820. Numerical simulation research of vortex-induced vibrations of the long circular cylinders with high mass-ratio

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Abstract. The two-degrees-of-freedom vortex-induced vibrations (VIV) of the long circular cylinders with high mass-ratio are numerically simulated with the software ANSYS/CFX. The VIV characteristic of the cylinder is analyzed in the different conditions (Ur = 3, 5, 6, 8, 10). When Ur is 5, 6, 8 and 10, the conclusion is different from the vortex-induced vibrations of the cylinder with low mass-ratio. When Ur is 3, the frequency of the drag force on the cylinder is twice of that of the lift force and the in-line VIV frequency of the cylinder is twice of that of the cross-flow VIV. The in-line VIV amplitude of the cylinder is much smaller than the cross-flow VIV amplitude. The motion trace is the crescent. When Ur is 5 and 6, the frequency ratio between the drag force and lift force is still 2, but the main in-line VIV frequency of the cylinder is mainly the same as that of the cross-flow VIV and the secondary in-line VIV frequency is equal to the frequency of the drag force. The in-line VIV amplitude is still very small compared with the cross-flow VIV amplitude. When Ur is up to 8 and 10, the in-line VIV frequency of the cylinder is the same as the main frequency of the cross-flow VIV which is close to the inherent frequency of the cylinder and is different from the frequency of the drag force or lift force. But the secondary cross-flow VIV frequency of the cylinder is equal to the frequency of the lift force. The amplitude ratio between in-line VIV and cross-flow VIV is about 0.5. When Ur is 5, 6, 8 and 10, the motion trace is mainly the oval.

Keywords: high mass-ratio, vortex-induced vibration, in-line VIV, cross-flow VIV, CFD.

Introduction

The interaction of fluid and solid can lead to the complex structure movement, and in some condition still can produce serious structure damage. The vortex-induced vibration is such a common fluid-solid coupling phenomenon. In the ocean engineering, with the development of oil and gas resources to the deep water, the vortex-induced vibration research of the deep water risers is very active. The mass-ratio is one of the important parameters which influence the vortex-induced vibration of the risers, and it has very big effect of the displacement and frequency of the vibration. In the researches of the riser's vortex-induced vibration, many scholars studied the influence of the mass-ratio [1-7]. In addition, in the condition of the low mass-ratio and damping ratio, Khalak and Williamson [8] studied the rigid cylinder vortex-induced vibrations and analyzed the force, the response displacement, the wake turbulence model and the change of the phase. Vandiver [9] firstly fond that the motion trace was "8" between the in-line and cross-flow directions, which showed the coupling between the two directions. Moe and Wu [10] gave the experiment research to analyze the two-degrees-of-freedom VIV characteristic of the elastic support cylinder.

In this paper using the software-CFX, the two-degrees-of-freedom of vortex-induced vibrations (VIV) of the circular cylinder with the high mass-ratio are numerically simulated. The VIV characteristic is analyzed in the different conditions (Ur = 3, 5, 6, 8, 10). The results show that when Ur is 5, 6, 8, and 10, the frequency of in-line VIV is mainly equal to that of cross-flow VIV, which is very different from the circular cylinder with low mass-ratio. Furthermore, the motion trace of the circular is mainly the oval, which is different from the "8" trace.

The Numerical Simulation

The fluid field uses the software-ICEM to mesh gridding. Firstly it is necessary to make the physical model discrete, which is also the gridding meshing. According to previous research, the gridding number will affect the accuracy of computation and the size of the calculation scale. Generally speaking, as the gridding number increases, the calculation accuracy will be improved, but at the same time calculation scale will increase, therefore in order to determine the gridding number, two factors should be considered comprehensively [11].

In order to eliminate the influence of different grids, increase the calculation precision and reduce the computation time, this paper uses symmetry meshing gridding and Hexahedron units. The grids around the risers and vortex loss area are meshed very close in order to increase the accuracy of the results. Other area uses the linear encryption methods and gradually increases the density of the grid in order to reduce the total amount of the grids. The fluid gridding is showed in the Fig. 1.

