博士論文（要約）

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）

Wei Chen
陳　威

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）

氏　　名　　陳　威（Wei Chen）

The present research is addressed to make clear hydrodynamics and motion characteristics of rotating cylinder and rotating pipe based on different flow velocities and rotating speeds. In order to thoroughly understand the hydrodynamics variation with increasing 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, a spring-mounted rotating cylinder model is constructed, three different motions have been found and “varying added mass” has been introduced. Finally, quasi-three dimensional simulations for a long rotating pipe are conducted, similar three motions have been found and the “varying added mass” has been reconfirmed.

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 a rotating pipe in flow, different from vortex induced vibration of normal riser, the motion of 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 flexible rotating pipe, the first need to confirm is how the hydrodynamics varies with the increase of rotation rate, as the mean lift shown in Figure 1 and the mean drag shown in Figure 2, the mean hydrodynamics variation of those researchers [1-6] are totally 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 characteristics of a long flexible riser has been conducted by many researchers, and huge amount of significant conclusions have been obtained, but for long flexible rotating pipe, the research on this aspect is immature. For the motion of spring mounted rotating cylinder and flexible rotating pipe. Several researches [8-11] have been conducted at relatively low rotation rate and the motion characteristics at high rotation rate are still unknown.

Based on these unknowns, the purposes of the present research area are as follows; first is to confirm the hydrodynamics characteristics with the increase of rotation rate of rotating cylinder in flow, then based on this, the second is to grasp the motion characteristics of long flexible rotating pipe in flow. In this paper, hydrodynamics with increasing rotation rate has been concluded by experiment and simulation, and then simulation results of a spring mounted rotating cylinder and a long rotating pipe have been analyzed and discussed.

The relevant Reynolds number, Strouhal number, rotation rate, reduced velocity, lift coefficient and drag coefficient are described as follows [12]:

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

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

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.

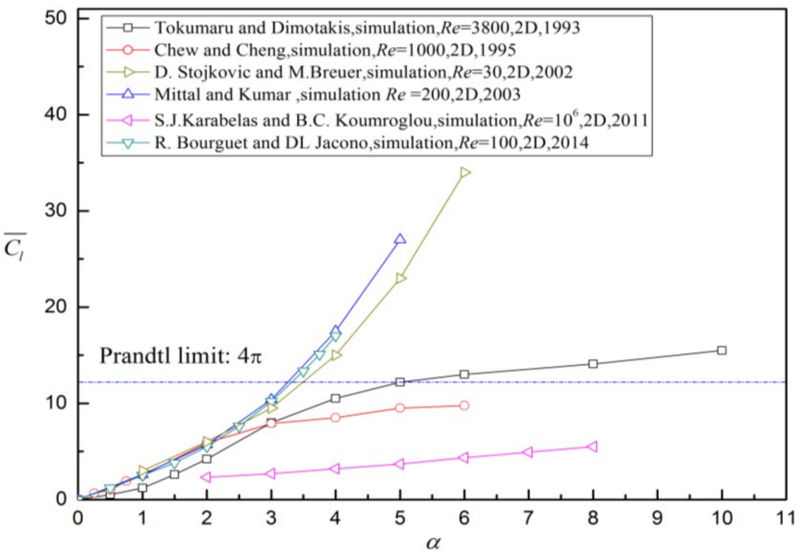


Figure 1 Mean Lift coefficient, $\overline{C_l}$, and versus rotation rate, α, from previous works.

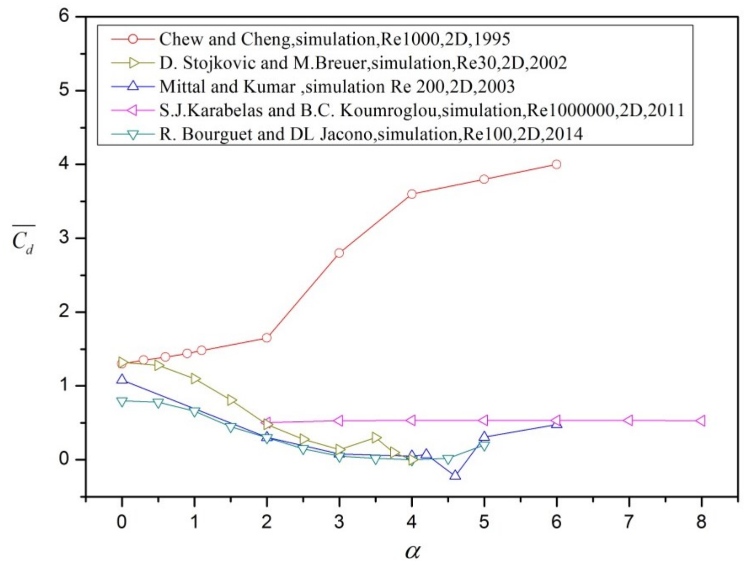


Figure 2 Mean drag coefficient, $\overline{C_d}$, versus rotation rate, α , from previous works (2D =two-dimensional).

2 Experimental investigation of rotating cylinders in flow

In order to get the hydrodynamics with increasing rotation rate, experiment is carried out, as shown in Figure 3(a). Four replaceable cylinders with the same length L=0.6m ,but different diameters (0.319 m, 0.267 m, 0.216m and 0.102 m) are tested (Figure 3(b)). The cylinders are linked with the shaft by bolts and the rotation of 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 six degrees of freedom.

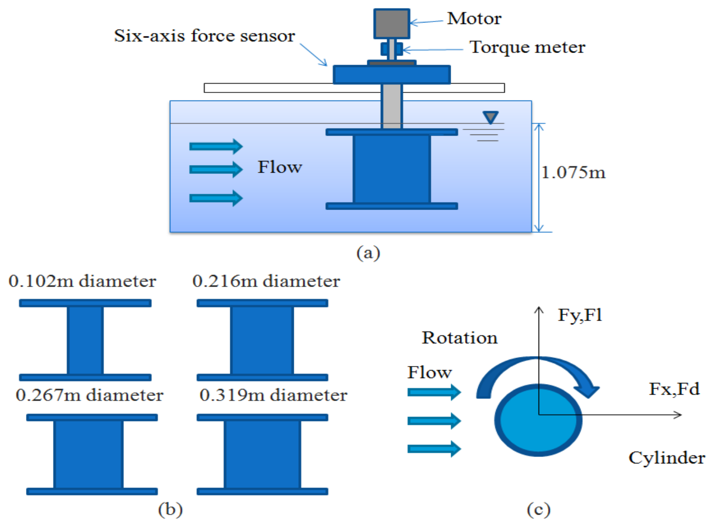


Figure 3 (a) Schematics of experiment setup, (b) four different diameter cylinders and (c) generated forces of rotating cylinders in flow

For the mean hydrodynamics, as shown in Figure 4, the mean drag initially decreases and then increases, finally, to be a certain constant with increasing rotation rate, the mean lift increases and then to be a certain constant with increasing rotation rate, the constants are considered to be determined by aspect ratio of cylinder, and the growth rate for mean drag decreases with increasing aspect ratio. If the aspect ratio of cylinders can be large enough, with the increase of rotation rate, the assumption that the mean lift exceeds the Prandtl's limit is supported by the present research.

