Electronic Supporting Information

Spring-assisted hybrid triboelectric-electromagnetic nanogenerator for harvesting low-frequency vibration energy and creating self-powered security system

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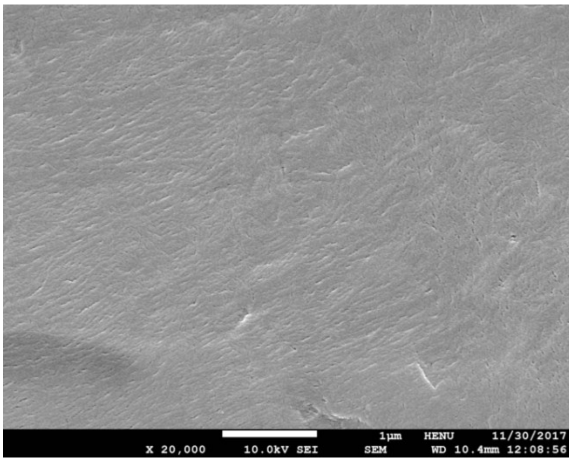

Fig. S1 The SEM image of the PTFE without surface nanostructures.

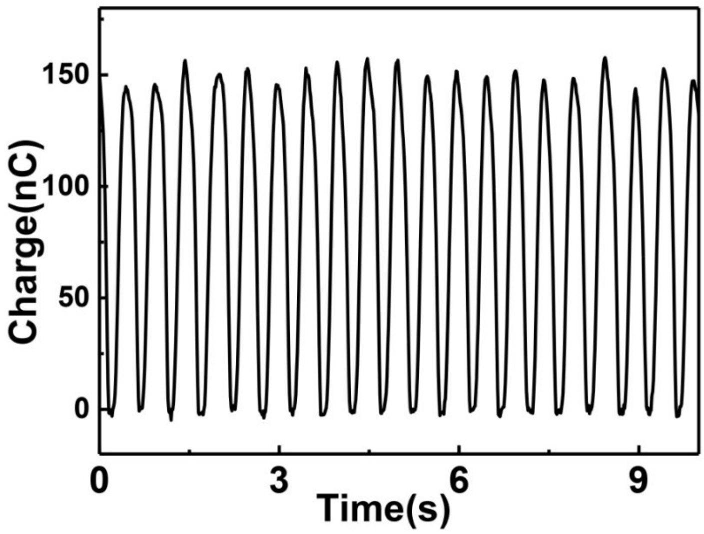

Fig. S2 The transferred charge of the TENG without the surface nanostructure of PTFE at a frequency of 2.0Hz.

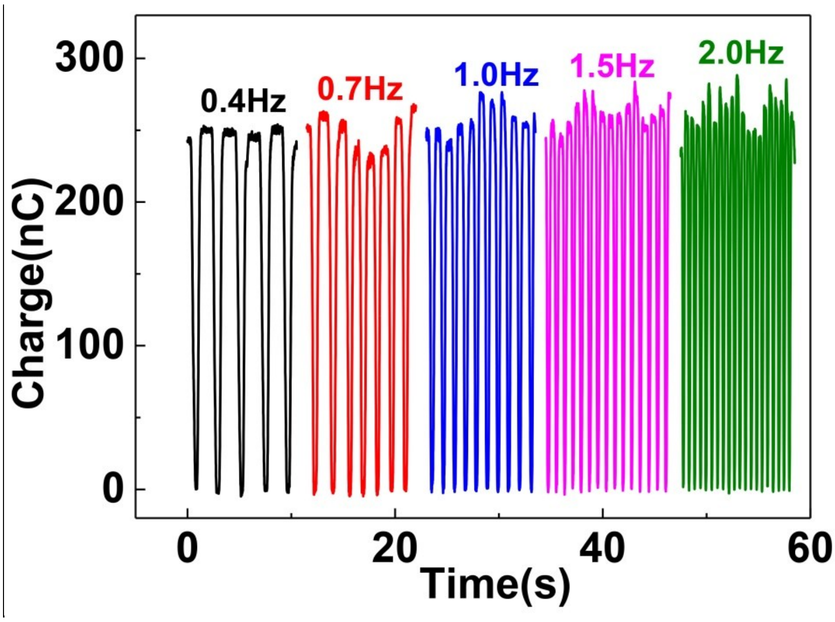

Fig. S3 Effect of the short circuit transferred charge of the TENG with the surface nanostructure of PTFE on operation frequency ranging from 0.4 to 2.0 Hz.

