Research Article

Influence of Shape and Piezoelectric-Patch Length on Energy Conversion of Bluff Body-Based Wind Energy Harvester

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The technology of scavenging ambient energy to realize self-powered of wireless sensor has an important value in practice. In order to investigate the effects of piezoelectric-patch length and the shape of front bluff body on energy conversion of the wind energy harvester by flow-induced vibration, the characteristics of a piezoelectric wind energy harvester based on bluff body are experimentally studied in this work. Four different section shapes of the bluff body, including triangular cylinder, trapezoidal cylinder, reverse trapezoidal cylinder, and square cylinder, are tested. The piezoelectric patch is attached on the leeward side of the bluff body. The lengths of piezoelectric patch are considered as $1.0D$ – $1.4D$ (D is the characteristic length of the bluff body). It is found that the length of the piezoelectric patch and the shape of the front bluff body play a vital role in improving the performance of wind energy harvester. For the reverse trapezoidal cylinder and square cylinder, the back-to-back vortex-induced vibration (VIV) and galloping phenomenon can be observed. In addition, the energy harvesting performance of the reverse trapezoidal cylinder piezoelectric harvester is the best. The maximum average peak voltage of 1.806 V and the output power of $P = 16.3\text{ }\mu\text{W}$ can be obtained when external resistance and the length of piezoelectric patch are $100\text{ K}\Omega$ and $1.1D$, respectively.

1. Introduction

In recent years, microelectromechanical systems (MEMS) have made great progress and sensors are gradually becoming intelligent, miniaturized, and wireless-networked [1–4]. Energy supply is increasingly becoming a bottleneck in its development. Traditional batteries and power wires cannot satisfy the functional requirements because of the short lifespan, complex route, and other shortcomings. Meanwhile, the development of large-scale and low-power integrated circuit technology makes the power consumption of electronic products continue to decrease, which has been dropped to milliwatt or even microwatt level [5]. Therefore, the technology of scavenging ambient energy to realize self-power of electronic equipment has been proposed and widely concerned. Traditional hydroelectric generators and

wind turbines, due to the mechanical losses of bearings, have caused lower efficiency during miniaturization [6]. However, the energy harvester based on flow-induced vibration (FIV) is simple in structure and easy to miniaturize and has no rotating parts, which has attracted a large amount of research [7–12].

FIV is a very complex physical phenomenon. When fluid flows around the structure, vortices are generated, and the structure is subjected to periodic forces caused by the vortices. The elastic structure may vibrate under the action of this force; this fluid-structure interaction is called FIV [13–18]. In particular, when the frequency of the fluid force approaches the natural frequency of the structure, the structure will generate a large vibration. Based on this phenomenon, many flow-induced vibration energy harvesters have been developed. A typical energy harvester is

Vortex-Induced Vibration for Aquatic Clean Energy (VI-VACE) converter, which utilizes FIV to convert mechanical energy into electricity energy through the principle of electromagnetic induction [19–21].

In a subsonic flow, bluff body may induce vortices shedding. Due to the alternating shedding of the vortex, the disturbance of the structure wake is more intense [22]. Thus, part of energy harvester is designed to place flexible piezoelectric materials in the wake of the cylinder. Taylor et al. [23] firstly proposed an energy harvesting device that uses the PVDF (polyvinylidene fluoride) flexible piezoelectric material to harvest energy from ocean and river. It consisted of a piezoelectric membrane or “eel,” which is fixed in the wake of bluff body. In the same year, Allen and Smith [24] found that resonance occurs when the vibration frequency of the “eel” closes to the vortex shedding frequency. Resonance is considered to be the optimal coupling for energy harvesting, and the damping effect of the “eel” on the flow field is negligible. Cellini et al. [25] proposed a water energy harvest device; they selected ion-exchange polymer metal composite on the piezoelectric material. Their experimental results showed that the efficiency of the output power is related to the load of the external circuit and the incoming flow velocity. The power of the device is $0.1 \mu\text{W}$ at a current velocity of 1.1 m/s when the parameters are optimal. PZT (Pb-based lanthanum-doped zirconate titanate) piezoelectric materials are also widely used in energy harvesting. Song et al. [26] presented an upright vortex-induced piezoelectric energy harvester (VIPEH), which is consisted of a piezoelectric (PZT) beam with a circular cylinder. At a resonance speed of 0.35 m/s , the maximum power is $84.49 \mu\text{W}$ and the energy density is 60.35 mW/m^2 . Hu et al. [27] developed a theoretical model to evaluate the optimal location of VIPEH in bluff body wake, which was verified by a series of experiments.

