Experimental study on underwater fin-shaped piezoelectric energy harvester based on wake galloping

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Abstract. This paper presents a novel piezoelectric energy harvester based on wake galloping in water. This harvester consists of a bluff cylinder and a fin connected with a macro fiber composite (MFC) piezoelectric plate. The fluid flows through the upstream bluff cylinder and produces alternating shedding vortices behind it. Vortex shedding produces periodic crosswise vortex-induced force to drive the fin and piezoelectric plate vibrating to generate electricity. An experimental platform was established and several prototypes of energy harvesters were fabricated. The experimental results show that, under different flow velocity domains, the harvesting effect of the bluff cylinder with a diameter of 30 mm is the most ideal for the energy harvester with a fin length of 20, 30 and 40 mm. When the fin length is 20 mm, the output voltage changes most smoothly. To obtain stable open circuit output voltage, the spacing distance between the bluff cylinder with a diameter of 25 mm and the fin should be controlled within 3D, while, the spacing distance between the bluff cylinder with a diameter of 30 mm and the fin should be controlled within 2D. When the bluff cylinder with a diameter of 30 mm, a spacing distance of 100 mm, and a flow velocity of 0.427 m/s, the maximum open circuit output voltage of 7.289 V can be obtained. The present work provides an effective experimental foundation for the research of underwater fin-shaped vehicle’s dynamic endurance.

Keywords: vortex-induced vibration; wake galloping; water flow; fin-shaped piezoelectric energy harvester; MFC

1. Introduction

The demand of low-power, portable, wireless electronic devices is increasing greatly, and the development of miniaturized and light-duty continuous power supply devices is the main research task at present [1-3]. Confronting with serious problems such as increased energy shortage and intensified greenhouse effect, water energy has been widely concerned by most scientists because of its advantages of non-polluting and low operating costs. Piezoelectric energy harvest device exists the benefits of less space demand, environmental protection and easy manufacture, etc. Thus it has a good development prospect and has become a research hotspot in engineering and academia [4-6]. In most of the recent studies, piezoelectric energy harvest devices were mostly studied in the air. The energy density of air is low, the volume of the energy harvester is large, and the effective output range is relatively narrow. The energy density of water is much higher than air, which demonstrates the benefits of compact-sized and high energy collection efficiency of the piezoelectric energy harvest device in water.

The common forms of flow-induced vibration are vortex-induced vibration, galloping, flutter and buffeting [7]. Based on the vortex-induced vibration, Xie et al. [8] found that when the vortex shedding frequency is in the vicinity of the first-order bending natural frequency of the circular tube, the output power is the largest. Acadian et al. [9] studied piezoelectric energy harvesters made of lateral cantilever piezoelectric beams and tail end cylinders. Gao et al. [10] proposed a inverted vertical wind vortex-
induced vibration piezoelectric energy harvester. Based on the wake galloping, Akaydin et al. [11, 12] switched the relative position of the cylinder and the piezoelectric vibrator through simulation and experiment, and analyzed the optimal energy output of the piezoelectric vibrator. Abdelkefi et al. [13] systematically analyzed the trapping energy characteristics of the traps of the cylinders with different cross-section shapes (rectangular, isosceles triangle and D-type body) at the end of the piezoelectric cantilever beam. Zhou [14] revealed the nonlinear dynamic mechanism of asymmetric tristable energy harvesters and enhanced the energy harvesting performance for different excitations. By changing the unstable equilibrium positions, a series of tristable energy harvesters with different dynamic characteristics can be obtained, which will benefit energy harvesting under various excitation conditions. Dai [15] developed a validated nonlinear distributed-parameter model for harvesting energy from vortex-induced vibrations. Investigated the effects of the cylinder’s tip mass and electrical load resistance on the synchronization region and performance of the harvester. Song et al. [16] studied the vortex-induced vibration piezoelectric energy harvester working in water flow and proposed a novel harvester equipped with two piezoelectric beams and two cylinders. It can be found from the literature that many piezoelectric energy harvesters have been designed and studied in air and in water. However, the piezoelectric energy harvester with a bluff cylinder and a fin connected with piezoelectric plate based on wake galloping in underwater is rarely reported.