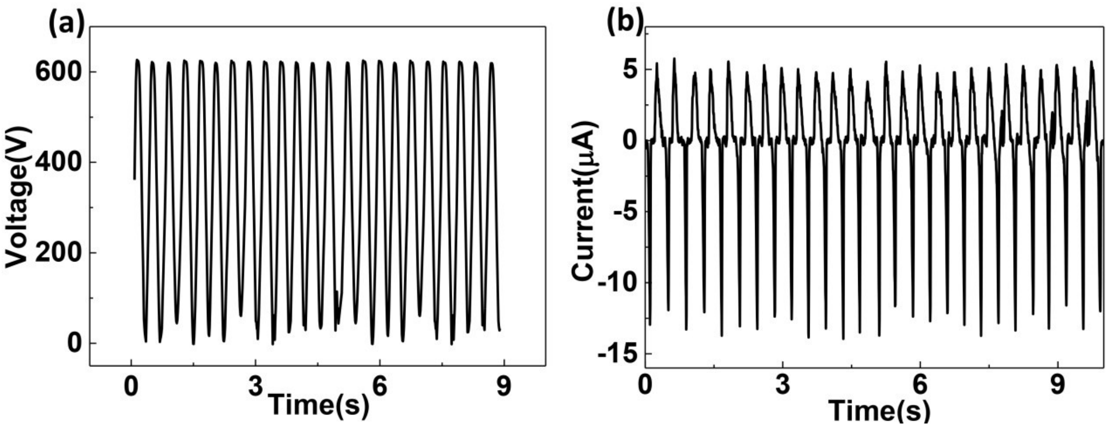

Fig. S4 The open-circuit voltage (V_{oc}) and the short-circuit current (I_{sc}) of the TENG at a frequency of 2.5Hz.

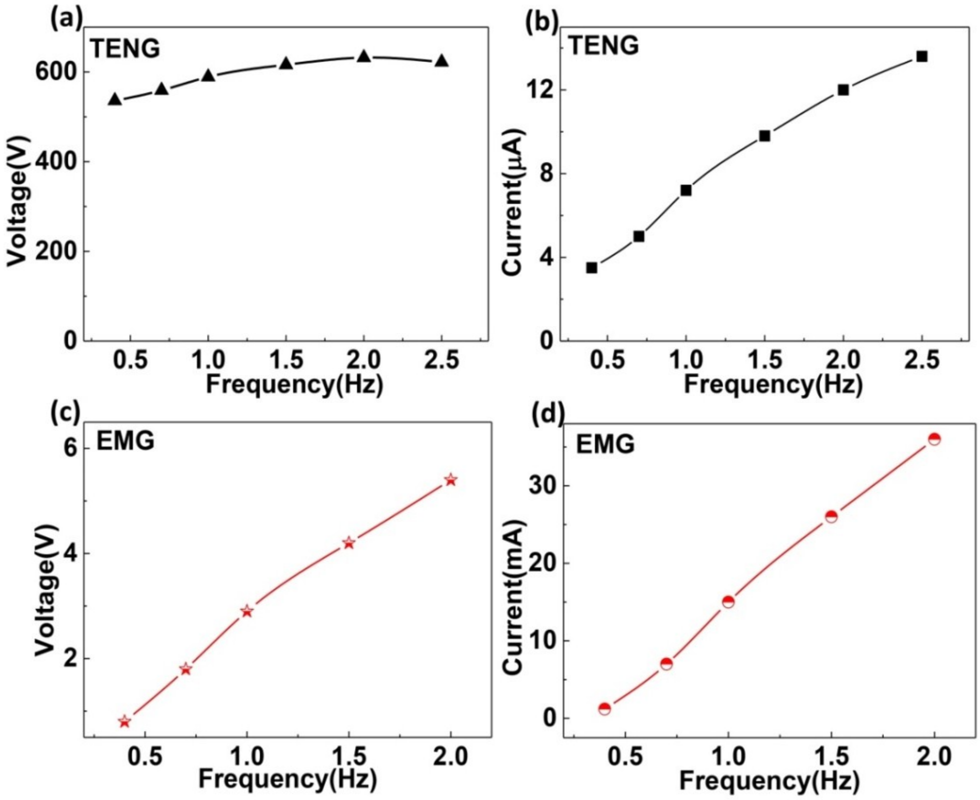

Fig. S5 (a, b) Dependence of the V_{oc} and I_{sc} of the TENG on frequency ranging from 0.4 to 2.5 Hz. (c, d) dependence of the V_{oc} and I_{sc} of the EMG with variable frequency ranging from 0.4 to 2Hz.