In addition, many wind-induced vibration energy harvesters have been proposed [12]. Lots of studies proved that it is feasible to harvest wind-induced vibration energy through piezoelectric materials [28–34]. However, improving the electromechanical conversion efficiency and power density for wind-induced vibration energy harvesters is an urgent problem to be solved. Hu et al. [35] experimentally evaluated the ability of attachments with different cross-section shapes on the circular cylinder to improve the efficiency of VIPEH. It was found that the installation of the triangular attachment on the cylindrical surface has the highest energy harvesting efficiency. Zhang et al. [36] conducted optimal experiments of VIPEH with different interference cylinder sections shapes. The results showed that, compared with the noninterfering cylinder, the energy harvesting efficiency can be significantly improved when the cross-sectional shape of the interference cylinder is square. When the wind speed is 2.36 and the spacing ratio is 0.9 , the average power can reach 803.4 mW , and the synchronization area is increased by 380% . Dai et al. [37] investigated the influence of the bluff body installation on energy harvesting for designing efficient energy harvesters. Wang et al. [38] proposed a method to improve the efficiency of VIPEH by

using Y-shaped attachment on bluff body. Therefore, improving energy harvester efficiency is of great significance for the application of VIPEH to practical engineering. More information on energy harvesting by flow-induced vibration can be found in the review article by Wang et al. [12].

In this study, the performance of harvester with different lengths of piezoelectric patch attached on the bluff body is experimentally investigated in an open-circuit wind tunnel. The influence of the cross-sectional shape of bluff body on the energy conversion is studied as well. Experimental wind speed ranges from 2 m/s to 13 m/s ($Re = 6800 \sim 44000$). The energy output of the piezoelectric patch in FIV is analyzed. The piezoelectric material of PVDF is applied in the experimental tests. The paper is structured as follows: First, Section 2 introduces the theory and model of piezoelectric energy harvesting. Section 3 describes the experimental equipment and some specific parameters. Then, Section 4 discusses the main experimental results of this study. Finally, Section 5 summarizes the most important results and conclusions.

2. Theory and Model of Piezoelectric Energy Harvesting

In this study, the piezoelectric patch with two ends, one fixed and the other free, is considered. Periodic forces on the piezoelectric patch are caused by vortices shedding, resulting in the deformation of the piezoelectric patch. As shown in Figure 1, l and $W(x)$ are the length and deflection of the piezoelectric patch, respectively. The bluff body is fixed by connecting the center (point O) of the bluff body to the support structure in the wind tunnel. Since the thickness of the piezoelectric patch is negligible compared with the width of the piezoelectric patch, it can be treated as a thin plate. Considering that it vibrates only in the z direction, there is only a displacement in the x direction. Therefore, the strain (ϵ_x) and stress (σ_x) in the x direction can be expressed as

$$\epsilon_x = z \frac{\partial^2 W}{\partial x^2} = zk_x, \quad (1)$$

$$\sigma_x = \frac{-Yz'}{1 - \nu^2} k_x,$$

where z' is the coordinate value of the piezoelectric patch along the thickness direction; W is the deflection in the z direction, the second derivative of which is the curvature k_x of the x direction; Y represents Young's modulus of the piezoelectric patch; and ν is the Poisson ratio. For the thin plate, the strain should be linearly distributed along the normal direction, and the strain on the upper and lower surfaces of the plate is the largest; that is, $z' = h/2$.

