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Flow feature of a pair of in-line forced oscillating 45 degrees staggered arranged circular cylinders

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Abstract. In order to understand the aspect of the mutual interference flow from two circular cylinders, the visual observation experiments was performed. The staggered arrangement angle was made into 45 degrees and the cylinder setting conditions were three kinds of distance ratios (L/d = 1.5, 2.5 and 5.5). The oscillating conditions were four kinds of amplitude ratios ($2a/d$ = 0.25, 0.5, 0.75 and 1.0), and the oscillation frequency ratio f/f_K in 28 steps. The Reynolds number was about 640. As the result of experiment, also in the case of staggered arrangement oscillating two circular cylinders, the lock-in phenomenon was observed. Four characteristic flow patterns at the time of lock-in were obtained by having oscillated two circular cylinders of staggered arrangement in the direction of the flow. Even if the mutual interference of two circular cylinders was in the state of appearing strongly, when the circular cylinder was oscillated, the lock-in phenomenon was observed. In a single circular cylinder and two circular cylinders of staggered arrangement, the distribution of the range and a flow pattern which carries out a lock-in differs. Distribution of the flow pattern of the 1st circular cylinder and distribution of the flow pattern of the 2nd circular cylinder change with distance ratios.

1 Introduction

Quite a bit of knowledge has been accumulated regarding flow around independent bluff cylinders, such as a circular cylinder, a triangular cylinder, and a square cylinder. In recent years, knowledge of flow around an independent bluff cylinder has been expanded form steady flow fields to unsteady flow fields. Yokoi and Hirao [1] investigated the effect of cylinder oscillation on vortex shedding and they classified flow pattern by flow visualization into five kinds by the configuration of vortex shedding and direction of vortex shedding. However, since the structure placed into the flow consists of two or more bluff cylinders in many cases, it is not known whether the knowledge of an independent bluff cylinder can be suitable as it is. Two or more simplest examples of combination of a structure are the cases where two circular cylinders have been arranged to the flow in parallel or in tandem. There are many reports of research which performed investigation of the flow characteristic or the flow feature by such circular cylinder arrangement. Sumner et al. [2] identified various flow patterns observed in the flow around two stationary cylinders arranged in a staggered configuration, and discussed the relation between the flow patterns and the vortex shedding frequencies in detail. As study of the vortex shedding in an unsteady flow, Sarpkaya and Cinar [3] varied the attack angle (α = 0, 30, 60 and 90 degrees) and distance ratio of two circular cylinders (L/d = 1.5~3.5), and performed investigation of fluid force which acts on each circular cylinder using an up righted U type oscillating water tank. Williamson [4] performed measurement of flow visualization and pressure simultaneously, and investigated the relationship between the vortex shedding from two circular cylinders, and fluid force. As a result, it was explained that the variation of a lift and the force between circular cylinders change with cylinder intervals. Chan [5] investigated in the flow the self oscillation of two circular cylinders arranged tandem, parallel and staggered, and surveyed the general formula to an oscillating response. Yokoi and Hirao [6, 7] investigated the feature of vortex shedding and the vortex formation from a pair of in-line forced oscillating parallel arranged circular cylinders of same or unequal diameter. And Yokoi [8] also investigated the flow patterns of vortex shedding from a pair of tandem arranged circular cylinders oscillating along the direction of flow. They show the variation of mean vortex shedding frequency, the "lock-in" pattern distribution in the lock-in region and representative flow patterns. However, there are few reports investigated at the arrangement angle between them. It is very important to experiment by varying an arrangement angle and to accumulate data, since the direction of flows, such as the direction of the wind, may change. Since the state where the steady flow was

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maintained is in a rare state industrially, accumulation of the data of an unsteady flow is desired.

The purpose of this study is accumulation of the basic data for comparison with the flow under unsteady flow. In this study, the arrangement angle was made into 45 degrees and the flow patterns of vortex shedding from two circular cylinders arranged staggered was investigated by visualizing water flow experiment.

