Numerical experiment of the vortex shedding from an oscillating circular cylinder in a uniform flow by the vortex method

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ABSTRACT

In this study, the flow features of vortex shedding from a circular cylinder forced-oscillating in the in-line direction were investigated by use of numerical simulation (vortex method) at the Reynolds number *Re*=500, with varied amplitude ratio and varied frequency ratio. The numerical experiment was performed at the two-dimensional calculation for incompressible and viscous flow. The circular cylinder was divided into 40 panels which distributed the vortices. Every calculation continued to more than non-dimensional time T = 200. The main parameters of numerical experiment were the oscillation amplitude ratio $2a/d$ (a: half-amplitude of cylinder motion, d: cylinder diameter), the oscillation frequency ratio f/f_K (f: cylinder oscillation frequency, f_K: natural Karman vortex shedding frequency). The amplitude ratio is three kinds, is 0.0, 0.25 and 0.5, respectively. The oscillation frequency ratio is 15 kinds, is from 0.2 to 3.0 every 0.2 steps. As a result of calculations, two typical flow patterns of the lock-in were shown, and it was confirmed that the calculated flow pattern were reasonable agreement with previous experiment results. The fluid force act on the oscillating cylinder was investigated. It was clarified that the amplitude of the lift coefficient was larger than the amplitude of the drag coefficient in the lock-in of alternate vortex shedding, and the amplitude of the drag coefficient was larger than the amplitude of the lift coefficient in the lock-in of simultaneous vortex shedding.

INTRODUCTION

If a circular cylinder is placed into a steady flow without a time change, vorttices will be discharged alternately. And a Karman vortex street is formed behind the circular cylinder. The Karman vortex is a very stable vortex street, and the vortex corresponding to the flow velocity is formed. That can also be said to be a natural synchronous phenomenon. Many of flows which exist really are what is called unsteady flow to which speed is changed in time. When unsteady, it is thinkable that the characteristics of the phenomenon differ compared with the case of being steady. It is industrially important to grasp the fluid force characteristic and the vortex shedding characteristic of the object put on the unsteady flow field. However, in order to realize an unsteady flow with sufficient accuracy, serious troubles are required in a laboratory. In order to experiment simple, in the laboratory, the object which exercises in the direction of flow was installed into the steady flow, so the relative unsteady flow is made. If the circular cylinder which is oscillating in the flow is placed, the vortex shedding which synchronized with circular cylinder oscillating frequency will be observed. This phenomenon was called "lock-in phenomenon" and, as for this "interference of the flow velocity change", research has been done by many researchers [1-4]. It is known that the flow pattern in the lock in state is divided roughly into the "alternate vortex shedding type" and the "simultaneous vortex shedding type". Although there is study which showed the flow pattern at the time of the lock-in, since the experiment is difficult, there is scarcely much study on the fluid force of acting on the body at the time of the lock-in. In order to study the phenomenon, the study which investigates fluid force is interesting, and important. Although the experimental study is difficult therefore, the numerical simulation using a computer is expected.

Since the vortex method which is the Lagrange type flow analyzing method does not need a calculation lattice unlike the region type analyzing method such as finite difference method and finite element method, analysis is easily possible also for the flow of the around of complicated shape. Moreover, since it is the technique of analyzing a flow by following the behaviour of the turbulent flow vortex more than the minimum vortex element size directly in Lagrange, it is possible to reproduce exactly the flow accompanied by large-scale separation and a large-scale reverse flow as well as the analysis of an unsteady flow. So, it is a technique suitable for cause investigation of phenomena made into a problem in engineering, such as a flow induced vibration excited by the flow. In this study, about the vortex shedding and the fluid force in the case from the circular cylinder which is oscillating in the direction of a flow, a systematic numerical simulation was performed and the time history of fluid force and flow pattern were investigated.

