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Influence of the Centre Distance between Counter-Rotating Control Rods and the Circular Cylinder on FIV Suppression

Tianqi Zhang[1]*, Zhaoyong Mao[1,2,3], Wenlong Tian[1,3], WenJun Ding[2,4,5] and Guanyong Yang[2]

[1]School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an 710072, China;
[2]Unmanned System Research Institute, Northwestern Polytechnical University, Xi'an 710072, China;
[3]Key Laboratory of Unmanned Underwater Vehicle, Northwestern Polytechnical University, Xi'an,710072, China;
[4]National Key Laboratory of Unmanned Aerial Vehicle Technology, Northwestern Polytechnical University, Xi'an,710072, China;
[5]Integrated Research and Development Platform of Unmanned Aerial Vehicle Technology, Northwestern Polytechnical University, Xi'an,710072, China.
Email: 2012zhangtianqi@mail.nwpu.edu.cn

Abstract. Flow-induced vibration (FIV) poses significant challenges in ocean engineering, necessitating effective suppression strategies. This study presents a numerical analysis of FIV suppression using computational fluid dynamics (CFD). This article mainly studied the influence of different centre distances between control rods and main cylinder on vibration suppression within reduced velocity range of 2-14. The focus was the relationship between the transverse flow amplitude and lift coefficient of the system at reduced velocity of 10. We analysed the near-wall vorticity and pressure fields to uncover the flow-regulation mechanisms. The results reveal that control rods disrupt wake vortices and reduce negative pressure in the wake region, thereby suppressing vibrations. Compared with the bare cylinder, the vibration peak in P1 mode decreased by 35.14%. Based on the results, increasing the rod-cylinder centre distance represents a viable strategy to enhance vibration suppression performance at high reduced velocities.
Keywords. Flow-induced vibration, Suppression, Computational fluid dynamics.

1. Introduction

Flow induced vibration (FIV) is a typical fluid structure coupling phenomenon. FIV is widely used in fields such as ocean engineering [1] and bridge engineering [2]. When the natural frequency approaches the vortex shedding frequency, the system enters lock-in state. This synchronization leads to amplitude amplification, and the resulting structural fatigue poses a critical requirement for vibration suppression [3].

Vibration suppression strategies are usually divided into passive and active control strategies. The main difference between these two methods lies in the requirements for external energy supply. Wang et al. [4] studied the vibration response of a cylindrical structure on a cactus like surface through numerical simulations. The peak value of the transverse amplitude ratio decreases by 57% in the range of Reynolds numbers (Re) from 8000 to 56000. Zhu et al. [5] found that adding baffles on the cylinder

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is an effective method to suppress vortex induced vibration (VIV). These studies represent passive vibration suppression that affects the amplitude of vibration by influencing the surface or wake of a cylinder. Ren et al. [6] reduced vibration amplitude by over 97% through active flow control guided by deep reinforcement learning. Li et al. [7] used the rotation of the main cylinder to improve the wake characteristics and completely suppress unsteady vortex shedding. Overall, the advantages of passive control are not only that it does not require external energy input, but also that its simple structure reduces the difficulty and cost of maintenance. The advantage of active control is excellent vibration suppression effect.

Based on the research of the aforementioned scholars, this article discusses a structure with high vibration suppression and low complexity. Suppress vibration through symmetrical reverse rotation of two smooth control rods. This article analysed the vibration suppression performance of control rods at different centre distances.

2. Problem Description

2.1. Physical Model

The two control rods rotate in opposite directions and they were symmetrically arranged in the downstream area of the main cylinder. These three cylinders together form a two degree of freedom (2-DOF) system, as show in figure 1. The diameter of the main cylinder in this article was 100mm and the diameter of control rod was 12mm. The angle between the line connecting the control rod and the cylinder and the horizontal was 30 degrees. The mass ratio of the system was 2.6, and the damping ratio was 0. The natural frequency of this system is 0.4 Hz. This article studies the difference between centre distances were 70mm and 80mm.

The transverse flow direction of the computational domain was set to 20D, where D was the diameter of the main cylinder. When the blockage rate in the cross flow direction was not greater than 0.05, the influence of the sidewall can be ignored [8]. The upstream length of the control rod was 10D, and the downstream length was 32D, as show in figure 2. The sidewall were symmetrical boundaries. The walls of the main cylinder and both control rods were no-slip wall surfaces. The velocity in the X direction in this article was the inflow velocity and which was constant and uniform at the inlet.

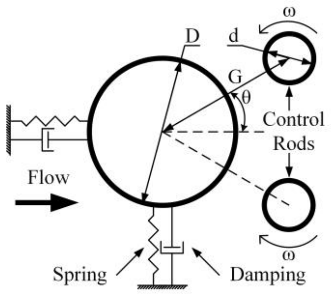

Figure 1. The 2-DOF System.

