Enhanced galloping energy harvester with cooperative mode of vibration and collision

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Abstract The low power and narrow speed range remain bottlenecks that constrain the application of small-scale wind energy harvesting. This paper proposes a simple, low-cost, and reliable method to address these critical issues. A galloping energy harvester with the cooperative mode of vibration and collision (GEH-VC) is presented. A pair of curved boundaries attached with functional materials are introduced, which not only improve the performance of the vibration energy harvesting system, but also convert more mechanical energy into electrical energy during collision. The beam deforms and the piezoelectric energy harvester (PEH) generates electricity during the flow-induced vibration. In addition, the beam contacts and separates from the boundaries, and the triboelectric nanogenerator (TENG) generates electricity during the collision. In order to reduce the influence of the boundaries on the aerodynamic performance and the feasibility of increasing the working area of the TENG, a vertical structure is designed. When the wind speed is high, the curved boundaries maintain a stable amplitude of the vibration system and increase the frequency of the vibration system, thereby avoiding damage to the piezoelectric sheet and improving the electromechanical conversion efficiency, and the TENG works with the PEH to generate electricity. Since the boundaries can protect the PEH at high wind speeds, its stiffness can be designed to be low to start working at low wind speeds. The electromechanical coupling dynamic model is established according to the GEH-VC operating principle and is verified experimentally. The results show that the GEH-VC has a wide range of operating wind speeds, and the average power can be increased by 180% compared with the traditional galloping PEH. The GEH-VC prototype
is demonstrated to power a commercial temperature sensor. This study provides a novel perspective on the design of hybrid electromechanical conversion mechanisms, that is, to combine and collaborate based on their respective characteristics.

**Key words** energy harvesting, wind energy, galloping, piezoelectric energy harvester (PEH)

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1 Introduction

The development of the Internet of Things has triggered the human desire for smart cities and smart life, however, is based on wireless sensors, and the sustainable powering of a large number of wireless sensors remains problematic[1]. On the other hand, as environmental problems are increasing in severity, concerns for green energy technologies are increasing[2]. To overcome these issues, wind energy is widely distributed in the environment, and is one of the most accessible green energy sources[3]. It can be harvested to power small electronic devices with low power consumption[4]. Traditional wind turbines are large in size, heavy in weight, high in cost, and low in efficiency, which limit their applications in self-powered integrated systems[5]. Therefore, it is necessary to develop small-scale wind energy harvesting technologies with low cost and high energy density[6].

There are mainly three types of electromechanical conversion mechanisms used for wind energy harvesting, i.e., the piezoelectric energy harvester (PEH)[7-8], the electromagnetic energy harvester (EMEH)[9], and the triboelectric nanogenerator (TENG)[10]. The galloping instability of a bluff body can cause self-sustained oscillations of the piezoelectric beam in the flow field, which is suitable for harvesting wind energy and has the characteristics of simple structure and strong applicability[11]. The shape of the bluff body is critical to the aerodynamic performance of the PEH. Zhou et al.[12] demonstrated a Y-shaped bistable piezoelectric wind energy harvester, which can enhance the energy harvester performance of low-speed wind flows by coherent resonance. Shi et al.[13] designed a piezoelectric wind energy harvester with a prismatic bluff body of triangular cross section for the wind velocity sensor, whose working wind speed range was from 4.45 m/s to 10 m/s. Zhou et al.[14] and Wang et al.[15] used a curved-plate bluff body, which provided more flexibility of design and possibility for improving the aerodynamic performance. The galloping energy harvester with a curved-plate bluff body oriented perpendicularly to the airflow can generate self-sustained oscillations at low wind speeds[16]. Vertical piezoelectric wind energy harvesters are also frequently used since they are more compact compared with horizontal harvesters[12]. However, the stiffness of the galloping-based PEH is a key design parameter. If it is high, it cannot operate at low wind speeds. If it is low, the displacement may be so large as to damage the piezoelectric sheet at high wind speeds.

