Wake of a Rotating Circular Cylinder

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Introduction

FLOW about a rotating circular cylinder is one of the classical problems of fluid mechanics. The Karman vortex street in the wake of a still circular cylinder is one of the most well-known phenomena in fluid mechanics. It is of interest how the vortex street is affected by the rotation of the cylinder. It is so far known by experiments that the Strouhal number of vortex shedding becomes larger as the rotating speed becomes higher and that the meandering of the wake due to the Karman vortex street disappears when the rotating speed of the cylinder is high enough,[1,2] that is, when the spin parameter, which is defined as the ratio of the peripheral speed of the cylinder surface to the uniform velocity, is about 2. The Reynolds number in which these experiments have been done is of order 10^4–10^5 so that it is rather high. Kimura and Tsutahara[3] simulated these phenomena by the discrete vortex method. Their simulation corresponds to very high Reynolds number flows because the diffusion of the vorticity is neglected. For a rather wide range of the Reynolds number, the initial stage of the flows about rotating circular cylinders has been studied numerically and experimentally by Badr and Dennis[4] and Badr and Coutanceau.[5] In Ref. 5, they have mentioned that at a Reynolds number of 10^3 a periodic variation appears in the time variation of the lift for the flow at the spin parameter of unity, but no periodic variation appears for the flow at a spin parameter of 3. However, the effect of the Reynolds number on these phenomena has never been explicitly described.

In this study, the effect of the rotation of the cylinder and that of the Reynolds number are investigated by experiments and numerical simulations.

Experimental Study

Some experiments were performed for obtaining the characteristics of the wakes of rotating circular cylinders over a wide range of Reynolds numbers. The details of the experiments will be omitted and a brief description will be presented.

For Reynolds numbers from 2×10^2 to 4×10^3, flow visualizations by the hydrogen bubble method and measurements of the velocity in the wake by a hot wire were done using a circulation water tank, with intensity of disturbance < 1%. For Reynolds numbers 3×10^4 to 7×10^4, only the measurements of the flow velocity were done using a still water tank and towing the model. In the former experiment, two circular cylinders were used. One was 1 cm in diameter and 10 cm in length, and the other was 3 cm in diameter and 12 cm in length. The circular cylinder used in the latter experiment was 10 cm in diameter and 30 cm in length. Circular disks of 12-cm diam were attached to both ends of the cylinder to keep the two dimensionality of the flow because the aspect ratio of the cylinder was small.

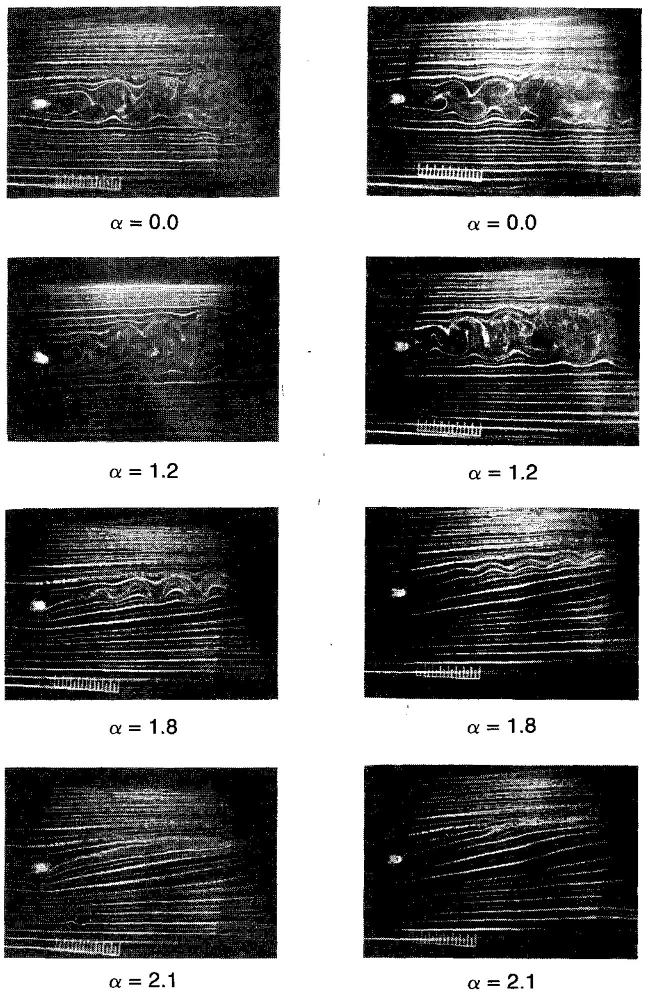
Figures 1 show the flow patterns at the Reynolds numbers of 2.8×10^2 and 3.7×10^2, in which α represents the spin parameter, that is, the ratio of peripheral velocity of the cylinder to the uniform flow velocity. These figures show that when the spin parameter becomes larger the amplitudes of the meandering of the wake due to the Karman-type vortex street become smaller, and at the same time the Strouhal number of the vortices that are shed from the cylinder becomes larger. Finally, the meandering disappears. They also show that the amplitude decreases faster when the Reynolds number is higher.