The deflection of the piezoelectric patch is

$$W = W(x) \sin(\omega t). \quad (2)$$

The constitutive equation for energy collection of one-dimensional transverse strain (tensile direction of piezoelectric patch) is as follows:

FIGURE 1: Piezoelectric patch vibration model.

$$\varepsilon_x = s_{11}\sigma_x + d_{31}E_z, \quad (3)$$

$$D_z = d_{31}\sigma_x + E_z\varepsilon_{33}, \quad (4)$$

where E_z is the electric field along the thickness direction of the piezoelectric patch; ε_{33} is the dielectric constant under a certain stress; D_z is the charge density per unit area. Equation (3) can be rewritten as

$$\sigma_x = \frac{(\varepsilon_x - d_{31}E_z)}{s_{11}}. \quad (5)$$

Plugging equation (5) into equation (4), the charge density produced by the piezoelectric patch is

$$D_z = \frac{d_{31}}{s_{11}}\varepsilon_x + \left(\varepsilon_{33} - \frac{d_{31}^2}{s_{11}}\right)E_z. \quad (6)$$

By using the surface integral of electric displacement, the expression of the electric charge produced by the piezoelectric patch is obtained as follows:

$$Q = \int_A D_A S dS = b \int_{l_0}^{l_1} (d_{31}\sigma_x + E_z\varepsilon_{33}) dx, \quad (7)$$

where l_0 and l_1 are the positions of the root and the end of the piezoelectric plate and S is the area of the piezoelectric electrode, which can be obtained from equation (3):

$$E_z = \frac{\varepsilon_x - s_{11}\sigma_x}{d_{31}}. \quad (8)$$

Bringing equation (8) into equation (7) gives

$$Q = \left[\frac{bEhd_{31}}{2} \left(s_{11} - \frac{1}{1-\nu^2} \right) + \frac{hb\varepsilon_{33}}{2d_{31}} \right] \times [\varphi(l_1) - \varphi(l_0)], \quad (9)$$

where $\varphi(l, t) = \partial W(x, t)/\partial x$ is the flexibility of the thin plate and $\varphi(l_0)$ and $\varphi(l_1)$ are the corresponding values of the root and the end of the plate at the time t , which can be obtained by experiments.

The equivalent circuit of piezoelectric harvester is shown in Figure 1 as well, where R and U_e represent external load resistance and external voltage, respectively, in which the dotted wire frame is the circuit model of piezoelectric patch.

From Figure 1,

$$i = \frac{C}{R} \frac{dU_e}{dt} + \frac{U_e}{R}. \quad (10)$$

Meanwhile,

$$i = \frac{dQ}{dt} = Q\omega \cos(\omega t). \quad (11)$$

Bringing equation (11) into equation (10), we get

$$C \frac{dU_e}{dt} + \frac{U_e}{R} = Q\omega \cos(\omega t). \quad (12)$$

The solution of the equation is

$$U_e = Ae^{-(t/RC)} + e^{-(t/RC)} \frac{Q\omega}{C} \int e^{t/RC} \cos(\omega t) dt. \quad (13)$$

With the increase of time, the general solution $Ae^{-(t/RC)}$ tends to 0. The voltage U_e , therefore, is mainly determined by the special solution; that is,

$$U_e = \frac{Q}{C} \sqrt{\frac{R^2C^2\omega^2}{1 + R^2C^2\omega^2}} \sin(\omega t + \alpha). \quad (14)$$

Output power is

$$P = \frac{U_e^2}{2R} = \frac{R^2\omega^2}{2R(1 + R^2C^2\omega^2)}. \quad (15)$$

The power in a fluid can be calculated as follows:

$$P_{\text{fluid}} = \frac{1}{2} \rho U^3 DL. \quad (16)$$

The conversion efficiency is defined as

$$\eta = \frac{P}{P_{\text{fluid}} \times \text{Betz_Limit}}, \quad (17)$$

where Betz Limit is 16/27.

