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A hybrid piezoelectric-triboelectric generator for low-frequency and broad-bandwidth energy harvesting

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ABSTRACT

In this paper, we report a hybrid generator to harness energy from low-frequency ambient vibrations. The generator is designed with a piezoelectric energy harvester (PEH) patch, a triboelectric nanogenerator (TENG) patch, a spring-mass system and an amplitude limiter. The spring-mass system receives energy from excitations and applies forces to the piezoelectric element and the triboelectric layers. The unique amplitude limiter is deliberately introduced into the system, not only achieving the desired frequency up-conversion effect, but also boosting the voltage responses significantly. The limiter also causes hardening nonlinearity and dynamic bifurcation triggering superharmonic resonance so that the generator resonates at a frequency of about 3 Hz. Furthermore, the proposed PEH adopts the strong compressive operation mode, and employs a truss mechanism to effectively amplify the impact forces. In experiments, open-circuit voltages are 58.4 V from PEH and 60 V from TENG under an excitation of 1.0 g at resonance. The hybridized generator is capable of achieving a maximum power of 19.6 mW from the two sources with matched impedances. The working bandwidths of the PEH and the TENG reach up to 5.39 Hz and 7.25 Hz, respectively, out of our targeted frequency domain [2.5 Hz, 10 Hz] due to the multiple resonances and nonlinearity. In the applications to charge capacitors, the high saturation voltage and relatively short charging time validate the effectiveness of our power management technique. Furthermore, the generator proves to be able to effectively scavenge energy from human body motions and charge a capacitor of 4.7 μF to 7.6 V in around 50 s, which indicates a great potential of practical applications in wearable devices.

1. Introduction

Renewable and sustainable energy is cumulatively receiving attention as conventional energy sources are revealing more and more issues such as pollutions, global warming and waste [1]. Researchers have been conducting studies via different approaches exemplified as solar [2], tidal [3] and hydroelectric [4] ones to employ energy with sustainability in large scales. As for small-scale energy conversion methods, which are revealing tremendous practical application potential in portable electronic devices, harvesting ambient energy through both piezoelectric and triboelectric materials have been heated focuses. The former displays the merits regarding miniaturization, efficiency and simplicity [5] and the latter exhibits advantages such as lightweight structure, cost-effective materials, flexible configuration, and efficient performance [6].

Traditional piezoelectric energy harvesters (PEHs) operate with high working efficiency only around resonant points in relatively high-frequency domains [1]. When excitation frequencies from the environment deviate from the resonant points, the performance such as output power runs down dramatically. Particularly when we target at many commonly seen energy sources such as wind, human body motion and tidal waves (frequency usually lower than 10 Hz), most PEHs become barely applicable as the resonant frequencies are usually dozens and even hundreds of hertz. A most effective approach is to develop PEH with very low resonant frequency to elicit efficiently electricity from the aforementioned energy sources. Joel et al. proposed an energy harvesting backpack with a mechanically amplified piezoelectric stack [7] and achieved a power output in micro scale under excitation with frequencies lower than 10 Hz. Zhang et al. proposed a multi-impact energy harvester with a proven better harvesting performance than the traditional cantilever models under low-frequency vibrations [8]. Gu presented a low-frequency PEH based on impacts with a compliant driving beam and two rigid generating beams and achieved an average power of 1.53 mW at 20.1 Hz under 0.4 g acceleration [9]. Other designs include that a high-efficiency compressive-mode PEH [10–12], impact induced nonlinear bistable and tristable harvesters [13–15], a

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two degree-of-freedom PEH [16] and a cantilever beam with a piezoelectric patch to harvest energy from human body motion [17]. These are remarkable advances to harness energy from relatively low frequency vibrations but not appropriate for our aimed frequency interval.

Another distinct approach with rapidly growing attention is the development of triboelectric generators. Triboelectric nanogenerator (TENG) is a new type of energy harvesting and sensing technology based on the conjunction of contact electrification and electrostatic induction [18]. Different operation modes have been developed for TENGs and sensors which are used based on the application of the system, type of excitation, and required outputs [19]. Due to the promising behavior of the TENG, it has been utilized for scavenging the existing energy in biomechanical activities [20], wind and water motion [21], and vibration [22]. Also, various sensory systems have been proposed based on the TENG for monitoring force and pressure [23], motion and trajectory [24], and biomechanical parameters [25]. In addition, hybridization of TENG with other energy harvesting technologies such as electromagnetic and piezoelectric energy harvesters has shown to be very effective for mechanical-to-electrical energy conversion [26]. Specifically, triboelectricity and piezoelectricity have been combined successfully in various configurations for mechanical energy harvesting and self-powered sensing [27].