In recent years, the TENG has attracted widespread attention because of its easy integration, miniature size, and suitability for low-frequency excitation[17]. Currently, most TENGs used for wind energy harvesting are rotating structures. Wang et al.[18] proposed a self-powered wind sensor system based on an anemometer TENG and a wind vane TENG. The rotating TENG with a high output voltage was used as a self-driving air cleaning system[19]. Liu et al.[20] developed a rotating TENG with a magnetic switch structure to harvest the wind energy with a peak power of 4.82 mW. Hybrid mechanisms can achieve both the individual TENG advantages with the advantages of other electromechanical conversion mechanisms[21]. Aiming to harvest weak energy from environment, a hybridized wind energy harvester with the TENG and EMEH composite mechanism was designed by Zhao et al.[22] to realize self-powered electronic equipment. Lu et al.[23] designed a swing-structured hybrid nanogenerator with a triboelectric-electromagnetic compound mechanism, which can harvest low-frequency
breeze in the environment. Rahman et al.[24] designed a hybridized nanogenerator based on three electromechanical conversion mechanisms, and realized power supply for wireless sensors in real-time environmental monitoring. A freestanding mode TENG and a rotating EMEH are integrated, and a self-powered wind speed sensor has been developed[25]. Fan et al.[26] proposed a hybrid energy harvester with EMEHs and TENGs to realize power for wind speed sensors. However, these rotating structures are somewhat complicated.

Moreover, the small-scale wind energy harvesting system based on the wind-induced vibration of the TENG has also been studied. A fluttering double-flag TENG for harvesting wind energy was proposed by Sun et al.[27] and the root mean square (RMS) power density was 10 mW/m². Wang et al.[28] designed a TENG-based wind barrier to harvest the wind energy produced by passing vehicles, which can monitor the condition of the wind barrier. Xu et al.[29] proposed a TENG based on the aeroelastic flutter, which could both harvest the flow energy and be used as a wind speed sensor. Aiming to harvest the high-altitude wind energy, Zhao et al.[30] presented a freestanding woven TENG flag based on the flow-induced vibration, and obtained the peak power density of 135 mW/kg. Zhang et al.[31] designed a galloping TENG based on the contact electrification between two flexible beams, and established a theoretical model to study the working mechanism and oscillating behaviors of the harvester. However, due to the insufficient contact of these TENGs based on flow induced vibration, the output power of these TENGs was relatively low.

Although there are many studies on wind energy harvesting, the power density and working wind speed span still urgently need to be further improved to realize self-powered energy applications. Therefore, we propose a galloping energy harvester with a cooperative mode of vibration and collision (GEH-VC), which achieves a wider working wind speed range and higher output power through a simple and low-cost structure. This paper focuses on combining and collaborating multiple mechanisms based on their respective characteristics rather than simply using them together. The TENG and PEH generate electricity in different states (vibration and collision). The TENG not only has no effect on the work of the PEH in the vibration state, but also acts as a regulation mechanism to improve the dynamic performance of the PEH. The vertical structure avoids the interference of objects behind the bluff body on the flow field, thereby increasing the width of the working area of the TENG without significantly increasing the effect on the aerodynamic performance of the galloping system. Moreover, the vertical structure can also enhance the contact force of the TENG due to the gravity of the bluff body. When the wind speed is high, the curved boundaries maintain a stable amplitude of the vibration system and increase its frequency, thereby avoiding damage to the piezoelectric sheet and improving the electromechanical conversion efficiency, and the TENG works with the PEH to generate electricity. Since the curved boundaries limit the excessive amplitude of the PEH under strong excitation, the stiffness of the PEH can be designed to be low so that it is easy to vibrate under weak excitation.