NUMERICAL CALCULATION

The numerical experiment apparatus was consisted of simulation software and a notebook type computer (NEC; LaVie LC958/T) as calculation hardware which are on the market. The software which named 'UzuCrise 2D ver.1.1.3 rev.H (College Master Hands Inc., 2006)' is used. This software used the vortex method which is based on the Lagrangian analysis. Since the vortex method is the grid-less method, it is suitable for the unsteady problem of such moving boundary. The vortex method is a direct viscid-inviscid interaction scheme, and the emanation of velocity shear layers due to boundary layer separation is represented by introduction of discrete vortices with viscous core step by step of time. In the present study, the flow was assumed incompressible and two-dimensional flow field. The configuration of circular cylinder was represented 40 vortex panels using a boundary element method. The separating shear layers were represented the discreet vortices, which were introduced at the separation points. The details of calculation technique of vortex method and accuracy of calculation are shown in Kamemoto [5, 6].

In the present study, the calculations were performed at the two-dimensional flow field for incompressible and viscous flow. A cylinder diameter d and main flow velocity U were determined as 16 mm and 0.04 m/s so that it could compare with the previous experimental result [7]. Since water is assumed as for test fluid, Reynolds number Re becomes 500. The configuration of circular cylinder was represented 40 vortex panels using a boundary element method. Its vortex panels are provided equally. Every calculation continued to until non-dimensional time T = 200.

The main parameters of numerical experiment were the oscillation amplitude ratio $2a/d$ (a: half-amplitude of cylinder motion, d: cylinder diameter), the oscillation frequency ratio f/f_K (f: cylinder oscillation frequency, f_K: natural Karman vortex shedding frequency). The oscillation amplitude ratio is three kinds, is 0.0, 0.25 and 0.5, respectively. Here, when the oscillating amplitude ratio is "0.0", it means circular cylinder stationary. The oscillation frequency ratio is 15 kinds, is from 0.2 to 3.0 every 0.2 steps.

The calculation experiment was performed in the following procedures. The case of the stationary circular cylinder is carried out first, and the case where the circular cylinder is oscillating in the direction of a flow after that is carried out. In order to grasp the flow field on the computer, and to determine for the vortex shedding frequency from the stationary single circular cylinder, it needs to be calculated in the case of the stationary circular cylinder. Secondly, the oscillating amplitude ratio is defined, the oscillating frequency ratio is varied, and systematic numerical computation is performed. If a series of numerical computation finishes, the oscillating amplitude ratio will be defined again and the numerical computation will be performed similarly. The arrangement of circular cylinders is shown in Fig. 1.

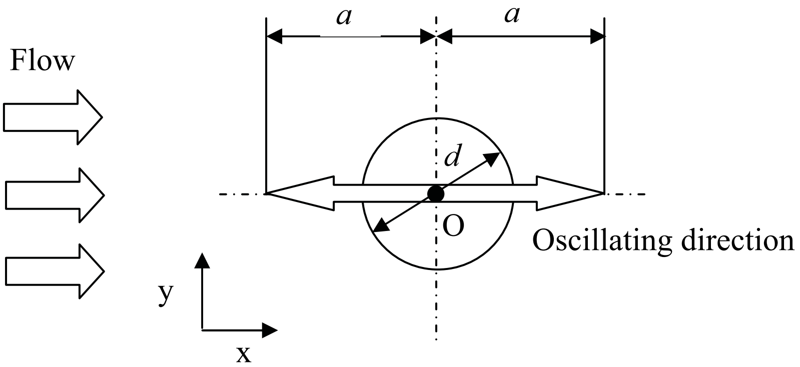
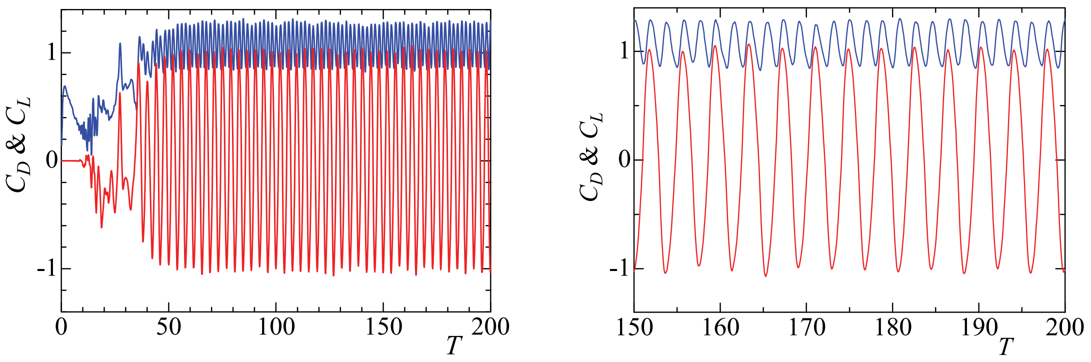