Numerical Analysis

The discrete vortex method was used to simulate the flows; only the outlines will be presented. The surface of the circular cylinder was divided into 14 segments, and a point vortex was introduced every time step at the center of each segment. The circulation of the vortex was determined by the difference of the flow velocity and the peripheral velocity of the cylinder and the length of the segment.

The vortices on the surface move with the rotating surface, and the vortices in the flowfield move with the local flow velocity. The diffusion of the vorticity by the viscosity was simulated by adding random numbers, whose average was zero and variance was $2\Delta t/Re$, to the migration of the vortices, where Δt is the time increment and Re is the Reynolds number. The effect of the Reynolds number is simulated by this random walk.[6]

Figures 2 show the distributions of the point vortices for the flows at various Reynolds numbers and a fixed spin parameter $\alpha = 1.8$. When the Reynolds number is 5×10^2 and 2×10^3, meandering exists, but when the Reynolds number is 5×10^3 or 10^4, the wakes are almost straight and no meandering exists.



a) $Re = 2.8 \times 10^2$ b) $Re = 3.7 \times 10^2$

Fig. 1 Flow patterns visualized by the hydrogen bubble method.

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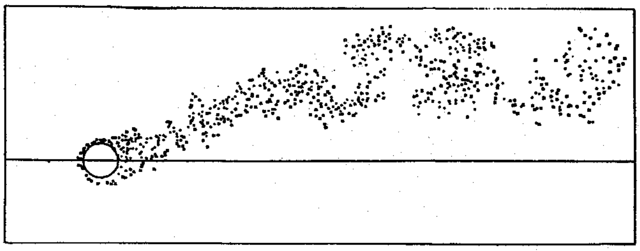
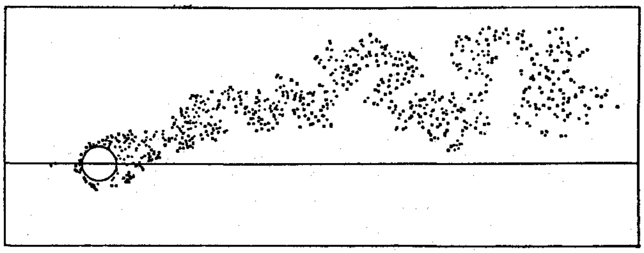
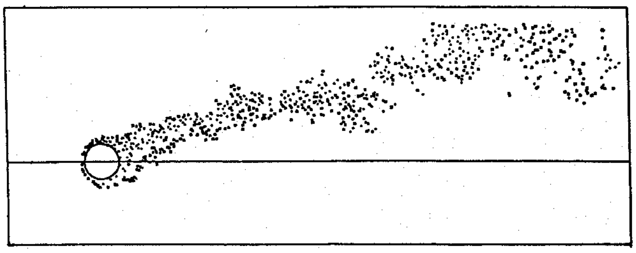
Figure 3 shows the relationship between the critical spin parameter and the Reynolds number. The critical spin parameter is the value at which the meandering disappears, but this value is not so definitive because the meandering decreases its amplitude gradually and disappears. Therefore, the critical value is defined here, by using the power spectra of the disturbances in the wake, as the value at which the height of the distinguished peak becomes < 2.5 times the average of the power spectra of all of the frequencies. The hatched regions represent the regions where the critical values obtained by the experiments exist. The dashed line is simply connected to two regions obtained by the experiments. The open circles represent the numerical calculation points where the meandering exists, and the filled circles represent the others. The two circles indicated by the arrows represent the calculation points for the Reynolds number of infinity. The decision of existence of the meandering was done by the flow pattern for the numerical simulations. This decision contains a great deal of uncertainty, but apparently the results agree well qualitatively with the experimental results.