Therefore, this work introduces an underwater fin-shaped energy harvester with a simple structure and a small volume, based on wake galloping in water, for effectively converting the kinetic energy of water into electrical energy. Prototypes of the energy harvester were fabricated, an experimental platform was built, and the flow-induced vibration energy harvesting experiments were conducted. Influences of velocity and structural parameters on the effect of energy harvesting was explored.

2. Structure design of the underwater fin-shaped piezoelectric energy harvester

Figure 1 shows a schematic diagram of the fin-shaped piezoelectric energy harvester. This harvester consists of a bluff cylinder and a fin-shaped piezoelectric vibrator. The rectangular piezoelectric beam is composed of MFC-8514-P2 (Smart Material Corp.) bonded to a copper substrate and has a width of 18 mm. The fluid passes through the bluff cylinder to generate alternating vortex, and the vortex shedding generates a periodic vortex force on both sides of the fin. The piezoelectric plate is excited to generate periodic bending vibration, and generates electric energy. On the one hand, the tail fin device can drop the natural frequency of the piezoelectric vibrator, so that the natural frequency of the harvester is close to the vortex shedding frequency, then the resonant phenomenon occurs. On the other hand, the flow force can be effectively increased by changing the diameter of the bluff cylinder, the width of the fin and the spacing distance from the fin to the bluff cylinder.
3. Experiments

Figure 2 shows the experimental system of the fin-shaped piezoelectric energy harvesting. This system consists of an open circulation water tunnel, a frequency converter, a submersible pump, a harvester, an NI data acquisition card (NI 9229), and a computer. The experimental variables include the water velocity $v$, the diameter of the bluff cylinder $D$, the length of the fin $a_f$, the width of the fin $b_f$, and the spacing distance from the fin to the bluff cylinder $L$. $L$ ranges from $D$ to $6D$. 47 groups of data were obtained to study the optimal harvesting effect under different parameters. For ease of description, the serial number of the harvesters with a same cylinder diameter and fin width is listed in Table 1.
Table 1. Energy harvesters with different parameters

| Label | Width of the fin \( b_f \) (mm) | Diameter of the bluff cylinder \( D \) (mm) |
|-------|---------------------------------|---------------------------------|
| H220  | 20                              | 20                              |
| H225  | 20                              | 25                              |
| H230  | 20                              | 30                              |
| H320  | 30                              | 20                              |
| H325  | 30                              | 25                              |
| H330  | 30                              | 30                              |
| H420  | 40                              | 20                              |
| H425  | 40                              | 25                              |
| H430  | 40                              | 30                              |

By changing the diameter of the bluff cylinder \( D \) and the spacing distance \( L \) between the center of the bluff cylinder and the fin, and the water speed ranges from 0.1 m/s to 0.5 m/s, the open circuit output voltage of the harvester are obtained by the experiments.

The harvesting effect of underwater piezoelectric energy harvester is characterized by the effective value of its open circuit output voltage. Detailed results and analysis will be analyzed and discussed in the following section.

4. Experimental results and discussion

Figure 3 shows the open circuit output voltages versus the various flow speed corresponding to the harvesters labeled as H220, H225 and H230, respectively. It can be found that, for a harvester with a fin length of 20 mm, the harvesting effect increases significantly with the increase of the spacing distance when the spacing distance is 1\( D \), 2\( D \) and 3\( D \). For all the energy harvesters, when the spacing distance reaches 4\( D \), the output voltage increases with the increase of water speed, but voltage values are not stable and some data oscillates.

As the spacing distance increases, the vortex-induced effect gradually decrease, the fin mainly vibrates by the impact of water flow. When the fin bends to one side, the water-facing area increases, and the flow force applied to the fin increases. The flow drives the piezoelectric plate to bend and generate electric energy. When the piezoelectric plate is bended to a certain extent, the force of piezoelectric cantilever beam acting on the fin is greater than the force of water flow, then the fin bounces back to the other side to produce electricity to continuously generating electrical energy. At certain time, there is no vortex near the fin, so the oscillation of the piezoelectric plate does not belong to the wake galloping.

