Energy Conversion and Management 91 (2015) 416–426

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Flow induced motion and energy harvesting of bluff bodies with different cross sections

Lin Ding [a,b], Li Zhang [a,*], Chunmei Wu [a,c], Xinru Mao [a], Deyi Jiang [b]

[a] Key Laboratory of Low-grade Energy Utilization Technologies and Systems of Ministry of Education of China, College of Power Engineering, Chongqing University, Chongqing 400044, China
[b] College of Resources and Environmental Science, Chongqing University, Chongqing 400044, China
[c] Mechanical & Industrial Engineering, University of Toronto, Toronto, ON M5S 3G8, Canada

ARTICLE INFO

Article history:
Received 30 April 2014
Accepted 14 December 2014
Available online 31 December 2014

Keywords:
Flow induced motion
Cross section
Hydrokinetic energy
Vortex induced vibrations
Galloping
Bluff body

ABSTRACT

The flow induced motion (FIM) and energy conversion of cylinders with different cross sections are investigated using two-dimensional unsteady Reynolds-Averaged Navier–Stokes simulations in the Reynolds number range of $10{,}000 < Re < 130{,}000$. The model for energy harvesting in FIM is established and verified by experimental measurements. For the PTC-cylinder (circular cylinder with passive turbulence control), square cylinder, Q-trapezoid I (quasi-trapezoid cylinder with the long edge as the windward side), and triangular prism, energy can be obviously harvested when $Re > 30{,}000$. The initial and upper branches of vortex induced vibration (VIV), transition from VIV to galloping, and galloping branch are clearly observed in the amplitude and frequency responses. The FIM responses of PTC-cylinder and Q-trapezoid I are stronger than the other cylinders. The maximum amplitude of $3.5D$ is achieved and 16 vortices are captured in one cycle in the fully-developed galloping branch. The optimum regime for energy harvesting is the VIV upper branch. And the PTC-cylinder and Q-trapezoid I have better performance on energy harvesting in FIM than other cylinders. The maximum energy efficiencies of 45.7% and 37.9% are achieved for Q-trapezoid I and PTC-cylinder respectively. Contrarily, the vibration of Q-trapezoid II (quasi-trapezoid cylinder with the short edge as the windward side) displays a quite different character with low amplitude and high frequency, and the vortex pattern is a constant 2S in the test *Re* range.

1. Introduction

Flow induced motion (FIM) of a rigid cylinder on end-springs in a steady transverse flow is a kind of widespread physical phenomenon caused by the excitations of the vortices shed. The vortex shedding alters the pressure distribution causing periodic lift forces to act on the cylinder that can eventually cause FIM [1]. FIM occurs frequently in many areas of engineering, such as bridges, chimneys, cables, offshore structures, and heat exchangers [2,3]. It is always treated as a destructive phenomenon due to the fatigue damage that may be potentially introduced. Many efforts have been made to suppress FIM in the previous researches. With entirely opposite objective of early researches, power of FIM has drawn attention as a means to harvest renewable clean energy [4,5]. The mechanical energy of a cylinder in FIM can be converted into usable electrical energy [5]. Until today, numerous devices have been designed to harvest energy in the ocean or river flow, such as the utilization of wave [6,7] and tidal current [8,9]. Specifically, VIVACE (Vortex Induced Vibration for Aquatic Clean Energy) converter was designed to extract clean and renewable hydrokinetic energy by utilizing FIM [5] and further developed in the Marine Renewable Energy Laboratory (MRELab) at the University of Michigan [10–15]. The simplest form of the VIVACE module is a single smooth circular cylinder mounted on springs with a power take-off system. In VIVACE converter, the mechanical energy of the cylinder in FIM is transmitted to drive a generator by a belt-gear system [5].

The experimental measurements on the laboratory prototype of VIVACE converter with circular cylinder were conducted by Bernitsas et al. [5,16]. Compared with other similar energy converters, such as Pelamis, Power Buoy, and Oscillating Water Column, the VIVACE converter generates much higher energy density [5]. In addition to the high energy density, the VIVACE converter satisfies all other requirements set by the California Energy Commission (CEC) and the Department of Energy (DOE) of the United States [8,9,17]. It is unobtrusive to the environment and compatible with marine life. VIVACE is based on readily available offshore

---

* Corresponding author. Tel.: +86 23 65103114.
E-mail address: lizhang@cqu.edu.cn (L. Zhang).

http://dx.doi.org/10.1016/j.enconman.2014.12.039
0196-8904/

technology implying robustness. Its design life can easily be 20 years. For the life cycle cost, Raghavan [17] concluded that the installation cost of a 100 MW VIVACE power plant is relatively high. However, due to consistency of availability of the energy source and low maintenance of VIVACE converter, the estimated electricity cost is competitive. Besides the advantage described above, the VIVACE converter can extract energy from low speed ocean or river currents and tides. It should be noted that the traditional ocean energy conversion devices (e.g. turbine and water-mill) are efficient only for flow speeds greater than 2 m/s [14]. However, the VIVACE converter can convert marine hydrokinetic energy to mechanical and subsequently renewable electrical energy in the ocean/tidal/river currents as slow as 0.4 m/s. The VIVACE converter is an innovative energy converter, which is modular, highly scalable, and flexible in the sense of geometry and configuration [5,16]. It can be designed, manufactured, and installed to generate electricity. Thus, the VIVACE converter can be applied in numerous areas, such as military, agricultural, desalination and hydrogen generation. It can power light houses, instrumentation stations, offshore platforms, idle ships etc.