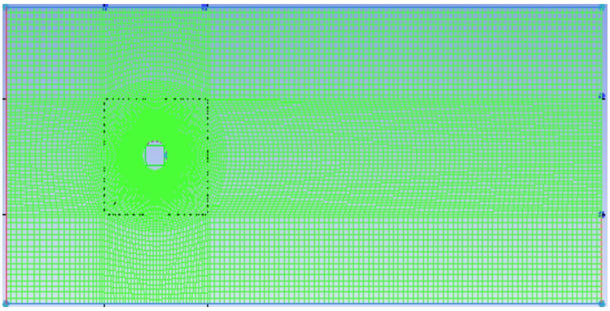


Fig. 1. Fluid field gridding

The CFX is the only large commercial software using full implicit coupled algorithm. The advancement of the algorithm and rich physical model make the ANSYS-CFX excellent in the accuracy, the calculation's stability, computing speed and the flexibility.

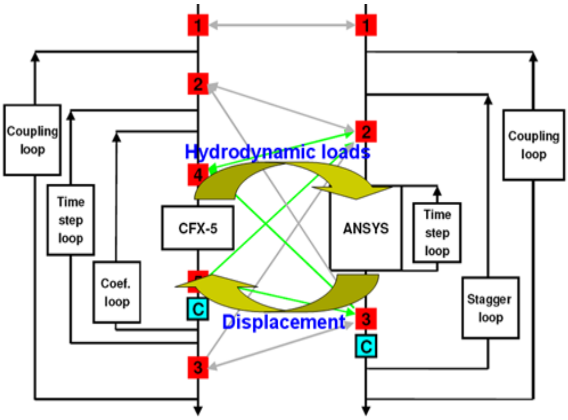


Fig. 2. The fluid-solid coupling

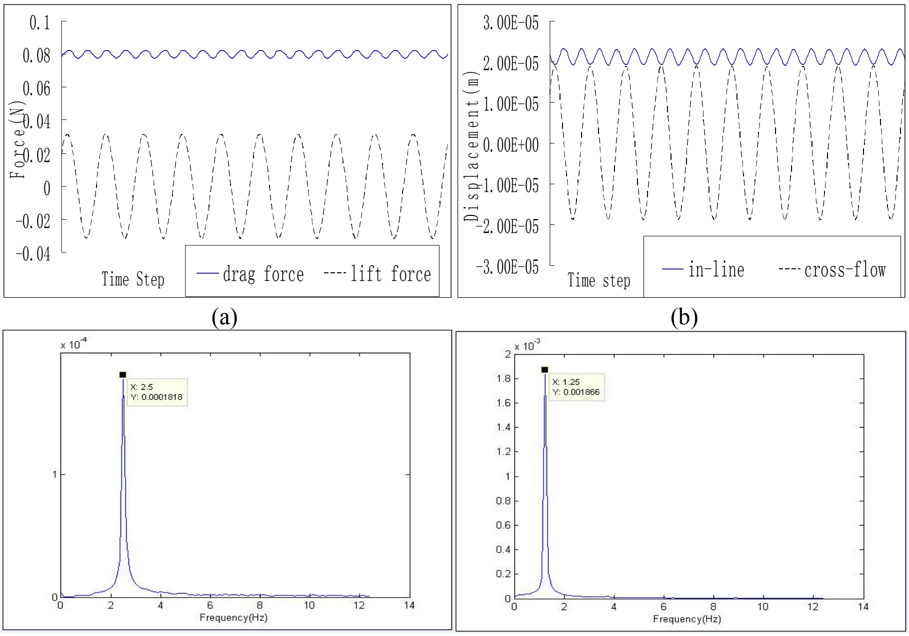
The Figure 2 shows the progress of the fluid-solid progress. Fluid-solid coupling mechanics is a mechanical branch which is generated by the fluid mechanics and solid mechanics. It is the subject which studies the solid and fluid interaction. The important feature of fluid-solid coupling mechanics is the interaction of two phase medium. The deformation solid will generate distortion and motion in the fluid field and the deformation and motion influence the fluid in turn which changes the fluid load distribution. This interaction will lead to all kinds of fluid-solid coupling phenomenon in different conditions. In fact, the fluid-solid coupling is a coupling phenomenon between the different physical fields [12]. It can be divided into three types: direct coupling, sequential coupling and synchronous solution. In order to study the vortex-induced vibrations, the paper mainly uses synchronous solution, which is synchronous two-way coupling. The synchronous solution coupling is that all the physical fields make the cycle according to the order at the same time which uses the two or more solver to transfer data in a specific time interval.

