Visualization Study on Flow Structures past a Rotating Circular Cylinder in a Uniform Stream

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Abstract: The present study is designed to experimentally investigate the flow field past a circular cylinder rotating uniformly in a uniform stream, and identify the wake vortex structures by varying the rotational speed ratio. When the rotational speed is faster, the flow in the boundary layer over the cylinder surface is under a strong centrifugal instability and a vortex structure similar to Taylor vortex around the circular cylinder. This vortex area breaks away from the circular cylinder under the influence of the flow in the outer layer. In the experiments, the Reynolds number dependency on flow structures is not negligible, and so that care should be directed to the selection of an experimental Reynolds number. In this study, experiments were conducted with $Re_y = 200$ and $800$ within a rotational speed ratio range of $0$ to $6$. Flow visualized images were obtained by the dye method and hydrogen bubble method, and were captured with the digital video camera. Wake patterns are divided into two main categories in terms of the rotational speed ratio; (i) regular vortex street within the lower speed range and (ii) disordered vortex structure within the higher range. There are three subcategories between two main-categories. It is shown that the deflection amount and width of the shear layer are changed with the rotational speed ratio.

Keywords: Wake, Flow Visualization, Three-Dimensional Vortex Structure, Centrifugal Instability

1. INTRODUCTION

It is an important engineering issue in relation to the occurrence of flow-induced vibration and/or airborne noise to investigate a large-scale structure formed behind a bluff body in a uniform flow [1-3]. When a circular cylinder is rotating around its axis, the wake is accompanied by several characteristic phenomena and more complicated in comparison with a case where the circular cylinder is not rotating. One reason for this difference is that the flow separation occurs not from the cylinder surface but from the inside of the fluid [4]. Another reason is that the secondary flow is induced by centrifugal instability [5]. These two flow phenomena exert a considerable influence on the separation point and the behavior of the separated shear layer, playing a dominant role in the formation process of the flow structure in the wake. One of the effective parameters is the ratio of the cylinder rotational speed, $U_c$, to the uniform flow velocity, $U_0$, which is denoted as $U_c^* = U_c / U_0$.

Swanson [6] overviewed the studies in Magnus force acting on a rotational body made by 1960. Koromilas and Telionis [7] examined an unsteady laminar separation using the flow visualization and with a laser Doppler velocimeter. In the numerical study, including the discrete vortex simulation by Ingham [8] and Cheng et al. [9], a number of research papers have been presented since the latter half of the 1980s.

This study is designed to experimentally treat the flow behind a circular cylinder rotating uniformly in a uniform stream, and identify the wake vortex structures by varying the rotational speed ratio $U_c^*$ and classify them accordingly. Since the dependency of this flow field on Reynolds number is not negligible, care should be directed to the selection of an experimental Reynolds number. In this study, experiment was conducted with $Re_y$ of 200 and 800, within a rotational speed ratio of $U_c^* = 0$ to $6$. In order to observe and identify the flow patterns, the flow fields were visualized by the dye method, and then the flow velocity pattern visualization was applied by using an ultrasonic velocity profile (UVP) monitor [10]. Variation in the wake vortex structure according to the change of the rotational speed ratio was examined.

2. EXPERIMENTAL PROCEDURE

The experiment was conducted in a water tunnel with an open test channel of 700 mm in width, 500 mm in depth and 2000 mm in length. There were acrylic resin windows on both sides of the test channel. Water was driven by an inverter-controlled semi-axial pump and a uniform flow was settled by a straightener and screens. On the other hand, the circular cylinder was rotated by an AC motor equipped with reduction gear and a toothed belt, and the cylinder rotational speed was obtained by counting the number of signals detected by an electromagnetic pickup.

Figure 1 shows the coordinate system. The $z$-axis is coincided with the circular cylinder axis, the $x$-axis is in the mainstream direction, and the $y$-axis is taken at right angles to both the axes. The circular cylinder is rotated in the direction as shown in Fig. 1. In the positive $y$ region, the cylinder surface speed is in the direction opposite to the mainstream direction, and in the negative $y$ region, the

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Fig. 2  Plan views of wakes behind the rotating circular cylinder at $Re_d = 200$.

Fig. 3  Top views of wakes behind the rotating circular cylinder at $Re_d = 200$. 