2 Design and operating principle

The GEH-VC can be integrated with wireless sensors to realize self-powered environmental monitoring and wireless signal transmission, as shown in Fig. 1(a), and thousands of self-powered integrated systems can realize sustainable and environmentally-friendly large-area environmental monitoring. The schematic diagram of the GEH-VC is illustrated in Fig. 1(b), which consists of a cantilever beam, a curved bluff body, and a pair of curved boundaries. The MFC means the macro-fibre composite. The Al film and fluorinated ethylene propylene (FEP) film are pasted successively on the cantilever beam by kapton, where the Al film acts as the electrode and the FEP film is the negative triboelectric material. The Al film on the curved boundaries is pasted by softer foam glue, and the Al film is both the electrode and the positive triboelectric material. The softer foam glue improves the contact between the FEP film and the Al film
when the beam fits with the boundary. The piezoelectric sheet is pasted on the root of the beam, making reasonable use of the available cantilever beam space. Figure 1(c) illustrates how the TENG regulates the dynamic performance of the vibration system. When the beam moves to the set displacement, collides with one of the boundaries, and then moves in the opposite direction, the vibration period will be shortened and the frequency will be increased (please see Movie S1 on https://link.springer.com/journal/10483/volumes-and-issues/43-7), which is beneficial to improving the electromechanical conversion efficiency. The boundaries prevent

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**Fig. 1** (a) A potential application, i.e., self-powered environment monitoring. (b) Design of the GEH-VC. (c) Operating principle of TENG boundaries. (d) Comparison of vertical and horizontal structures in the flow field (color online)
excessive displacement of the beam, and the vibration amplitude is stable in most cases, so that the piezoelectric sheet can work reliably and stably. The contact-separation between the functional materials on the beam and the curved boundaries, respectively, can generate electricity through triboelectrification and electrostatic induction. The vertical structure avoids the interference of objects behind the bluff body on the flow field, thus increasing the width of the boundaries (i.e., the working area of the TENG) without significantly increasing the effect on the aerodynamic performance of the system. The vertical structure can also enhance the contact force of the TENG due to the gravity of the bluff body. The pressure distributions of the vertical structure and the horizontal structure in the flow field are shown in Fig. 1(d). It can be found that the negative pressure of the horizontal structure is mainly distributed around the geometric boundaries. Since there is no object behind the vertical structure of the bluff body, the pressure difference between the front and the rear is significantly higher than that of the horizontal structure. A greater pressure difference can increase the periodic lateral lift of the bluff body. Thus, the vertical structure is more conducive to enhancing the dynamic performance, and has the feasibility of increasing the boundary area (that is, the working area of the TENG).

Figure 2 describes the operating process of the GEH-VC. Figures 2(e)–2(h) are the operating process of the PEH. The electromechanical conversion modes and the motion forms match each other, which is beneficial to improving the utilization of energy and space. When the bluff body vibrates under the flow action, the piezoelectric beam vibrates and deforms, which results in a potential difference on its surface due to the piezoelectric effect. The piezoelectric beam vibrates, producing a continuous alternating current (AC) voltage. Moreover, Figs. 2(i)–2(p) are the operating process of the TENG, which consists of two generating units. The two generating units are symmetrical in structure. Take one of them as an example to illustrate the operating process of the TENG. When the FEP film on the beam is in contact with the Al film on the curved boundary, the electrons on the Al film are transferred to the FEP film. Therefore, the Al film is positively charged, and the FEP film is negatively charged. When the beam leaves the curved boundary, there is a potential difference between the Al film on the beam and the Al film on the curved boundary, thereby generating current in the load circuit. As the beam vibrates, it periodically contacts and separates from the boundary, and the electrons periodically move back and forth between the Al film on the beam and the Al film on the curved boundary.

3 Results and discussion

For the PEH, the electromechanical coupling coefficient, the capacitance, and the external resistance are $\gamma$, $C_p$, and $R_p$, respectively. The voltage is $V_p$. For the TENG, the charge and load resistance of generating unit $i$ ($i = 1, 2$) are $Q_i$ and $R_i$, respectively. The relative dielectric constant, the thickness, and the area of the FEP film are $\varepsilon_{tF}$, $d_F$, and $S$, respectively. The vacuum dielectric constant is denoted as $\varepsilon_0$. According to the operating principle of the GEH-VC, the electromechanical coupling dynamic equation of the GEH-VC vibration system can be used to describe its dynamic and electrical characteristics as follows[15]:

$$\begin{align*}
m\ddot{x} + c\dot{x} + kx - mg\left(\frac{x}{7} - \frac{1}{6}\left(\frac{x}{7}\right)^3\right) - \gamma V_p &= F_w - F_b, \quad (1) \\
C_p\frac{dV_p}{dt} + \frac{V_p}{R_p} + \gamma \frac{dx}{dt} &= 0, \quad (2) \\
R_1\frac{dQ_1}{dt} &= -\frac{Q_1}{S\varepsilon_0}\left(\frac{dF}{\varepsilon_{tF} + x_m - x} + \frac{\sigma(x_m - x)}{\varepsilon_0}\right), \quad (3) \\
R_2\frac{dQ_2}{dt} &= -\frac{Q_2}{S\varepsilon_0}\left(\frac{dF}{\varepsilon_{tF} + x_m + x} + \frac{\sigma(x_m + x)}{\varepsilon_0}\right). \quad (4)
\end{align*}$$
where $m$, $c$, and $k$ are the equivalent mass, the damping, and the stiffness, respectively, $x$ is the generalized displacement of the vibration system, and $x_m$ is the maximum generalized displacement. The height and cross-sectional width of the bluff body are $H$ and $D$, respectively. The air density is $\rho$, the flow speed is $v_w$, and the aerodynamic force $F_w$ can be calculated as:

$$F_w = \frac{1}{2} \rho v_w^2 DH \left( a_1 \frac{\dot{x}}{v_w} - a_3 \left( \frac{\dot{x}}{v_w} \right)^3 \right),$$

where $a_1$ and $a_3$ are empirical coefficients. $F_b$ is the resistance when the vibration system tends to break through the maximum generalized displacement due to the boundaries. An additional
damp \( c_b \) and an additional stiffness \( k_b \) are used to express \( F_b \) as follows:

\[
F_b = \begin{cases} 
  c_b \dot{x} + k_b(x - x_m), & x > x_m, \\
  0, & -x_m \leq x \leq x_m, \\
  c_b \dot{x} + k_b(x + x_m), & x < -x_m.
\end{cases}
\]  

(6)

The effects of the external load on the voltage RMS and the average power of the TENG (one generating unit of the TENG and a width of 10 mm) and the PEH are analyzed through experiments, as shown in Fig. 3. The wind speed of 7 m/s is moderate in the experiments, and the wind speed in the environment is generally around this wind speed. Therefore, the effect of the external resistance on the output performance of the proposed harvester is studied at a wind speed of 7 m/s. It is evident from the figure that the average power first rises and then falls as the resistance increases. When the load resistance is 100 MΩ, the average power of one generating unit of the TENG reaches the maximum value of 45.2 µW. When the load of the PEH is 2 MΩ, the average power reaches the peak value of 75.7 µW. To enable comparison using the same conditions, optimal resistance is used in the subsequent experiments.

![Fig. 3](image)

**Fig. 3** Average powers of one generating unit of (a) the TENG \((w = 10 \text{ mm})\) and (b) the PEH as the external load varies (color online)