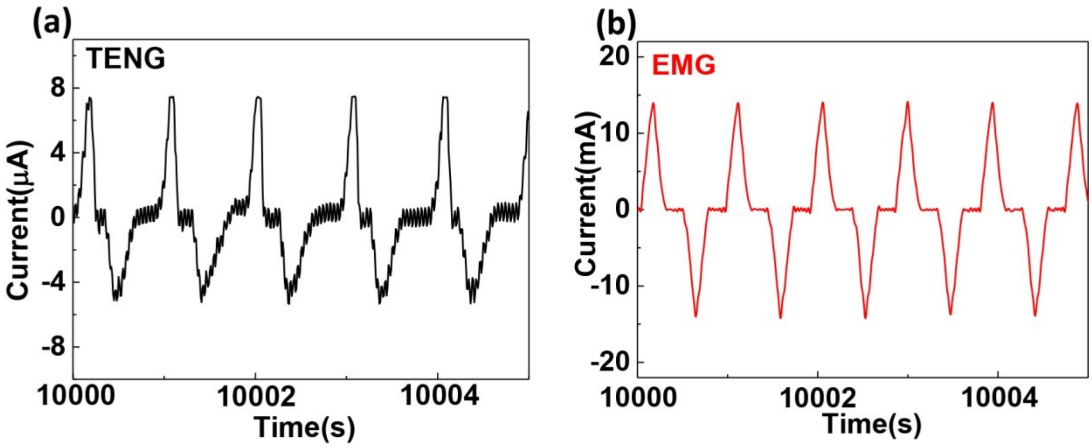

Fig. S6 Short-circuit current of the TENG (a) and EMG (b) was measured at 10000 cycles with a frequency of 1Hz.

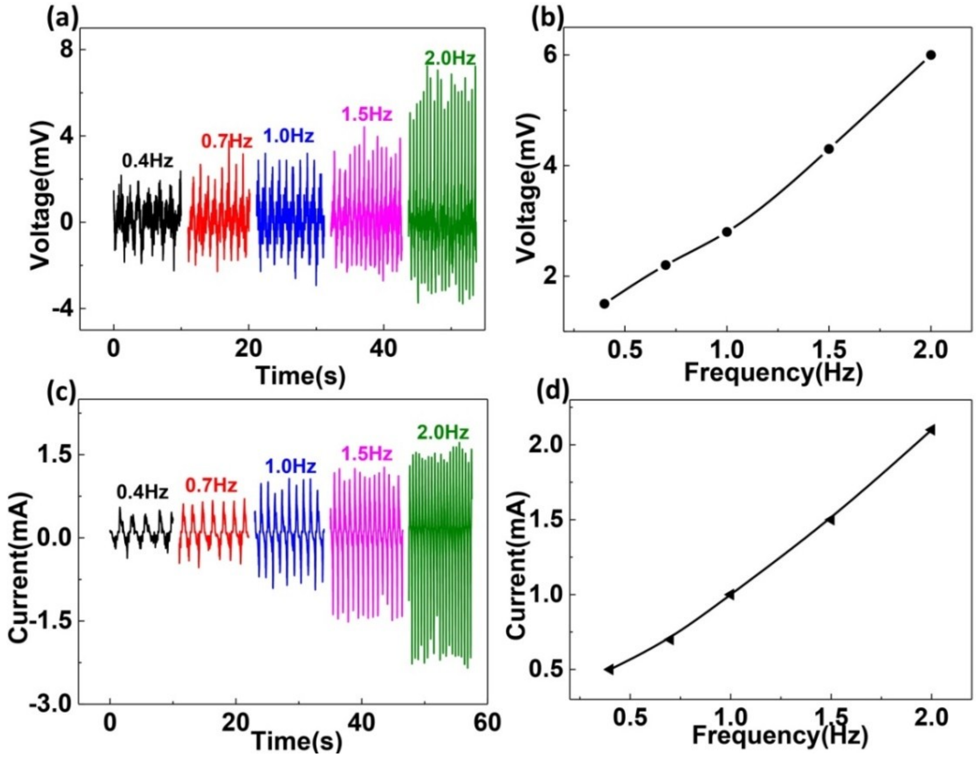

Fig. S7 Electrical output performances of the spring itself as coil at frequencies ranging from 0.4 to 2.0 Hz**.** The V_{oc} (a) and I_{sc} (c) at different frequencies. Dependence of the V_{oc} (b) and I_{sc} (d) on frequency.