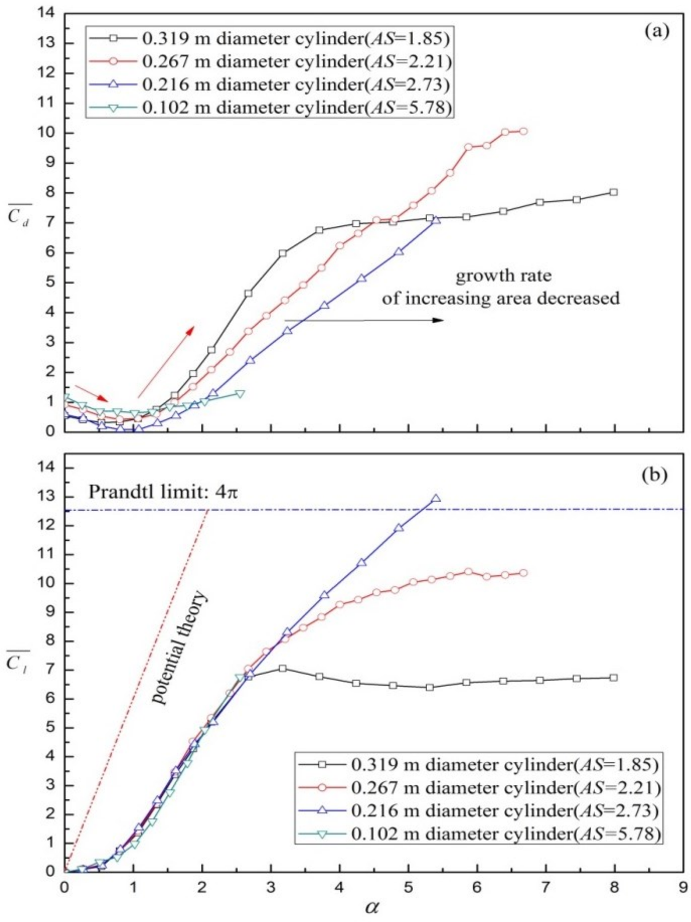


Figure 4 (a) The means of the drag coefficient, $\overline{C_d}$, and (b) lift coefficient, $\overline{C_l}$, for different cylinders at flow velocity 0.3 m/s versus rotation rate, α .

In order to better describe the mean hydrodynamics variation with the increase of rotation rate, three areas are defined based on the variation of mean hydrodynamics, as shown in Figure 5; a) initial area(which indicates at the initial stage): the $\overline{C_d}$ decreases slightly to a minimum and $\overline{C_l}$ increases slightly; b) increasing area(which means values dramatically increasing in this area): the $\overline{C_d}$ and $\overline{C_l}$ are dramatically increasing and values of $\overline{C_l}$ are larger than $\overline{C_d}$; c) equivalent area(which manifests the mean lift and drag are equivalent and close to each other in this area): the $\overline{C_l}$ and $\overline{C_d}$ remain constant, the values of $\overline{C_d}$ and $\overline{C_l}$ are close to each other and the $\overline{C_d}$ is a little larger than $\overline{C_l}$. The range of these areas is considered to be determined by the aspect ratio of cylinder.

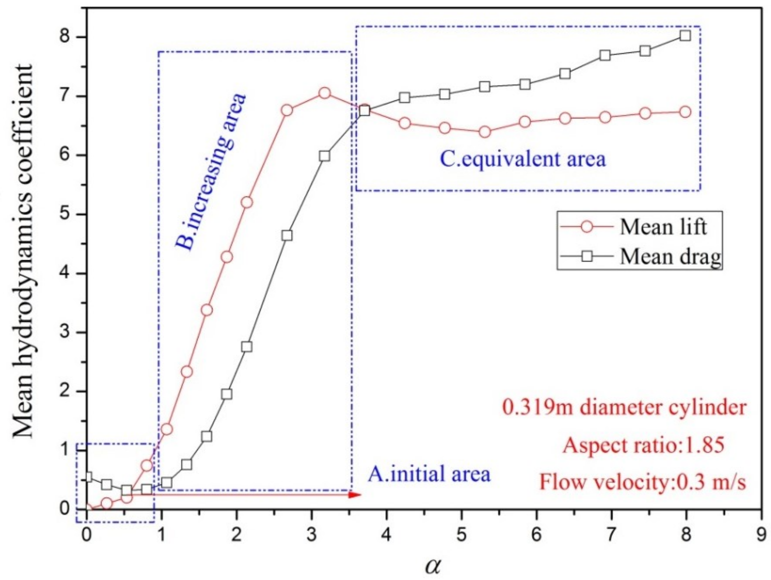
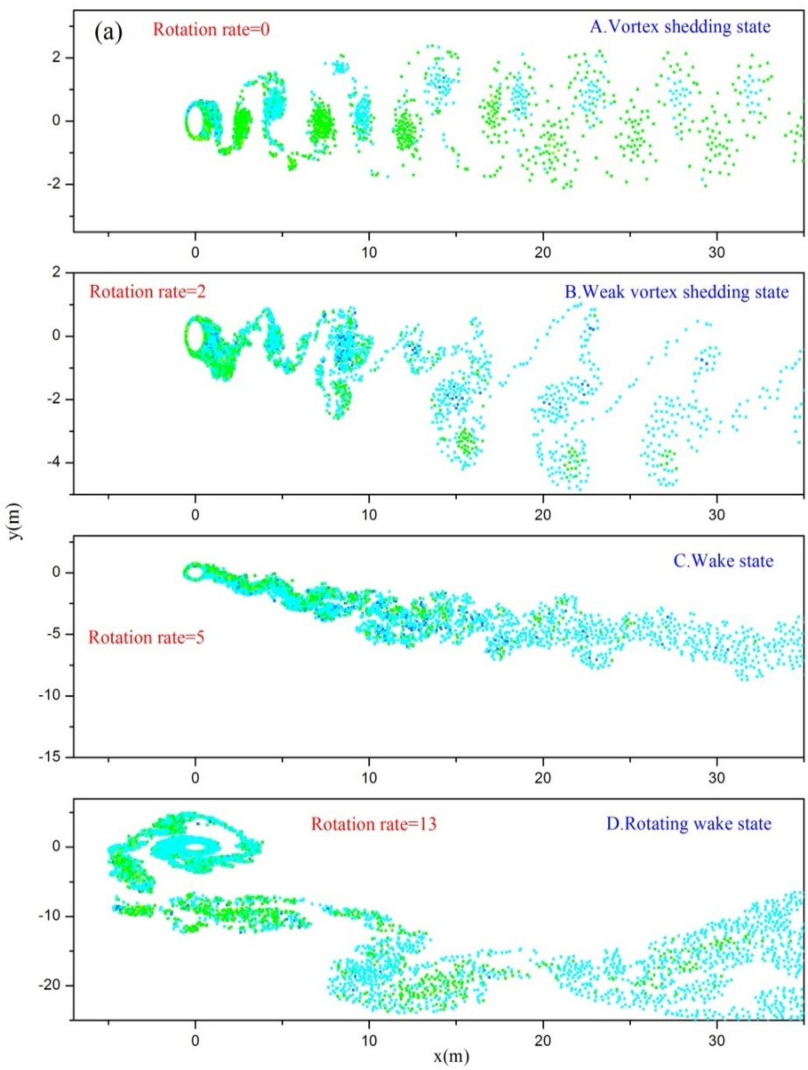


