STUDIES ON WAKE VORTICES (I): AN EXPERIMENTAL STUDY ON THE STRUCTURE OF THE VORTEX STREET BEHIND A CIRCULAR CYLINDER OF FINITE LENGTH

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https://doi.org/10.5109/7156983

出版情報：Reports of Research Institute for Applied Mechanics. 1 (4), pp.131-144, 1952-12. 九州大学応用力学研究所

Reports of Research Institute for Applied Mechanics
Vol I, No. 4 December, 1952.

STUDIES ON WAKE VORTICES (I)

AN EXPERIMENTAL STUDY ON THE STRUCTURE OF THE VORTEX STREET BEHIND A CIRCULAR CYLINDER OF FINITE LENGTH

By Sadatoshi TANEDA

1. Introduction. The structure of the two-dimensional vortex street generated behind a circular cylinder of infinite length in a uniform flow of a fluid was studied experimentally by many authors and an appropriate explanation was provided by the well-known theory of von Kármán. So far as the two-dimensional case is concerned, we thus have some knowledges at present.

In the case of a finite cylinder, on the other hand, the vortex street has been studied neither experimentally nor theoretically and nothing seems to be known concerning its structure. Since, however, any vortex filament cannot end inside the fluid, we must suppose that the vortices either interconnect with each other or terminate somewhere on the boundary surface in a three-dimensional arrangement. How does it take place in reality? The present author planned to solve this problem chiefly from the experimental point of view.

In this report the method and the results of the photographic observations of the wake behind a moving cylinder of finite length are described and a stable structure of the three-dimensional "Kármán Vortex Street" is induced.

2. Apparatus and Method of Observation. A small carriage to which a metallic cylinder of circular cross-section was fixed upright was towed by a phonomotor through a steel wire at a uniform velocity along straight rails mounted over a glass vessel of water (40 cm in length, 30 cm in breadth and 45 cm in depth). Fig. 1 shows the general arrangement of the apparatus. The diameter of the cylinder was varied from 2 mm to 10 mm.

In order to visualize the motion of water below the free surface, aluminum dust was suspended in the water. Mixing a small quantity of aluminum dust with alcohol and pouring it into the water, the dust diffuses quickly and soon becomes suspended in water uniformly. Then if we illuminate it by a sheet of intense light through a narrow slit, we can easily observe the motion of water in the illuminated layer. A 500 W. incandescent lamp served as the source of light. As it was equipped with a line-filament, the light passed the slit became practically parallel with-

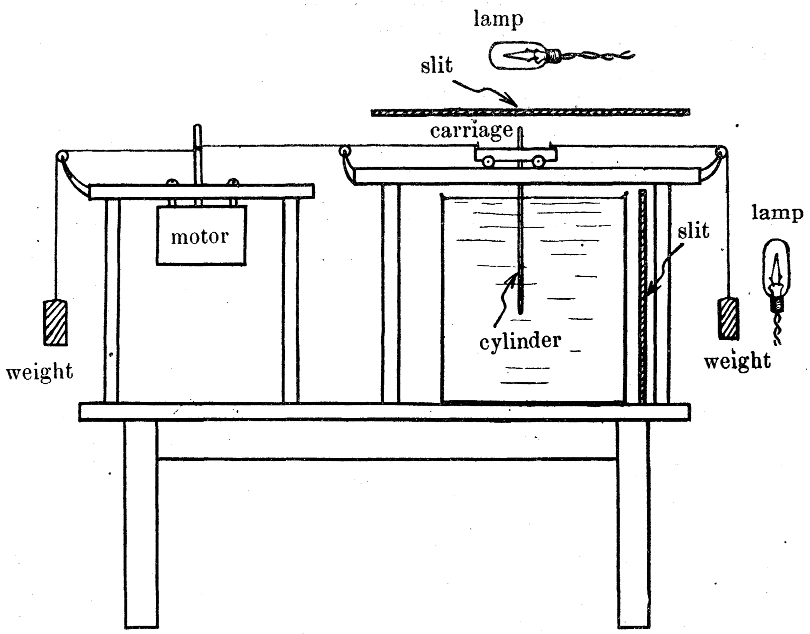


Fig. 1 Schematic Diagram of the Apparatus.

out inserting any system of lenses. Photographs were taken using ordinary panchromatic films and powerful developer.