2 Experimental apparatus and method

2.1 Outline of experimental apparatus

The experimental apparatus consists of a closed circuit water channel, a cylinder oscillator, a set of visual apparatus and set of data record equipment. The closed circuit water channel is a vertical circulation type of 5.8 m in length, 1.2 m in width, and 2.5 m in height, and the volume of water is 4 tons. The water channel is consisted of water flow generation equipment (2 axial flow type pumps), rectification device, test section and 4 corner parts with guide vanes. The test section is 2 m in length, 0.8 m in width, 0.4 m in depth, and the flume structure with the surface of the water. In the test section, the window made of the glass of 1.5 m in length and 0.4 m in width has been installed in the both sides wall and the bottom for the observation. The velocity distribution in the test section was ± 1.5 % against main flow velocity 0.4 m/s from depth 50~350 mm and the test section center in the direction of width within the range of ± 300 mm. There is a set of rail orbit on the flume flange and a carriage is set up.

The oscillator which installed CCD (charge-coupled device) camera and test cylinder, the visualization apparatus are loaded into the carriage. The cylinder oscillator is using a Scotch-yoke mechanism and the oscillator consists of a small-sized variable AC motor with a controller, a turn disk and a connecting rod. The amplitude of oscillation is set by changing the rotation radius of connecting edge on the turn disk, while the frequency of oscillation is controlled by changing the revolution speed of the turn disk.

The circular cylinders are made from hollow aluminium with 16 mm of outside diameter, 14 mm calibres, and 600 mm length. The cylinders of them without end plates are mounted vertically in a free-surface water channel, where its bottom end is free and its top end is clamped to an oscillator. Thus the circular cylinder is given a longitudinal sinusoidal oscillation. The arrangement of circular cylinders is shown in figure 1. For convenience, front side and rear side cylinders are called the “1st cylinder” and “2nd cylinder”, respectively.

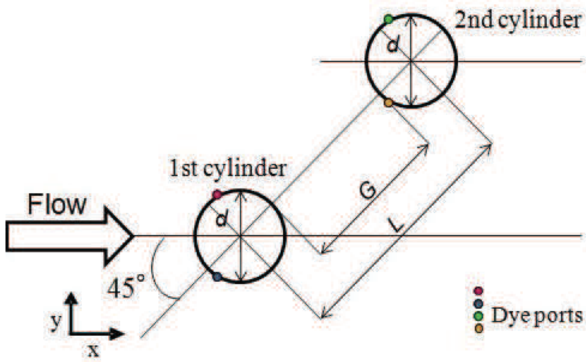

Fig. 1. Coordinate system and definition of symbols. The small circles with a color show the position where a tracer oozes. Each tracer oozing position is a position of 60 degrees from a front stagnation point. Here, $L = G + d$.

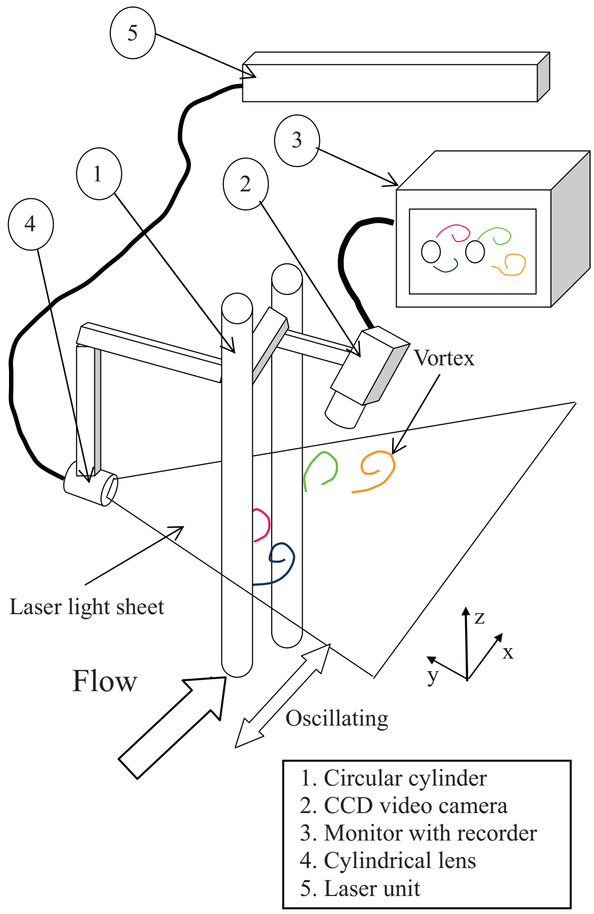

Fig. 2. Schematic diagram of the layout of flow visual apparatus. The camera is attached so that it may move with movement of the circular cylinder. The laser light sheet is not used for photography using poster paint.