Figure 5 The mean hydrodynamics coefficient, $\overline{C_d}$ & $\overline{C_l}$, of the cylinders at flow velocity 0.3 m/s versus rotation rate, α .

3 Simulation of rotating cylinder in flow

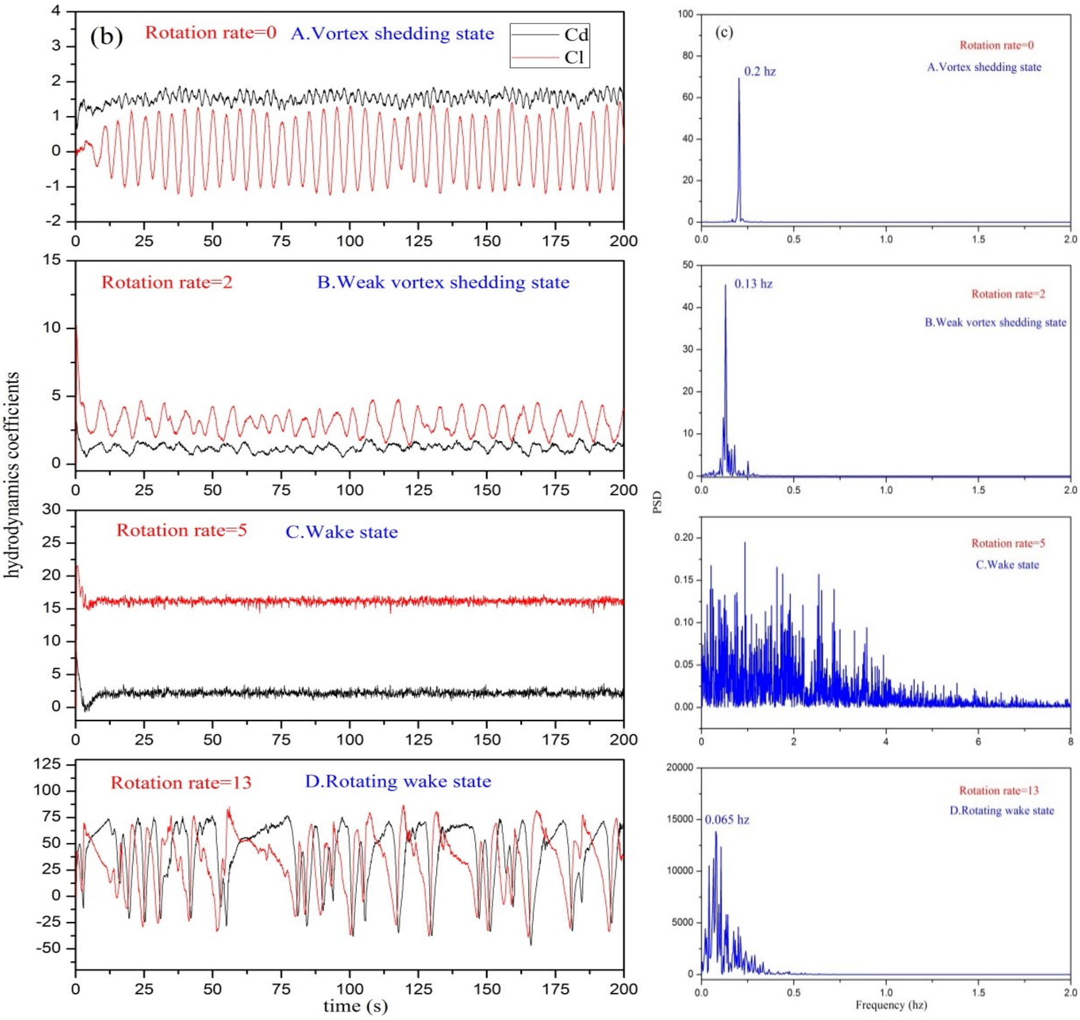
As the experimental investigation of hydrodynamics characteristics of rotation cylinders are limited to aspect ratio from 1.85 to 5.78, in order to understand hydrodynamics characteristics at a wider range, two-dimensional discrete vortex method simulation has been conducted for a fixed rotating cylinder at rotation rate varies from 0 to 19 at $\mathrm{Re}=10^5$ in flow.

