Bionic dragonfly staggered flapping hydrofoils triboelectric-electromagnetic hybrid generator for low-speed water flow energy harvesting

Lu Dong\textsuperscript{a,b,1}, Jianyang Zhu\textsuperscript{a,b,1}, Hengyu Li\textsuperscript{b,c,1}, Jiacheng Zhang\textsuperscript{a,b}, Da Zhao\textsuperscript{b}, Zhong Lin Wang\textsuperscript{b,c,d,*}, Le Gu\textsuperscript{a,*}, Tinghai Cheng\textsuperscript{b,c,*}

\textsuperscript{a} Key Laboratory of Metallurgical Equipment and Control Technology Ministry of Education, Wuhan University of Science and Technology, Wuhan, Hubei 430081, China
\textsuperscript{b} Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, China
\textsuperscript{c} Guangzhou Institute of Blue Energy, Knowledge City, Huangpu District, Guangzhou 510555, China
\textsuperscript{d} Georgia Institute of Technology, Atlanta, GA 30332-0245, United States
\textsuperscript{1} These authors contributed equally to this work.
\textsuperscript{*} Corresponding authors’ E-mail: zhong.wang@mse.gatech.edu, hitribology@163.com, chengtinghai@binn.cas.cn.

Abstract

Water flow energy harvesting with triboelectric nanogenerators (TENGs) is in the spotlight. However, existing front-end energy harvesting structures have drawbacks, such as traditional turbines requiring higher flow speed to start-up, and devices based on vortex-induced vibration exhibiting a lock-in phenomenon, which severely limits the performance of the TENGs in low-speed water environments. Here, a bionic dragonfly flapping hydrofoils-driven triboelectric-electromagnetic hybrid generator (BDFH-TEHG) is reported. The dragonfly-wing-like staggered tandem hydrofoil configuration enables the BDFH-TEHG continuous energy harvesting in the entire time domain. Meanwhile, the power generation part and front-end structure parameters are optimized to enhance the electrical output of the harvester. As a result, the BDFH-TEHG exhibits a low starting flow speed, and efficient power generation at different flow speeds. At the flow speed of 0.21 m/s, the triboelectric nanogenerator (TENG) and electromagnetic generator (EMG) achieve peak powers of 4.19 mW and 8.01 mW, respectively. Furthermore, the BDFH-TEHG can power the wireless water quality sensor and provide early warning successfully for agricultural activities. This work provides a valid method for low-speed water flow energy harvesting, toward practical applications of water environment monitoring in smart agriculture.

Keywords: flapping hydrofoil, triboelectric-electromagnetic hybrid generator, energy harvesting, low-speed water flow, staggered tandem configuration

1. Introduction

The commitment to building a resource-saving and environment-friendly society has motivated the application of zero-carbon energy [1-4]. Among various renewable
energies, water flow energy stands out as a highly promising clean energy source, characterized by large reserves, high energy density, good predictability, and so on [5,6]. Conventionally, water flow energy is converted into electrical power by electromagnetic generators (EMGs) [7,8]. However, the vast majority of the water flows in human daily life at a low-speed of about 1 m/s [9], and the poor stability and reliability in low-speed water flow of the single EMG is not preferably adapted to such environments [10,11]. Therefore, it is imperative to provide a hybrid energy-conversion strategy to harvest energy from low-speed water environments.