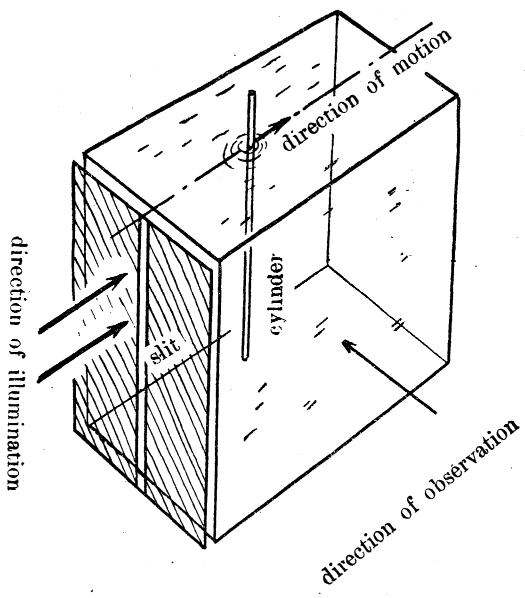


Fig. 2

3. Details of Experiment. When the light comes into the water with suspended aluminum dust (§ 2) we see innumerable tiny particles continually twinkling in the dark background just like as the scattered stars in the Milky Way. Of course the brightness distributes homogeneously over the illuminated section so far as any motion of water does not occur.

However, as soon as the cylinder begins to move, observing the illuminated section from the side as is shown in Fig. 2, there appears periodically striped pattern of brightness behind the moving cylinder (see Plate 1). Plate 2 is the birds-eye-view of the horizontal section at 4 cm below the water surface photgraphed under the same condition as that of Plate 1, and clearly shows the appearance of the Kármán's vortex street. Plate 1 can, therefore, be regarded as a side-view of the vortex street itself, and we notice at once the following fact; the water below the edge of the cylinder does not move at all, in the other words, the vortices do not extend downward beyond the cylinder. This is contrary to the first expectation that the vortex tubes would be elongated to the bottom of the

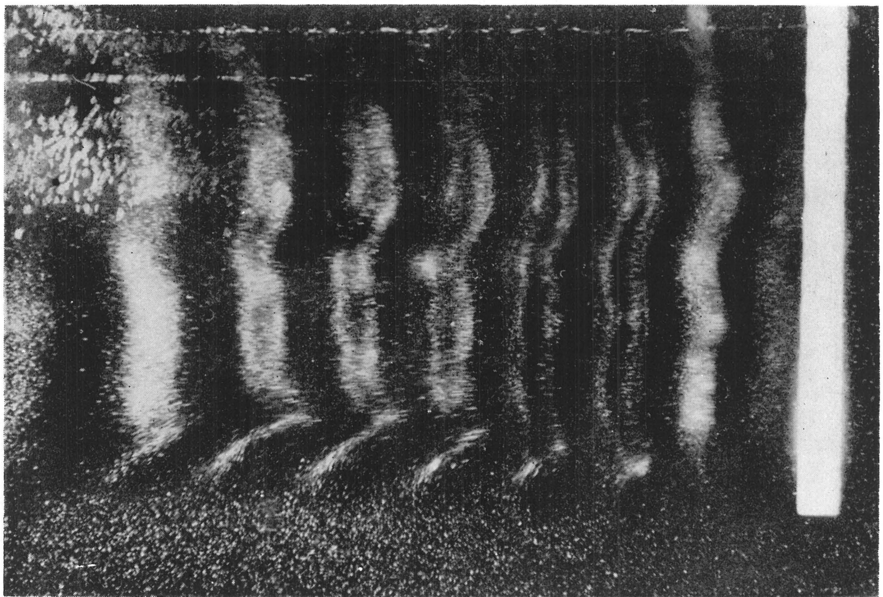


Plate 1

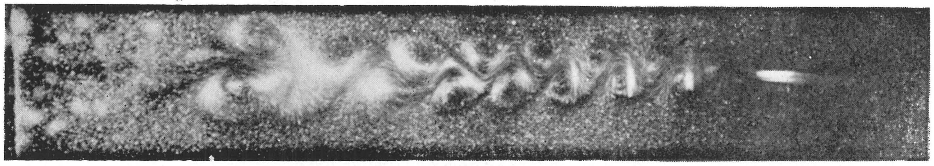


Plate 2

vessel, or at least to a considerable distance below the cylinder. In fact, the vortex wake, though slightly, contracts upwards as it moves downstream.

Now in order to study the structure of the vortex street more closely, the next question must be solved. To what motion of water do correspond the bright and dark zones of Plate 1? It may appear at first sight of the photographs as if the aluminum dust resulted to distribute ununiformly in accordance with the brightness, i. e., became dense in brighter zone and sparse in darker one.