2.2 Outline of flow visualization

A schematic diagram of the layout of flow visual apparatus is shown in figure 2. The horizontal section of the flow at a depth of 140 mm below the water surface which was enough for observation was visualized by the laser light sheet technique which was based on the dye injection method. The visualized flow patterns were monitored by the CCD video camera which set above the surface of the water. In this experiment, an argon gas laser beam (4 W maximum power) was conducted to a cylindrical lens, which spread it into a two-dimensional laser light sheet. In the plane of the laser light sheet, the flow was visualized by means of tracer ink (Rhodamine B and poster paints (turquoise, fluorescent pink, fluorescent green and fluorescent orange) with same specific gravity of water), which oozed out from two dye ports at plus-minus 60 degree from the front stagnation point of the circular cylinder. The visualized flow patterns were monitored by the CCD video camera and recorded on video recorder.

2.3 Experimental parameters

The main experimental parameters given by the distance ratio L/d (the ratio of cylinder distance L to the outside diameter of cylinder d), the oscillation frequency ratio f/f_K (the ratio of circular cylinder oscillation frequency f to natural Karman vortex's frequency f_K), the amplitude ratio $2a/d$ (the ratio of half amplitude of cylinder motion a to the outside diameter of cylinder d) and the main flow velocity in the test section U. The distance ratio L/d was changed three stage (L/d = 1.5, 2.5 and 5.5). The oscillation frequency ratio f/f_K was varied from 0.0 to 7 (28 steps), and the amplitude ratio $2a/d$ was set 0.25, 0.5, 0.75 and 1.0. The arrangement angle was made into 45 degrees. The main flow velocity U was 0.041 m/s which correspond to Reynolds number about 640 ($Re = Ud / \nu$, where ν is the kinematic viscosity of water).

2.4 Experimental procedure

At first step, the flow velocity of the test section is set up by inputting operation frequency into the operator control panel of the closed circuit water channel. One circular cylinder is installed into an aimed flow and tracer ink is oozed. The tracer ink was oozed into the flow from two dye ports on a stationary circular cylinder and the visualized aspects of separated wake flow were recorded on video tapes. The natural Karman vortex shedding frequency f_K was measured by counting the visualized vortices shed from the stationary circular cylinder for a certain period of time. (In this experiment, the value of Karman vortex frequency f_K was 0.45 Hz.)

The second steps, after setting up the distance ratio L/d and the arrangement angle α, the tracer ink is made to ooze from each circular cylinder, and each vortex flow is observed without cylinder oscillation.

The third steps, the setup of the oscillating amplitude a and the setup of the oscillating frequency f were performed and the tracer ink is made to ooze from each circular cylinder, and each vortex flow is observed. Here, the cylinder distance L, the half-amplitude of oscillation a and the cylinder oscillation frequency f were set to be desired values of the distance ratio L/d, the amplitude ratio $2a/d$ and the oscillation frequency ratio f/f_K. The visualized flow feature from the oscillating cylinders was monitored and recorded on video recorder. The vortex shedding frequency f_{VK} was obtained from the number and the measurement time of past vortex at the observation point. The cylinder oscillation frequency f was calculated by measuring an oscillation cycle. The measurement technique of vortex shedding frequency is the primitive technique which plays video and is performed by viewing of man. Neither image-processing equipment nor image-processing software is used for the measurement. The value of the standard deviation of the Strouhal number obtained in this experiment was 0.004.