For the present simulation, four different vortex shedding states(vortex shedding state, weak vortex shedding state, wake state and rotating wake state) are found after analysis of the results, corresponding to these four different states, the wake vortex distribution, hydrodynamics and corresponding frequency analysis of lift coefficient at rotation rate 0, 2, 5 and 13 are shown in Figure 6 (a) ,(b) and (c), the characteristics of these four states are as follows: A)Vortex shedding state; the vortexes periodically shed from two sides of cylinder and the periodical hydrodynamics can be observed and the vortex shedding frequency followed Strouhal number 0.2 can be viewed, as the rotation rate 0 in figure. B) Weak vortex shedding state; the vortex shedding have been weakened and the vortex shedding frequency decreases, as the rotation rate 2 in figure. C) Wake state; the vortex shedding disappears and in contrast to that, the wake is steady, corresponding to the relatively steady hydrodynamics, as the rotation rate 5 in figure. D) Rotating wake state; the wake is not steady but rotates around cylinder and then separates from cylinder and the huge fluctuation of hydrodynamics can be observed, several peaks can be observed in the frequency spectrum, as the rotation rate 13 in figure.



(a)

Figure 6 (a) Wake vortex distributions under different rotation rates.



(b) (c)

Figure 6 (b) Time histories of the hydrodynamics and (c) corresponding frequency of lift under different rotation rates.

Based on these four different wake states, as the variation of rotation rate, vortex shedding, weak vortex shedding, wake and rotating wake areas are divided, combining the defined initial, increasing and equivalent areas for the present experiment, the corresponding relationship between these areas of the two divisions has been confirmed, as shown in Figure 7, boundary of the initial and increasing areas is in the weak vortex shedding area, at where the vortex shedding has gradually been weakened and then disappear, corresponding to the mean drag gradually decreases to a minimum, the weak vortex shedding area actually can be regarded as transitional area for the vortex shedding and wake areas, and represents the ending of the initial area and beginning of the increasing area. The equivalent area is corresponding to the rotating wake area, in which the mean hydrodynamics remains steady as rotating wake dominated the flow and the effect of incoming flow have been dramatically weakened. The range of initial, increasing and equivalent areas is consider to be determined by aspect ratio, which explains the range of these areas of the present simulation is much wider than that of the experiment.

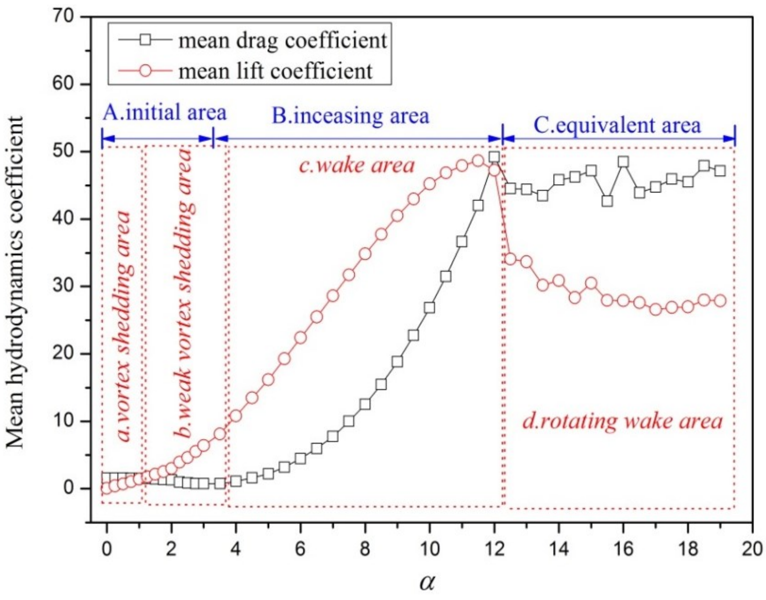
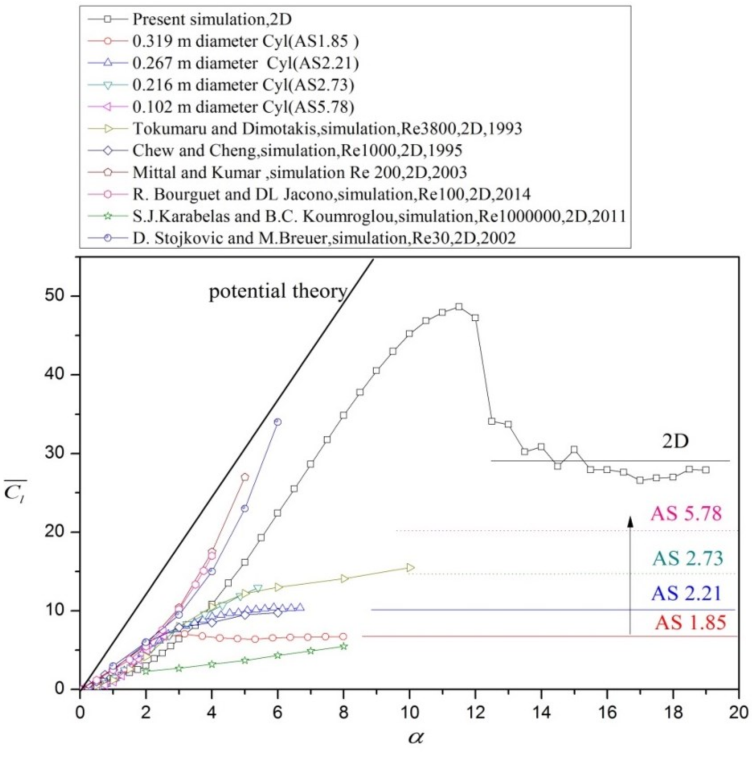
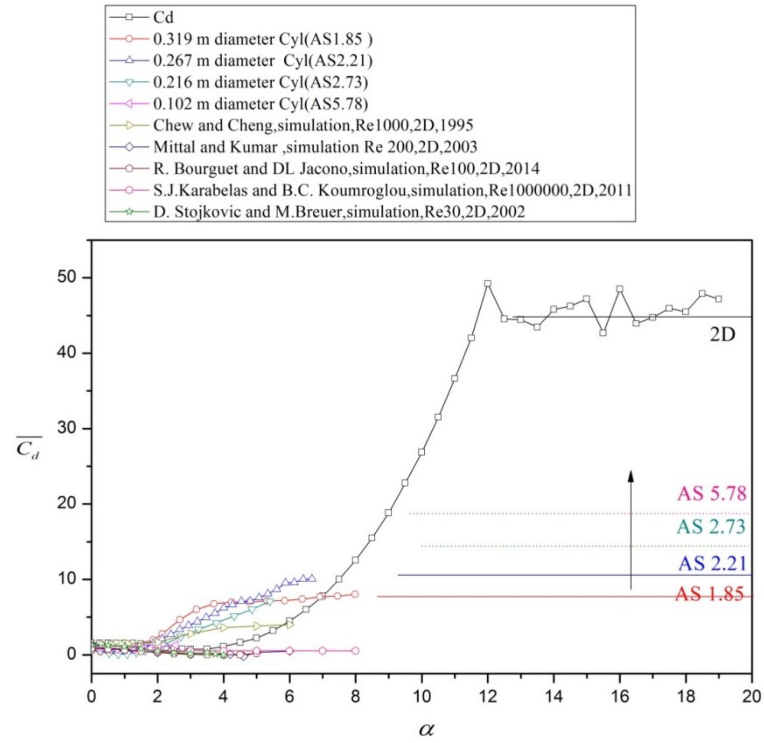