The further experiment shows, however, that this is not the case. The aluminum dust distributes always uniformly, whether the motion of water occurs or not. The experimental proof can be obtained as follows: the wake was photographed from both sides at the same time (Plates 3a and 3b) and examining these two pictures carefully, it is found that the bright zone in one picture just corresponds to the dark in the other and exactly vice versa. Thus we must imagine that the brightness in a picture should relate to the direction of the local flow, not to the density of aluminum dust. In fact, each piece of aluminum dust has a flaky shape, as is microscopically observed, and so only those flakes which has a definite direction can reflect the light into the camera. In still water these small flakes are orientated at random, but when the motion of water sets in they are definitely orientated by the local flow. Thus the pieces arranged so as to reflect the light to the one side cannot be seen from the opposite and accordingly the bright and dark zones alternate in two side-views.

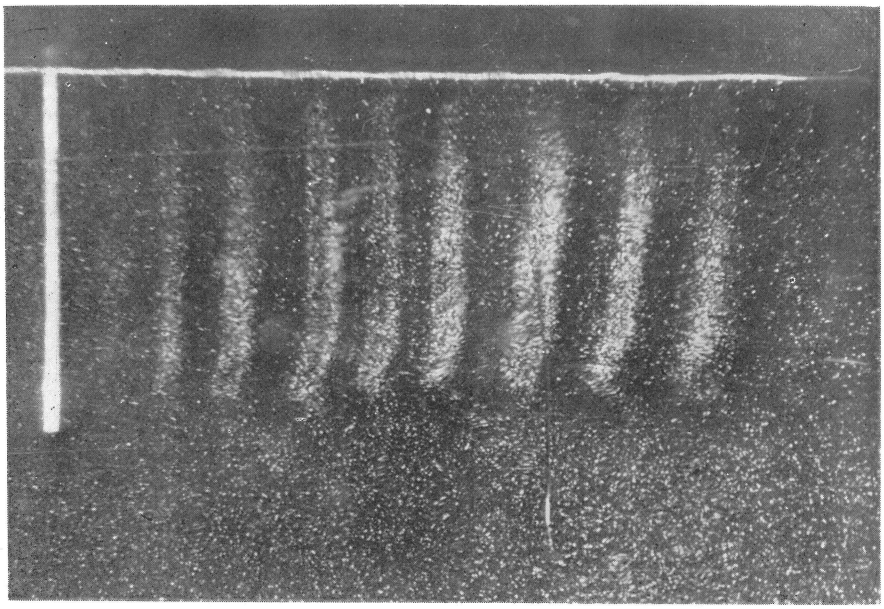


Plate 3a

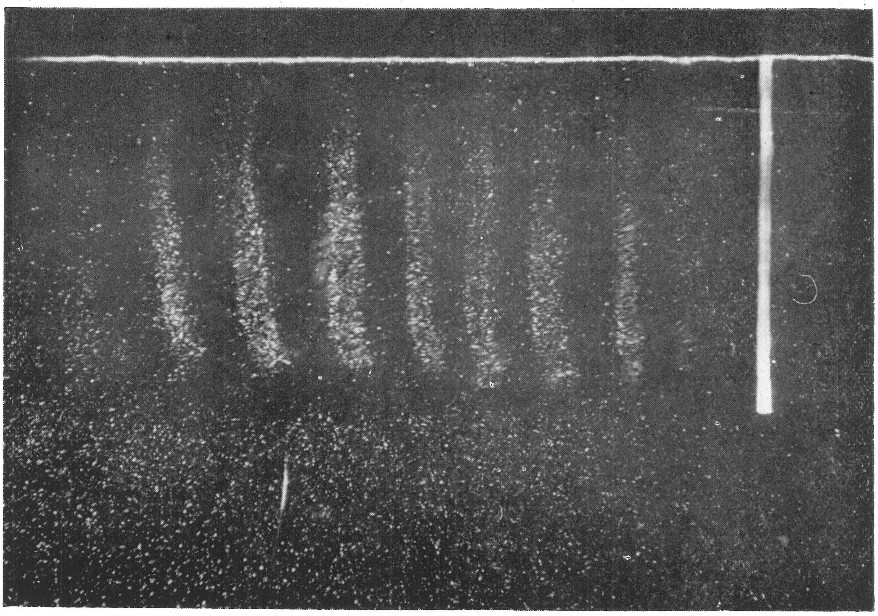


Plate 3b

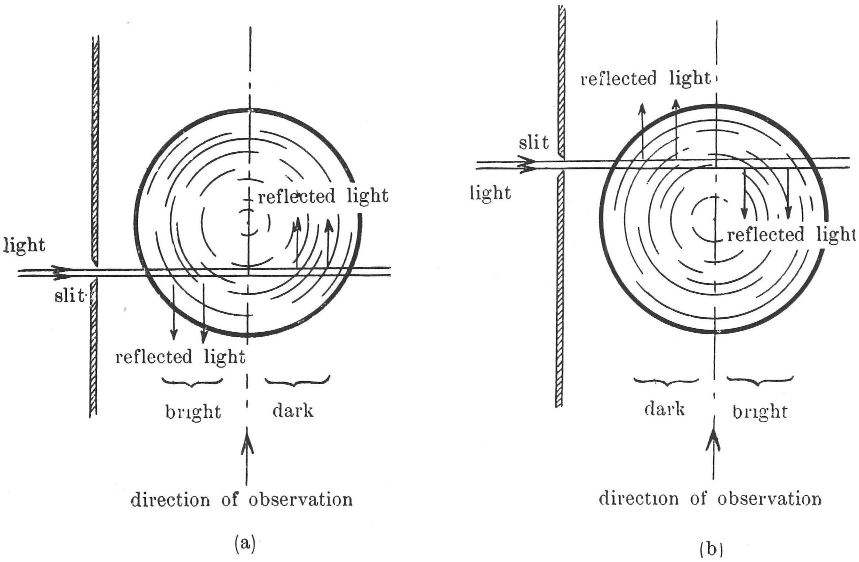


Fig. 3