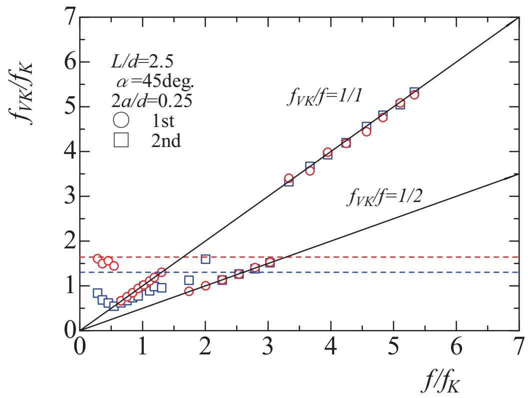

Fig. 3. The diagram for explaining the lock-in. Data show in the case of L/d = 2.5, $2a/d$ = 0.25. If data is plotted on the solid line, it means the lock-in.

3 Experimental results and discussion

3.1 Vortex shedding characteristics

It is one of the most interesting things in this study to investigate the mutual interference of the two circular cylinder wakes in an unsteady flow. The arrangement angle of two circular cylinders was made into 45 degrees from the experimental result in steady flow, the distance ratio L/d, the amplitude ratio $2a/d$, and the oscillation frequency ratio f/f_K were varied, and experiment investigation was performed. An example which investigated the variation of the vortex shedding frequency by circular cylinder oscillation is shown in figure 3. The abscissa is the oscillation frequency ratio f/f_K and the ordinate is the vortex shedding frequency ratio f_{VK}/f_K. Two solid lines in the figure have the ratio of the vortex shedding frequency in case of the cylinder oscillation f_{VK} and the circular cylinder oscillating frequency f and mean the "lock-in" status. Therefore, the occurrence of lock-in can be assumed when experiment data are shown on the line. Those dashed lines mean the vortex shedding frequency from each circular cylinder when the circular cylinder is not oscillating. The red dashed line and the blue dashed line show the vortex shedding frequency of the 1st cylinder in stationary case, and the vortex shedding frequency of the 2nd cylinder in stationary case, respectively. The circle symbol is experimental result of the 1st cylinder, and the square symbol is experimental result of the 2nd cylinder. The lock-in phenomena were seen even if the mutual interference of two circular cylinders was in the state of appearing strongly. Here, the lock-in shown on the line of f_{VK}/f = 1/2 calls it "A (alternate vortex shedding) lock-in", and the lock-in shown on the line of f_{VK}/f = 1/1 calls it "S (simultaneous vortex shedding) lock-in".

Figure 4 shows the range which "A lock-in" and "S lock-in" generate in all distance ratio and all amplitude ratios. Lock-in data is divided by three distance ratios (L/d = 1.5 and 2.5 and 5.5), and the data of the 1st circular cylinder and the data of the 2nd circular cylinder

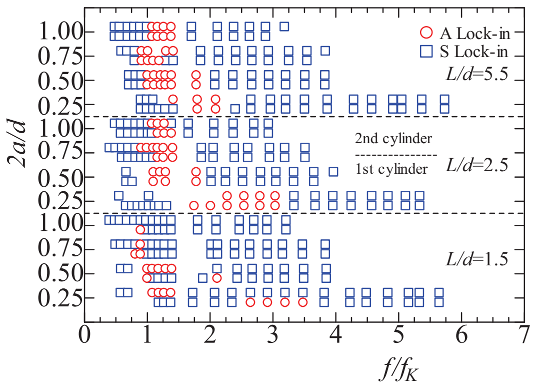

Fig. 4. Lock-in range and lock-in state distribution.