The diameter of the circular cylinder is 0.01 m, the length is 2.5 m, the slenderness ratio is 250, and the mass-ratio is 119.4. The fluid material is water, the density is 997 kg/m^3, and the dynamic viscosity is $1.005 \cdot 10^{-3}$ Pa$\cdot$s. The calculation turbulence model is k-Omega model and the inherent frequency is 2.1 Hz.

Results and Discussion

In order to study the VIV characteristic of the cylinder with high mass-ratio, the different condition is chosen which is that *Ur* is 3, 5, 6, 8 and 10.

Ur = 3. Firstly, discuss the condition when *Ur* is 3.



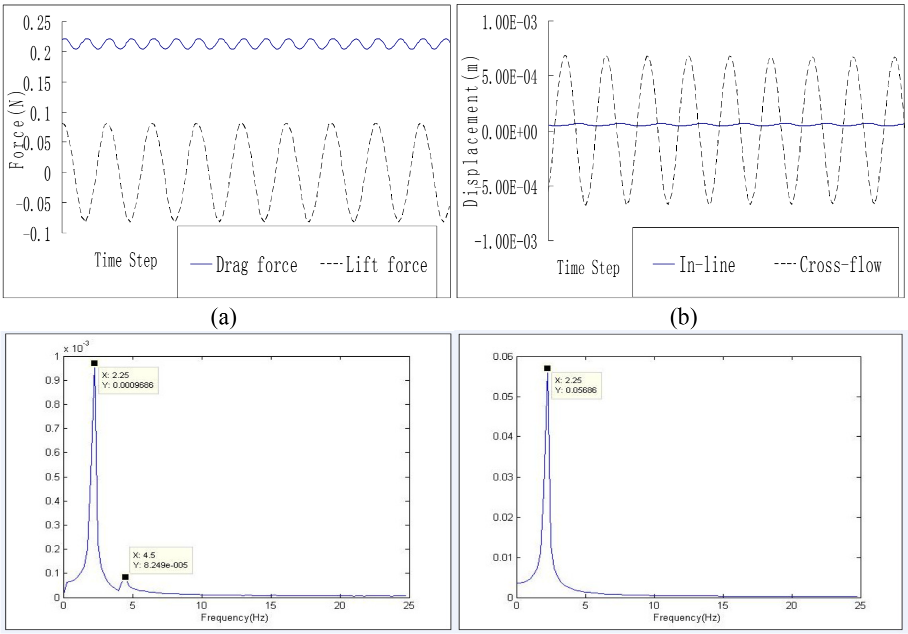
(a) (b)

(c) (d)

Fig. 3. The VIV characteristic of the cylinder under *Ur* = 3. (a) time history curve of the drag and lift force; (b) time history curve of displacement of in-line and cross-flow; (c) power spectra curve of in-line displacement; (d) power spectra curve of cross-flow displacement

In the Figure 3, Figure (a) shows that the frequency of drag force is 2.5 Hz, the frequency of lift force is 1.25 Hz. The Figure (c) and (d) show that the frequency of in-line VIV is 2.5 Hz, the frequency of cross-flow VIV is 1.25 Hz, and they both have the only peak frequency. The frequency of drag force is twice of that of lift force, and the frequency of in-line VIV is twice of that of cross-flow VIV. The frequency of in-line VIV is the same as that of drag force and the frequency of cross-flow VIV is the same as that of lift force. The in-line VIV is caused by the drag force, but the cross-flow VIV is caused by the lift force. This is consistent with the traditional vortex-induced theory. The Figure (b) show that the amplitude of in-line VIV is $1.90 \cdot 10^{-6}$ m, the amplitude of cross-flow VIV is $1.89 \cdot 10^{-5}$ m, and the amplitude ratio is 0.1. The amplitude of in-line VIV is small compared to that of cross-flow VIV.