Lastly, how the orientation of the aluminum flake relates to the direction of the flow? To clarify this, water filled in a glass cylinder was rotated. Then observing it from a side by light through a slit it is found that, as is seen in Fig. 3, the left-hand half is bright in the case "a" and the right-hand half is bright in "b" irrespectively of the direction of the rotation. But the result became converse if either of the direction of the incident light or the direction of the observation was reversed. This fact teaches us that the faces of the flakes are always parallel with the direction of the local flow. Presumably this is caused by the presence of the velocity gradient across the stream-lines (see Fig. 4). Applying this result to the case of the vortex street, we can suppose the actual flow pattern as is illustrated in Fig. 5, where "a" denotes the brightzone and "b" the dark one. Now owing to the results of these preliminary experi-

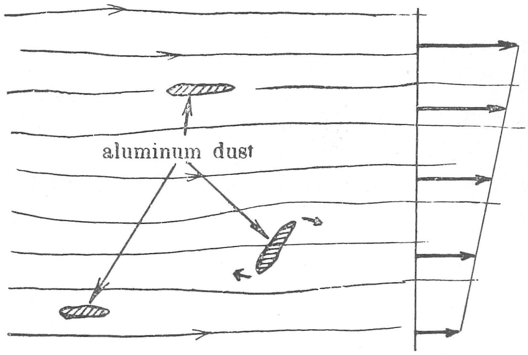


Fig. 4

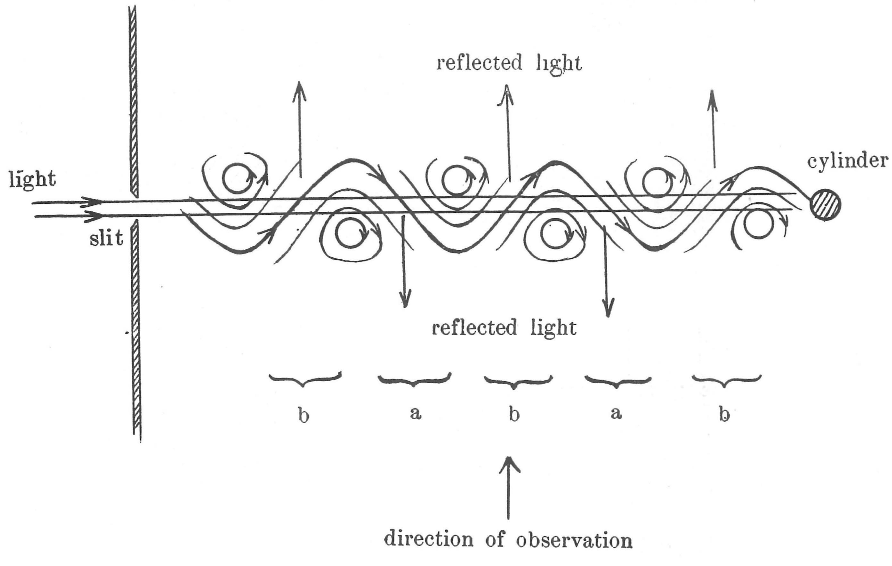
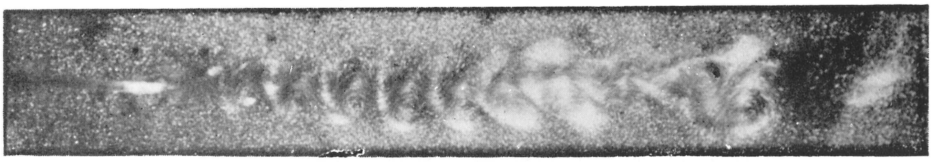


Fig. 5

ments we can analyse the photographs to study the structure of the vortex street. Plates 4 ~ 10 are the examples of the photographs of the "Kármán Vortex Street" taken from the various directions under different conditions.