are shown in every amplitude ratio ($2a/d$ = 0.25, 0.5, 0.75 and 1.0). The lower row is data of the 1st circular cylinder, and the upper row is data of the 2nd circular cylinder. The red circle symbol and the blue square symbol show "A lock-in" and "S lock-in", respectively. Although the range of the oscillation frequency which carries out the lock-in also to the 1st cylinder and the 2nd cylinder was about the same in the high oscillation frequency side, differing was found with the 1st cylinder and the 2nd cylinder at the low oscillation frequency side. It is found that the configuration of the lock-in of the 1st circular cylinder differs from the configuration of the lock-in of the 2nd circular cylinder. And if it is not based on those distance ratios but the amplitude ratio increases, the range which a lock-in generates can be seen tend to narrow. When the distance ratio is small L/d = 1.5, as compared with other distance ratios, generating of the "A lock-in" is seen few. The vortex shedding has been rolled by the separating shear layer. Although this separating shear layer is mainly generated by the flow from the upstream side, the re-circulation flow from the down stream side also originates greatly. If development of the re-circulation flow is not enough, the early twins vortex formation looked at by the start flow will be intermittently repeated synchronizing with circular cylinder oscillation, and, as a result, the "S lock-in" will occur. It is one of the most interesting things in this study to investigate the influence of oscillation of the flow in the state where the mutual interference of two circular cylinders appears strongly. When the mutual interference of two circular cylinders oscillated the circular cylinder also in the state of appearing strongly, the lock-in phenomenon was observed. Although the range of the oscillation frequency which carries out the lock-in also to the 1st circular cylinder and the 2nd circular cylinder was the same in the high oscillating frequency side, the difference was seen with the 1st circular cylinder and the 2nd circular cylinder at the low oscillating frequency side. When the amplitude ratio was varied, the range which carries out the lock-in also changed. And the variation was seen also to an inside, like the range of a simultaneous vortex shedding type lock-in (lock-in of f_{VK}/f = 1/1) spreads. When a distance ratio is L/d = 1.5, the unique phenomenon has occurred. When the 1st circular cylinder is an alternate vortex shedding type lock-in ("A Lock-in"), with the 2nd circular cylinder, the simultaneous vortex shedding type lock-in ("S Lock-in") has produced it. When a distance ratio is L/d = 2.5, in beyond oscillation frequency ratio f/f_K = 0.6, the tendency which carries out a lock-in also to the 1st circular cylinder and the 2nd circular cylinder is seen. Moreover, the unique phenomenon was obtained also here. It is that the lock-in configuration changes with amplitude ratios. For example, when the case of the amplitude ratio $2a/d$ = 0.25 and the amplitude ratio $2a/d$ = 0.5 was compared, it was an alternate vortex shedding type lock-in in the range of oscillating frequency ratio f/f_K from1.8 to 3 at the time of amplitude ratio $2a/d$ = 0.25, but at the time of amplitude ratio $2a/d$ = 0.5, it was a simultaneous vortex shedding type lock-in. When the distance ratio was L/d = 5.5, in the 1st circular cylinder and the 2nd circular cylinder, the difference did not almost have the range of the appearance oscillation frequency of an alternate vortex shedding type lock-in and a simultaneous vortex shedding type lock-in. And also it was almost the same as the vortex shedding frequency from a stationary circular cylinder until it began to have carried out lock-in, when the amplitude ratio was small.

3.2 Flow feature in the lock-in state

Four characteristic flow patterns at the time of lock-in were obtained by having oscillated two circular cylinders of staggered arrangement in the direction of the flow. Those flow patterns are shown in figure 5. The case where the simultaneous vortex shedding lock-in of both of circular cylinders is being carried out is shown in figure 5(a). Two twin vortex streets which became independent mutually to the pair of circular cylinder wake can be seen. The flow patterns with which the simultaneous vortex shedding lock-in and the alternate vortex shedding lock-in combined are shown in figures 5(b) and 5(c). In figure 5(b), the 1st cylinder shows the simultaneous vortex shedding lock-in, and the 2nd cylinder shows the alternate vortex shedding lock-in. On the other hand, in figure 5(c), it is the opposite combination. The 1st cylinder shows the alternate vortex shedding lock-in, and the 2nd cylinder shows the simultaneous vortex shedding lock-in. The case where the alternate vortex shedding lock-in of both of circular cylinders is being carried out is shown in figure 5(d). The pair vortex of mushroom section shape is discharged from both of circular cylinders, and one pair of alternate vortex streets is formed.

