論 文 の 内 容 の 要 旨

論文題目 Research on the Characteristics of Hydrodynamics and Motion of the Rotating Pipe in Flow

（流れ中において回転する円筒構造物の流体力及び運動特性に関する研究）

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The present research is addressed to make clear the hydrodynamics and motion characteristics of the rotating cylinder and rotating pipe based on different flow velocities and rotating speeds. In order to thoroughly understand the hydrodynamics variation as increase of rotation rate of rotating cylinder, experiment and simulation of fixed rotating cylinder model are conducted. A good agreement of the experimental results and simulation results has been confirmed. Based on the confirmation of hydrodynamics of rotating cylinder, the spring-mounted rotating cylinder model is constructed, several motion paths have been found and “varying added mass” has been introduced. Finally, quasi-three dimensional simulations for long rotating pipe are conducted, similar motion paths have been found and the “varying added mass” has been confirmed.

1. Introduction

Rotating pipe as a practical key part is used at many fields of ocean engineering, such as the scientific drilling and offshore drilling. For the rotating pipe in the flow, different from vortex induced vibration of the normal riser, the motion of the rotating pipe will be more complicated based on the combination of the flow and rotation.

In order to understand the hydrodynamics and motion characteristics of long drilling pipe, the first need to confirm is how the hydrodynamics varies as the increase of rotation rate, as the mean lift shown in the figure 1, the mean lift variation of those researchers [1-6] are total different. Some arguments still exist at several aspects, such as whether the Prandtl's limit [7] can be exceeded and whether the minus of mean drag appears. So far, investigation of general characteristics of long flexible riser has been conducted by a lot of researchers and huge amount of significant conclusions have been obtained, but for the long rotating pipe, the research on this aspect is immature.

In this paper, hydrodynamics variation as the rotation rate has been confirmed by experiment and simulation, and then simulation results of spring mounted rotating cylinder and long rotating pipe has been analyzed and discussed.

2. Relevant parameters of rotating cylinder in flow

The relevant Reynolds number, Strouhal number, rotation rate， reduced velocity， lift coefficient and drag coefficient are described as following[8]:

$$Re = \frac{U_\infty D}{\upsilon} \qquad S_t = \frac{f_v D}{U_\infty} \qquad \alpha = \frac{\varpi D}{2U_\infty} \tag{1}$$

$$U_r = \frac{U_\infty}{f_n D} \qquad C_l = \frac{F_l}{\frac{1}{2}\rho D L U_\infty^2} \qquad C_d = \frac{F_d}{\frac{1}{2}\rho D L U_\infty^2} \tag{2}$$

Where F_l and F_d are the hydrodynamic forces at the cross flow direction and in-line direction, respectively, ρ is the density of water and υ is the viscosity coefficient, D is the diameter of the cylinder, L is the length of the cylinder and U_∞ is the flow velocity, ϖ is the rotation angular velocity, f_v is the vortex shedding frequency and f_n is the natural frequency.

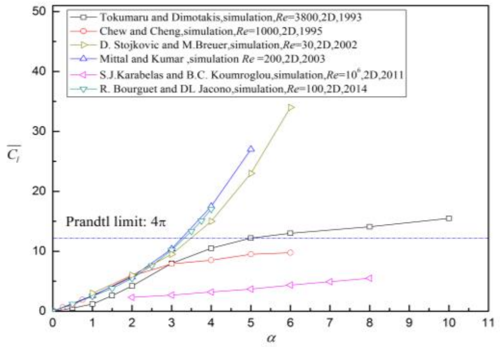


FIG. 1 Mean Lift coefficient, $\overline{C_l}$, and versus rotation rate, α , from previous works

3. Experimental condition and results

In order to get the hydrodynamics variation as the rotation rate, experiment is carried out as shown in the figure 2(a). Four replaceable cylinders with the same length $L = 0.6$ m , but different diameters (0.319 m, 0.267 m, 0.216m and 0.102 m) are tested (Figure 2(b)). The cylinders are linked with the shaft by bolts and rotation of the cylinder is controlled by an electric motor through a gear installed inside the system. A six-axis force sensor installed in the system is used to detect the forces and moments for the six degrees of freedom.