PEHs and TENGs operate with quite different dynamic and electric characteristics. TENGs require relative motion between different triboelectric materials with high voltage and high matching impedance. In contrast, PEHs demand large deformation of the material itself with relatively lower voltage and lower matching impedance. Combination of the two transduction methods from kinetic energy to electricity, or hybridization of the energy harvesting techniques, can improve the transduction efficiency so that more mechanical energy in the motion of the excited system can be converted into electrical power [28–30]. Salauddin et al. reported a design of a hybridized electromagnetic-triboelectric harvester from human body motion. Utilizing the Halbach magnet, the harvester exhibited very high power output [31]. Zi et al. presented a triboelectric–pyroelectric–piezoelectric hybrid cell composed of a sliding mode TENG and a pyroelectric–piezoelectric nanogenerator. Taking advantage of the mechanical energy and friction-induced thermal energy, the cell achieved outstanding performance with a compact size and high power density under ultra-low frequency sliding excitation [32]. Wang et al. reported a triboelectric–piezoelectric–pyroelectric hybridized nanogenerator and realized notable charging performance [33]. Zhang et al. developed a magnetically levitated piezoelectric/triboelectric hybrid generator with excellent charging and powering performance [34]. Zhu et al proposed and investigated a flexible hybrid triboelectric and piezoelectric energy harvester using PDMS/MWCNT and PVDF [35]. Wang et al. studied and realized a flexible nanogenerator based on (PVDF-TrFE) nanofibers and PDMS/MWCNT thin composite membrane, conducted experiments under ultra-low excitation frequency (1–5 Hz) and achieved macro-scale power output [36]. Zhu et al. presented a d-arched sensor consisting of piezoelectric-triboelectric energy harvesting unit [37].

In this paper, we report a novel scheme of the hybridization of a compressive-mode piezoelectric energy harvester and a triboelectric generator to enhance the transduction efficiency. The key work includes: first, low resonant frequencies with a distributed design of the energy conversion elements and mechanically excited mechanism; second, high power outputs with the force amplification effect by an originally introduced truss mechanism and impact due to an amplitude limiter; and third, desirable adaptability as we utilize dynamic bifurcation to trigger multiple resonances and take advantage of hardening nonlinearity for wide working bandwidth. Experimental results indicate that: first, the dynamic behavior is characterized with superposition of hardening nonlinear and harmonic responses; second, the dynamic phenomenon of superharmonic resonance that we employ leads to a much lower resonant frequency than the primary one; third, the impact can effectively convert up the frequency of applied forces so that the matching impedance of the device is reduced dramatically to achieve comparatively much higher output power; and last but not least the integrated charging of the hybrid system shows better performance than that of each separate one.

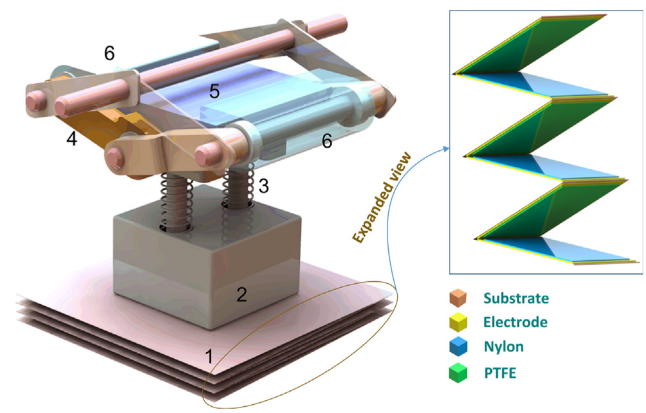

Fig. 1. Structural configuration of the generator. Key components are listed as: 1. triboelectric patch. 2. proof mass. 3. linear spring. 4. truss mechanism. 5. piezoelectric plate. 6. piezo plate holders.

2. Design of the generator

The structural configuration of the generator, shown in Fig. 1, is comprised of three modules: the piezoelectric patch, a spring mass system and the triboelectric patch of multiple units. In the piezoelectric module, a piezoelectric plate is encompassed by two holders. Two sets of truss mechanisms are connected symmetrically to the holders. The truss mechanism consists of four linkages forming a quadrilateral shape. The linkages are connected via joints. A rod through the top joint is employed for the generator to be fixed onto a host structure. Another rod through the bottom joint connects the piezoelectric patch and the spring-mass system. The spring-mass system is deliberately separated from the transduction units (both piezoelectric and triboelectric) so that the resonant frequency of the structure can be designed to be low (lower than 10 Hz). Attached to the bottom of the proof mass is the top layer of the triboelectric patch with an unfolded view to show details in Fig. 1.

When the generator is exposed to base excitation, the motion of the proof mass leads to the deformation of the spring, imposing a vertical force to the bottom joint. After the transmission of the linkages, the direction of the force is altered to be horizontal and the magnitude of the force is amplified. Thus a compressive and a tensile force, as shown in Fig. 2, are applied onto the piezoelectric element alternatively. Meanwhile, we added a stopper under the mass so as to limit the

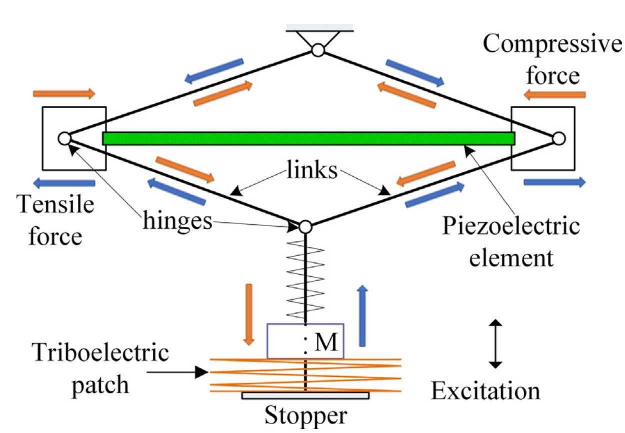

Fig. 2. Force transmission in generator.