When the fin plate is swinging, it is subject to the resistance force of water. When the force of the flow is equal to the resilience of the piezoelectric cantilever beam, and the fin speed and acceleration are both zero. Hence, the fin cannot be bounced back and shows a near-stationary state in the water, the harvesting effect plummeted sharply. When the flow velocity changes, the piezoelectric plate is disturbed and continues to move, and the state of swinging is temporarily restored.

When the fin is gradually stopped due to the resistance, the harvesting effect decreases. As the flow velocity increases, this phenomenon will occur repeatedly several times. Accordingly, the open circuit output voltage will rise or fall. When the flow speed continues to increase and the flow impact force is completely greater than the maximum resilience of the piezoelectric plate, the piezoelectric plate will be permanently bent. Therefore, it is necessary to pay much attention to the water speed during the experiment to avoid the piezoelectric plate damage.

Figure 3. Open circuit output voltages of the harvesters labeled H220, H225 and H230.

Figure 4 shows the open circuit output voltages of the harvesters labeled H320, H325 and H330. Comparing the 2\( D \) distance curves in Figure 3(a) to Figure 4(a), Figure 3(b) to Figure 4(b), it is found
that when the diameter of the bluff cylinder is constant and the width of the fin changes from 20 mm to 30 mm, the harvesting effect does not make much difference. This result shows that the diameter of the bluff cylinder increases, the vortex and the vortex-induced force increases. While the water-facing area of the fin increases, the quality and the inertia of the fin decrease the natural frequency. The vortex cannot vibrate the fin better. Hence, the difference between the two sets of curves is not large.

The 3D spacing distance curve in Figure 4(a) shows a steady growth trend. It indicates that the vortex is roughly at the 3D position behind the center of the bluff cylinder. The 3D spacing distance curve in Figure 4(b) shows an upward trend. It indicates that the vortex is not exactly at the 3D spacing position behind the center of the bluff cylinder, the fins are not only subjected to partial vortex-induced forces, but also the impact of irregular flow, which makes the energy harvest effect fluctuate. The 2D spacing distance curve in Figure 4(c) is better than that of Figure 3(c), because the large diameter of the bluff cylinder generates a large vortex, which is enough to overcome the inertia and resistance caused by the increase area of the fin. Therefore, the harvesting effect is enhanced. After the spacing distance reaching 4D, the vortex-induced effect is weak, and there is no significant difference in the harvesting effect. And it starts to be unstable.

From Figure 4(c), it can be found that the output voltage increases steadily at low flow velocities, and the output voltage is unstable at high flow velocities when the spacing distance is 3D. This is because the water resistance to the fin is proportional to the flow velocity at this water speed period. When the flow velocity increases, although there are much vortexes, the flow resistance is greater than the vortex-induced force. When the velocity of the fin reduced, the vortex-induced force is greater than the resistance. These repeats make vibration of the fin no longer stable, then affect the output voltage.

Figure 4. Open circuit output voltages of the harvesters labeled H320, H325 and H330

Figure 5 shows the variation of open circuit output voltages of the harvesters labeled H420, H425 and H430 with the flow speed and the spacing distance. From Figure 5, it can be found that the large fin area and resistance make the harvesting effect no longer regular when the harvester is in a small spacing distance and a low flow velocity.

Figure 5. Open circuit output voltages of the harvester labeled H420, H425 and H430

The results reveal that vortex-induced vibration is a result of interaction between fluid and solid. Due to the coupling of fluid and solid, when the flow velocity meets certain conditions, the falling frequency of the vortex would be harvested by the natural frequency of the solid, and remains near the natural
frequency, not the frequency of its own. This phenomenon is called frequency-locking phenomenon. When the frequency-locking phenomenon occurs, as the flow velocity increasing, the falling frequency of vortex does not change. Hence the value of open circuit output voltage remains substantially unchanged in this velocity range.