3.3 Flow pattern distribution

The vortex shedding from the single circular cylinder which oscillates in the direction of a flow is divided roughly into an alternate vortex shedding and a simultaneous vortex shedding, and the case where replacement of an alternate vortex shedding and a simultaneous vortex shedding and the direction of a vortex shedding change like a pendulum is observed [1]. In the case of staggered arrangement oscillating two circular cylinders, the case of the vortex shedding of

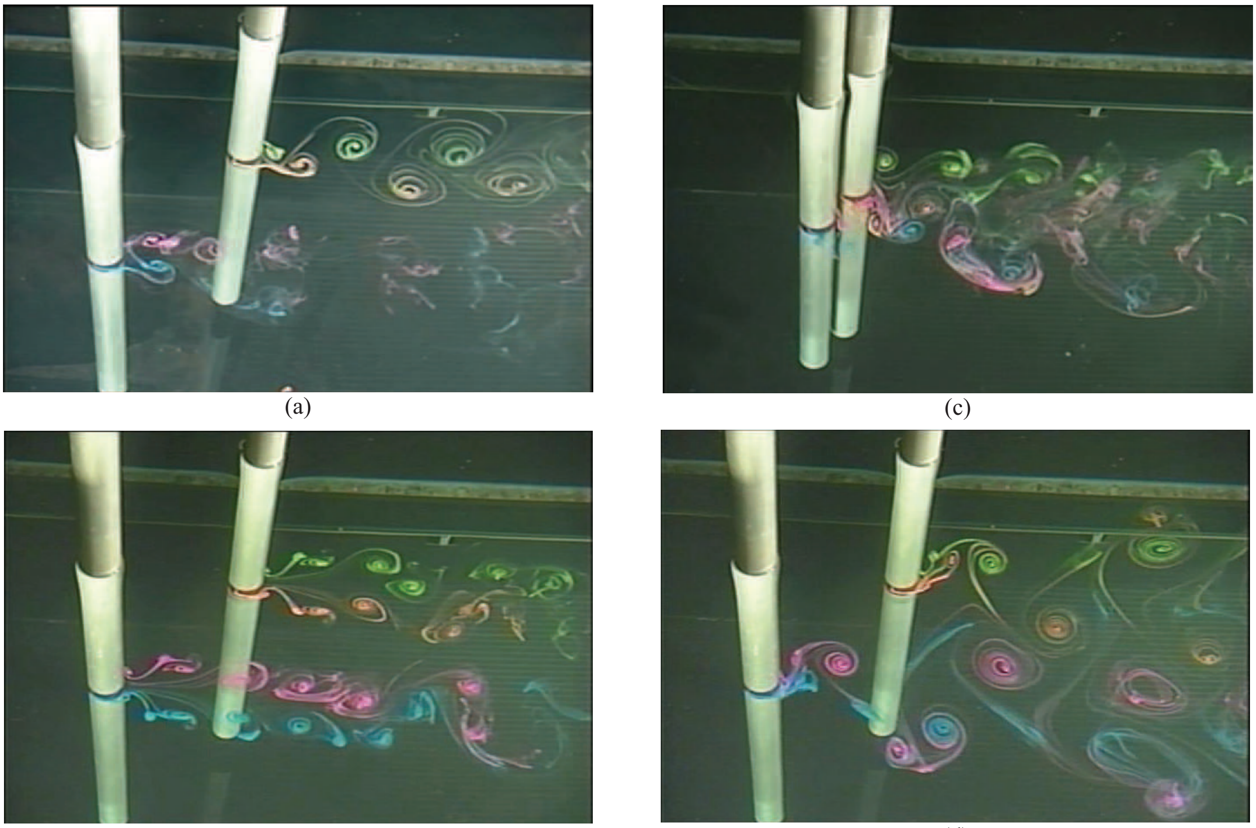

Fig. 5. Characteristic flow patterns of two circular cylinders of 45 degrees staggered arrangement at the cylinder oscillation case; (a) $L/d = 5.5$, $2a/d = 0.50$, $f/f_K = 2.1$, (b) $L/d = 5.5$, $2a/d = 0.25$, $f/f_K = 2.4$, (c) $L/d = 1.5$, $2a/d = 0.50$, $f/f_K = 2.1$, (d) $L/d = 5.5$, $2a/d = 0.50$, $f/f_K = 1.8$