Ur = 5 and *Ur* = 6. This part discusses the two conditions when *Ur* is 5 and 6.



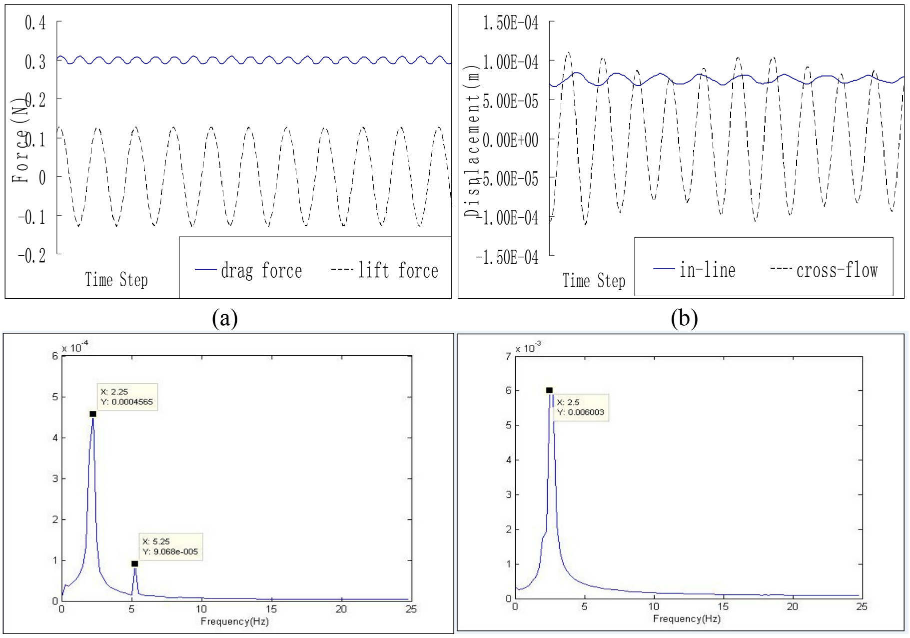
(a) (b)

(c) (d)

Fig. 4. The VIV characteristic of the cylinder under *Ur* =5. (a) time history curve of the drag and lift force; (b) time history curve of displacement of in-line and cross-flow; (c) power spectra curve of in-line displacement; (d) power spectra curve of cross-flow displacement

In the Figure 4, Figure (a) shows that the frequency of drag force is 4.25 Hz and the frequency of lift force is 2.25 Hz. The frequency of drag force is mainly twice of that of lift force. The Figure (c) and (d) shows that the main frequency of in-line VIV is 2.25 Hz and the frequency of cross-flow VIV is 2.25 Hz. This shows that the frequency of in-line VIV is equal to that of cross-flow which is the same as the frequency of lift force. But there is the secondary VIV frequency – 4.5 Hz in the in-line VIV, which is mainly equal to the frequency of the drag force. The in-line VIV and the cross-flow VIV are both caused by the lift force, but the in-line VIV is also influenced by the drag force. This is obviously different from the traditional VIV theory. The Figure (b) shows that the amplitude of in-line VIV is $1.34 \cdot 10^{-5}$ m, the amplitude of cross-flow VIV is $6.65 \cdot 10^{-4}$ m, and the amplitude ratio is 0.02, which is lower than that under *Ur* = 3. The Figure (b) also shows that the amplitude of in-line VIV is mainly up to the balance position, when the amplitude of cross-flow VIV is up to maximum, and the amplitude of cross-flow VIV is mainly up to the balance position, when the amplitude of in-line VIV is up to maximum. The phase angle is very close to 90 degrees.