Figure 7 Relationship between these areas of two different divisions.



(a)

Figure 8 Comparison of (a) mean lift coefficient, $\overline{C_l}$, versus rotation rate, α, of the present simulation, the present experiment and previous works (2D =two-dimensional, AS is aspect ratio).



(b)

Figure 8 Comparison of (b) mean drag coefficient, $\overline{C_d}$, versus rotation rate, α , of the present simulation, the present experiment and previous works (2D =two-dimensional, AS is aspect ratio).

The similar variation of mean hydrodynamics with the increase of rotation rate for the present simulation and experiment have been confirmed, as shown in Figure 8, for the mean lift, firstly increases and then remains steady with increasing rotation rate, for the mean drag, initially decreases and then increases and finally remains steady with increasing rotation rate, and with the increase of aspect ratio of cylinder, the mean hydrodynamics is close to those of the two-dimensional model.

Based on the confirmed hydrodynamics characteristics of fixed rotating cylinder, In order to prepare for grasping the motion characteristics of long flexible pipe in flow, two-dimensional simulation of a spring mounted rotating cylinder at $\mathrm{Re}=10^5$ have been conducted, the mass ratio is 2.7 and the structural damping is 0, the original reduced velocity changes from 1 to 14 and the rotation rate varies from 0 to 16.

Based on the different rotation rates, with the increase of original reduced velocity, the motion has been generated, the motions of spring mounted rotating cylinder has been concluded and three kinds of motions have been found under different rotation rates in the present simulation. A) VIV Motion; this kind of motion is induced by the vortex shedding and mainly vibrates in the cross-flow direction, as the motion at original reduced velocity 5 of rotation rate 0 in Figure 10. B) Reverse direction motion; definition of reverse direction is shown in Figure 9, the motion frequency is lower than that of VIV and the moving direction is opposite to self-rotation direction of cylinder, as the motion at original reduced velocity 5 of rotation rate 3 in Figure 10, and the reverse direction also have been found in the flexible rotating pipe results of Inoue and Rheem[11]. C) Same direction motion; definition of reverse direction is shown in figure 9, the motion frequency is higher than that of VIV and the moving direction is same as the self-rotation direction of the cylinder, as the motion at original reduced velocity 9 of rotation rate 9 in Figure 10. Especially, for the motion at original reduced velocity 9 of rotation rate 5, the combination of the reverse direction motion and same direction motion can be observed.

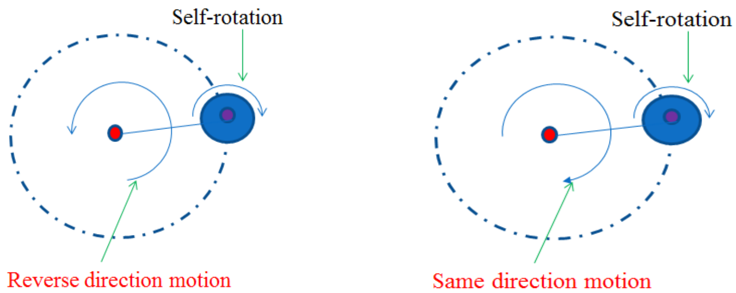


Figure 9 Explanation of the reverse direction motion and same direction motion.

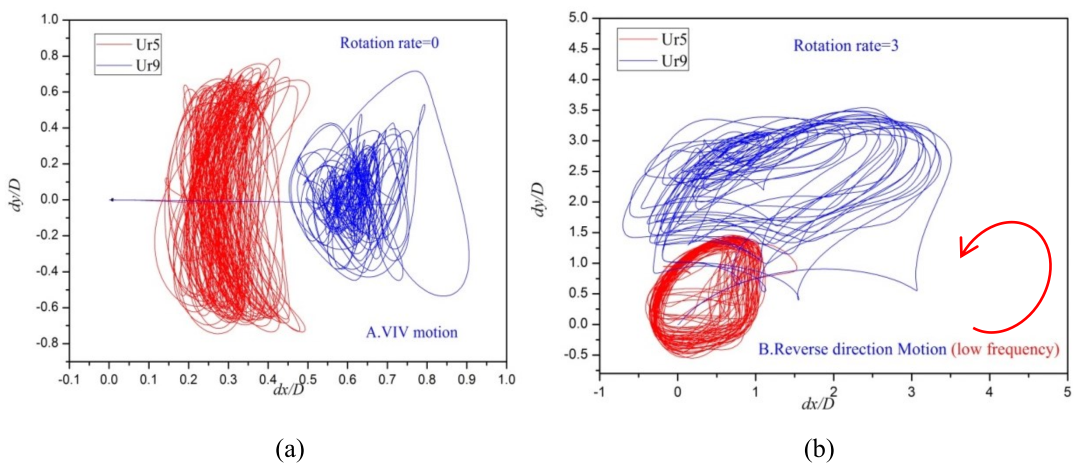
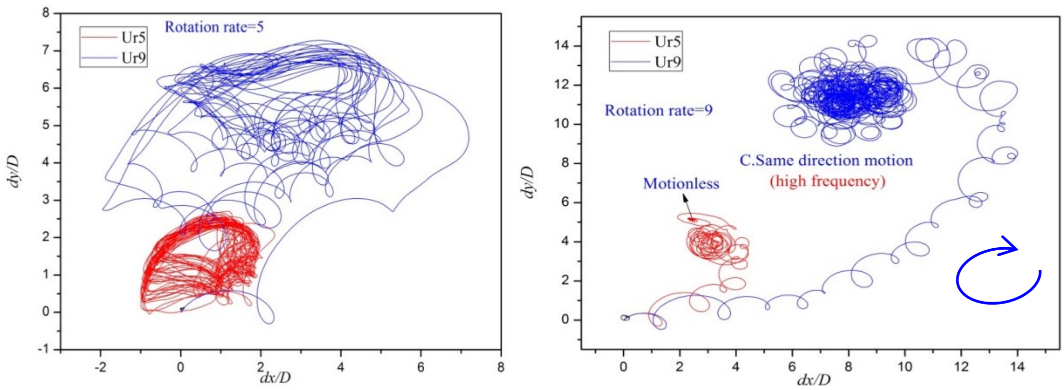