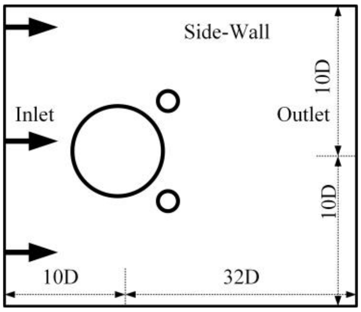

Figure 2. Computational domain.

2.2. Mathematical Description

This article adopted the two-dimensional numerical simulation method of transient calculation. The computational model was calculated using the Reynolds-averaged Navier-Stokes (RANS) equation in Fluent. The fluid around the system was incompressible and constant density [9]. So the simplified RANS expressed as

$$\partial \overline{u}_i / \partial x_i = 0 \tag{1}$$

$$\partial \overline{u_i} / \partial t + \partial \overline{u_i u_j} / \partial x_j = -\partial \overline{p} / \rho \partial x_i + \nu \nabla^2 \overline{u_i} - \partial \overline{u_i' u_j'} / \partial x_i \tag{2}$$

The motion equation of 2-DOF system [10] expressed as

$$F_x(t) = m\ddot{x} + C\dot{x} + kx \tag{3}$$

$$F_y(t) = m\ddot{y} + C\dot{y} + ky \tag{4}$$

where m is the mass of 2-DOF system, C is damping of the system which value is 0 in this paper. k is stiffness of the system which expressed as

$$k = 4\pi^2 f_n^2 (m + m_{add}) \tag{5}$$

where m_{add} is the added mass of the system [11]. The reduced rotational speed of control rods is 0.8 in this article. And angular velocity of control rod is ω . λ is reduced rotational speed, expressed as

$$\lambda = \omega d / 2U \tag{6}$$

where U is incoming flow velocity. f_n is natural frequency. U_r is reduced velocity, expressed as

$$U_r = U / f_n D \tag{7}$$

2.3. Mesh Independence Validation
The calculation model used in this article was Shear Stress Transport (SST) k-ω turbulence. So the mesh y+ value of this model was less than 1 [12]. The height of the first layer of mesh near the wall can be determined by this y+ value as show in figure 3.

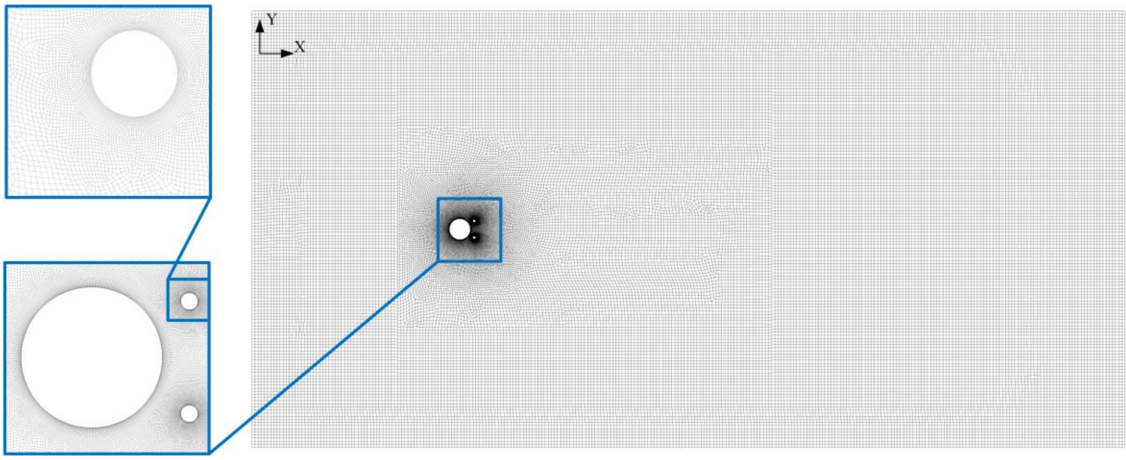

Figure 3. Mesh of near the wall of cylinder.

This article compares three different meshes and computational results. The reduced velocity was Ur=4 and the control rod speed was 0 in calculation conditions. The percentage values in the table 1 were the difference between the previous calculation results. This article used G3 mesh for calculation.

Table 1. Mesh independence validation.

Mesh	Elements	Ay/D
G1	33,000	0.1822
G2	51,000	0.1867 (2.47%)
G3	72,000	0.1884 (0.91%)

3. Results and Analysis

3.1. Flow Induced Vibration Response

This article studies three modes separately. In P0 mode, there was only a bare cylinder without control rods. The centre distance between the control rod and the main cylinder is 70mm in P1 mode. And value of P2 was greater than that of P1 mode, as shown in table 2.