The preceding method enables us to know the structure of the vortices

↓

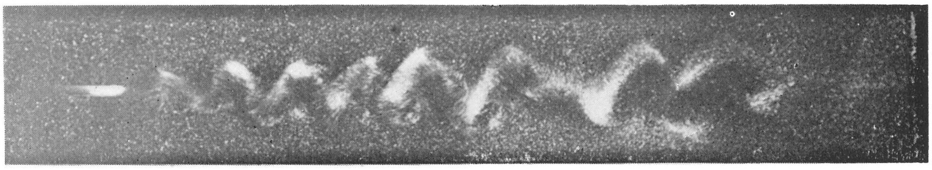


a. Horizontal section (7 cm above the lower end of the cylinder.)

↓

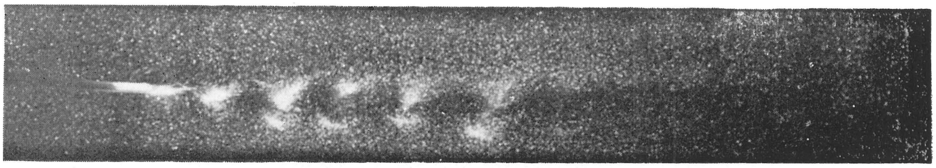
b. (2.8 cm)

↓

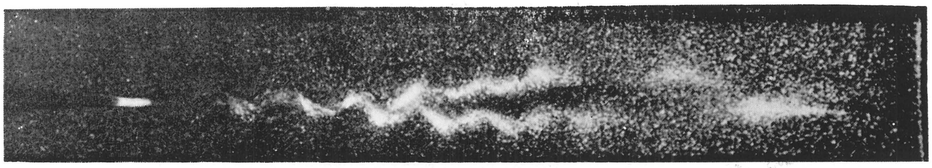


c. (2 cm)

↓



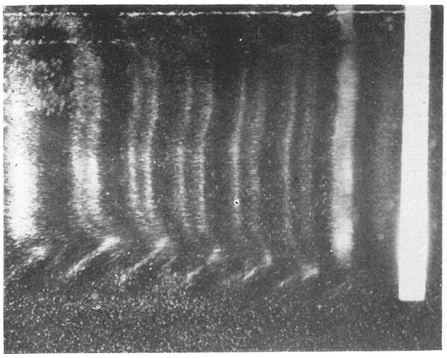
d. (1 cm)

 ←

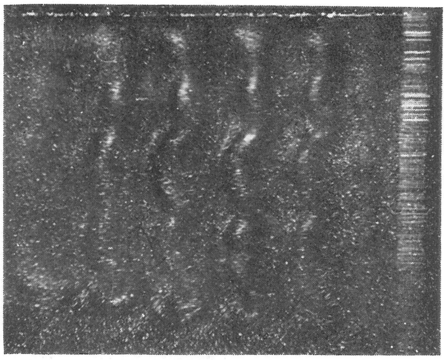
e. (1 cm)

Plate 4. R = 60

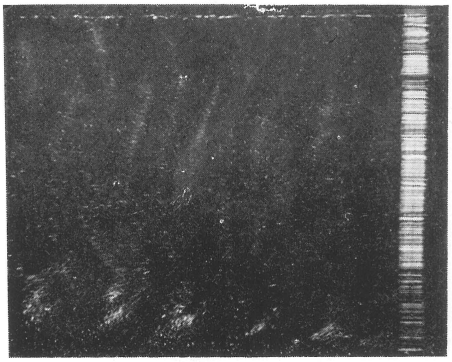
(Arrows show the direction of illumination)



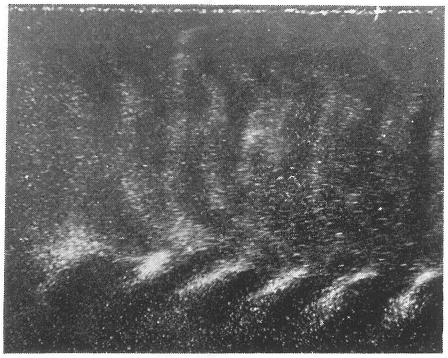
a. Central section.



b. Central section.



c. Vertical section (4 mm aside from the center)



d. Central section. (40 cm behind the cylinder)