Fig. 1 Coordinate system and definition of symbols (O: the coordinate origin).

RESULTS AND DISCUSSIONS

In order to verify the calculation software to be used, the experimental result and calculation result of a stationary circular cylinder were compared. The time history of the fluid force (a drag component and lift component) of acting on a stationary circular cylinder is shown in Fig. 2. Figure 2 (a) is a time history from the non-dimension time $T = 0$ to $T = 200$, and Fig. 2 (b) expands the section from the non-dimension time $T = 150$ to $T = 200$. The drag oscillation lurking in periodic oscillation and lift oscillation of the lift produced by formation of a Karman vortex street is expressed. The relationship whose oscillation frequency of the drag is twice the oscillation frequency of the lift is shown. The following results were obtained after non-dimension time $T = 150$. Here, the diagram which defines the quantity about the fluid force is shown in Fig. 3. The average value of drag coefficient was $C_{DAVE} = 1.08$ and the root mean square value of amplitude of drag coefficient was $A_{CD} = 0.15$. The average value of lift coefficient was $C_{LAVE} = 0.00$ and the route mean square value of amplitude of lift coefficient was $A_{CL} = 0.73$. The average Strouhal number for which it determined from the lift oscillating period T was $St_{AVE} = 0.26$. The Strouhal number is defined by $St = fd/U = d/\Delta tU = 1/T$. When the Reynolds number is $Re = 500$, it is known that the experimental value of Strouhal number St is about 0.2. Although it seems that this calculation result is highly calculated as compared with an experimental result, it seems that this calculation has obtained the comparatively good calculation result since a two dimensional calculation result becomes higher than an experimental result about 30 to 40%. When the Karman vortex shedding frequency f_K was calculated from the average value of Strouhal number, the Karman vortex shedding frequency was $f_K = 0.65$ Hz.



(a) (b)

Fig. 2 Time histories of drag and lift coefficients,
(blue and red lines show drag and lift coefficients, respectivery).