In the Figure 5, Figure (a) shows that the frequency of drag force is 5.25 Hz and the frequency of lift force is 2.5 Hz. The frequency of drag force is mainly twice of that of lift force. The Figure (c) shows that the main frequency of in-line VIV is 2.25 Hz, which is equal to the main frequency of in-line VIV under *Ur* = 5. With the increase of flow velocity, the main frequency of in-line VIV does not increase, but is the same as that of in-line VIV under *Ur* = 5. There is the secondary VIV frequency – 5.25 Hz in the in-line VIV, which is equal to the frequency of the drag force. The in-line VIV is also influenced by the drag force. The Figure (d) shows that the frequency of cross-flow VIV is 2.5 Hz, which is equal to the frequency of the lift force and not equal to that of cross-flow VIV under *Ur* = 5. The conclusion can be obtained that the cross-flow VIV is mainly caused by the lift force. The Figure (b) shows that the amplitude of in-line VIV is $6.28 \cdot 10^{-6}$ m, the amplitude of cross-flow VIV is $1.04 \cdot 10^{-4}$ m, and the amplitude ratio is 0.06, which is lower than that under *Ur* = 3.



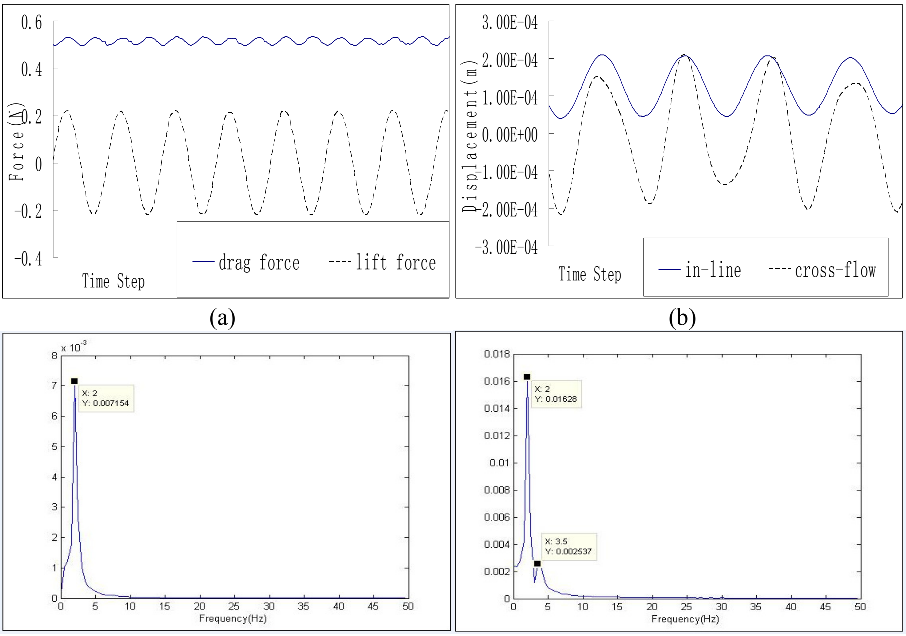
(a) (b)

(c) (d)

Fig. 5. The VIV characteristic of the cylinder under *Ur* = 6. (a) time history curve of the drag and lift force; (b) time history curve of displacement of in-line and cross-flow; (c) power spectra curve of in-line displacement; (d) power spectra curve of cross-flow displacement

Ur = 8 and *Ur* = 10. This part discusses the two conditions when *Ur* is 8 and 10.