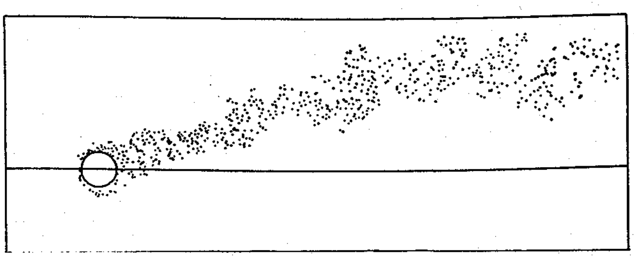
a) $Re = 5 \times 10^2$



b) $Re = 2 \times 10^3$



c) $Re = 5 \times 10^3$



d) $Re = 1 \times 10^4$

Fig. 2 Distributions of the point vortices.

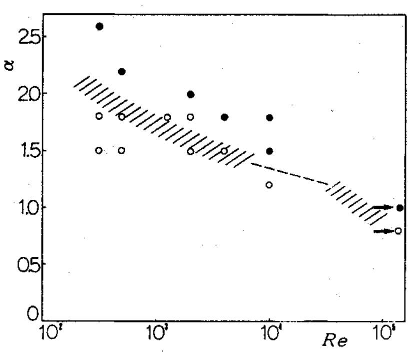


Fig. 3 Relationship between the critical spin parameter and the Reynolds number.

Discussion

For the effect of increasing the spin parameter, Kimura and Tsutahara[3] discussed that the point vortices of opposite directions are promoted to mix and are suppressed to combine to bulks of vortices. It will be inferred from the vorticity distribution, which is not shown in this paper, that the combination of the vortices to bulks are rather promoted faster when the spin parameter becomes larger; therefore, the Strouhal number becomes larger and the sizes of the bulks become smaller. Finally, the vortices cannot form the bulks and the meandering in the wake disappears.

The effect of the Reynolds number will be explained as follows. When the Reynolds number is small, that is, the random walk becomes large, the vortices are suppressed to combine and, therefore, the bulks become larger in size and the frequency to form the bulks becomes larger. This results in the existence of the meandering even in the flows at large spin parameters.

Conclusions

Experimental study and numerical simulations for the two-dimensional flows about a rotating circular cylinder were done, and the conclusions obtained are as follows.

1) As the spin parameter becomes large, the meandering in the wake becomes smaller in amplitude and the frequency of the vortices shed from the cylinder (Strouhal number) becomes larger.

2) The meandering disappears at some value of the spin parameter.

3) The phenomena in 1) and 2) strongly depend on the Reynolds number. When the Reynolds number is large, the Strouhal number becomes large and the critical spin parameter at which the meandering disappears becomes small.

4) By the discrete vortex method, the phenomena in 1) and 2) were simulated and the mechanism was explained as the kinematics of the point vortices.

References

[1]Diaz, F., Gavalda, J., Kawall, J. G., Keffer, J. F., and Giralt, F., "Asymmetrical Wake Generated by a Spinning Circular Cylinder," *AIAA Journal*, Vol. 23, No. 1, 1985, pp. 49–54.

[2]Tanaka, H., and Nagano, S., "Study of Flows About a Rotating Circular Cylinder," *Journal of the Japan Society of Mechanical Engineers*, Vol. 38, No. 310, 1972, pp. 1343–1352 (in Japanese).

[3]Kimura, T., and Tsutahara, M., "Flows About a Rotating Circular Cylinder by the Discrete-Vortex Method," *AIAA Journal*, Vol. 25, No. 1, 1987, pp. 182–184.

[4]Badr, H. M., and Dennis, S. C. R., "Time-Dependent Viscous Flow Past an Impulsively Started Rotating and Translating Circular Cylinder," *Journal of Fluid Mechanics*, Vol. 158, 1985, pp. 447–488.

[5]Badr, H. M., Coutanceau, M., Dennis, S. C. R., and Menard, C., "Unsteady Flow Past a Rotating Circular Cylinder at Reynolds Number 10^3 and 10^4," *Journal of Fluid Mechanics*, Vol. 220, 1990, pp. 459–484.

[6]Chorin, A. J., "Numerical Study of Slightly Viscous Flow," *Journal of Fluid Mechanics*, Vol. 57, Pt. 4, 1973, pp. 785–796.