Plate 5. R = 60

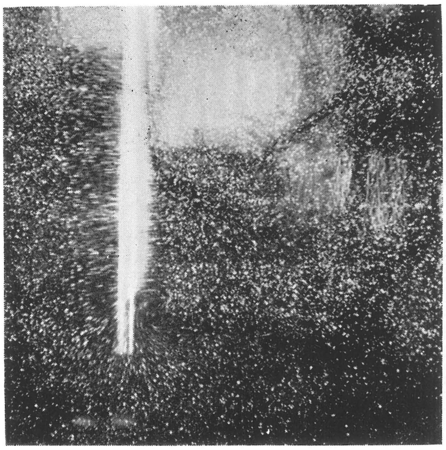


Plate 6.

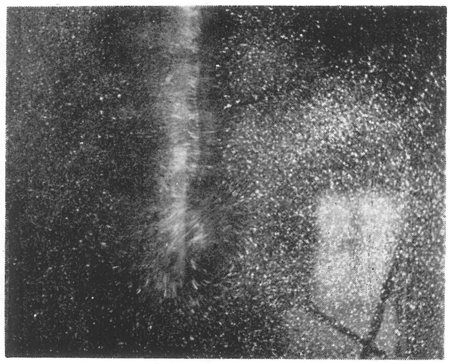
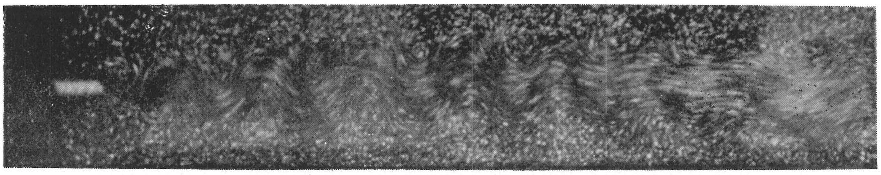
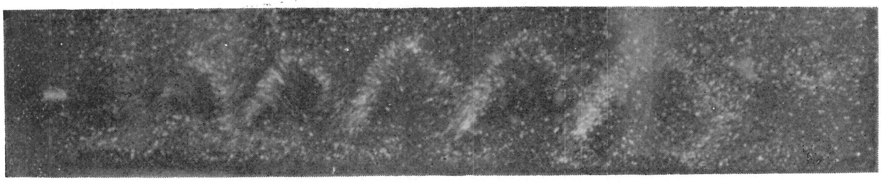


Plate 7.

(Plates 6 and 7 were photographed from behind.)

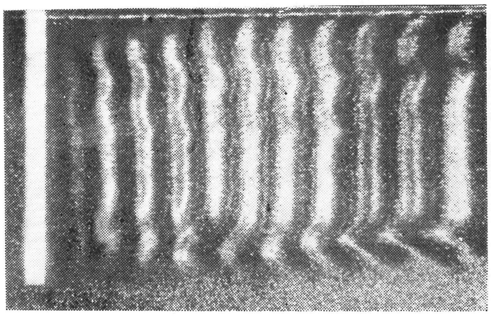


a. Horizontal section (8 cm above the lower end of the cylinder.)

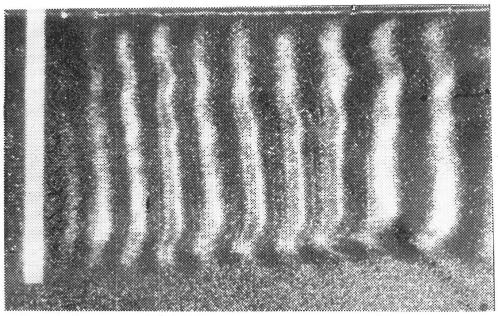


b. (1.7 cm)

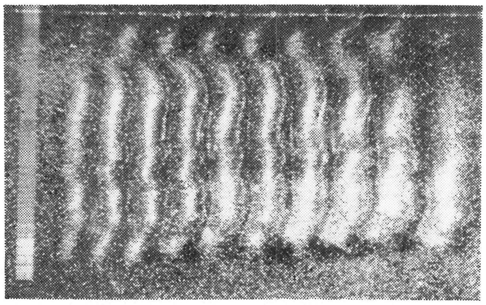
Plate 8. R = 75



a. Central section.