The beam and the boundaries of the horizontal structure are placed behind the bluff body. In the vertical structure, the beam and the boundaries are placed vertically below the bluff body. The simulation results show that the boundaries in the vertical structure have less influence on the flow field of the bluff body, so that the vertical structure has a better aerodynamic performance. Further experiments are carried out to verify the design advantages of the vertical structure. The prototypes of the vertical structure and the horizontal structure are made for comparison. Both structures have equal sizes, and the boundary width is 10 mm. Figure 4 shows the comparison between the output performances of the vertical and horizontal structures of the GEH-VC. We find in the experiments that for the horizontal structure, the objects behind the bluff body affect the aerodynamic performance of the system. For the PEH, the starting wind speed of the two structures is 2 m/s. Due to the boundaries, the amplitudes of the beam are approximately the same. Therefore, the voltages and average powers of the PEH are approximately the same for both structures. For the TENG, the starting operating wind speed of the vertical structure is 3 m/s, while the horizontal structure starts at 4 m/s. The vertical beam is more easily deformed due to the gravity of the bluff body, which makes the TENG work at lower wind speeds. The output performance of the vertical structure of the TENG is higher than that of the horizontal structure of the TENG. First, in the vertical structure, there is no object behind the bluff body to influence the aerodynamic performance of the system.
Second, when the beam is in contact with the boundaries, the bluff body gravity also acts on the functional materials of the TENG. These reasons make the functional materials on the beam and on the boundaries, respectively, contact more comprehensively, improving the performance of the TENG. The boundaries of the vertical structure are not behind the bluff body. Thus, the boundaries have a relatively small impact on the aerodynamic performance of the system. On this basis, the boundary width can be increased to improve the electrical performance of the TENG.

![Fig. 4](image)

**Fig. 4** Comparison of the voltage amplitudes and average powers of the vertical and horizontal structures with \( w = 10 \text{ mm} \) (color online)

When the wind speed is 2 m/s, 7 m/s, and 12 m/s, the voltage responses of the GEH-VC are obtained from the simulations and experiments, respectively, as shown in Fig. 5. Three beam widths, i.e., 10 mm, 15 mm, and 20 mm, are used. The corresponding TENG working areas are 0.001 m\(^2\), 0.0015 m\(^2\), and 0.002 m\(^2\), respectively. The output voltages of two generating units of the TENG are plotted on a graph. At low wind speeds, a greater beam stiffness results in a smaller vibration amplitude. As the beam width and stiffness increase, the PEH voltage amplitude and frequency decrease. As the wind speed increases, the beam gets in contact with the boundaries, and the vibration frequency increases. At a higher wind speed (12 m/s), as the beam width increases (increase in the TENG working area), the TENG voltage increases. There are differences between the simulation and experimental results. The possible reason is that the wind speed fluctuates in the experiment, the measurement error, and the prototype machining and assembly errors. Nevertheless, the simulation and experimental results are consistent in the trend.

The main purpose is to observe the effect of the boundary width on the TENG performances. Moreover, the beam dynamic response can be estimated through the PEH electrical response. Thus, the MFC size is not changed. Figure 6 depicts the relationship between the electrical response and the beam width at different wind speeds. When the wind speed is low, as the beam width increases, the electrical responses of the TENG and the PEH decrease, and the wind speed at which the TENG starts to work increases accordingly. This is because when the beam width increases and its stiffness increases, the beam is more difficult to vibrate under a weak aerodynamic force. The vibration frequency of the beam and the contact force between the functional materials of the TENG increase with the wind speed, and the electrical response of the TENG increases accordingly. Although the boundaries limit the displacement of the beam vibration at high wind speeds, the voltage and average power still increase with the increase in the wind speed, because the vibration frequency of the beam increases along with the PEH electromechanical conversion efficiency. When the wind speed is high, there is almost no difference in the PEH output for various boundary widths, while the TENG voltage...
amplitude and average power increase significantly with the boundary width. For \( w = 20 \text{ mm} \) and the wind speed of 12 m/s, the TENG voltage amplitude and average power are 245.8 V and 180.0 \( \mu \text{W} \), respectively. Such values represent the increases of 17% and 24%, respectively, compared with those for \( w = 10 \text{ mm} \). The increase in the boundary width can increase the TENG working area and the electrical performance at high wind speeds. However, greater rigidity also requires the greater wind speed for the TENG to operate.

