The numerical simulation of the changes of lock-in phenomenon produced from an in-line oscillating circular cylinder by the vortex method

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Abstract. This study carries out a numerical simulation about changes of the lock-in phenomenon of the single circular cylinder which is oscillating in the direction of a flow. As for the calculation method of this study, the vortex method was used. The calculation was carried out by Reynolds number $Re = 500$. The oscillating amplitude ratio was $2a/d = 0.25$ and the range of oscillating frequency ratio $ff_x$ was 0 to 3. In order to know the reliability of the calculation method, the flow aspect and fluid force of the stationary single circular cylinder were investigated, and it compared with the existing experimental result. The result was well in agreement. Also in calculation of the oscillating single circular cylinder, two typical flow patterns when a lock-in occurs were expressed. The relationship of the drag and lift was also found. The aspects of the flow of the situation which the lock-in does not produce was investigated. In the situation which the lock-in does not produce, there is no particular flow pattern and it became clear that two typical vortex shedding configurations interchanged and appeared. It was found that the character of such a complicated flow can also be expressed by the vortex method.

1. Introduction
If a circular cylinder is placed into a steady flow without a time change, vortices 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 are 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 are many studies treating the aspect of the flow of the state of the lock-in, there are few studies treating the aspect of the flow of a non-lock-in state. The flow of the non-lock-in state is complicated. So, it is important to observe such flows. Probably, the special flow pattern of the non-lock-in state does not exist, but is considered that the alternate vortex shedding and the simultaneous vortex shedding have repeated the appearance intermittently. By flow visualization experiment, Yokoi and Hirao [5] are observing intermittent replacement of the alternate vortex shedding and the simultaneous vortex shedding, and have reported the rate. The author carried out the simulation for those lock-in states, and showed the validity of the vortex method. 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. In this study, the result of having carried out the numerical simulation about the flow aspect and fluid force in the non-lock-in state is reported.

2. 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 [6, 7].

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 [8]. 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 0.00 and 0.25, 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 $(2a/d = 0.25)$, the oscillating frequency ratio is varied, and systematic numerical computation is performed. The arrangement of circular cylinders is shown in Fig. 1.

3. 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-dimensional time $T = 0$ to $T = 200$, and Fig. 2 (b) expands the section from the
non-dimensional 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-dimensional 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 $C_{\text{DAVE}} = 1.08$ and the root mean square value of amplitude of drag coefficient was $A_{\text{CD}} = 0.15$. The average value of lift coefficient was $C_{\text{LAVE}} = 0.00$ and the route mean square value of amplitude of lift coefficient was $A_{\text{CL}} = 0.73$. The average Strouhal number for which it determined from the lift oscillating period $T$ was $S_{\text{LAVE}} = 0.26$. The Strouhal number is defined by $S_{\text{t}} = \frac{f d}{U} = \frac{d}{\Delta t U} = \frac{1}{T}$. When the Reynolds number is $Re = 500$, it is known that the experimental value of Strouhal number $S_{\text{t}}$ 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.

![Figure 1](image1.png)

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

![Figure 2](image2.png)

(a) Figure 2. Time histories of drag and lift coefficients, (blue and red lines show drag and lift coefficients, respectively).
It calculated in the condition which produces the alternate vortex shedding lock-in and the simultaneous vortex shedding lock-in for authorization of this calculation method. The result is shown in Fig. 4 with a previous experimental result [8]. The feature of the alternate vortex shedding lock-in and the feature of the simultaneous vortex shedding lock-in can be seen well expressed in calculation. The natural Karman vortex lock-in, the alternate vortex shedding lock-in, and the simultaneous vortex shedding lock-in are in the state where the flow pattern is being fixed. In such the state, it was found that the vortex method can be suitable good.

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

Figure 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 observed by the flow visualization experiment [5] that two flow patterns interchange intermittently and appear in the state of the non-lock-in at the time of circular cylinder oscillation. In calculation of the vortex method, it is one of the most interesting matters whether such a state can be expressed. The non-lock-in state is divided into the following three regions. It is the case of circular cylinder oscillation frequency lower than the circular cylinder oscillation frequency which the alternate vortex shedding lock-in produces. The aspect of the flow in this case is an alternate vortex shedding similar to the Karman vortex. It is the case of circular cylinder oscillation frequency higher than the circular cylinder oscillation frequency which the simultaneous vortex shedding lock-in produces. Since the aspect of the flow in this case has strayed off from the simultaneous vortex shedding lock-in, it is an alternate vortex shedding similar to the Karman vortex. In other than these, replacement of those flow patterns is generated. Accordingly, it is the case of circular cylinder oscillation frequency lower than the circular cylinder oscillation frequency which the simultaneous vortex shedding lock-in produces in circular cylinder oscillation frequency higher than the circular cylinder oscillation frequency which the alternate vortex shedding lock-in produces. For imagining the aspect of the flow pattern, it is important to investigate the fluid force.

The time histories of the drag coefficient $C_D$ and the lift coefficient $C_L$ in case oscillating amplitude ratios $a/d = 0.25$ are shown in Fig. 5. 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. 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 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 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 Figs. 5(k) - 5(o).

The discovery which is the worthiest by this study was obtained. The example is shown in Fig. 6. It shows the flow pattern at the time of oscillation frequency ratio $f/f_c = 1.6$. Figure 6 (a) is visible to the alternate vortex shedding type of mushroom shape. Figure 6 (b) seems for a twins vortex to incline and to carry out the vortex shedding simultaneously. The time history of the fluid force of this state is shown in Fig. 5 (h). The oscillating period of the drag coefficient synchronizes with the circular cylinder oscillating period. On the other hand, the oscillating period of the lift coefficient is 1.5 times the circular cylinder oscillating period, and has strayed off from the lock-in. As a result, although the vortex shedding near the circular cylinder is carried out simultaneously, the phenomenon in which the discharge direction changes occurs. So, the vortex shedding which occurs simultaneously will change the discharge direction like a pendulum. Since the deflection width of the pendulum depends on the magnitude of the amplitude of the lift coefficient, when the amplitude is small, the direction of a vortex shedding becomes in the direction of a direct down-stream. Accordingly, the vortex to which the boundary layer separation rolled simultaneously is discharged by the balance of fluid force becomes alternate arrangement, or becomes simultaneous arrangement. It was able to express replacement of the vortex shedding in the vortex method.
Figure 5. Time histories of drag and lift coefficients in the case of oscillation amplitude ratio \( \frac{a}{d} = 0.25 \) (blue and red lines show drag and lift coefficients, black line is cylinder motion).
4. 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 and the flow pattern of natural lock-in state were well in agreement with the aspect of the previous experiment visualization result.

(2) 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.

(3) The replacement of two flow patterns was expressed by the pendulum vortex shedding phenomenon and the magnitude of the lift which acts on the circular cylinder.

(4) It was found that the vortex method can be suitable also at such a complicated flow field.

(5) As future work, to investigate the dependability of Reynolds number and verification experiments of the numerical computation result are desired.

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