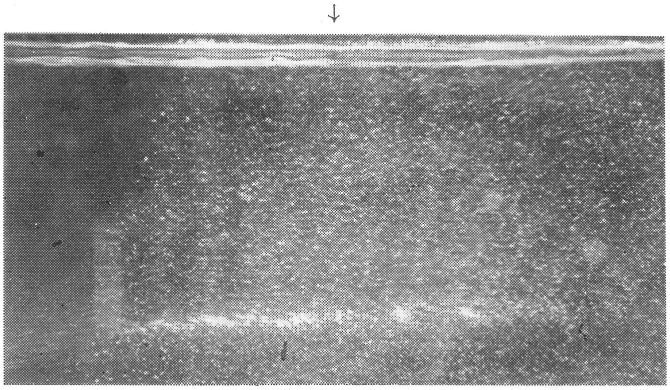


b. Vertical section (2.5 mm aside from the center.)

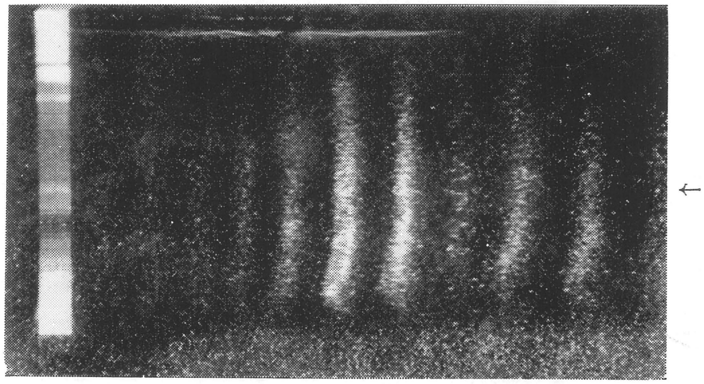


c. Vertical section (5 mm aside from the center.)

Plate 9. R = 50



a.



b.