3. Experimental Setup

As can be seen from Figure 2, the experiment is carried out in the wind tunnel with a 30 cm × 40 cm test section. The models of the FIV cylinder are presented in Figure 3. There are four different section shapes of the bluff body in our work: triangular cylinder, trapezoidal cylinder, reverse trapezoidal cylinder, and square cylinder. The length of the cylinder is $L = 215$ mm, characteristic length is $D = 50$ mm, and $d = 1/2D$ (short side of the trapezoidal cylinder). The bluff body locates upstream; the piezoelectric patch is mounted on the leeward side of the bluff body, which is fixed with splint and connected with a resistance. It should be noted that the optimal resistance value will change when the lengths of the piezoelectric patch are different. For better output measurement, resistance value of $R = 100$ K Ω is considered. In order to realize the conversion of mechanical energy into electrical energy, a flexible piezoelectric material such as PVDF was selected. PVDF is easily deformed under the action of wind force. The detailed parameters of PVDF are listed in Table 1. The working length of the PVDF piezoelectric patch ranges from $1D$ to $1.4D$, the width is

45 mm, and the thickness is 200 μm . The voltage of the resistance, the vibration of the piezoelectric patch, and wind speed are measured by Agilent U2300A, laser displacement sensor, and hot-wire anemometer, respectively.

4. Results and Discussion

4.1. Influences of Wind Speed on Energy Harvesting. A square cylinder with a PVDF piezoelectric patch of size $l = 1.1D$ is analyzed firstly as a reference case. Figure 4 presents the output voltage of the piezoelectric patch under different wind speeds. The peak value of voltage increases gradually as the wind speed increases from 3 m/s to 12 m/s. At wind speed $U = 6$ m/s, the maximum voltage reaches 1.4 V, which is about one order larger than that of $U = 3$ m/s. The maximum voltage reaches 2.5 V at $U = 12$ m/s, which is twice as much as $U = 6$ m/s. This can be attributable to the enhancement of wake disturbance, and the larger the wind speed is, the stronger the wake disturbance is. The deformation of piezoelectric patch increases with the increase of wake intensity. These results illustrate that wind speed will significantly affect the voltage output of the harvester.

For the purpose of further reflecting the voltage output characteristics of the harvester, the average value of the peak voltage (V_{peak}) is obtained by calculating the mean of the absolute values of all peak voltages in this study. The power is calculated through $P = U^2/2R$. Figure 5 shows the mean peak voltage and power of harvester. The voltage growth process is relatively slow as the wind speed increases from 2 m/s to 3.6 m/s; the output voltage is low in this wind speed range. At $U = 4$ m/s~6.5 m/s, the voltage increases rapidly. This is caused by the lock-on between vortices shedding and the vibration of cylinder. The piezoelectric patch, at the same time, is driven to produce a large deformation. The maximum output voltage and power of the square cylinder-piezoelectric patch system of $l = 1.1D$ at a wind speed of 6.3 m/s are 1.065 V and 0.57 μW , respectively. Then the voltage drops slightly. The square cylinder is in a transition phase. However, the mean peak voltage curve shows a rapid growth process when the wind speed is beyond a critical value of $U_{ci} = 8.53$ m/s. The piezoelectric patch near the fixed end begins to vibrate, so that the vibration amplitude of the piezoelectric patch is greatly increased. This is because the occurrence of vibration causes a large vibration of the piezoelectric patch. A VIV and galloping phenomenon are observed. At $U = 12.90$ m/s, the maximum voltage and output power are 1.595 V and 12.70 μW , respectively.

Figure 6 shows the voltage frequency spectra for the square cylinder-piezoelectric patch system of $l = 1.1D$. It is noted from Figure 6 that the output voltage of the base frequency is 20 Hz at $U = 3$ m/s. There is a small peak at 10 Hz. This is due to the fact that the piezoelectric patch has only the tail flutter at this time, which causes lots of non-linear fast vibrations. At $U = 6$ m/s, the dominant frequency of the output voltage is 18 Hz. The frequency spectrum shows a small peak at 36 Hz, which means that the vibration is unstable. The small second peak is the previous transition phase, which is featured by a high-frequency vibration and small amplitude. At $U = 9$ m/s, the dominant frequency of

the output voltage is maintained at 18 Hz. There are many similar peaks near the base frequency. This is due to the fact that the vibration of the piezoelectric patch is not as regular as the case of $U = 6$ m/s. At $U = 12$ m/s, the base frequency is 15 Hz, and the amplitude of the base frequency is significantly reduced. It represents that the amplitude response of harvester evolved into galloping, featured by a low-frequency vibration and large amplitude.