Figure 10 Motions of the spring mounted rotating cylinder at rotation rates (a) 0 and (b) 3. (The definition of low frequency and high frequency is based on frequency values of these motions).



(c) (d)

Figure 10 Motions of the spring mounted rotating cylinder at rotation rates (c) 5 and (d) 9. (The definition of low frequency and high frequency is based on frequency values of these motions).

In order to confirm why these motions have been generated, the frequency analysis of motion at original reduced velocity 5, 7 and 9 under different rotation rates has been shown in Figure 11, the VIV (vortex induced vibration) motion is induced by vortex shedding and the frequency remains relatively steady, for the same direction motion at relative high-frequency, the frequency of this motion is larger than that of vortex shedding and much smaller than the corresponding rotation frequency of cylinder, the generation reason for this motion is still unknown, but the relationship that the frequency of this motion increases with increasing rotation rate can be achieved. For the reverse direction motion with low frequency, the frequency decreases with increasing rotation rate, this similar phenomenon have been observed in flexible rotating pipe results of Kato and Rheem [10]. Same peak frequency can be observed for this motion and corresponding hydrodynamics, the frequency is considered to be the natural frequency of cylinder system, the decreasing of natural frequency of cylinder system is due to the added mass of system increases with increasing rotation rate.

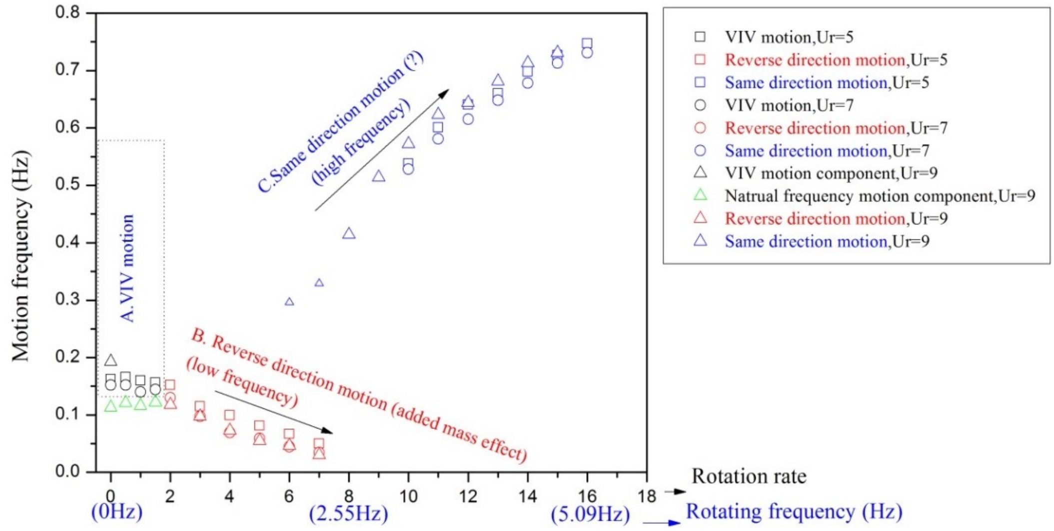


Figure 11 Motion frequency in cross-flow direction versus rotation rate
at different original reduced velocities.

In order to confirm the relationship between added mass coefficient and rotation rate, the frequency analysis of displacement in cross-flow direction for different rotation rates have been conducted, and the added mass coefficients at different rotation rates have been plotted in Figure 12, at $0 \le \alpha \le 1$, the added mass coefficient is around 1, the same as the defined original added mass coefficient, at the $1 < \alpha \le 2$, the added mass coefficient gradually increases, vortex shedding have been weakened and the vortex shedding frequency decreases in this range, which indicates point vortex particles does not shed to flow immediately, but gathering around the cylinder and moving with cylinder together, which results in the added mass gradually increases with increasing rotation rate, as rotation rate larger than 2, vortex shedding have been dramatically weakened and the motion is locked by the natural frequency of cylinder system and added mass dramatically increases with increasing rotation rate.

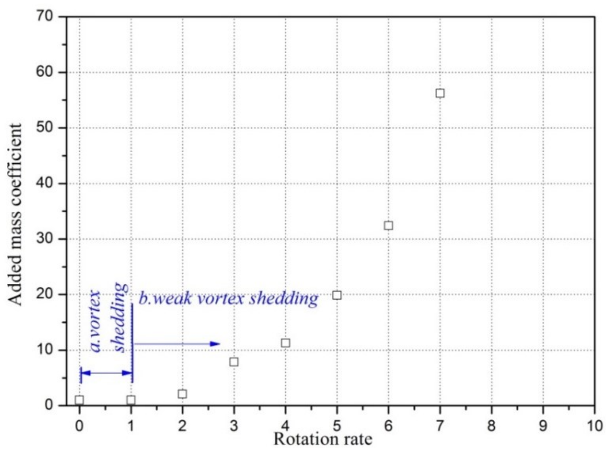


Figure 12 Added mass coefficients versus rotation rate of the cylinder system.

