μm×300μm are formed. The remaining Si$_3$N$_4$/SiO$_2$ double layer serves as the mask for bulk silicon
etching, and the etching thickness is approximately 210μm. After the formation of silicon cup, PDMS
(Sylgard 184, Dow Corning, polymer: curing agent=10:1 mass ratio) is poured in, cured at 45℃, and
peeled off. The thickness of PDMS is controlled by calculating total mass, and is approximately
0.4mm from the cone to the base. The fabricated PDMS pyramid arrays are shown in Figure 3(a).

Figure 2. Fabrication process flow.

Then, PMMA spacer is formed using Computer Numerical Control (CNC) machining of the
transparent acrylic material. The outside and inside dimensions of the PMMA spacer are 20mm×
20mm and 12mm×12mm, respectively. The two electrodes and inner rotor are made of stainless steel.
The dimensions of the electrodes and inner rotor are 20mm×20mm and 10mm×10mm, respectively.
PDMS pyramid arrays are stuck directly to the electrodes due to the viscosity of silicon rubber, and are
cut into 11mm×11mm pieces so as to fit inside the PMMA spacer. The assembly part of the device is
shown in Figure 3(b). Finally, two electrodes with frictional surface and PMMA spacer is stuck
together to form a complete sandwich structure, with the inner rotor freely placed inside. Different
structural parameters are adopted: spacer height $g=3$mm, 5mm, 10mm; rotor thickness $d=1$mm, 3mm,
8mm. The complete device is shown in Figure 3(c).

Figure 3(d) shows the testing rig, in which the device is clamped between two PMMA fixtures and
is tested under horizontal vibration. The PMMA fixtures are fixed to the electromagnetic shaker, and
the acceleration and frequency is controlled by function generator. A 3-axis accelerometer is also
mounted in the front of the PMMA fixture to record excitation acceleration. Generated electrical
signals are recorded using oscilloscope.
Figure 3. (a) PDMS pyramid arrays; (b) parts for assembly; (c) photo of entire device; (d) testing rig.

4. Results and Discussion

Figure 4 shows the measured voltage-time traces generated on a single electrode. The device is of structural parameters as: $g=3\text{mm}$, $d=1\text{mm}$, and vibration frequency is 20Hz. As acceleration increases from 1.2g, 1.6g, to 1.8g, maximum voltage increases from 3.3V, 4.1V, to 6.5V. Increased vibration acceleration results in stronger impacts and larger contact force, and thus increases triboelectric output voltage. But the number of impacts per cycle decreases as acceleration increases. The number of impacts is shown by the number of voltage peaks per cycle, which is less than one per cycle @1.8g, one per cycle @ 1.6g, and two per cycle @1.2g. Because the inner rotor is freely moving and impacting, the number of impacts is correlated not only to external vibration parameters, but also to the relative position and pitch attitude of the inner rotor. It is speculated that, for 1.2g acceleration, the inner rotor might collide with the testing frictional surface at two different edges consecutively due to different pitch attitude. For the relatively large acceleration of 1.8g, it is possible that the relative position of the inner rotor is close to the opposite frictional surface, so that less than one impact per cycle is recorded.

The frequency response of the device also exhibits strong nonlinearity. As is shown in Figure 5(a), at fixed spacer height $g=10\text{mm}$, smaller rotor thickness $d$ results in higher output voltage at lower frequency range, and vice versa. Figure 5(b) shows that, at fixed rotor thickness $d=1\text{mm}$, an optimal
spacer height $g=5\,\text{mm}$ exists for maintaining high output voltage at lower frequency range and wider bandwidth. In Figure 5(c), rotors are of the same free length (approximately 1.2mm, considering the height of PDMS pyramid arrays). The device with $g=5\,\text{mm}$ and $d=3\,\text{mm}$ generates highest output voltage in 25~30Hz frequency range, while the device with $g=3\,\text{mm}$ and $d=1\,\text{mm}$ generates highest output voltage in the remaining test frequency range. In all six different traces shown in Figure 5, the device with $g=5\,\text{mm}$ and $d=1\,\text{mm}$ functions optimally in the $<$25Hz low frequency range. Despite low output voltage, the device with $g=10\,\text{mm}$ and $d=8\,\text{mm}$ exhibits flattest frequency response and widest bandwidth. Such dynamic characteristics are very different from the traditional spring-mass-damper energy harvester, and implies the potential diverse application of the devices in low frequency, wideband, and selected frequency range in accordance to different structural parameters.

![Figure 5](image1)

**Figure 5.** Frequency responses of devices (a) with the same spacer gap but diverse rotor thicknesses; (b) with the same rotor thickness but diverse spacer gaps; (c) with the same free length but diverse volumes.

### 5. Application

The proposed device ($g=3\,\text{mm}$ and $d=1\,\text{mm}$) is applied in large amplitude human motion environment. Figure 6 shows the foot swinging condition, and the device is mounted in the rear part of the shoe, as is shown in Figure 6(a). The knee of the tester is almost still while the foot is swinging back and forth at around 2Hz frequency and around 30cm amplitude. Figure 6(b) shows the measured output voltage, with maximal peak-to-peak voltage of 18V.

![Figure 6](image2)

**Figure 6.** (a) Device mounted in the rear part of the shoe. (b) Measured output voltage.

Figure 7 shows the arm swinging condition in the running process, and the device ($g=3\,\text{mm}$ and $d=1\,\text{mm}$) is placed on the arm, as is shown in Figure 7(a). Limited by the wiring length, the tester runs in situ during test, and the swing of the arm is approximately 5Hz in frequency and 40cm in amplitude. Figure 7(b) shows that the device generates maximally 45V peak-to-peak voltage. Such results prove the suitability of proposed device in large amplitude, low frequency and wideband applications.
Conclusion
A novel vibro-impact type triboelectric energy harvester is presented, which effectively converts external vibration to large contact force. The conversion is achieved through vibro-impact dynamics, which is of strong non-linearity. Fabricated device exhibits diverse number of impacts per cycle in voltage-times traces due to different accelerations, and exhibits diverse low frequency, wideband, and selected frequency range in frequency response curves due to different structural parameters. The proposed device is applied in wearable applications. In foot swinging condition @2Hz 30cm, maximal peak-to-peak voltage reaches 18V. In arm swinging condition @5Hz 40cm, the device generates maximally 45V peak-to-peak voltage. These results prove the viability of proposed device in large amplitude and wideband applications.

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