4.2. Effects of Length of Piezoelectric Patch on Energy Output.

In order to optimize the energy harvesting of the square cylinder-piezoelectric patch system, the performances of piezoelectric patch with different lengths are presented in Figures 7 and 8. For the cases of $l = 1.3D$ and $1.4D$, the voltage increases slowly with the wind speed, and its voltage output is higher than the case with $l = 1.0D$, $1.1D$, and $1.2D$ at low wind speed. At medium and high wind speeds, the output voltages for the cases of $l = 1.3D$ and $1.4D$ are significantly smaller than those of $l = 1.0D$, $1.1D$, and $1.2D$. The VIV and galloping phenomenon are observed at $l = 1.0D$, $1.1D$, and $1.2D$, and the voltage increases monotonically with wind speed when the wind velocity beyonds critical wind speed (U_{ci}). Critical wind speed (U_{ci}) is the minimum velocity required for galloping. For $l = 1.0D$, $1.1D$, and $1.2D$, the resonant wind speed decreases as the length of the piezoelectric patch increases. After the resonance, there will be a relatively stable transition phase of the output voltages and power. When the wind speed continues to increase until beyond critical wind speed (U_{ci}), the whole piezoelectric patch starts vibration, and the output voltages and power become larger. The piezoelectric patch of $l = 1.1D$ produces the best performance for harvesting power when the wind speed exceeds 6.3 m/s. The maximum voltage and power of the square cylinder-piezoelectric patch system can reach 1.596 V and 12.70 μW , respectively. It should be mentioned that the VIV and galloping phenomenon result in an improved efficiency of the harvester and the bandwidth of harvester depending on the length of piezoelectric patch.

4.3. Effects of Bluff Body Cross-Sectional Shape on Voltage Output.

Figures 9 and 10 show the effect of geometry on the energy output of the harvester. The length of piezoelectric patch is $1.1D$, which is the best value from the results of section 4.2. It can be seen from Figures 9 and 10 that the average peak voltage and power trend of triangular cylinder are similar to those of the trapezoidal cylinder, which approaches linear growth.

The length of the leeward edge of triangular and trapezoidal cylinder is longer than the windward side. The flow boundary layers separate at the edge of the leeward side, and the separation point is no longer affected by the bluff body. Therefore, the shedding vortex directly acts on the piezoelectric patch; the voltage and power output of the two cylinders are similar. The difference is that the windward side of the trapezoidal cylinder will stimulate the separation of the boundary layer, and energy output of the trapezoidal cylinder-piezoelectric patch system is higher at low wind speeds.

FIGURE 2: Wind tunnel. 1, wind tunnel test section; 2, fixed device; 3, square cylinder-piezoelectric patch system; 4, laser displacement sensor; 5, data acquisition instrument; 6, computer; 7, entrance of wind tunnel; 8, air-induced section.

FIGURE 3: Physical model of bluff body-piezoelectric patch system: (a) square cylinder; (b) triangular cylinder; (c) trapezoidal cylinder; (d) reverse trapezoidal cylinder.

TABLE 1: Parameters of PVDF piezoelectric patch.