5. Conclusions
In this paper, a novel piezoelectric energy harvester based on wake galloping in water was proposed. Experiments of energy harvesting were carried out. The experimental results show that when the width of the fin is 20 mm, the output voltage changes most smoothly with changing flow velocity. When the bluff cylinder diameter is 25 mm, the fin length is 20 mm, the spacing distance is 4D, and the flow velocity is 0.427 m/s, the harvesting effect has the highest open circuit output voltage of 7.289 V. This result is better than that of the air fin-shaped piezoelectric energy harvester with a bluff cylinder diameter of 25 mm, a fin width of 40 mm, a spacing distance of 110 mm, and the air velocity of 2.5 m/s, in which the highest open circuit output voltage is 6.63 V, as reported by Weinstein et al. [17].

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References
[1] Erturk A, Sodano H A, Renno J M and Inman D J 2008 Modeling of Piezoelectric Energy Harvesting from an L-shaped Beam-mass Structure with an Application to UAVs Journal of Intelligent Material Systems and Structures 20 529-44
[2] Xiang J, Wu Y and Li D 2015 Energy harvesting from the discrete gust response of a piezoaeroelastic wing: Modeling and performance evaluation Journal of Sound and Vibration 343 176-93
[3] Yang Z, Zhou S, Zu J and Inman D 2018 High-Performance Piezoelectric Energy Harvesters and Their Applications Joule 2 642-7
[4] Dunnmon J A, Stanton S C, Mann B P and Dowell E H 2011 Power extraction from aeroelastic limit cycle oscillations Journal of Fluids and Structures 27 1182-98
[5] Liu Y, Chen W, Liu J and Shi S 2013 A rectangle-type linear ultrasonic motor using longitudinal vibration transducers with four driving feet IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 60 777-85
[6] Liu Y, Liu J, Chen W and Shi S 2012 A u-shaped linear ultrasonic motor using longitudinal vibration transducers with double feet IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 59 981-9
[7] Jung H J and Lee S W 2011 The experimental validation of a new energy harvesting system based on the wake galloping phenomenon Smart Materials & Structures 20 55022-31(10)
[8] Xie J, Yang J, Hu H, Hu Y and Chen X 2012 A piezoelectric energy harvester based on flow-induced flexural vibration of a circular cylinder Journal of Intelligent Material Systems and Structures 23 135-9
[9] Akaydin H, Elvin N and Andreopoulos Y 2012 The Performance of a Self-Excited Fluidic Energy Harvester Smart Materials and Structures 21 025007
[10] Gao X, Shih W H and Wan Y S 2013 Flow Energy Harvesting Using Piezoelectric Cantilevers With Cylindrical Extension IEEE Transactions on Industrial Electronics 60 1116-8
[11] Akaydin H D, Elvin N and Andreopoulos Y 2010 Energy Harvesting from Highly Unsteady Fluid Flows using Piezoelectric Materials Journal of Intelligent Material Systems & Structures 21 1263-78
[12] Akaydin H D, Elvin N and Andreopoulos Y 2010 Wake of a cylinder: a paradigm for energy harvesting with piezoelectric materials Experiments in Fluids 49 291-304
[13] Abdelkefi A, Yan Z and Hajj M R 2014 Performance analysis of galloping-based piezoaeroelastic energy harvesters with different cross-section geometries Journal of Intelligent Material Systems & Structures 25 246-56
[14] Zhou S and Zuo L 2018 Nonlinear dynamic analysis of asymmetric tristable energy harvesters for enhanced energy harvesting Communications in Nonlinear Science and Numerical Simulation 61 271-84

[15] Dai H, Abdelkefi A, Ni Q and Wang L 2014 Modeling and Identification of Circular Cylinder-based Piezoelectric Energy Harvesters Energy Procedia 61 2818-21

[16] Song R, Shan X, Lv F, Li J and Xie T 2015 A Novel Piezoelectric Energy Harvester Using the Macro Fiber Composite Cantilever with a Bicylinder in Water Applied Sciences 5 1942-54

[17] Weinstein L A, Cacan M R, So P M and Wright P K 2012 Vortex shedding induced energy harvesting from piezoelectric materials in heating, ventilation and air conditioning flows Smart Materials & Structures 21 45003-12(10)