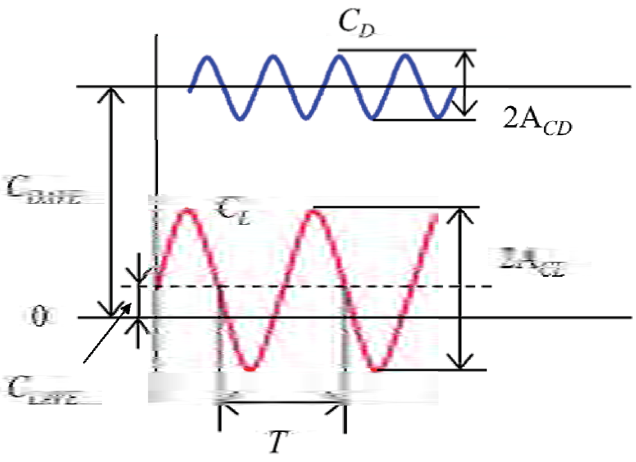
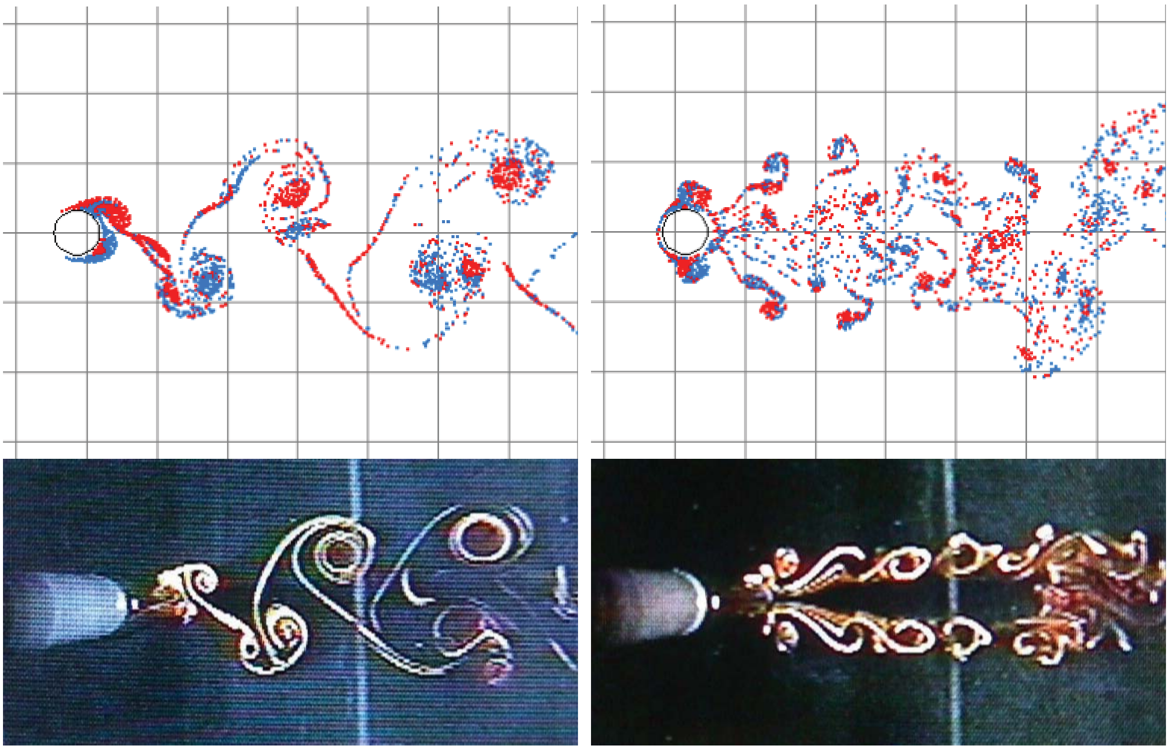


Fig. 3 The definition of the magnitude of the drag coefficient or the lift coefficient, and the definition of the oscillating period.