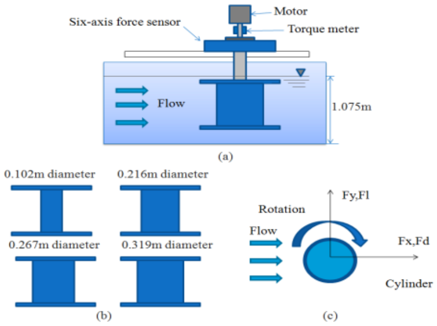


FIG. 2 (a) Schematics of experiment setup. (b) Four different diameter cylinders. (c) Generated forces of rotating cylinders in flow

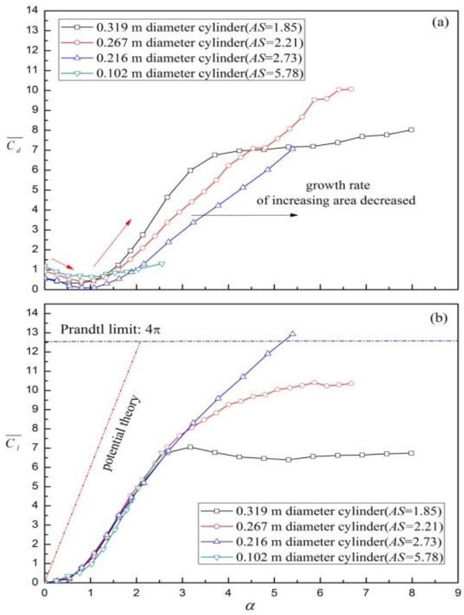


FIG. 3 (a) The means drag and (b) mean lift coefficient for different cylinders at flow velocity 0.3 m/s versus rotation rate.

The mean hydrodynamics coefficients for different cylinders are shown in Figure 3,the similar variation can be observed for the different cylinders, the drag decreases and then increases as the increase of rotation rate and the growth rate at increasing area decreases as the increase of aspect ratio, while, the lift increases as the increase of rotation rate, at large rotation rates, the mean hydrodynamics for the different cylinders gradually diverges and becomes different constant values at different rotations rates. The constant values of hydrodynamics and the rotation rates for the inflection points are strongly dependent on the aspect ratio of the cylinders.

4. Numerical method for rotating cylinder in flow

A discrete vortex method is applied for the simulation[8];Navier-Stokes equation can be simplified to the form:

$$\frac{\partial q}{\partial t} = -\frac{\nabla p}{\rho} \tag{3}$$

Where q is the surface vorticity, p is the surface pressure gradient, t is the time and ρ is the density.

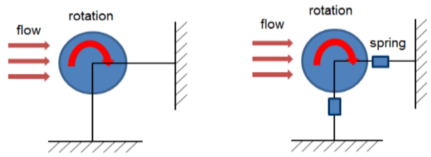
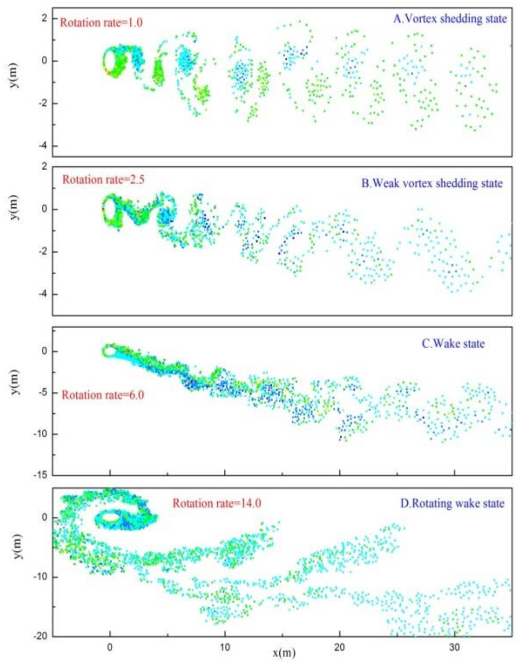


FIG. 4 Two dimensional fixed rotating cylinder model and spring-mounted cylinder model

The two dimensional fixed rotating cylinder model and spring-mounted rotating cylinder are shown in the figure 4, for the fixed rotating cylinder, as the rotation rate increasing, four different wake vortex distributions(vortex shedding state, weak vortex shedding state, wake state and rotating wake state) have been found, the different wake vortex states and corresponding hydrodynamics are shown in the figure 5,agreement of the wake vortex states and hydrodynamics characteristics can be observed. The mean hydrodynamics coefficients are compared with the experiment results in Figure 6, the final constant values of the hydrodynamics are different because of the effect of aspect ratio, but the similar variation tendency of simulation and experiment results can be observed, which indicates the present simulation method is reliable.