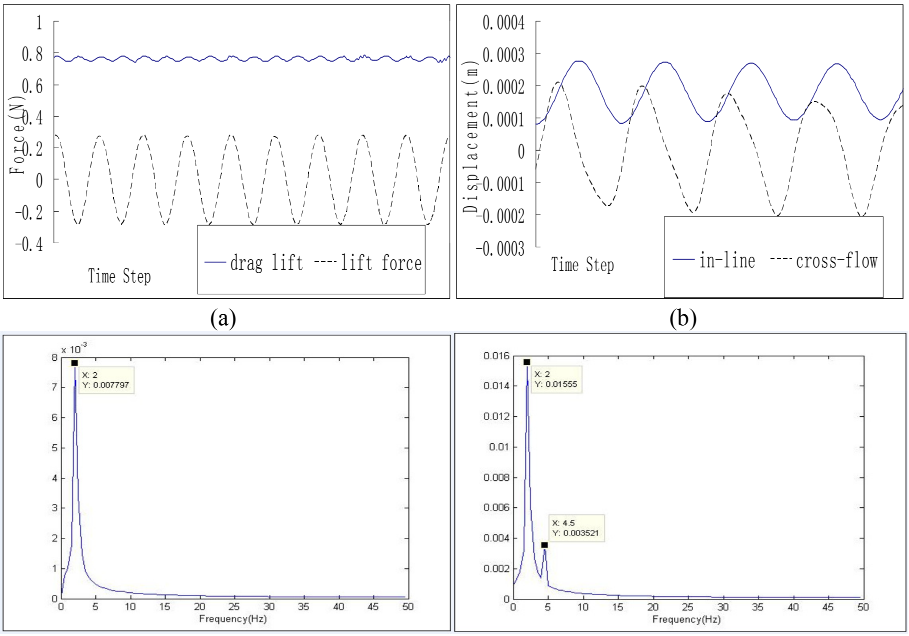
In the Figure 6, Figure (a) shows that the frequency of drag force is 7.5 Hz and the frequency of lift force is 3.5 Hz. The frequency of drag force is mainly twice of that of lift force. The Figure (c) and (d) shows that the frequency of in-line VIV is 2 Hz and the main frequency of cross-flow VIV is 2 Hz. This shows that the frequency of in-line VIV is equal to that of cross-flow. It is not the same as the frequency of drag force and also not the same as that of lift force, but is very close to the inherent frequency of the cylinder. The two-degrees-of-freedom VIV of the circular cylinder is caused by the self-excited vibration, which has nothing to do with the applied loads. But there is the secondary VIV frequency – 3.5 Hz in the cross-flow VIV, which is equal to the frequency of the lift force. The cross-flow VIV is mainly caused by the self-excited vibration and also influenced by the lift force. The Figure (b) shows that the amplitude of in-line VIV is $8.53 \cdot 10^{-5}$ m, the amplitude of cross-flow VIV is $1.50 \cdot 10^{-4}$ m, and the amplitude ratio is 0.56, which is larger than that under *Ur* = 3, 5 and 6. The in-line amplitude is nearly up to the half of the cross-flow amplitude. The Figure (b) also shows that the amplitudes of in-line VIV and cross-flow VIV are almost up to the minimum and maximum at the same time and the phase angle is very small.



(a) (b)

(c) (d)

Fig. 6. The VIV characteristic of the cylinder under *Ur* = 8. (a) time history curve of the drag and lift force; (b) time history curve of displacement of in-line and cross-flow; (c) power spectra curve of in-line displacement; (d) power spectra curve of cross-flow displacement



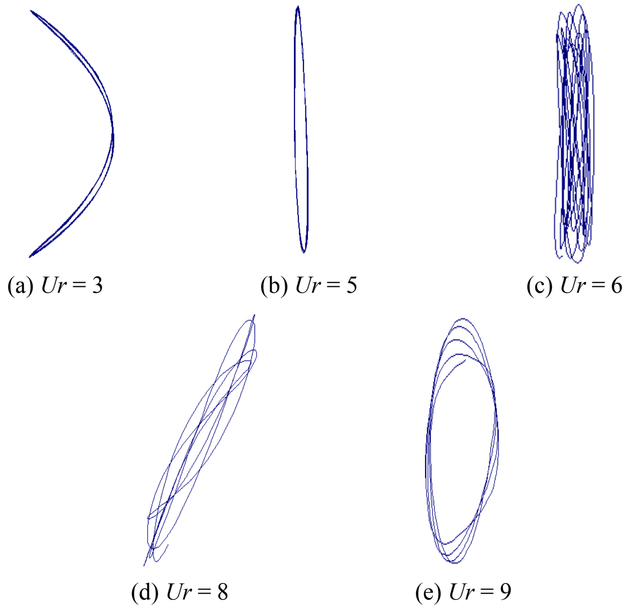
(a) (b)

(c) (d)

Fig. 7. The VIV characteristic of the cylinder under *Ur* = 10. (a) time history curve of the drag and lift force; (b) time history curve of displacement of in-line and cross-flow; (c) power spectra curve of in-line displacement; (d) power spectra curve of cross-flow displacement