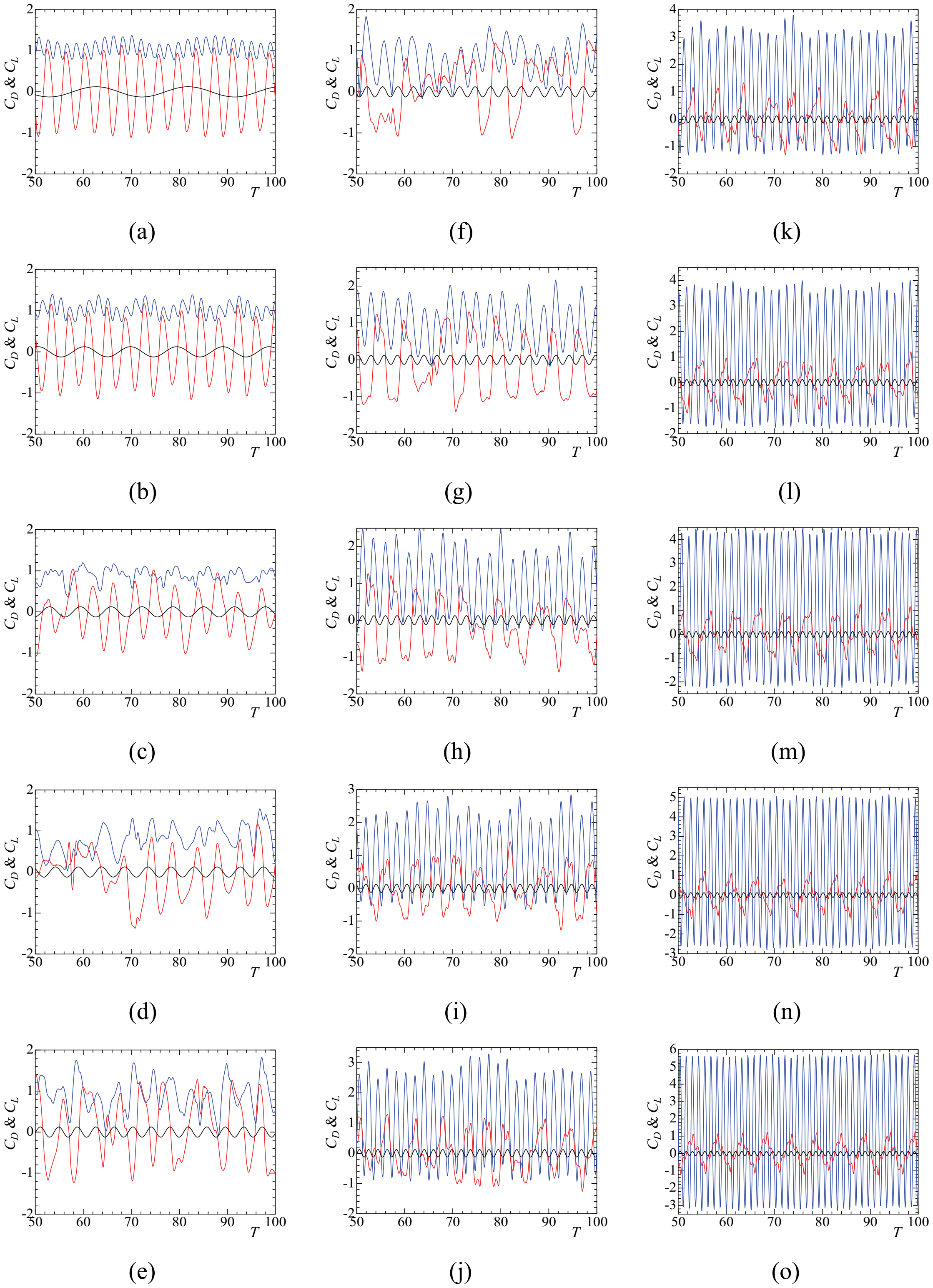
When forced oscillation of the circular cylinder is carried out, it is one of the most interesting things of this study to investigate how fluid force changes. Before performing a systematic numerical experiment, the numerical simulation was performed on the oscillating conditions which the alternate vortex shedding lock-in and the simultaneous vortex shedding lock-in generate. One example of the flow patterns obtained by calculation is shown in Fig. 4. Here, the flow visualization photographs [7] in the similar experimental condition are shown for comparison. Figure 4(a) is simulating the aspect of alternate vortex shedding lock-in. The direction of vortex shedding changes and an aspect that the vortex shedding is performed alternately is shown. An aspect that the vortex discharged from the circular cylinder constitutes a vortex pair which differs in a rotatory direction, respectively, and the vortex street of mushroom shape like the section of a mushroom is formed is expressed well. Figure 4(b) is simulating the aspect of a simultaneous vortex shedding lock-in. An aspect that the vortex of mushroom shape is simultaneously discharged from cylinder both sides, and the characteristic aspects of cylinder wake are shown. Since the characteristic flow patterns by the lock-in are expressed well, the high reliability and the usefulness of this calculation technique are found.



(a) (b)

Fig. 4 Two kinds of lock-in flow patterns, (a) shows an alternate vortex shedding type flow pattern and (b) shows the simultaneous vortex shedding type flow pattern, respectively.

