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Numerical investigation on the effect of the cross-sectional aspect ratio of a rectangular cylinder in FIM on hydrokinetic energy conversion

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ABSTRACT

FIM (Flow Induced Motion) is a kind of widespread and high-energy phenomenon. In application, FIM could be used to harvest hydrokinetic energy from ocean/river currents. In this study, a spring-mounted rectangular cylinder were numerically investigated in a flow domain for the ranges of 7500 < Reynolds number <187500 (0.1 m/s < flow speed <2.5 m/s) to examine the effect of its cross-sectional aspect ratio on the FIM responses and hydrokinetic energy conversion. Results indicate that in general, high aspect ratio has a negative effect on FIM. When the aspect ratio increases from 1/6 to 1.5, the FIM amplitude is gradually suppressed. When the aspect ratio reaches up to 2.0, both VIV (Vortex Induced Vibration) and galloping won't occur at any flow speed. For energy harvesting, when the aspect ratio decreases from 2 to 1/4, the converted power shows the increasing trend. The maximum FIM energy conversion efficiency also accordingly increases to 15.5%. It should be noted that when the aspect ratio reduces to 1/6, the maximum power keeps the increasing trend; however, the total energy conversion efficiency is not further enhanced, which implies the optimal aspect ratio for energy harvesting is around 1/4.

1. Introduction

In recent years, the increased concerns on energy, resources, and environment promote the development of renewable energy technology [1,2]. Ocean hydrokinetic energy is one of the potential energy sources mostly considered. Only ocean tidal and current energy is about 22 000 TWh [3]. The annual world electricity consumption is about 19 000 TWh. Obviously, the available tidal and current energy has exceeded the annual world electricity consumption. Therefore, in recent years, different converters have been developed to harvest energy from ocean/river [4–6]. Now the FIM (Flow Induced Motion) phenomenon has been utilized to harvest hydrokinetic energy from slow-speed ocean/river currents. FIM/VIV (Vortex Induced Vibration) energy conversion has become an available and potential technology and can bring great economic benefits. According to the cost comparisons between conventional and alternative sources of energy and the FIM/VIV energy converter (FIM/VIV energy converter: 0.055$/kWh; Wind energy converter: 0.069$/kWh; Solar: 0.489$/kWh [7]). In addition, compared with other energy converters, the FIM energy converter is robust and could extract energy in a very broad range of flow speed.

FIM of a spring-mounted slender cylinder is referred as an induced oscillatory motion of a cylinder by a passing flow that generates alternating lift around the body [8–11]. VIV (Vortex Induced Vibration) and galloping are the most common FIM phenomena. As the flow velocity increases, VIV appears first. VIV is a kind of nonlinear oscillation, synchronization to FIM phenomenon [12–14]. For an extensive literature review about VIV and galloping, one can refer to Bernitsas et al. [6,7] and Williamson et al. [13–16], where many records of researches with clear evidence of the phenomenon can be found. In particular, VIVACE (Vortex Induced Vibration Aquatic Clean Energy) converter was invented by Bernitsas et al. [17,18] at the University of Michigan. The converter used VIV to harness energy from ocean/river currents at low flow velocities, starting at flow velocity = 0.2–0.4 m/s [3,19,20]. The research about the converter at the University of Michigan was done experimentally by Lee et al. [21] and Sun et al. [6,22,23]; and numerically by Ding et al. [11,20]. Compared with VIV, galloping occurs at higher flow speed. VIV is a nonlinear oscillation, broad-

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Nomenclature

U	Flow speed
L	Length of rectangular cylinder
W	Width of cross-section
H	Height of cross-section
f_{osc}	Oscillating cylinder frequency
A	Amplitude of oscillation
M	Total mass of FIM system
m_{add}	Added mass
m_{disp}	Displaced fluid mass
v	Kinematic viscosity
K	Spring stiffness
T_{OSC}	Period of oscillation
C_{total}	System damping coefficient
$\xi_{total} = C_{total}/(2\sqrt{M \cdot K})$	Damping ratio
$Re = UH/v$	Reynolds number
$A^* = A/H$	Amplitude ratio
$m^* = M/m_{disp}$	Mass-ratio
$\alpha = W/H$	Cross-sectional aspect ratio
$f_{n,water} = (1/2\pi)\sqrt{K/(M + m_{add})}$	Cylinder's natural frequency
$U^* = U/(f_{n,water} \cdot H)$	Reduced velocity

range, synchronization phenomenon between the oscillatory lift created by the alternating von Kármán vortex street in the wake of a bluff body and the body's elastic. VIV is a phenomenon self-limiting in amplitude. However, galloping is a high-amplitude and low-frequency FIM phenomenon and is more vigorous than VIV. Galloping is an instability phenomenon caused by geometric asymmetry due to the body cross-sectional geometry or the flow due to upstream turbulence. It results in unlimited amplitude response until the elastic structure is damaged as the flow velocity increases [3]. Then, galloping has been gradually introduced into the energy converter [24]. As a result, the FIM hydrokinetic energy converter has a high amplitude response starting at low flow speed using VIV and without upper limit in flow speed using galloping [3,6].