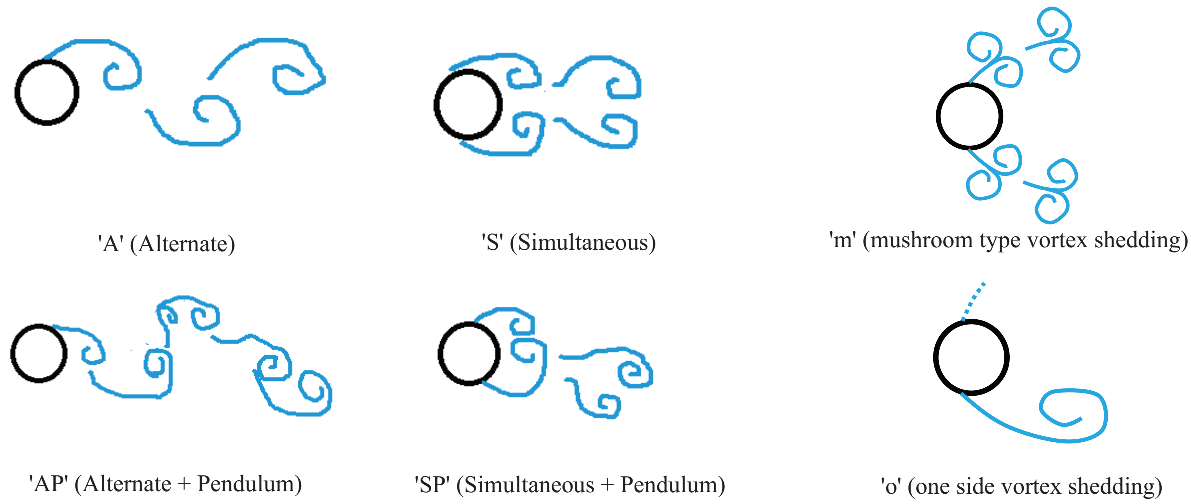

Fig. 6. Sketches of the vortex shedding situation from an oscillating cylinder.

mushroom section shape and a one-sided vortex shedding was added, and the flow pattern was classified. The sketches of the vortex shedding situation are shown in figure 6. Here, the vortex shedding of alternate situation was called 'A' (Alternate), and the vortex shedding of simultaneous situation was called 'S' (Simultaneous). The case where the direction of vortex shedding changed like a pendulum was named 'P' (Pendulum), the case where the direction was alternately changed at the time of vortex shedding was called 'AP', and the case where the direction was simultaneously changed at the time of vortex shedding was called 'SP'. The vortex shedding of mushroom section shape situation was named 'm' (mushroom type vortex shedding), and the one-sided shedding situation was named 'o' (one-sided vortex shedding).

Distribution of the flow pattern formed of the vortex shedding from each circular cylinder in oscillating two circular cylinders by which 45 degrees staggered arrangement was carried out. Figures 7-9 show the case of distance ratio L/d = 1.5, L/d = 2.5, and L/d = 5.5, respectively. The abscissas and ordinates of each figure