Figure 7 shows the comparison of the average power of the GEH-VC and the traditional
galloping PEH under the same conditions. The vibration amplitude of the GEH-VC is rather small at low wind speeds, and the beam does not come in contact with the boundaries, that is, only the PEH works in the GEH-VC, and the average power is almost the same as the traditional galloping PEH. The GEH-VC vibration amplitude increases with the wind speed until the beam comes in contact with the boundaries. Then, the vibration amplitude no longer increases with the increase in the wind speed, but the vibration frequency increases with the increase in the wind speed. The vibration amplitude of the traditional galloping PEH increases with the wind speed. Although the GEH-VC has a smaller vibration amplitude, it exhibits a higher vibration frequency than the traditional galloping PEH. Thus, there is little difference in their output powers. The vibration amplitude of the prototype with a traditional structure at 6 m/s is already too large (see Movie S2 on https://link.springer.com/journal/10483/volumes-and-issues/43-7), resulting in a risk of damage to the piezoelectric sheet. Although increasing the stiffness of the beam can increase the tolerance of the traditional galloping PEH at a high wind speed, it is difficult to vibrate at a low wind speed. The total average power of the GEH-VC is 180% higher than that of the traditional galloping PEH. The total average power of the GEH-VC can reach 282.8 μW (with the wind speed of 12 m/s). This comparison proves that the GEH-VC can start operating from very low wind speeds while remaining reliable at high

![Wind speed about 6 m/s](image)

**Fig. 7** Comparison of the GEH-VC and the traditional galloping PEH under the same conditions: (a) experimental setup and (b) average power (color online)
wind speeds. Additionally, the total output power of the GEH-VC is higher.

As shown in Fig. 8(a), 400 LEDs in the laboratory are powered by the TENG (see Movie S3 on https://link.springer.com/journal/10483/volumes-and-issues/43-7). For further application, the AC voltage of the PEH and the TENG are processed into the direct current (DC) voltage and then charge the capacitor together. Figure 8(b) shows the charging voltage curves of various capacitors of the GEH-VC after hybrid circuit processing at 12 m/s. Figure 8(c) shows the application where the GEH-VC is used to power the temperature sensor. First, the GEH-VC takes about 12 minutes to charge the 220 μF capacitor to 3 V, and then powers the temperature sensor for about 25 seconds (see Movie S4 on https://link.springer.com/journal/10483/volumes-and-issues/43-7).

Fig. 8  (a) Lighting 400 LEDs by using the TENG. (b) Charging voltage curves of various capacitors of the GEH-VC after hybrid circuit processing. (c) Application in powering the commercial temperature sensor (color online)

4 Conclusions

The presented study provides a novel perspective on the design of hybrid electromechanical conversion mechanisms, that is, to combine and collaborate based on their respective characteristics. A GEH-VC is designed based on this concept. The GEH-VC differs from the traditional hybrid mechanisms. The TENG and the PEH generate electricity in different states (vibration and collision), respectively. The TENG has no effect on the work of the PEH in a vibration state, and the TENG acts as a regulation mechanism to improve the dynamic performance of the PEH. The experimental results show that the vertical structure of the GEH-VC improves the performance compared with the horizontal structure. The increase in the boundary width can increase the TENG working area and the output power. The results show that the GEH-VC can start operating from very low wind speeds while remaining reliable at high wind speeds. The output power is increased by 180% over the traditional galloping PEH at the wind speed of
6 m/s. It is demonstrated that the GEH-VC can power commercial temperature sensors. The GEH-VC has the potential to power the wireless sensors of the Internet of Things, with the advantages of sustainability, convenience, and environmental protection.

5 Experimental procedures

Step 1 Preparing the GEH-VC

The FEP membrane (50 µm in thickness) and Al electrode (10 µm in thickness) were glued to the beam through kapton. The Al electrodes were pasted on the TENG boundaries by foam glue. Thus, the TENG was fabricated. A curved bluff body was fabricated with polylactic acid (PLA) by a 3D printer and was fixed to the free end of the beam. A piezoelectric sheet (M2807-P2, purchased from Smart Material Corp.) was adhered to the root of the beam.

Step 2 GEH-VC characterization

A DH-5922 dynamic signal analyzer produced by DONGHUA was used to measure the voltage generated by the prototype in real time and input the data into the computer. An anemometer (TES-1341) was employed to measure the wind speed.

Supporting information

Supporting information is available online https://link.springer.com/journal/10483/volumes-and-issues/43-7.

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