Triboelectric nanogenerator (TENG) was first invented by Wang’s group based on triboelectrification and electrostatic induction effect [12-15]. This emerging technology offers a novel method for harvesting ambient mechanical energy [16], including vibration energy [17,18], water wave energy [19,20], and breeze energy [21,22]. With the merits of light-weight [23,24], cost-effectiveness [25,26], and high power density in low-frequency [27,28], a series of TENG devices have been developed for harvesting water flow energy and they exhibit excellent output performance at a certain flow-speed [29,30]. However, effectively harvesting low-speed water flow energy remains a significant challenge for these existing TENGs [31]. This is mainly attributed to the traditional energy harvesting structure of the TENGs having bottlenecks, such as the rotating turbine technology requiring a higher flow speed (2.6-3.6 m/s) to operate [32]. Moreover, although the devices based on vortex-induced vibration are usually applied in low-speed water flow environments, they experience large-amplitude oscillation only within a specific range of flow speeds known as the lock-in region [33,34]. Thus, there is an urgent to explore a new solution for effectively converting the low-speed water flow energy into electricity. As we all know, animals have developed a sophisticated self-adaptive system in nature, and their behavior can offer insights into the structure design of the harvester [35-37]. Taking inspiration from this, developing a harvester based on the bionic principle for low-speed water flow energy harvesting presents significant potential.

In this work, inspired by the fact that dragonflies can simultaneously flap their fore and hind wings with a certain phase difference to realize high lift and thrust, a bionic dragonfly staggered flapping hydrofoils triboelectric-electromagnetic hybrid generator (BDFH-TEHG) is developed. A fluid-structure interaction analysis is carried out to understand the operating principle of the BDFH-TEHG. Owing to the dragonfly-wings-like staggered tandem hydrofoil design, the BDFH-TEHG can realize continuous energy harvesting. Most importantly, the test results show that the BDFH-TEHG can achieve self-start at the flow speed of 0.21 m/s, and exhibits excellent electrical output in different flow speeds. At 0.21 m/s, the peak powers of 4.19 mW and 8.01 mW can be attained by the TENG and EMG, respectively. In the demonstration part, the BDFH-TEHG can supply power for the wireless water environmental detection systems by harvesting water flow energy, and further provide early warning and timely protection successfully for agricultural irrigation. This study offers a novel method for promoting the practical applications of the hybrid generator in the low-speed water flow environment, as well as the digital transformation of agriculture.
2. Results and discussion

2.1. Structure and operating principle of BDFH-TEHG

The inspiration for this concept derives from the fact that dragonflies simultaneously flap their fore and hind wings with a certain phase difference (see Fig. 1a). The overall details of the BDFH-TEHG are exhibited in Fig. 1b. It consists of two flapping hydrofoils in staggered tandem configuration along the flow direction, a pair of crank-connecting rod-based transmission mechanisms, and a hybrid generator (TENG+EMG) serving as the power generation part. The fore and hind hydrofoils are mechanically coupled by three gears. The reciprocating linear motion of the flapping hydrofoil is converted into the monodirectional rotating motion of the crank by the transmission mechanism, and then the kinetic energy is transferred to the output shaft with the assistance of the passive gear. The transmission ratio between the intermediate passive gear and the output shaft is 1:3, which is beneficial for achieving a high-frequency output. Furthermore, a pair of gears with a transmission ratio of \( i = \frac{Z_2}{Z_1} \) is mounted to the end of the connecting rod and the pivoting axis respectively to adjust the pitching angle of the hydrofoils. It should be mentioned that the initial pitching angle is fixed at 30°, depending on the length of the connecting rod and the radius of the crank. For the power generation part, the TENG adopts the flexible blade structure to reduce the wear for prolonging the service life, and the copper electrodes are attached to the substrate. The EMG consists of 4 magnets mounted on the bottom of the rotor and 4 coils mounted on the bottom of the stator. The force exerted on the flapping hydrofoil drives the crank to rotate with the help of the connecting rod, and the transmission process of force is shown in Fig. 1c. Meanwhile, the reason for the lift generation is the pressure difference that exists on both surfaces of the hydrofoil, as given in Fig. 1d. The photographs of the BDFH-TEHG are presented in Fig. S1.

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To better understand the dynamic characteristics of the two hydrofoils, a computational fluid dynamics (CFD) analysis is conducted by Fluent software and the computation flow chart of the fluid-structure interaction is plotted in Fig. 2a. The corresponding boundary conditions and computational domain in the simulation are depicted in Fig. S2. The pressure contour around the two hydrofoils obtained from the simulation is shown in Fig. 2b. It can be found that the alternating lift can be generated by deflecting the direction of the angle of attack.

