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Experimental investigation on the efficiency of circular cylinder-based wind energy harvester with different rod-shaped attachments

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HIGHLIGHTS

- Aerodynamic modification was used to improve efficiency of wind energy harvester.
- Two small-size rods with three shapes were attached on the main circular cylinder.
- Rods significantly expanded the instability wind-speed range of circular cylinder.
- Triangular rods exhibited better performance than circular and square shapes.

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ABSTRACT

The performance of a circular cylinder-based piezoelectric wind energy harvester with two small-size rod-shaped attachments on the main circular cylinder was experimentally investigated. The rod had three different cross-sectional shapes: circular, triangular, and square. The two rods were attached on two sides of the main circular cylinder at a series of circumferential locations. They were parallel to the cylinder axis and symmetrical to the stagnation line. It was found that attaching these three rod types at the circumferential locations of 45° and 60°, harvested power continuously beyond the critical wind speed. It was, therefore, dramatically superior over both the plain circular cylinder and the cases with other attachment locations. Additionally, the output voltage for a circumferential location of 60° was greater than that 45° one over the whole working wind speed range. Furthermore, attaching the triangular rods on the main circular cylinder showed a better performance than the other two rod types. The force measurement results indicated that the circular cylinder with triangular rods at the circumferential location of 60° had larger transverse force coefficients than the other two rod type cases, verifying the findings in the energy harvesting tests. Therefore, it is recommended to attach two triangular rods at the circumferential location of 60° on the main circular cylinder in order to enhance the performance of a circular cylinder-based wind energy harvester.

1. Introduction

Due to the inherent simplicity and great potential of the wind energy harvesting technique, numerous studies have investigated the development of this technique in the past few years [1–3]. A series of comprehensive reviews have been made recently on the state of the art of wind energy harvesting techniques. Andrew et al. [4] reviewed various designs of piezoelectric wind energy harvesters and the relevant factors, such as the type of wind-induced vibration and shape of bluff body. Abdelkefi [5] made a review on various types of aeroelastic energy harvesting techniques, including vibration mechanisms and representative mathematical models developed during the last few years. Shaikh et al. [6] summarized various energy harvesting sources that can be used by wireless sensor networks, and also identified challenges for developing a cost-effective, efficient, and reliable energy harvesting system. Another comprehensive review on renewable energy harvesting techniques by vortex-induced motions, such as fluttering, transverse and torsional galloping, buffeting, and vortex-induced vibration, was reported by Rostami et al. [7]. McCarthy et al. [8] exclusively discussed wind energy harvesters based on the fluttering phenomenon. For

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applications on aerospace vehicles, Li et al. [9] reviewed the relevant energy harvesting techniques by means of flow-induced vibrations.

Designing an efficient wind energy harvester or improving its efficiency is a big challenge and has been the subject of numerous studies. Wind-induced vibration of the tip bluff body is the sole source of kinetic energy for the wind energy harvester and is very sensitive to the geometric shape of the bluff body. Therefore, geometric shape is a crucial parameter that governs the performance of the harvester. Yang et al. [10] compared various cross-sectional shapes of the tip bluff body of a small scale wind energy harvester. The experimental results indicated that the square-sectioned tip body was superior among the tested shapes including square, rectangle, triangle, and D-shape. Kluger et al. [11] evaluated the effects of geometric shape and size of the tip body of a transversely galloping-based wind energy harvester experimentally and theoretically. Abdelkefi et al. [12] developed a coupled nonlinear model to examine effects of cross-sectional shape on the performance of the harvester and found that the shape significantly affects the galloping onset wind speed. Ding et al. [13] performed 2D unsteady RANS simulations to study the flow-induced motion and energy conversion of a cylinder with various cross-sectional shapes. These included circular sections with passive turbulence control (PTC-cylinder), square sections, Q-trapezoid sections, and triangular sections. It was found that PTC-sections and Q-trapezoid sections exhibited larger flow-induced motion responses than the other sections and hence performed better for energy harvesting. These studies have demonstrated that the geometric shape plays a crucial role in determining the efficiency of wind energy harvester.

Another effective way to enhance the efficiency of an energy harvester is to combine aerodynamic and base excitations. Bibo and Daqaq [14] analytically studied a piezoelectric energy harvester based on a combination of base excitations and wind-induced vibrations. They also investigated concurrent energy harvesting from wind-induced vibrations and ambient vibrations [15]. It was reported that integrating the two types of vibrations significantly improves the power density. Dai et al. [16] theoretically examined the performance of an energy harvester harnessing energy from both base excitations and vortex-induced vibrations concurrently. It was found that the efficiency of this harvester was 1.5 times that of two separated harvesters. Zhao and Yang [17] innovatively utilized a mechanical stopper to develop a broadband energy harvester which can concurrently harvest energy from both base excitation and wind-induced vibration. The mechanical stopper forced the excitation frequencies of the two vibrations to lock into each other.