Parameter	Value
Thickness tolerance	$\pm 3\% \sim \pm 5\%$
Piezoelectric strain constant d_{31}	$17 \pm 2.1 \text{ PC/N}$
Piezoelectric strain constant d_{33}	21 PC/N
Relative dielectric constant	9.5 ± 1.0
Young's modulus	2500 MPa
Density ρ	$1.78 \times 10^3 \text{ kg/m}^3$

The flow boundary layers of the reverse trapezoidal cylinder and the square cylinder separate at the windward side. The air is directly acting on the windward side D ($D > d$). For these cases, the disturbance of trapezoidal and

square cylinder to the flow field is obviously larger than that of triangular and trapezoidal cylinder. Especially when the flow speed $U \geq 4 \text{ m/s}$, the output voltage and power are rapidly increasing. When $U = 6.3 \text{ m/s}$, the resonance phenomenon occurs, which leads the amplitude of the piezoelectric patch to increase suddenly. The energy conversion efficiency of reverse trapezoidal cylinder and square cylinder reaches the maximum values. Beyond critical wind speeds, the energy output of the reverse trapezoidal cylinder performed better for harvesting power. The maximum voltage and output power are 1.806 V and $16.30 \mu\text{W}$, respectively. For the reverse trapezoidal cylinder and square cylinder, the separation points are fixed at the windward side and the separated shear layers have great influence on the pressure

FIGURE 4: Voltage output of piezoelectric patch under different wind speed.

FIGURE 5: Mean peak voltage and power curve.

FIGURE 6: Voltage frequency spectra for piezoelectric patch under different wind speeds.

FIGURE 7: V_{peak} of square cylinder with different piezoelectric-patch lengths.

FIGURE 8: Power of square cylinder with different piezoelectric-patch lengths.

FIGURE 9: V_{peak} of the harvester with different cross-sectional geometries.

FIGURE 10: Power and conversion efficiency of the harvester with different cross-sectional geometries.

distribution around the after body, and then a large fluctuation in the lift force and a large vibration amplitude of the cylinder can be observed, so that the output voltage and energy of energy harvesters are higher.

Obviously, Figure 9 shows that the VIV and galloping phenomenon are observed for the reverse trapezoidal cylinder and the square cylinder. Figure 11 is plotted to see more clearly

the working conditions of the VIV and galloping phenomenon. Apparently, this phenomenon is observed in the reverse trapezoidal and square cylinders when $l = 1.0D - 1.2D$. This phenomenon results in an improved efficiency of the harvester. Therefore, it is concluded that the occurrence of galloping is determined by the length of piezoelectric patch and the cross-sectional geometry of bluff body.

FIGURE 11: The phenomenon of VIV and galloping summary chart.

5. Conclusions

A series of experimental tests are performed in the wind tunnel to study the effects of body shape and piezoelectric-patch length on energy conversion by FIV in this work. The major conclusions are summarized as follows:

- (1) Wind speed will significantly affect the voltage output of the harvester. For the reverse trapezoidal cylinder and square cylinder, the FIV can be divided into lock-in region and galloping region in the range of experimental wind speed. However, there is only one region for triangular cylinder and trapezoidal cylinder, where voltage monotonously increases as the wind speed increases. The reverse trapezoidal and square cylinders with $l = 1.0D$ – $1.2D$ can be continuously harvested when exceeding the critical wind speed.
- (2) For the reverse trapezoidal cylinder and square cylinder, the VIV and galloping phenomenon can be observed at $l = 1.0D$, $l = 1.1D$, and $l = 1.2D$. For $l = 1.0D$, $l = 1.1D$, and $l = 1.2D$, the critical wind speed decreases as the length of the piezoelectric patch increases. In the range of experimental wind velocity, effect of the length of piezoelectric patch on the energy harvesting of reverse trapezoidal cylinder and square cylinder is small.
- (3) Transition phase from VIV to galloping is featured by a small amplitude and a high-frequency vibration. Galloping is featured by large amplitude and a low-frequency vibration.
- (4) Both of the length of the piezoelectric patch and the geometry of the bluff body are the key factors that affect the energy output. At $l = 1.1D$, the performance of energy harvester in reverse trapezoidal cylinder and square cylinder is better than that in triangular and trapezoidal cylinders. The maximum voltage and output power are 1.806 V and $16.30\text{ }\mu\text{W}$, respectively.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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