On this basis, the force acting on the device can be represented in Fig. 2c, and the step-by-step detailed movement of the staggered tandem hydrofoils in one flapping cycle can be described as follows: In the initial state, the hind hydrofoil moves to the limiting position, and the lift is diminished gradually with the pressure difference on both surfaces decreasing to 0. Whereas the fore hydrofoil drives the crankshaft to keep rotating due to the existence of the phase difference between the two hydrofoils ($t/T=0.00$). The swing motion of the connecting rod further ensures the hind hydrofoil regains a certain angle of attack (AOA), and the two hydrofoils provide the driving force for the output shaft simultaneously ($t/T=0.00-0.25$). When the fore hydrofoil...
reaches the limiting position, the crankshaft is driven by the hind hydrofoil to rotate \((t/T=0.25)\). Then the fore hydrofoil reverses the AOA, and the two hydrofoils perform flapping motion in opposite directions \((t/T=0.25-0.50)\) until the hind hydrofoil reaches the other limiting position \((t/T=0.50)\). Subsequently, the hind hydrofoil reverses the flapping direction to align with the fore hydrofoil \((t/T=0.50-0.75)\) until the fore hydrofoil reaches the limiting position \((t/T=0.75)\). Finally, the two hydrofoils return to the initial position together \((t/T=0.75-1)\) and an operating cycle is completed. The more detailed operating principle of the BDFH-TEHG and pressure distribution around two hydrofoils are presented in Figs. S3 and S4.

Benefits from the staggered tandem configuration, the two hydrofoils can alternately achieve the flapping speed \((V)\) peaks with a certain phase difference, as shown in Fig. 2d. This characteristic ensures that at least one hydrofoil drives the output shaft in the entire time domain. Therefore, the output shaft can be continuously excited to generate a relatively constant speed (Fig. 2e), which is conducive to realizing continuous power generation in the water flow. The operating principle of the TENG in one cycle is sketched in Fig. S5.

![Diagram](image)

**Fig. 2.** Fluid-structure interaction study of the two hydrofoils. (a) Computation flow chart of fluid-
structure interaction. (b) Pressure distribution around the two hydrofoils. (c) Motion state of the BDFH-TEHG in one flapping cycle. (d) Flapping speed of the fore and hind hydrofoils. (e) Angular speed of the passive gear and the output shaft.