(a) $U_c^* = 0$

(b) $U_c^* = 1.75$

(c) $U_c^* = 1.85$

(d) $U_c^* = 2.25$

(e) $U_c^* = 3.0$

(f) $U_c^* = 3.5$

(g) $U_c^* = 5.0$
cylinder surface speed is in the same direction as the mainstream direction. After the flow around a wing, the former is called “pressure side” and the latter “suction side.” The diameter of the circular cylinder was \( d = 10 \) mm at the reference Reynolds number, \( Re_d = U_0 d / \nu = 200 \) (uniform velocity \( U_0 = 20 \) mm/s), and \( d = 20 \) mm at \( Re_d = 800 \) (\( U_0 = 40 \) mm/s). The rotational speed ratio of the circular cylinder, \( U_c^* = U_c / U_0 = \omega(d/2) / U_0 \), was varied within a range of 0 to 6 (angular speed \( \omega = 0 - 24 \) rad/s).

For the flow visualization, the electrolytic precipitation method and the dye image method using Uranine were utilized. Both the methods are the same in that the cylinder surface is used as a dye source. Since the three-dimensional nature of the flow field, i.e., variation in the z-direction, was not negligible, the laser-light-sheet technique was utilized to grab images visualized in the x-y plane. The laser used was Ar-ion laser with an output of 500 mW. On the other hand, the electrolytic precipitation method was utilized to observe the three-dimensional nature of the flow in the span direction, and the x-z plane was illuminated with a straight tube type of high pressure mercury lamp.

The visualized images were grabbed with a digital video camera (SONY TRV900) and recorded in a mini DV tape. The captured images were transferred from a DV recorder to a PC, and processed on the PC. A necessary range of pixels were cut out of the captured images with a frame rate of 30 fps, and then connected to each other in chronological order, based on Taylor’s hypothesis.

Ultrasonic velocity profiler (UVP) measurement is conducted, in which an ultrasonic beam is emitted into the water and the ultrasonic Doppler-echoes from the seeding particles within the water are detected and analyzed. Met-Flow Model X3-PS with an ultrasonic transducer (basic frequency of 4 MHz and beam diameter of 5 mm) was used in the present study. Detail descriptions for the measurement principle are referred to Takeda [10].

The ultrasonic beam was directed in parallel with the y-direction, and instantaneous velocity dataset, \( \vec{v}(y, t) \), was measured. Under this measuring condition, the time interval was about 38 ms, and the space intervals was 2.22 mm. The instantaneous velocity profile dataset is divided into the mean component and the fluctuating component, and expressed as \( \vec{v}(y, t) = \vec{V}(y) + v(y, t) \). The fluctuating component profiles are analyzed by a digital signal processing technique, as referred to Inoue et al. [11].

### 3. RESULTS AND DISCUSSION

#### 3.1 Flow visualizations by the dye images

The dye released from the cylinder surface was illuminated with a laser light sheet in parallel with the x-y plane and with a mercury lamp, respectively. The images captured in these methods are shown in Figs. 2 and 3. The rotational speed ratios of the shown images were \( U_c^* = 0, 1.75, 1.85, 2.25, 3.0, 3.5 \) and 5.0 at \( Re_d = 200 \). As evident from these figures, changes in the wake pattern due to the rotational speed ratio \( U_c^* \) are significant.

At \( U_c^* = 0 \), a vortex street subjected to alternative shedding due to the roll-up of the separated shear layer is observed. Also at \( U_c^* = 1.75 \), the shear layer separated on the pressure side and suction side was rolled up, respectively. However, flow regularity and two dimensionality at \( U_c^* = 1.75 \) is obviously highlighted as compared with the flow at \( U_c^* = 0 \). It should be noted in this visualization method that the dye is released from the circular cylinder surface but the flow separation points are not existent on the circular cylinder surface except for the case at \( U_c^* = 0 \). The dye supply to the separated shear layer is not so reliable as seen at \( U_c^* = 0 \). The dye is carried out of the surface through the boundary layer adhered to the circular cylinder surface and rotating together, and carried away to the downstream by the flow in the outer layer. In the photo of the case at \( U_c^* = 1.75 \), the separated shear layer from the pressure side is visualized as a layer with a high dye concentration, while no such layer is seen on the suction side.

At \( U_c^* = 1.85, 2.25 \) and 3.0, the layer with a high dye concentration is not observed on the pressure side or the suction side, and a very narrow dead water area is seen behind the circular cylinder. There is little dye pattern appeared showing the vortex street in the wake, but only dye streaks have feebly ordered features. When the rotational speed is faster, the flow in the boundary layer is under a strong centrifugal instability, and a vortex structure similar to Taylor vortex around the circular cylinder [5].
vortex receives a supply of dye from the circular cylinder surface, forming a banded area with a high dye concentration. This vortex area breaks away from the circular cylinder under the influence of the flow in the outer layer. These behaviors are clearly seen in the photos of $U_\ast^* = 3.5$, as shown in Figs. 2(f) and 3(f). The complicatedly winding dye patterns fill in the broad layer almost disorderly. At a higher rotational speed ratio of $U_\ast^* = 5.0$, the boundary layer on the circular cylinder appears turbulent, and dye patterns of various scales, like turbulent eddies, can be seen in the wake shear layer.