For the VIVACE converter, the enhancement of FIM becomes important for extracting more hydrokinetic energy from fluid flows. Vortex induced vibration (VIV) and galloping are the most commonly encountered FIM phenomena. There are several comprehensive reviews of VIV for a single circular cylinder, including articles by Blackburn et al. [18], Sarpkaya [19], Williamson and Govardhan [20], Bearman [21], and Wu et al. [22]. The amplitude, frequency, and vorticity distributions are the most important characteristics that can effectively describe and quantify FIM. Khalak and Williamson [23–25] classified the VIV regimes into three branches based on the amplitude response of a circular cylinder, which are the initial branch, upper branch, and lower branch. But the amplitude response in Feng's experiment [26] only shows the initial and lower branches. This is because the experiments performed by Feng [26] were tested in air environment and the oscillatory system had a much higher mass ratio. On the other hand, passive turbulence control (PTC) in the form of selectively distributed surface roughness for circular cylinder was introduced in MRELab [10,14]. Chang et al. [10] investigated the circular cylinder with PTC by experiment and found that the flow over the cylinder surface altering in a way that generates higher lift, which is shown a better synchronization with the motion of cylinder. They demonstrated that the circular-section cylinder with attachment could experience large amplitude galloping oscillations. Furthermore, Williamson and Roshoko [27] summarized experimental results and classified the vortex pattern by the number of vortices shed per vibration cycle of cylinder. The different vortex patterns associated with specific FIM regimes have been designated as 2S, 2P, and P + S [27], where 2S and 2P stand for two single and two pairs of vortices shed per cycle, respectively.

Compared with the investigations on FIM of circular cylinder, the studies on the non-circular section cylinders are relatively less. The square cylinder and triangular prism are the familiar non-circular bluff bodies. Zhao et al. [28] investigated the effect of orientation on FIM of the square cylinder by finite element method and found that both the vibration amplitude and the lock-in regime are affected by the angle of attack. Nemes et al. [29] examined the influence of the orientation of the square cylinder on FIM as well. They reported that a low-mass ratio cylinder can undergo combination of both VIV and galloping in a narrow range of flow approaching angle. Barrero–Gil and Fernandez–Arroyo [30] also observed the phenomenon that VIV appears combined with galloping when the value of $m^*\zeta$ bellows a critical value, where m^* is the non-dimensional mass and ζ is the structural damping ratio. For the square cylinder with high mass ratio, Manzoor et al. [31] found that the transition between VIV and galloping is different from that of low mass ratio cases. Amandolese and Hemon [32] observed a transient regime followed by a limit cycle oscillation regime when the square cylinder is in the lock-in region. On the other hand, the flow around a triangular prism is more complex. Iungo and Buresti [33] carried out the experiments of low aspect-ratio triangular prisms in a wind tunnel by varying the wind direction. They concluded that the fluctuating cross-flow forces and vortex shedding vary significantly with flow orientation and aspect ratio. The decrease in aspect ratio is generally accompanied with increasing vortex shedding frequency. Alonso et al. [34–36] systematically analyzed the transverse galloping stability of triangular cross-section bodies and confirmed that the stability to transverse translation galloping of triangular prisms are both cross-sectional geometry and angle of attack dependent. Moreover, most of the efforts in FIM research have been concentrated on body dynamics and flow status, the energy utilization of FIM for the cylinders with different cross sections warrants further investigation. Therefore, the aim of present study is to systematically investigate the flow induced motion and energy harvesting of bluff bodies with different cross sections.

Based on the model of VIVACE converter, two-dimensional unsteady Reynolds-Averaged Navier–Stokes simulations are conducted to investigate the energy conversion and the behavior of the flow around the cylinders with different cross sections at $10{,}000 < Re < 130{,}000$. In this paper, the physical and mathematical models are established in Sections 2 and 3. In Section 4, the numerical approach is described and the mathematical model for energy harvesting in FIM is verified by experimental measurements. The results of amplitude, frequency, and vortex patterns of different cross-section cylinders are presented in Section 5. The effects of cross section shape on FIM response and energy harvesting of bluff body are discussed as well. Conclusions from the study are presented in Section 6.

2. Physical model

Since the transverse amplitude of a bluff body in FIM is much higher than the streamwise amplitude, the influence of streamwise vibration is not considered in the present study. The motion of the bluff body is modeled by the classical mass-spring-damper system with one degree of freedom. The physical models of cylinders with different cross sections are depicted in Fig. 1, including the circular cylinder with passive turbulence control (PTC-cylinder), square cylinder, quasi-trapezoid cylinder, and the triangular prism. The elements of each oscillatory system are a rigid cylinder of streamwise projection diameter D, supporting linear springs of stiffness K, and the system damping C_{system} of the transmission mechanism and power take-off. Each cylinder oscillates in y-direction which is perpendicular to its axis and the flow velocity. Detailed descriptions of each cylinder are as follows:

(a) *Circular cylinder with PTC:* Passive turbulence control is introduced to enhance FIM of a circular cylinder and to extract more hydrokinetic energy from fluid flow. The type and the positions of PTC are determined based on the studies of MRELab [10,13], which show that PTC can expand the VIV upper branch and initiate fully developed galloping at lower reduced velocity for some selected circumferential locations of the roughness strips. PTC consists of selectively located surface roughness with thickness 0.847 mm, which is on the order of the boundary layer thickness and affects FIM profoundly [13]. As shown in Fig. 1a, two straight roughness strips are attached to the surface of the circular cylinder symmetrically. The angle $\alpha_{PTC} = 20°$, which is measured in degrees from the front stagnation point of the corresponding