4 Simulation of the flexible rotating cylinder in flow

In order to grasp the motion characteristics of flexible rotating pipe in flow, the discrete vortex method quasi-three dimensional time domain model of a flexible rotating pipe has been constructed, for the long flexible rotating cylinder, the finite element model of the flexible pipe has been constructed, as shown in Figure 13, the length is 120m, solid diameter is 0.25m, density is 7800kg/m3, elasticity modulus is 2.1e11N/m2 and the top tension equaled the cylinder gravity in water.

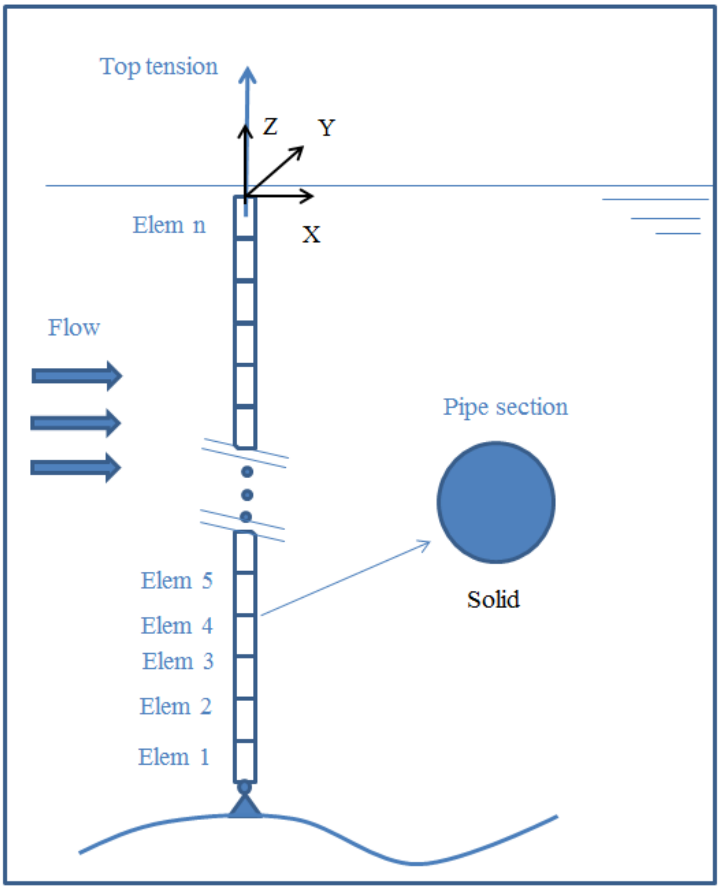


Figure 13 The finite element structural model of flexible pipe.

The RMS of the amplitude of long flexible pipe (without rotation) in cross flow direction is shown in Figure 14, the first, second and third order modal vibration shape with large amplitude can be observed at flow velocity 0.12m/s, 0.29m/s and 0.53m/s, respectively. The reason is that the vortex shedding frequencies are close to natural frequencies of the cylinder system at these flow velocities and the resonance happens.

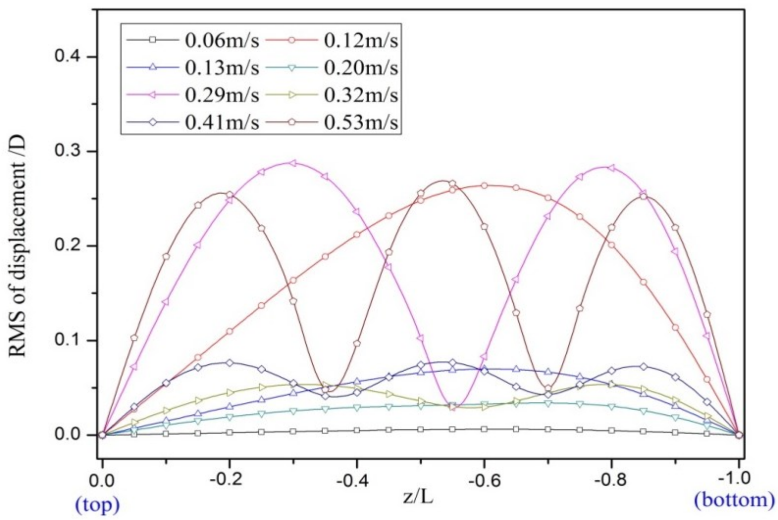


Figure 14 RMS of displacement in cross-flow direction of the long flexible pipe at different flow velocities.

Taking the rotation into consideration, the time history of displacement of the long flexible rotating pipe middle position in cross-flow direction at flow velocity 0.12 m/s based on different rotation rate is shown in Figure 15, as the rotation rate increased, the mean displacement inclines to the cross-flow direction due to the generated lift force. The amplitude of the displacement dramatically decreases at rotation rate 1 and then dramatically increases at rotation rate 2, which is considered that the motion characteristics of the cylinder have been varied. The dramatic frequency decreasing phenomenon can be observed at rotation rate 3.

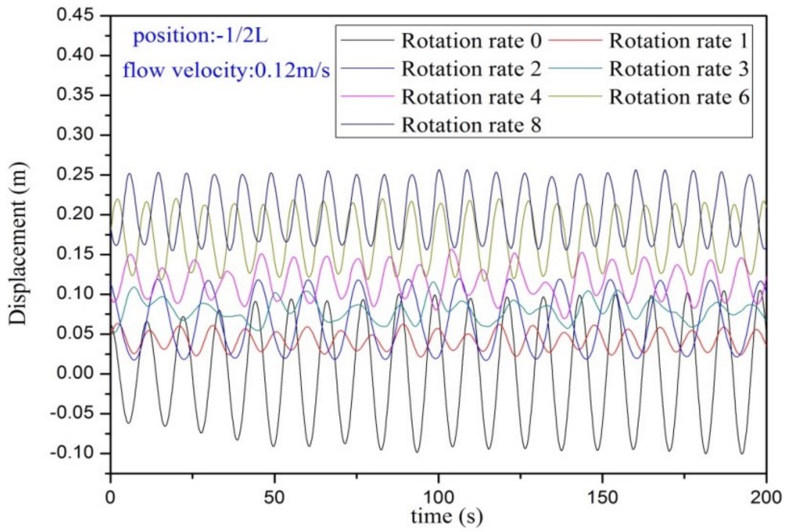


Figure 15 Time history of the displacement at the middle of the long flexible pipe in cross-flow direction under different rotation rates at flow velocity 0.12 m/s.