Experimental investigations on FIM have been extensively performed in the early studies, but mainly focused on circular cylinders. Williamson et al. [13–15] investigated the VIV responses of circular cylinders. Therein, various branches of VIV amplitude curves were identified. Similar results were also obtained by Bernitsas et al. and Kim et al. [3,7,22–27]. Lee et al. [28] reported that a single-cylinder (D = 8.9 cm, H = 91.4 cm) converter generated power as slow as 0.4 m/s, and the power reached up to 15.85 W at flow speed of 1.11 m/s. Besides, a series of numerical investigations using different CFD (Computational Fluid Dynamics) method have also been conducted to simulate the FIM response. Govardhan and Williamson et al. [15,16] investigated VIV and the shedding mode of vortices using 2- and 3-dimensional numerical simulations. Wu et al. [29] have studied VIV for a circular cylinder at low Reynolds number using CFD simulation. Ding et al. [11,20] have analyzed the FIM of different bluff bodies via CFD method based on OpenFOAM codes. Later, Tang et al. [30] and Joly et al. [31] investigated the galloping of a square cylinder using CFD software, Fluent. These investigations all indicated that numerical methods could reasonably predict integrated properties of FIM, such as vortex patterns, forces, and motions.

According to the existing studies, for a smooth circular cylinder, galloping will not appear at any speeds. Consequently, most researches were conducted on PTC (Passive turbulence control) circular cylinders [20,22–27,32,33]. Ding et al. [11] reported the changes in responses of the FIM with different cross-sections. Joly et al. [31] found that galloping of a square cylinder could be observed when Reynolds number is larger than 140. Compared with circular cylinders, there is an important advantage that galloping of a rectangular cylinder could normally and steadily appear as expected. A motivation for the present study stems from the works carried out by some previous research groups [3,15,34], which inspire us the need to investigate the FIM energy conversion of a rectangular cylinder when its cross-sectional aspect ratio is varied. Until now few studies were focused on FIM energy harnessing of rectangular cylinders. Mannini et al. [34] studied the interference of VIV and galloping on a rectangular cylinder. Nemes et al. [35], Cui et al. [36] and Zhao et al. [37] investigated the effect of flow incidence angle on the FIM response of square/rectangular cylinders. Nevertheless, the effect of aspect ratio of a rectangular cylinder on the FIM energy conversion has not been known clearly yet. Consequently, it is worthy of studying the FIM response of a rectangular cylinder with different aspect ratios.

The objective of this study is to investigate the effectiveness of the cross-sectional aspect ratio of a rectangular cylinder in FIM on hydrokinetic energy conversion and to obtain the optimal aspect ratio for yielding the highest energy conversion efficiency. Numerical simulations of various FIM energy converters were carried out to accomplish this task in a wide range of flow speed, i.e. 0.1 m/s $< U <$ 2.5 m/s (or $7500 < Re < 187500$, where Re is a Reynolds number). Slender rectangular cylinders characterized by different cross-sectional aspect ratios were studied in detail. The cross-sectional aspect ratios change from 1/6 to 2.0. The numerical results were verified by the experimental data. To the authors' knowledge, this is the first attempt to systematically investigate the role played by the cross-sectional aspect ratio of an oscillating rectangular cylinder on energy conversion. The results suggest that decreasing the aspect ratio tends to enhance the power extraction and the total energy conversion efficiency. The optimal aspect ratio was identified to be roughly 1/4.

2. Geometry configuration

2.1. Physical model

The FIM hydrokinetic energy converter consists of a rectangular cylinder, springs, transmission mechanisms and a generator [7,38]. Fig. 1(a) shows a schematic of a converter. The rectangular cylinder drives the generator through the transmission mechanisms. The FIM hydrokinetic energy converter is placed horizontally on the seabed with one side perpendicular to the flow. It has been verified that the transverse (vertical) FIM amplitude of a cylinder is much larger than that from the streamwise induced motion [3,11]. Therefore, only the transverse (vertical) response is allowed by the transmission mechanisms. The minimum submergence depth for the FIM energy converter should exceed 0.5m. In this case, the effects of free surface could be ignored. A simplified physical including a combined spring and damping systems is depicted in Fig. 1(b), where K represents the spring stiffness constant and C_{total} denotes the total system damping coefficient from the transmission mechanisms and the generator.

Rectangular cylinders with different aspect ratios are shown in Fig. 2, where W and H represent the cylinder dimensions respectively in streamwise and vertical directions. $\alpha = W/H$ denotes the cross-sectional aspect ratio (also known as *Width to Height Ratio*) of the rectangular cylinder. A series of FIM system were built based on the selected 7 different aspect ratios, i.e. 1/6, 1/4, 1/2, 1.0, 1.2, 1.5 and 2.0. A smaller value of aspect ratio α means that the rectangular cylinder is very thin and the height of the rectangular cylinder is