In the Figure 7, Figure (a) shows that the frequency of drag force is 9 Hz and the frequency of lift force is 4.5 Hz. The frequency of drag force is twice of that of lift force. The Figure (c) and (d) shows that the frequency of in-line VIV is 2 Hz and the main frequency of cross-flow VIV is 2 Hz. This shows that the frequency of in-line VIV is equal to that of cross-flow. It is not also the same as the frequency of drag force and also not the same as that of lift force, but is very close to the inherent frequency of the cylinder. This is completely the same as the condition under *Ur* = 8. The two-degrees-of-freedom VIV of the circular cylinder is caused by the self-excited vibration, which has nothing to do with the applied loads. But there is the secondary VIV frequency – 4.5Hz in the cross-flow VIV, which is equal to the frequency of the lift force. The cross-flow VIV is mainly caused by the self-excited vibration and also influenced by the lift force. The Figure (b) shows that the amplitude of in-line VIV is $9.32\cdot10^{-5}$ m, the amplitude of cross-flow VIV is $1.75\cdot10^{-4}$ m, and the amplitude ratio is 0.53. The in-line amplitude is nearly up to the half of the cross-flow amplitude, because with the increase of the flow velocity, the amplitude of in-line VIV increases and the amplitude of cross-flow VIV decreases slightly. This is consistent with the fact that the amplitude of in-line VIV gets bigger with the increase of the flow velocity. The Figure (b) also shows that the amplitude of in-line VIV is mainly up to the balance position, when the amplitude of cross-flow VIV is up to maximum, and the amplitude of cross-flow VIV is mainly up to the balance position, when the amplitude of in-line VIV is up to maximum. The phase angle is very close to 90 degrees.

The Analysis of Motion Trace. This part discusses the motion traces under the different *Ur*.



(a) *Ur* = 3 (b) *Ur* = 5 (c) *Ur* = 6

(d) *Ur* = 8 (e) *Ur* = 9

Fig. 8. Motion trace under the different *Ur*

The Figure 8 shows the motion trace under the different *Ur*. The Figure (a) shows that motion trace is the crescent. The Figure (b) shows that motion trace is the regular oval. The Figure (c) shows that motion trace is the irregular oval, the oval begins to tilt, the tilt angle is small, and the motion trace is very chaotic. The Figure (d) shows that motion trace is the tilt oval, the tilt angle is about 45 degrees, and the motion trace is chaotic. The Figure (e) shows that motion trace is the orderly oval and the amplitude of the in-line VIV obviously increases. From Figure (b) to Figure (e), the motion trace shows the changing process from the irregular oval to the irregular oval, then to the regular oval.

Conclusions

The two-degrees-of-freedom VIV of the circular cylinder with high mass-ratio is numerically simulated with the software ANSYS/CFX. The VIV characteristic is analyzed in the different conditions ($Ur = 3, 5, 6, 8, 10$). The conclusion can be obtained:

(1) When Ur is 3, the frequency of in-line VIV is twice of that of cross-flow VIV which is equal to the frequency ratio between drag force and lift force, and the in-line amplitude is much smaller than the cross-flow amplitude.

(2) When Ur is 5 and 6, the frequency ratio between the drag force and lift force is still 2, but the main frequency of in-line VIV is mainly the same as that of cross-flow VIV and the secondary frequency of in-line VIV is equal to the frequency of the drag force. The in-line amplitude is still very small compared with the cross-flow amplitude.

(3) When Ur is up to 8 and 10, the frequency of in-line VIV is the same as the main frequency of cross-flow VIV which is close to the inherent frequency of the cylinder and is different from the frequency of drag force or lift force. But the secondary frequency of cross-flow VIV is equal to the frequency of the lift force. The amplitude ratio of the VIV between in-line and cross-flow direction is about 0.5.

(4) When Ur is 3, the motion trace of the circular cylinder is the crescent. When Ur is 5 and 10, the motion trace is both the regular oval. When Ur is 6 and 8, the motion trace is both the irregular oval and motion trace is very chaotic.

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