It is the greatest interest matter of this study to investigate change of fluid force. The time histories of the drag coefficient C_D and the lift coefficient C_L in case oscillating amplitude ratios a/d are 0.25 and 0.5 are shown in Fig. 5 and Fig. 6, respectively. As for the time history, the range by the non-dimension time 50-100 is shown, a red line shows the lift coefficient, a blue line shows the drag coefficient, and a black line shows the motion of circular cylinder, respectively. It is found with the increase in the oscillation frequency ratio that change is looked at by the magnitude of the amplitude of the drag coefficient and the magnitude of the amplitude of the lift coefficient. And if the circular cylinder oscillating amplitude ratio becomes large, it will be found that the tendency becomes remarkable. When the oscillation frequency ratio is small, it can be seen that the amplitude of lift coefficient is larger than the amplitude of drag coefficient. On the other hand, when the oscillation frequency ratio is large, the amplitude of drag coefficient is seen be larger than the amplitude of lift coefficient. Here, the "lock-in" is that the vortex shedding frequency from the circular cylinder synchronizes with circular cylinder oscillation frequency. So, it takes notice of the relationship between the waveform of circular cylinder oscillation, the waveform of a drag coefficient, and the



(a) (f) (k)

(b) (g) (l)

(c) (h) (m)

(d) (i) (n)

(e) (j) (o)

Fig. 5 Time histories of drag and lift coefficients in the case of oscillation amplitude ratio a/d = 0.25 (blue and red lines show drag and lift coefficients, black line is cylinder motion); (a) $f/f_K = 0.2$, (b) $f/f_K = 0.4$, (c) $f/f_K = 0.6$, (d) $f/f_K = 0.8$, (e) $f/f_K = 1.0$, (f) $f/f_K = 1.2$, (g) $f/f_K = 1.4$, (h) $f/f_K = 1.6$, (i) $f/f_K = 1.8$, (j) $f/f_K = 2.0$, (k) $f/f_K = 2.2$, (l) $f/f_K = 2.4$, (m) $f/f_K = 2.6$, (n) $f/f_K = 2.8$, (o) $f/f_K = 3.0$

waveform of a lift coefficient. The case where the lift coefficient is oscillating with the period twice the period of the circular cylinder oscillation is the alternate vortex shedding type lock-in. On the other hand, the case where the drag coefficient is oscillating synchronizing with the period of the circular cylinder oscillation is the simultaneous vortex shedding type lock-in. In the magnitude