2.2. Electrical characteristics of BDFH-TEHG

As mentioned above, the kinetic energy of flapping hydrofoils is converted into the rotational energy of the output shaft to drive the generator for operation. Therefore, an experimental platform is set up to examine the rotational energy harvesting capability of the power generation part (Fig. 3a). A stepper motor is applied to provide the rotation speeds of 30-180 rpm and the triboelectric materials and magnet sizes are optimized to enhance the electrical performance of the power generation part. Fig. 3b illustrates the detailed material types (fluorinated ethylene propylene (FEP), polyvinyl chloride (PVC), and Kapton) and magnet sizes information (20 mm, 25 mm, and 30 mm). The electrical output capabilities of various triboelectric materials are systematically explored. From Fig. 3c, the triboelectric material of FEP can ensure the TENG attains the highest output performance, and the open-circuit voltage ($V_{OC}$) rises from 1120 V to 3200 V, the short-circuit current ($I_{SC}$) rises from 6.45 $\mu$A to 31.92 $\mu$A and the transferred charge rises from 285 nC to 354 nC within the rotation speed range of 30-180 rpm. Fig. S6 plots the detailed experimental measurement results of the TENG. For the EMG, the $V_{OC}$ and $I_{SC}$ are discussed under various magnet diameters, which are plotted in Fig. 3d. The enhancement of the electrical characteristics of the EMG is facilitated by the increase in magnet diameter. Therefore, the 30 mm diameter is selected as the candidate magnet dimension in the subsequent research, the $V_{OC}$ rises from 3.81 V to 22.17 V, and the $I_{SC}$ rises from 2.22 mA to 12.94 mA within the corresponding rotation speed range. Fig. S7 plots the detailed experimental measurement results of the EMG.
The dynamic behavior of the flapping hydrofoil is closely related to the kinematic parameters, such as the pitching-center location $X_p/C$, pitching amplitude $\theta_m$, and phase difference $\beta$ between the two hydrofoils. Fig. 4a sketches all these characteristic parameters in detail, and they are optimized in the water with a flow speed of 0.61 m/s. In Fig. 4b, the electrical characteristics of the harvester are discussed under various pitching-center locations. It can be observed that the higher output current can be attained by both the power generation units at the $X_p/C$ ratio of 1/3. Then Fig. 4c explores the effects of the pitching amplitude $\theta_m$ ($20^\circ$, $30^\circ$, $40^\circ$, $45^\circ$, $50^\circ$, and $60^\circ$) on the electrical characteristics of the BDFH-TEHG. Within a certain range, a rise in the pitching amplitude $\theta_m$ is advantageous for enhancing the electrical output of the BDFH-TEHG. However, the overlarge pitching amplitude $\theta_m$ will deteriorate the dynamic performance of the hydrofoil, which further results in a decrease in the electrical characteristic.

Subsequently, the dependence of the electrical characteristic of the BDFH-TEHG on the phase difference between the two hydrofoils is evaluated, adopting a pitching-center location of $1/3C$ and a pitching amplitude of $45^\circ$. The waveform of the short-circuit current under different phase differences is presented in Fig. 4d. The results show that under phase differences of $30^\circ$ and $150^\circ$, the driving force provided by the
hydrofoils is not sufficient for the output shaft to operate normally, and hence there is no electrical signals output. When the two hydrofoils keep a phase difference of 90°, the maximum output current can be achieved by the power generation part, which illustrates the energy harvesting capability of the BDFH-TEHG is fully exploited. Other detailed electrical characteristics of the BDFH-TEHG exhibit similar variation trends in Fig. S8. In addition, the 90° phase difference can attain a continuous electrical signal in the entire time domain, which demonstrates that achieving stable power generation through the dragonfly-wings-like staggered tandem design is feasible. Meanwhile, the fast Fourier transform (FFT) is applied to process the electrical signals of the TENG, which is displayed in Fig. S9. It can be found that compared to other phase differences, the phase difference of 90° contributes to enhancing the output frequency of the electrical signals. The parameter combination of $X_p/C=1/3$, $\theta_m=45°$ and $\beta=90°$ exhibits preferable output characteristics, which is attributed to the two surfaces of the hydrofoil having a greater pressure difference. Fig. S10 displays the pressure comparison of two typical cases (optimum case and worst case) and Video S1 shows the pressure distribution during the movement of the two hydrofoils.