Table 2. Mode and centre distance.

Mode	P0	P1	P2
Centre distance/mm	Bare	70	80

This article calculated the reduced velocity of 2-14, corresponding to the Re range of 8000-56000. The 2-DOF system with control rods had good vibration suppression effect in both P1 and P2, as show in figure 4. The peak value in P1 mode has decreased by 35.14% compared to the peak value in P0 mode. The advantage of P1 mode is that it has a stronger vibration suppression effect within the range of reduced speed of 5-7. The peak value in P2 mode has decreased by 23.92% compared to the peak value in P0 mode. The advantage of P2 mode is that it has a stronger vibration suppression effect than P1 in the range of reduced speed greater than 11. The vortex shedding frequency ratio of P0-P2 modes is shown in figure 5. This article focuses on the vibration response of three modes under the condition of Ur=10.

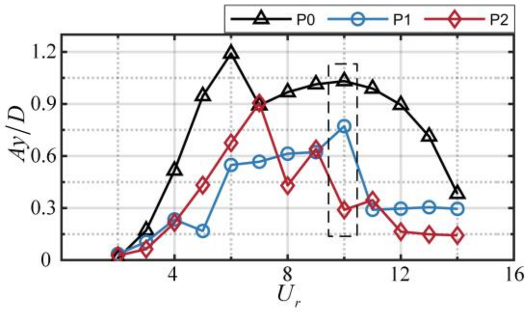

Figure 4. Transverse flow amplitude ratio.

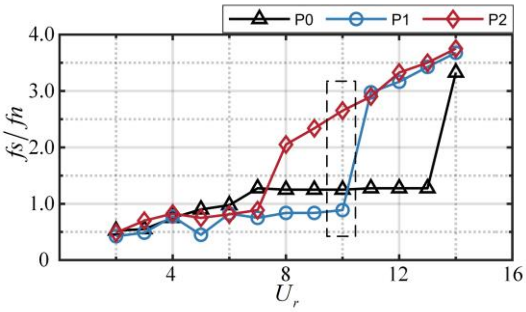

Figure 5. Frequency ratio.

3.2. Transverse Flow Amplitude and Frequency Ratio

Figure 6 shows the variation of transverse flow amplitude and lift coefficient in P0 modes. The vibration exhibits regular changes in P0 mode. The main frequency of lift coefficient and amplitude have same frequency ratio of 1.25.

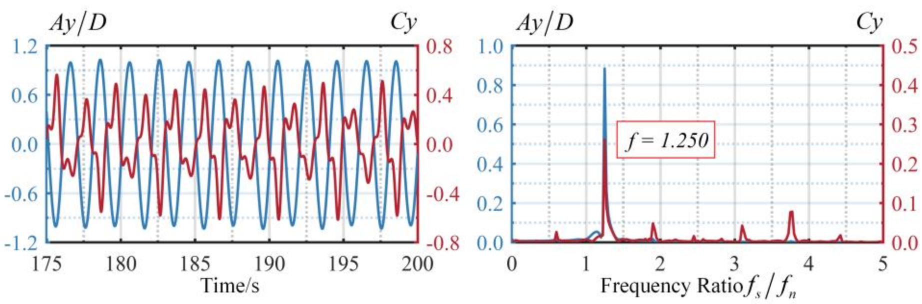

Figure 6. Transverse flow amplitude and frequency ratio at Ur = 10 in P0 mode.

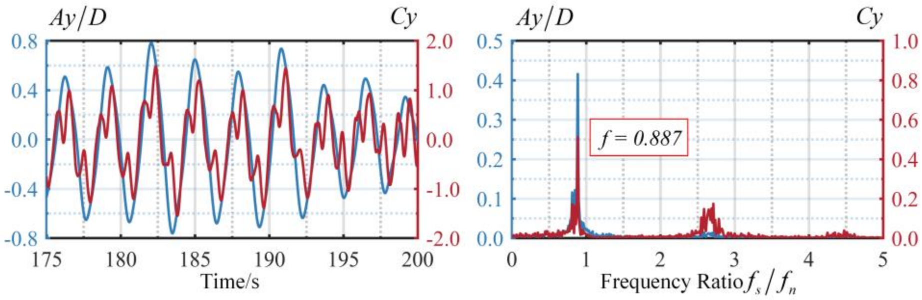

Figure 7. Transverse flow amplitude and frequency ratio at Ur = 10 in P1 mode.