Apart from the aforementioned two aspects, i.e. optimizing geometric shape of tip bluff bodies and combining multiple kinetic sources, several techniques have also been adopted. These include using nonlinearities to improve the performance by hardening or softening effects [3,18,19], optimizing the harvesters' performance by achieving bi-stable and tri-stable configurations [20,21], adjusting orientation of tip bluff body [22], and optimizing the electric circuit [23,24].

Amongst strategies used to improve the efficiency of wind energy harvesters, aerodynamic modifications on bluff bodies are becoming a popular choice due to high efficiency and simplicity [25–27]. Hu et al. [25] fitted fins to various corners of a square prism to form the kinetic energy source of a galloping-based piezoelectric energy harvester. They found that attaching fins to the leading corners improves the efficiency of the energy harvester by up to 2.5 times. Another recent study by Hu et al. [26] found that attaching two small-scale cylindrical rods on two sides of the circular cylinder parallel to the cylinder axis and symmetrical to the stagnation line at $\theta = 60^{\circ}$ greatly expands the aeroelastic unstable range of the circular cylinder. In that study, the attached cylindrical rods had a circular cross section. Zhu et al. [28] investigated the use of rotational pentagram impeller on a circular cylinder, and compared the performance with a bare cylinder using computational fluid dynamics (CFD) analysis. Laneville and Matsumoto[29] studied aerodynamic behaviors of a circular cylinder, fitted with a rectangular protrusion dramatically changing the aerodynamic properties of the circular cylinder. Zheng et al. [30] studied the use of fairing devices on the circular cylinder as vortex-induced vibration (VIV) suppression mechanism. It was reported that due to the interaction of VIV and galloping forces, onset speed of galloping may fall significantly, which causes start of galloping at much lower speeds even within the synchronization region. Although it may not be good for vibration-suppression devices, it can have significant advantage in energy harvesting systems.

Parkinson et al. [31–34] were among the few earliest researchers who highlighted that the combined effect of VIV and galloping may cause large oscillations at much earlier speeds than predicted by VIV and galloping phenomena separately. Song et al. [27] investigated the performance of a circular cylinder with two plates attached at the trailing end of the cylinder. The study showed that due to the attached plates, the restriction on the amplitude beyond the synchronization region is removed, and hence the system vibrates beyond the synchronization region of the plain cylinder due to galloping. Assi et al. [35] also used a splitter plate with different lengths and porosity at the trailing end of a circular cylinder and reported that the galloping phenomenon starts early in this case due to VIV interaction. The results suggest that attachments can produce beneficial effects, however, this needs to be investigated to determine what actually causes this improvement. Is it a combination of vortex induced vibrations and galloping? If this is the case, then how do these two phenomena interact with each other to effect the overall performance? Mannini et al. [36] carried out wind tunnel experiments to investigate the interaction of galloping and vortex shedding for various Scruton numbers. In another study, Mannini et al. [37] highlighted that quasi-steady approximation in predicting threshold speed of galloping may fail due to the interaction of VIV and galloping forces, especially for lower Scruton numbers. It is pertinent to mention that most of the research to date has analyzed the combined effects of galloping and VIV for prismatic cylinders or splitter plate fitted circular cylinders, whereas, the use of such attachments on circular cylinder for energy harvesting systems has not been explored well. This particular case of unsteady galloping needs to be investigated in detail to take full advantage of the VIV-galloping based energy harvesters.

In the present study, attaching rods with circular, triangular, and square cross-sectional shapes on the main circular cylinder of a wind energy harvester was experimentally tested. The impacts on the efficiency of the circular cylinder-based energy harvester were evaluated. The transverse force coefficients of the circular cylinder with those rods were acquired via force measurement tests in the wind tunnel. Based on the transverse force coefficients and the quasi-steady theory, the observations in the wind energy harvesting tests were interpreted.

2. Experimental setup and measurements of the aerodynamic loads and harvested power

2.1. Piezoelectric wind energy harvesting tests

In this study, the experimental tests were conducted in an open-circuit wind tunnel with a 50 cm × 38 cm test section, as shown in Fig. 1. The flow turbulence intensity was approximately 1.5%. The wind energy harvesting system under investigation was the same used in Hu et al. [26], as shown in Fig. 2(a). The working length, width, and thickness of the steel substrate were 20 cm, 2.6 cm, and 0.95 cm, respectively. The circular cylinder was of length $H = 24$ cm and diameter $D = 4.8$ cm. A piezoelectric layer (MFC-M8514-P2, Smart Material Corp.) was bonded onto the base of the cantilever substrate and was connected to an electrical load resistance R. It should be mentioned that the considered value of the load resistance was $5 \times 10^{6}\,\Omega$ for the rest of this study. This value was selected in the optimal range to produce the highest values of harvested power.

The natural frequency of the energy harvesting system was approximately equal to 6.1 Hz. Two small-sized rods were bonded to two