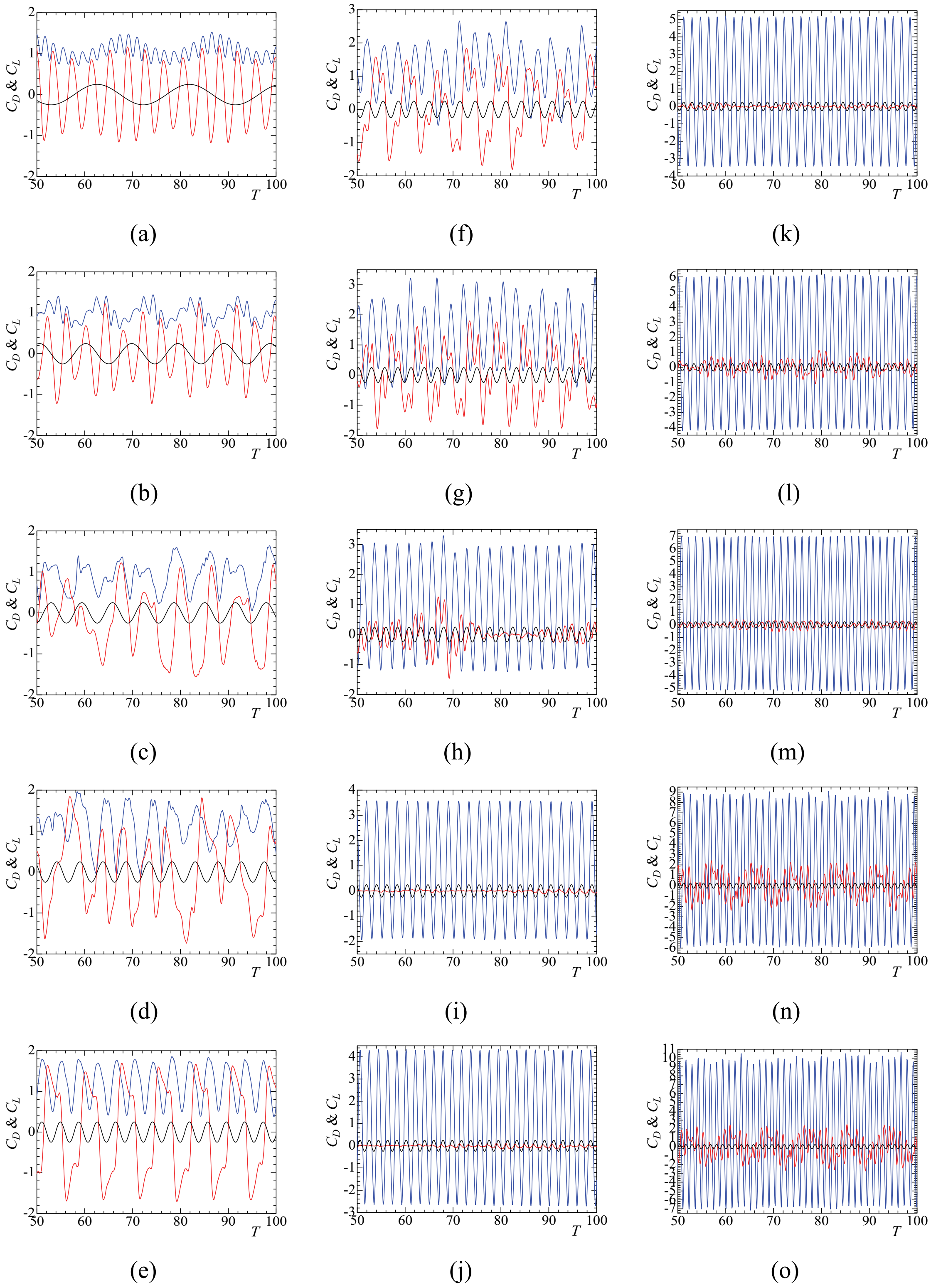


Fig. 6 Time histories of drag and lift coefficients in the case of oscillation amplitude ratio a/d = 0.50 (blue and red lines show drag and lift coefficients, black line is cylinder motion); (a) f/f_K = 0.2, (b) f/f_K = 0.4, (c) f/f_K = 0.6, (d) f/f_K = 0.8, (e) f/f_K = 1.0, (f) f/f_K = 1.2, (g) f/f_K = 1.4, (h) f/f_K = 1.6, (i) f/f_K = 1.8, (j) f/f_K = 2.0, (k) f/f_K = 2.2, (l) f/f_K = 2.4, (m) f/f_K = 2.6, (n) f/f_K = 2.8, (o) f/f_K = 3.0

relationship of the lift coefficient and the drag coefficient, when the amplitude of the lift coefficient is large, it becomes the alternate vortex shedding, and when the amplitude of the drag coefficient is large, it becomes the simultaneous vortex shedding. In Fig. 5, the alternate vortex shedding type lock-in is shown in Fig. 5(g), and the simultaneous vortex shedding type lock-in is shown in Fig. 5(k)