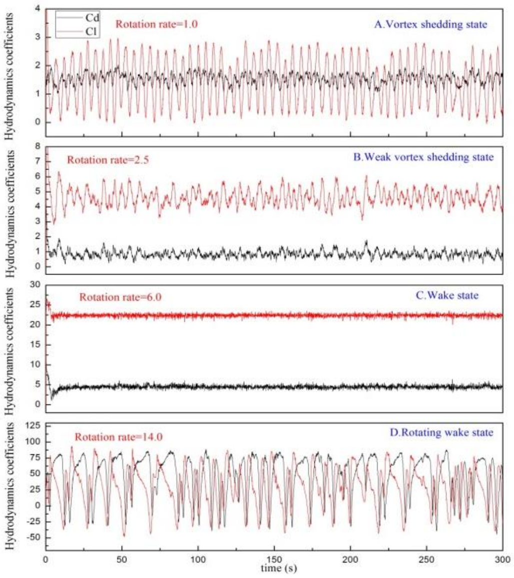


FIG. 5 Wake vortex distributions and corresponding hydrodynamics at different rotation rates

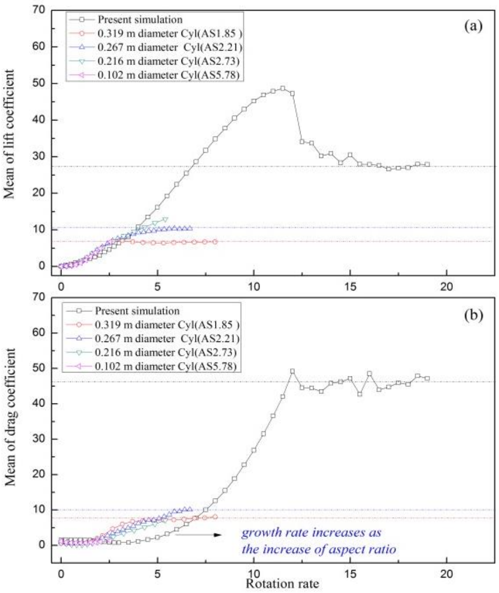


FIG. 6 Comparison of the hydrodynamics coefficient for the simulation and experiment

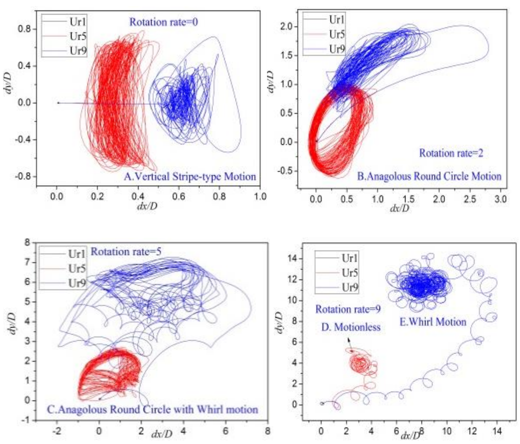


FIG. 7 Five different motion types of rotating cylinder

For the spring-mounted rotating cylinder model shown in the Figure 4, five different motion paths have been found based on different rotation rate and reduced velocity, as shown in the figure 7, As the rotation rate increasing, large oscillation is generated and the oscillation frequency decreases, the reason is considered that the added mass increases as the increase of rotation. The relationship of the added mass coefficient and rotation rate is illustrated in the figure 8,when rotation rate smaller than 2,added mass coefficient is 1 and once the rotation rate larger then 2,added mass dramatically increases as the increase of rotation rate because of wake vortex particles gathering around the cylinder.

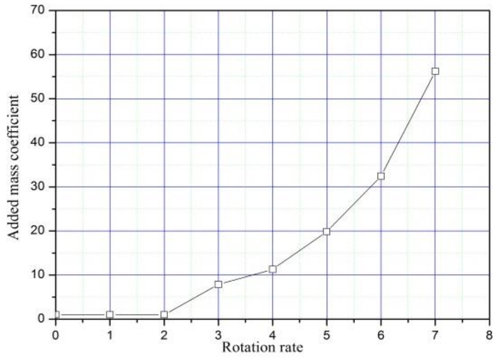


FIG. 8 Relationship of added mass and rotation rate

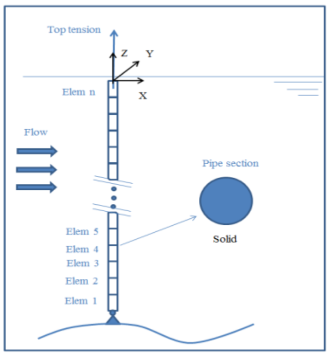


FIG. 9 Three dimensional model of the riser in flow

Based on the two dimensional simulation method, combining strip theory, the quasi-three dimensional finite element model of the drilling pipe is constructed, as shown in the figure 9, the length is 120m, solid diameter is 0.25m, density is 7800kg/m^3, elasticity modulus is 2.1e11N/m^2 and the top tension equals the cylinder gravity in water.