With the increase of rotation rate, the VIV, reverse direction and same direction motions have been generated, frequency of the displacement at middle of the long flexible pipe in cross-flow direction under different rotation rates at flow velocity 0.12 m/s is shown in Figure 16, and the frequency characteristics of these motions is similar to that of the two-dimensional spring mounted rotating cylinder in Figure 11. For the VIV motion induced by vortex shedding, the frequency remains steady. For the same direction motion, the generation reason is still unknown, but the frequency increases with increasing rotation rate can be observed. For the reverse direction motion, the frequency decreases with increasing rotation rate, similar to the results of the spring mounted rotating cylinder simulation and flexible rotating pipe experimental results of previous researchers, the frequency decreases with increasing rotation rate due to the added mass of flexible rotating pipe system increases with increasing rotation rate.

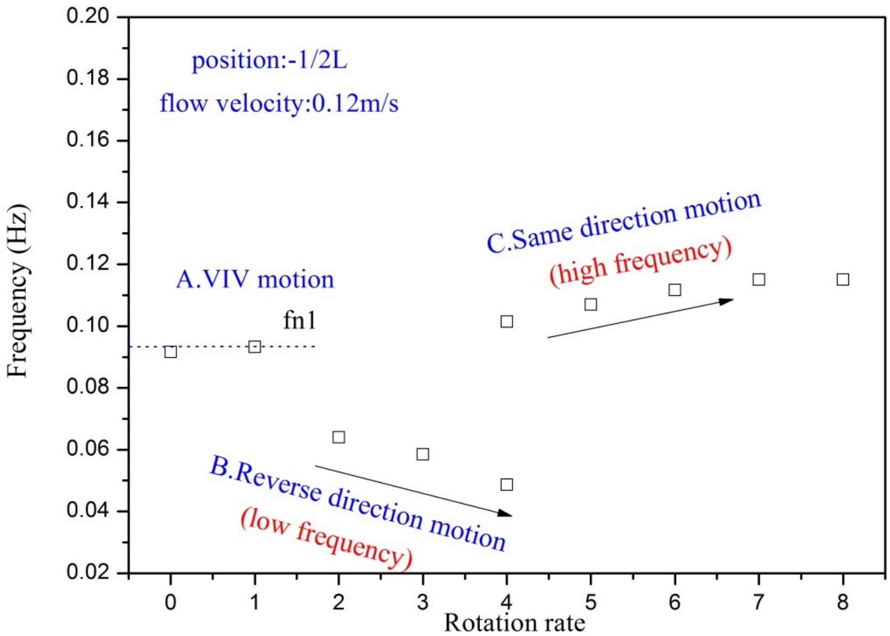


Figure 16 Frequency of the displacement at the middle of the long flexible pipe in cross-flow direction under different rotation rates at flow velocity 0.12 m/s.

5. Conclusion

As the introduction indicated, for the rotating cylinder, many researchers are still confused by the relationship between hydrodynamics and rotation rate, argument that whether Prandtl's limit can be exceeded still exists, whether Strouhal number increases with increasing rotation rate still has not been confirmed. For the motion of spring mounted rotating cylinder and flexible rotating pipe, several researches have been conducted at relatively low rotation rate and the motion characteristics at large rotation rate are still unknown.

Based on these unknowns, the purposes of the present research are as follows; first is to confirm hydrodynamics characteristics with the increase of rotation rate of rotating cylinder in flow, the second is to grasp the motion characteristics of flexible rotating pipe in flow. In order to get hydrodynamics characteristics of rotating cylinder in flow, experiment with rotating cylinders in flow and simulation of fixed rotating cylinder in flow have been conducted. For the purpose to grasp the motion characteristics of flexible rotating pipe in flow, simulation of spring mounted rotating cylinder and flexible rotating pipe have been conducted.

Through the comparison of the experiment and simulation for rotating cylinder in flow, agreement of hydrodynamics characteristics in the same area with the increase of rotation rate has been confirmed. Relationship between these areas of the two different divisions has been illustrated and aspect ratio effect has been concluded, based on these, hydrodynamics characteristics of rotating cylinder in flow at large rotation rate have been confirmed.

Through the simulation of a spring mounted rotating cylinder in flow, three motions have been found and the reasons for these motions have been illustrated, which is beneficial for investigation of motion characteristics of flexible rotating pipe in flow.

Through the discussion of simulation for a spring mounted rotating cylinder and simulation for a flexible rotating pipe in flow, the similar three motions have been found and corresponding reasons have been illustrated, agreement of these results indicates that the motion characteristics of flexible rotating pipe have been grasped.

References

1. Tokumaru PT, Domotakis PE. (1993) The lift of a cylinder executing rotary motions in uniform flow. J Fluid Mech 255: 1

2. Chew YT, Cheng M, Luo SC (1995) A numerical study of flow past a rotating circular cylinder using a hybrid vortex scheme. J Fluid Mech 299:35

3. Mittal S, Kumar B (2003) Flow past a rotating cylinder. J Fluid Mech 476: 303

4. Bourguet R and Jacono DL (2014) Flow-induced vibrations of a rotating cylinder. J Fluid Mech 740: 342

5. Karabelas SJ, Koumroglou BC (2012) High Reynolds number turbulent flow past a rotating cylinder. Appl Math Model 36: 379

6. Stojkovic D, Breuer M, Durst F (2002) Effect of high rotation rates on the laminar flow around a circular cylinder. Phys Fluids 14: 3160

7. Prandtl L (1925) The magnus effect and wind powered ships,Naturwissenschaften 13: 93

8. Bourguet R. and Jacono D. L., (2014) Flow-induced vibrations of a rotating cylinder. J. Fluid Mech. 740: 342.

9. Banafsheh S. A. and Yahya M. S. (2015) An experimental investigation of vortex-induced vibration of a rotating circular cylinder in the cross-flow direction. Phys. Fluids. 27: 067101.

10. Rheem C., K. and Kato K., (2011) A basic research of the VIV response of a rotating circular in flow. Proceeding of the ASME 30th international conference on ocean, offshore and arctic engineering (OMAE) 2011-49561.

11. Inoue T. and Rheem C. K., (2012) Experimental research on the VIV response of rotating drill pipe in flow. Hydrodynamics in Marine Technology, 407-416.

12. Lewis RI. Vortex element method for fluid dynamic analysis of engineering systems [M].Cambridge university press, 2003.