Figure 7 shows the amplitude of vibration in P1 mode and main frequency of vibration decreased compared to P0. The vibration amplitude was the smallest in P2 mode as show in figure 8. But the frequency of lift coefficient is much higher than the frequency of vibration amplitude. The frequency ratio in all modes were far from the lock-in frequency ratio.

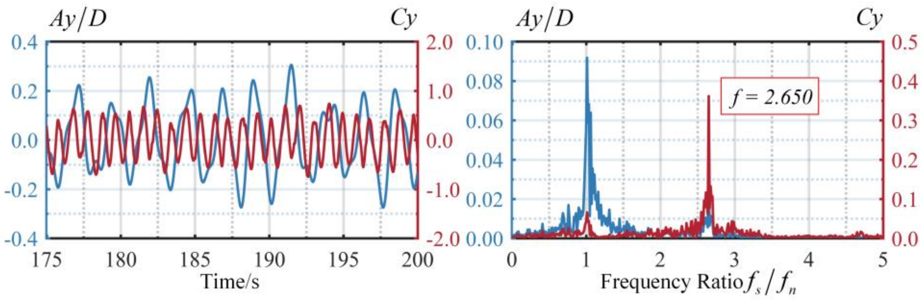

Figure 8. Transverse flow amplitude and frequency ratio at Ur = 10 in P2 mode.

3.3. Control Rods Flow Control Mechanism

Figure 9 shows the vorticity and pressure contours of P0-P2 at Ur=10 near the wall of the 2-DOF system which located peak points of upward motion. Compared with P0, the control rods of P1 and P2 can both break the wake vortex. A larger centre distance of P2 can ensure the separation of wake vortices within a smaller amplitude. Compared with P0, the lower the negative pressure intensity in the wake vortex region broken in the pressure field, the more positive it is for the reduction of amplitude. Compared with P1, the negative pressure area of P2 is more concentrated on the rear side of the main cylinder.

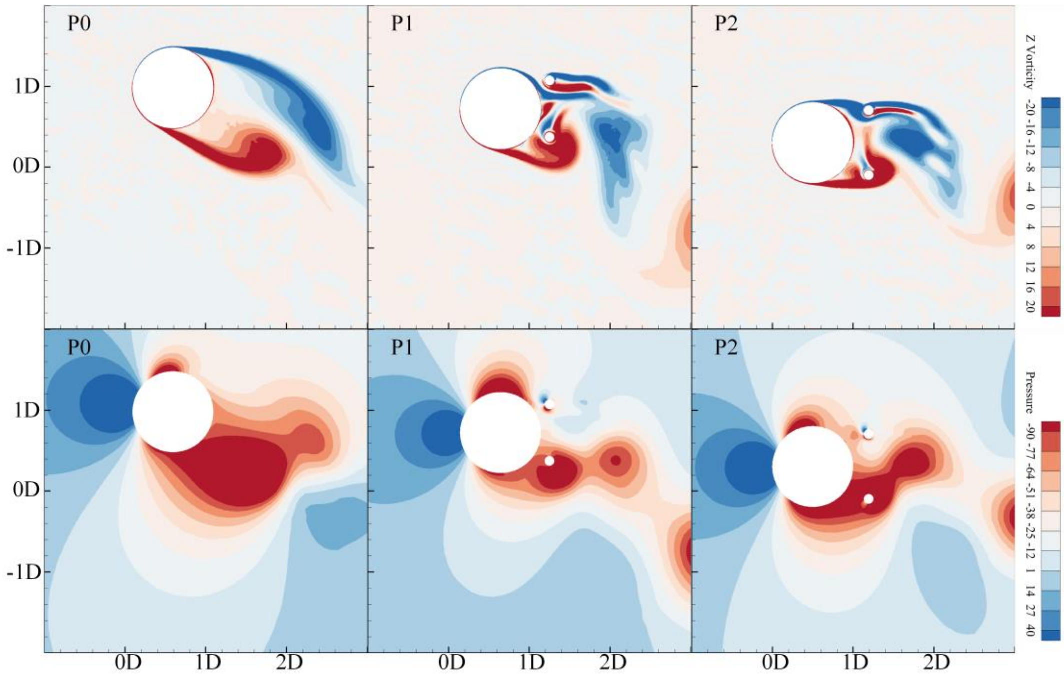

Figure 9. Vorticity and pressure contours of P0-P2 at Ur=10.

4. Conclusions

This article studies the hydrodynamic characteristics of control rods with different centre distances, leading to the following conclusions:

1) The rotating control rods were beneficial for the suppression the vibration of the main cylinder.

2) The control rods can affect the main frequency change of lift by breaking the wake vortex, thereby affecting the peak lift.

3) Increasing the centre distance can enhance the suppression performance of the system at high reduced velocity, but it will affect the suppression performance at low reduced velocity.

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