The RMS of the amplitude of the long pipe (without rotation) at cross flow direction is shown in the figure 10, the first, second and third order modal vibration shape can be observed at flow velocity 0.12m/s, 0.29m/s and 0.53m/s, respectively. The reason is that the vortex shedding frequency is closing to the natural frequencies of the cylinder system at these flow velocities.

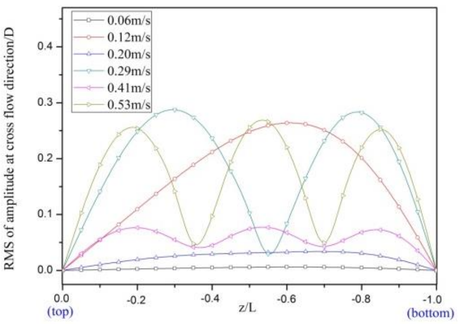


FIG .10 RMS of the Amplitude at cross flow direction (without rotation).

Taking the rotation into consideration, time history of the motion at middle of the pipe at cross flow direction of flow velocity 0.12m/s under different rotation rate is shown in the figure 11(a) and corresponding frequency analysis is shown in the figure11 (b), as rotation rate increasing, frequency of motion decreases until rotation rate 4, the reason is considered the added mass increases as the increase of rotation rate, which is agreeing with those of two dimensional spring mounted cylinder. Once rotation rate larger than 4, rotating wake will dominate the motion and the frequency gradually increase as the increase of rotation rate, agree with the results of two dimensional rotating cylinder model.

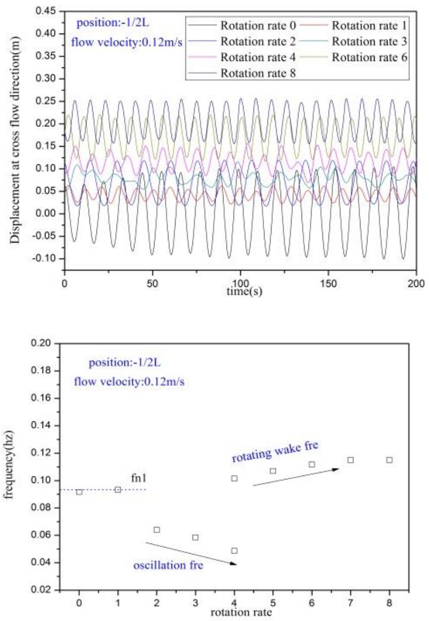


FIG .11 (a) Motion at cross flow direction and (b) corresponding motion frequency analysis

The motion paths at middle of the cylinder at flow velocity 0.12m/s under different rotation rates is shown in the figure 12, the motion paths varies from vertical strip type to analogous round circle motion type and then becomes the combination of analogous round circle and whirl motion type at rotation rate 3, which is similar to the findings for two dimensional spring-mounted cylinder model, while, analogous round circle motion type reappears from rotation rate 4 because of the rotating wake.

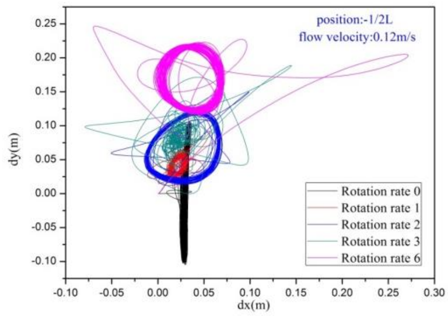


FIG. 12 Motion paths at middle of the cylinder at flow velocity 0.12m/s under different rotation rates

5. Conclusion

The hydrodynamics variation as increase of rotation rate for the rotating cylinder has been confirmed by the experiment and simulation. For the fixed rotating cylinder simulation, four different wake vortex distributions have been found and corresponding hydrodynamics characteristics have been illustrated. For the spring-mounted rotating cylinder model, five motion paths have been found and "varying added mass" is proposed and illustrated. Finally, quasi-three dimensional simulations for long rotating pipe have been conducted. Similar motion paths have been found in two and three dimensional simulation and the conclusion that added mass increase as increase of rotation rate has been confirmed.

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