Calculation of resonance frequency of spring in the HG

The natural frequency of the spring in the HG device can be derived from the following formula

$$f_n = \frac{1}{T} \tag{S1}$$

Where f_n is the natural frequency of the spring, T is the motion period of the spring. If mass of spring bearing load is defined as m, the stiffness coefficient of the spring is labelled as k, the motion period of the spring can be expressed as

$$T = 2\pi \cdot (\frac{m}{k})^{\frac{1}{2}} \tag{S2}$$

The stiffness coefficient of the spring can be obtained from the following formula

$$F = k \cdot x \tag{S3}$$

Merging Equations (S1) - (S3) and the known parameters, we can get that the natural frequency of the spring of the device is about 10.4 Hz, which is far more than the test frequency ($\leq$ 2 Hz) of the HG device. The resonance frequency of the HG device under forced vibration can be derived from the following formula [1, 2]

$$f = f_n/\sqrt{1 - 2D^2} \tag{S4}$$

Where *D* is the damping ratio, $D = c/(2\sqrt{km})$, *c* is the damped coefficient of friction materials. It is well known that the Al has low damping ratio (about 10^{-4}), and the friction coefficient of PTFE is also small. Therefore, we can ignore the damping ratio of the friction materials in the HG device, implying *D* is about zero. In this case, the resonance frequency of the device is approximately equal to the natural frequency of the spring ($f \approx f_n$) from the Equation (S4). Thus we can neglect the influence of the resonance frequency in the HG device measurement due to that the resonance frequency of the device is much larger than the driven frequency.

Derivation of Ampere force of the copper coils

Accompanied by the movement of the spring, the magnet moves up and down in the copper coils and thus the magnetic flux crossing the copper coils will continuously vary. According to the Lenz's law, it will generate an induced electromotive force *E* in the copper coils. If we define *B*, *L* and *V* as the magnetic field intensity at the position of the coil, length of the copper wire and running velocity, respectively, the following formula can be obtained.

$$E = BLV \tag{S5}$$

The resistance of the copper coils is labelled as R, which can be expressed as $R = \rho \frac{L}{A}$, where ρ, L and A are the resistivity, length and cross-sectional area of the copper coils, respectively. If the diameter of the copper wire is defined as d, the cross-sectional area of the copper wire could be expressed as

$$A = \frac{\pi}{4} d^2 \tag{S6}$$

Merging Equations (S5), (S6) and the expression formula of resistance R, we can get the current in the copper coils as

$$I = \frac{E}{R} = \frac{BLV}{\rho \frac{L}{A}} = \frac{\pi BV}{4\ \rho} d^2 \tag{S7}$$

When the hybrid nanogenerator operated, a cavity formed between the two specific sleeves, whose height, inner and outer diameters are named as h, D_1 and D_2, respectively. Since the copper coils were put in the cavity, the total length of the copper coils can be expressed as

$$L \approx \frac{\pi}{2} (D_2^2 - D_1^2) \frac{l}{d^2} \tag{S8}$$

An energized wire is subjected to Ampere force in a magnetic field if the direction of current in the wire is not parallel to that of magnetic field, which can be expressed as

$$F = BIL \tag{S9}$$

Merging Equations (S7) - (S9), one can have

$$F = \frac{\pi^2}{8} \cdot \frac{D_2^2 - D_1^2}{\rho} \cdot l \cdot V \cdot B^2$$

(S10)

Based on above analyses, the obstruction force during the spring motion is proportional to the length of the copper coils, the speed of operation and the square of the intensity of the magnetic field. In like manner, the Ampere force of the spring itself as a coil can be derived. However, as shown in Fig. 3e and Fig. S7c, the current induced in the spring is much less than that induced in the copper coils. Moreover, the length of the spring is far shorter than that of the copper wire, the latter is about 100 times longer than the former. The average speed of the spring is about half of the coil in the process of the device operation. In addition, it is very difficult to estimate the magnetic field intensity of the spring because the whole magnet is located in the middle of the spring and the spring is far away from the magnet. Considering the above factors, the Ampere force generated in the spring is much smaller than that produced in the copper coils and thus can be neglected.

References

1 L. Feng, G. L. Liu, H. Y. Guo, Q. Tang, X. J. Pu, J. Chen, X. Wang, Y. Xi, C. G. Hu, *Nano Energy*., 2018, **47**, 217.

2 Y. Yuan, H. L. Zhang , J. Wang, Y. H. Xie, S. A. Khan, L. Jin, Z. C, Yan, L. Huang, T. S. Pan, W. Q. Yang , Y. Lin, *Mater. Res. Express.,* 2018, **5**, 015510.

Supporting Movies

Movie S2. 40 green LEDs showing the "HENU" word in series connected to the

TENG.

Movie S3. LEDs in mixed parallel/series circuit showing Xidian University in Chinese with the power from a hybrid nanogenerator.

Movie S4. A monitor showing time, temperature, and humidity with the power from a hybrid nanogenerator.

Movie S5. A displace panel dynamically showing a complicated logo image with the power from a hybrid nanogenerator.

Movie S6. A self-powered surveillance sensor and alarm system powered by a hybrid nanogenerator installed under the bicycle cushion

Movie S7. Bicycle warning safety lights powered by a hybrid nanogenerator.