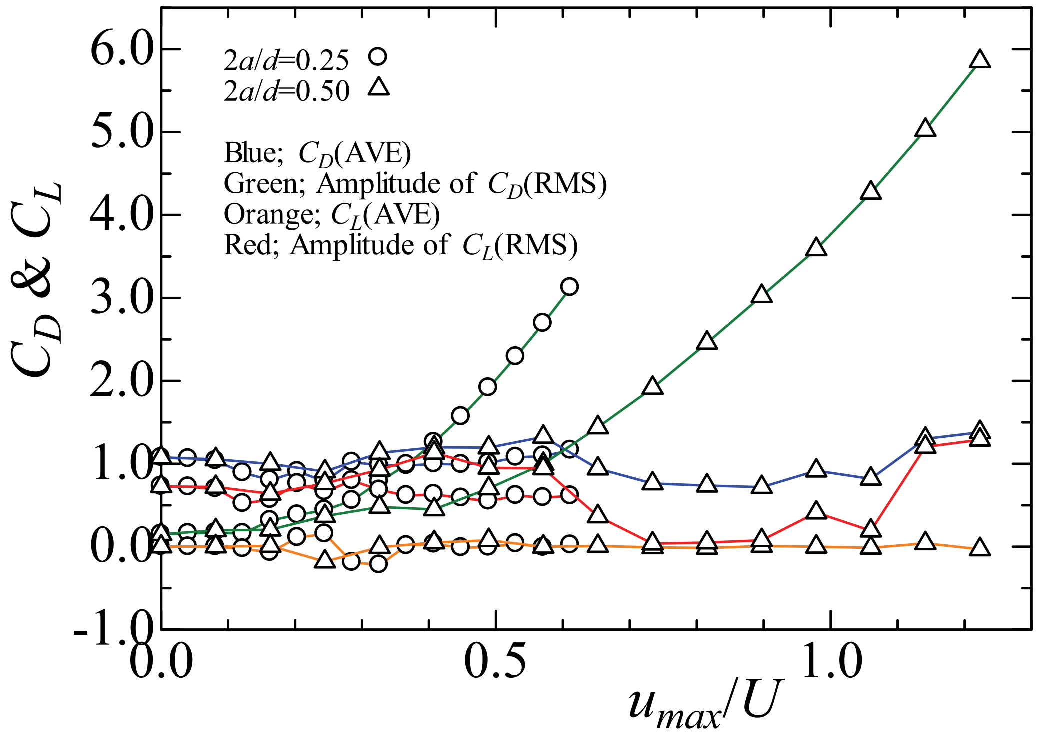


Fig. 7 The variation of fluid force component act on single oscillating cylinder, $u_{max}/U = 2(a/d)(f/f_K)(\pi St)$

- Fig. 5(o). In Fig. 6, the alternate vortex shedding type lock-in is shown in Fig. 6(e) - Fig. 6(g), and the simultaneous vortex shedding type lock-in is shown in Fig. 6(i) - Fig. 6(o).

The aspects of a variation of fluid force are shown in Fig. 7. An abscissa is the velocity ratio u_{max}/U and an ordinate is each component of fluid force. Here, the velocity ratio defined as $u_{max}/U = 2a/d \cdot f/f_K \cdot (\pi St)$. Since an oscillation frequency ratio f/f_K is constant value, this figure means the variation of the fluid force over the variation of an oscillating amplitude ratio $2a/d$. In the case of low velocity ratio, although the value of drag coefficient C_{DAVE} is smaller than a stationary value, the value of the lift coefficient C_{LAVE} scarcely changes to the stationary value. The value of the amplitude of drag coefficient AC_{DRMS} is increasing while the value of amplitude ratio $2a/d$ increases. On the other hand, although the amplitude of lift coefficient AC_{LRMS} scarcely changed the amplitude ratio to $2a/d = 0.5$, the amplitude of lift coefficient became suddenly small value from velocity ratio $u_{max}/U = 0.65$. In the case of high velocity ratio, the value of drag coefficient C_{DAVE} and the value of lift coefficient C_{LAVE} scarcely change to the stationary case. The value of amplitude of drag coefficient is large and the value of drag coefficient AC_{DRMS} tends to increase with increase of amplitude ratio $2a/d$. However, the value of amplitude of lift coefficient AC_{LRMS} will become smaller than the value of stationary cylinder case at $2a/d = 0.25$ and 0.5, the amplitude of lift coefficient became suddenly large value from the velocity ratio $u_{max}/U = 1.14$.

CONCLUSIONS

A systematic numerical simulation of the flow around a circular cylinder which oscillates in the direction of a flow using the vortex method was performed. The following conclusions were obtained.

(1) The flow pattern of two kinds of lock-in states was well in agreement with the aspect of a previous experiment visualization result.

(2) It is found with the increase in the oscillation frequency ratio that change is looked at by the magnitude of the amplitude of the drag coefficient and the magnitude of the amplitude of the lift coefficient.

(3) In the magnitude relationship of the lift coefficient and the drag coefficient, when the amplitude of the lift coefficient is large, it becomes the alternate vortex shedding, and when the amplitude of the drag coefficient is large, it becomes the simultaneous vortex shedding.

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