![Fig. 4. Structure optimization of the BDFH-TEHG. (a) Research parameters of the flapping hydrofoil. (b) Current characteristics of the TENG and EMG at various pitching-center locations. (c) Current characteristics of the TENG and EMG at various pitching amplitudes. (d) Current characteristics of the TENG and EMG at various phase differences.](image-url)
The water pump powered the flowing water with speeds of 0.21-0.61 m/s to evaluate the energy harvesting capability of the optimized BDFH-TEHG from low-speed water flows. From Fig. 5a(i), the starting water flow speed of the BDFH-TEHG is 0.21 m/s. Under the flow speed range of 0.21-0.61 m/s, the open-circuit voltage ($V_{OC}$) of the TENG rises from 1460 V to 2180 V, and the short-circuit current ($I_{SC}$) rises from 9.12 μA to 18.18 μA, respectively. A similar trend is observed in Fig. 5a(ii), the $V_{OC}$ of the EMG rises from 6.08 V to 12.62 V and the $I_{SC}$ rises from 3.90 mA to 7.57 mA, respectively. The experimental measurement details are plotted in Fig. S11 and corresponding values of the TENG and EMG are presented in Tables S1 and S2. Moreover, the load current ($I_R$) and peak power ($P_R$) of the two power generation units are explored at the flow speed of 0.21 m/s. According to the formula $P_R = I_R^2R$, a peak power of 4.19 mW can be attained by the TENG at the matched resistance of 100 MΩ and a peak power of 8.01 mW can be attained by the EMG at the matched resistance of 1.7 kΩ, which is illustrated in Fig. 5b. At 0.61 m/s, the retention rate of the electrical output is tested in the flowing water, and the experimental results indicate that the TENG and EMG maintain about 92.6% and 100% of the initial electrical output performance after 6 hours, respectively (Fig. 5c).

The capability of the BDFH-TEHG to charge capacitors with various capacities is tested in Fig. 5d. Fig. 5d(i) plots the circuit scheme of the BDFH-TEHG powering for the capacitor. The charging characteristics of different power generation units are texted in Fig. 5d(ii). It is observed that the TENG-charged capacitor attains a voltage of 18.2 V within 300 s, while the EMG-charged capacitor attains a voltage of 9.9 V within 25 s and then maintains a constant level, which suggests that the charging capability is closely related to the inherent output characteristics of the generator. Particularly, the voltage characteristic decides the ultimate charging level, and the high current output contributes to accelerating the charging speed. Complementing the advantages of the TENG and EMG enables the capacitor to attain a higher voltage (25.0 V) at the same time. More capacitors with different capacities (10-470 μF) are charged by the hybrid generator for 85 s, attaining a voltage of 26.4 V, 22.4 V, 18.2 V, 13.9 V, 9.4 V, and 6.8 V, respectively, which proves the BDFH-TEHG has excellent charging capability, which is illustrated in Fig. 5d(iii).
Fig. 5. Electrical output capabilities of the BDFH-TEHG. (a) Electrical output capabilities of the BDFH-TEHG in the flowing water with speeds of 0.21-0.61 m/s. (b) Curves of the load power characteristic of the BDFH-TEHG with various resistances. (c) Retention rate test of the electrical output. (d) Load capacitance characteristic of the BDFH-TEHG.

2.3. Applications of BDFH-TEHG

As the typical low-speed water flow environment, irrigation channels are an indispensable part of human life and play an essential role in agricultural activities. Water quality information (such as the potential of hydrogen (PH), electrical conductivity (EC), water temperature (TEMP), and salt) is necessary for the normal growth of crops. Thus, the BDFH-TEHG shows great application prospects to be arrayed in an irrigation channel to harvest water flow energy and supply power for the wireless water quality sensor, which can provide early warning and timely protection for irrigation activities in smart agriculture, as presented in Fig. 6a. The photograph of the BDFH-TEHG supply power for lights emitting diodes (LEDs) is presented in Fig. 6b(i). From Fig. 6b(ii) and Video S2, the BDFH-TEHG successfully lights 630 LEDs in the simulation irrigation channel with a speed of 0.61 m/s, which can supplement lighting for crops during nighttime, effectively promoting plant growth. Fig. 6c illustrates the circuit scheme of a wireless water quality sensor driven by the BDFH-TEHG. The photograph of the BDFH-TEHG supply power for the water quality monitoring system is given in Fig. 6d(i). From Fig. 6d(ii) and Video S3, the BDFH-TEHG can power a wireless water quality monitoring sensor as the capacitor of 0.22 F is charged to 3.3 V within 3500 s (Fig. 6d(iii)) in the flowing water with a speed of 0.61 m/s.
m/s. When any water quality index, such as PH exceeds the threshold (5.50-8.50), the monitoring system can successfully realize early warning.