Figures 4(a)-(g) show plan views of the wakes with the rotational speed ratios of $U_\ast^* = 0, 1.0, 1.85, 3.0$ and 5.0 at $Re_\ast = 800$. This Reynolds number is larger than the critical Reynolds number of a non-rotating circular cylinder, and according to Williamson [12], the flow field in the present condition belongs to a different flow regime from the one at $Re_\ast = 200$, i.e., a three-dimensional wake-transition regime. However, changes in the wake pattern due to the rotational speed ratio are in a similar manner to at $Re_\ast = 200$.

3.2 Reconstructed dye images and contour maps of lateral velocity component

Contrast between the dye patterns shown in Fig. 4 and the flow field is considered at a location relatively near to the circular cylinder, $x/d = 3$. The visualized images are reconstructed based on Taylor’s hypothesis and shown in Fig. 5. The flow field is obtained from the $y$-direction UVP measurement at $x/d = 3$, and shown as a contour map of the fluctuating velocity $v(y, t)$ in Fig. 6. In this figure, the solid line represents the positive fluctuating velocity contour and the broken line the negative fluctuating velocity contour. The results are shown as to the cases with the ro-
tional speed ratios $U^*_c = 0, 1.0, 1.85, 3.0$ and $5.0$, respectively.

In contrast of dye patterns between the flow fields with $U^*_c = 0$ and $1.0$, there is a difference in dye concentration, there is agreement in the fundamental structure that the cylindrical vortex areas are arranged alternately with the center axis between them and these two areas are connected staggeringly. There is a good agreement in fluctuating velocity contour between these rotational speed ratios, representing the $y$-direction velocity field induced to the cylindrical vortices of the staggered arrangement. At $U^*_c = 1.85$, there is no dye pattern corresponding to the well-organized cylindrical vortices, but rather the dye pattern like zigzagged lines is dominant. In correspondence with the weakening of the cylindrical vortices, there is no longer the orderliness in the $v$-fluctuation pattern, and the fluctuation amplitude is considerably weakened in comparison with that at $U^*_c = 0$ and $1.0$.

On the other hand, the dye pattern at $U^*_c = 3.0$ forms a widening layer of streaky, high-dye-concentration area originated in Taylor vortex, and its coherence is low. This is also clearly seen in the $v$-fluctuation contour map. Furthermore, the fluctuation energy within the layer is considerably low. Lastly, in the flow field at $U^*_c = 5.0$, like in the flow field at $U^*_c = 3.0$, the visualized pattern is seen with dye lumps filled in the wide layer. In comparison with these two flow fields, the layer at $U^*_c = 5.0$ is considerably wider, the individual dye lumps are of more complicated shape and of more minute segmentation, and the dye concentration is lower. However, there is an organized velocity fluctuation area seen in the $v$-fluctuation contour map. This implies the generation of an organized motion whose image is different from that of the flow at $U^*_c \leq 3.0$.

More spatio-temporal information of the fluctuating velocity field can be yielded by analyzing the UVP dataset. For example, spatial eigenmodes of velocity profile can be calculated with the proper orthogonal decomposition [11]. For the present flow, these analyses should be made in our future work.

4. CONCLUSIONS

Results in the present study are put together, this flow field is classified, and the boundary values of the rotational speed ratios are shown in approximate numerical values as follows:

(i) $0 \leq U^*_c \leq 1.25$ : The flow structure is that the staggered arrangement of the cylindrical vortex is dominant, and the deflection amount of the center coordinates of the vortex street increases linearly along with the rotational steer ratio.

(ii) $1.25 < U^*_c < 1.85$ : The width of the wake shear layer is narrower in comparison with the lower rotational speed ratio, and the deflection amount of the wake center coordinates decreases due to the increase in the rotational speed ratio.

(iii) $1.85 < U^*_c < 3$ : The width of the shear layer and the fluctuation energy contained in the shear layer decrease, together with the lowering of the coherence of fluid motions, along with the increase in the rotational speed ratio.

(iv) $3 < U^*_c < 4$ : The flow in the shear layer is inactive, and the width of the shear layer and the fluctuation energy also take the minimum value, but only the deflection amount of the flow in the shear layer increases.

(v) $U^*_c \geq 5$ : The disordered vortex structure like turbulent eddy is dominant, and the width of the shear layer and the fluctuation energy increase again.

REFERENCES