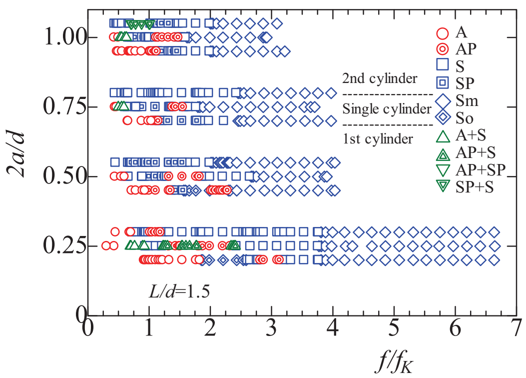

Fig. 7. Flow pattern distribution in the case of $L/d = 1.5$

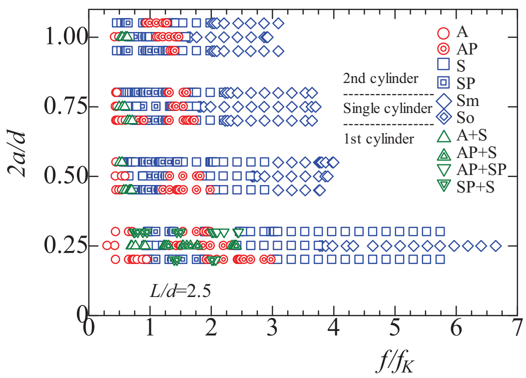

Fig. 8. Flow pattern distribution in the case of $L/d = 2.5$

are an oscillation frequency ratio and an amplitude ratio, respectively. In each figure, data is shown by the three-tier pile for every amplitude ratio. The middle is the flow pattern of the single circular cylinder case for comparison. The lower row is the flow pattern of the vortex shedding from the 1st circular cylinder. The upper row is the flow pattern of the vortex shedding from the 2nd circular cylinder. The symbol in the figure is divided roughly by the vortex shedding configuration. The alternate vortex shedding (A) is shown by ○ mark system (red in the figure). The simultaneous vortex shedding (S) is shown by □ mark system (blue in the figure). The intermingled vortex shedding (A+S) is shown by △ mark system (green in the figure). Here, in the legend in the figure, a character symbol 'P' means pendulum, a character symbol 'm' means a mushroom section shape vortex shedding, and a character symbol 'o' means a one-sided vortex shedding, respectively. And also it means that the place which does not have data all over the figure is in the state which cannot do a count without the ability recognizing as vortex. In every distance ratio, if an amplitude ratio increases, it is shown that the oscillation frequency range which can observe a vortex becomes narrow. Here, distribution of the flow pattern in the 1st circular cylinder and the 2nd circular cylinder is compared. When a distance ratio is $L/d = 5.5$, flow pattern distribution of both of circular cylinders is not based on an amplitude ratio, but is about the same. However, those flow pattern distributions differ from the case of single circular cylinder. In particular, in $2a/d = 0.25$, a difference is seen for an amplitude ratio by high oscillating frequency ratio and low oscillating frequency ratio side. In other amplitude ratios, a difference is seen at a low oscillating frequency ratio side. If distance ratio L/d is made small and circular cylinders are brought close, the effect of mutual interference will be seen begin to appear. By the low oscillating frequency ratio side in which especially f/f_K is smaller than 3, the difference with a remarkable flow pattern of both circular cylinders is seen.

4 Conclusions

In two circular cylinders of the staggered arrangement which made the arrangement angle 45 degrees, as a result of investigating about the aspect and the vortex shedding characteristic of the flow at the time of making it oscillate

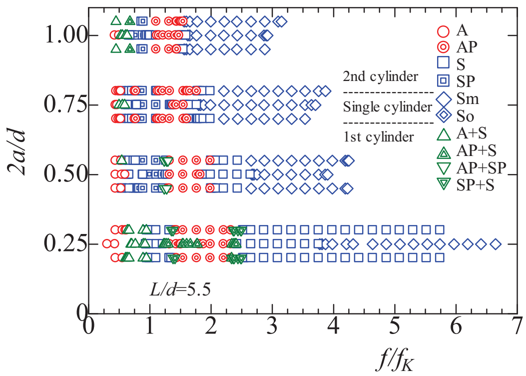

Fig. 9. Flow pattern distribution in the case of $L/d = 5.5$

in the direction of a flow about three kinds of distance ratios, the following conclusions were obtained.

(1) Even if the mutual interference of two circular cylinders was in the state of appearing strongly, when the circular cylinder was oscillated, the lock-in phenomenon was observed.

(2) The situation of the lock-in and distribution of the flow pattern were found.

(3) Four kinds of typical flow patterns at the time of lock-in were obtained.

References

1. Y. Yokoi, K. Hirao, Trans. Jpn Soc. Mech. Eng. **74**-746, 2099-2108(2008)
2. D. Sumner, S. Price, M. P. Paidoussis, J. Fluid Mech. **411**, 253-303(2000)
3. T. Sarpkaya, M. Cinar, Proceedings of Annual Offshore Technology Conference, **12**-2, 333-340(1980)
4. C. H. K. Williamson, J. Fluid Mech. **155**, 141-174(1985)
5. S. S. Chen, Trans. ASME J Pressure Vessel Technology, **108**-4, 382-393(1986)
6. Y. Yokoi, K. Hirao, Trans. Jpn Soc. Mech. Eng. **74**-748, 2466-2475(2008)
7. Y. Yokoi, K. Hirao, J. Fluid Scie. & Tech., **4**-2, 401-414(2009)
8. Y. Yokoi, *15th International Symposium on Flow Visualization*, Minsk Belarus, DVD-ROM, ISFV15-006(2012)