**Fig. 6.** Applications of the BDFH-TEHG in the irrigation channel. (a) Application prospect of the BDFH-TEHG for self-powered water quality sensor. (b) The BDFH-TEHG lights 630 LEDs in water. (c) Circuit scheme of the water quality sensor powered by the BDFH-TEHG. (d) The monitoring system of water quality powered by the BDFH-TEHG.

### 3. Conclusions

In summary, a BDFH-TEHG is developed for realizing energy harvesting from the low-speed water flow. A fluid-structure interaction analysis is conducted to understand the dynamic characteristics of the two hydrofoils. The dragonfly-wings-like staggered tandem hydrofoil design is newly implemented to realize continuous electrical output in the entire time domain. In addition, a series of experiments are conducted to optimize the triboelectric materials, magnet sizes, and front-end structure parameters that affect the output capability of the harvester. As a result, the BDFH-TEHG can achieve low flow speed start-up (0.21 m/s), as well as efficient power generation in different water flow environments. Specifically, the TENG achieves the output voltage range from 1460 V to 2180 V and output current range from 9.12 μA to 18.18 μA, and the EMG achieves the corresponding output voltage range from 6.08 V to 12.62 V and output current range from 3.90 mA to 7.57 mA at the water flow conditions of 0.21-0.61 m/s. The peak powers of 4.19 mW and 8.01 mW can be attained.
by the TENG and EMG at the low-speed of 0.21 m/s. In the demonstration part, the BDFH-TEHG is deployed in a simulation irrigation channel to harvest water flow energy for powering the wireless water quality sensor, and further providing early warning and timely protection for agricultural irrigation. This study offers a promising strategy based on the bionic principle to harvest energy from low-speed water flow, which is essential to the development of digital agriculture.

4. Experimental section

4.1 Fabrication of the BDFH-TEHG

The BDFH-TEHG consists of two hydrofoils, a pair of transmission mechanisms, and a hybrid generator (TENG+EMG) serving as the power generation part. The NACA0015 foil is fabricated by 3D printing technology out of polylactic acid (chord length: 200 mm, span length: 250 mm). The flapping displacement of the two hydrofoils is 200 mm, which is determined by the length (200 mm) of the connecting rod and the radius (100 mm) of the crank. The connecting rod is fabricated by 3D printing technology out of aluminum alloy material and the crank is fabricated by acrylic. The flow direction distance of the two hydrofoils is 250 mm, which is mechanically coupled by three gears with a module of 2.5 and teeth number of 50. The pitching angle adjust mechanism includes two gears (module: 2.5, center distance: 75 mm), by adjusting the number of teeth on two gears to attain various pitching angles. For the power generation part, the triboelectric material of the TENG adopts FEP films (length: 73 mm, width: 45 mm, and height: 0.1 mm). The TENG comprises 20 grids, with every 10 interphase grids forming a single electrode, all of which are attached to the substrate (outer diameter: 160 mm, inner diameter: 150 mm). The EMG can be divided into the magnet (diameter: 30 mm, thickness: 3 mm) and the coil (diameter: 30 mm, thickness: 3 mm).

4.2 Measurement of the BDFH-TEHG

A stepper motor (57HBP102AL4-TFA, Shidaichaoqun, China) is applied as an excitation source to drive the hybrid generator to operate at different speeds, and six water pumps (AQ12000DP, Huitian, China) are used to provide the different water flow conditions. A current meter (LS300-A, Zhuoma, China) is adopted to measure the flow speed. The output voltages of the TENG are recorded by an electron oscillograph (DS2202A, RIGOL, China), and other electrical characteristics of the BDFH-TEHG are measured by an electrometer (6514, Keithley, USA). The data is attained by a data acquisition card (USB-6211, National Instruments, USA) and recorded by LabVIEW software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Data Availability

The data underpinning the findings of this study can be obtained from the corresponding author upon making a reasonable request.

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