Plate 10. R = 39

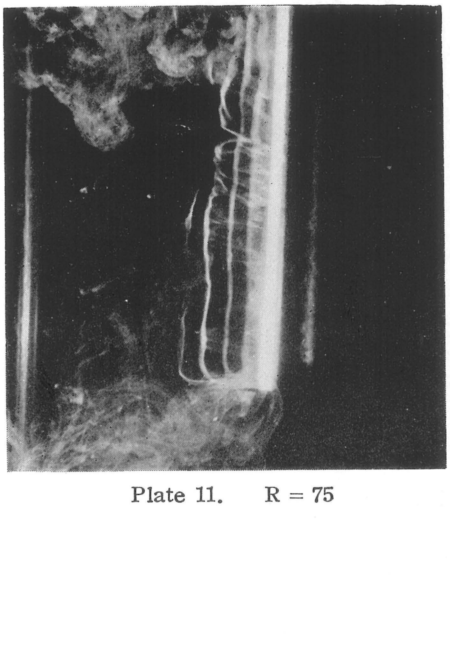


Plate 11. R = 75

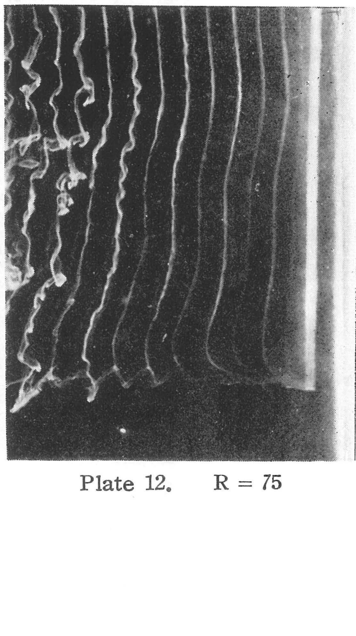


Plate 12. R = 75

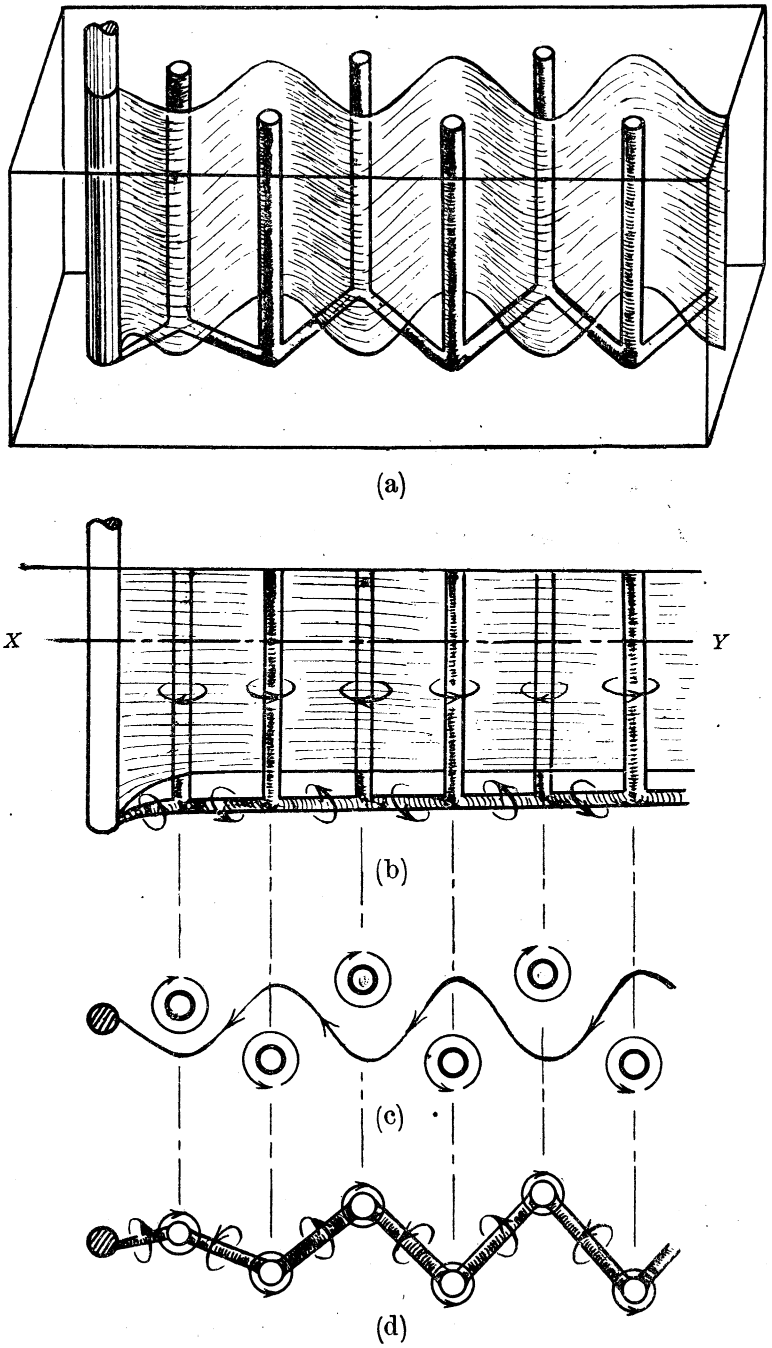


Fig. 6

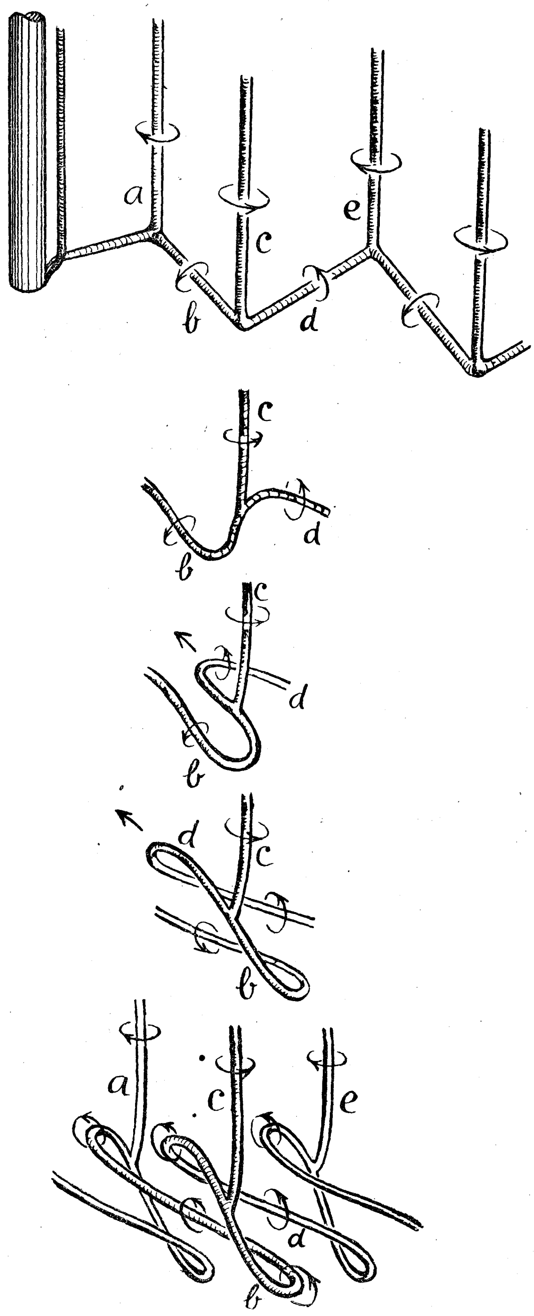


Fig. 7
Process of Deformation.

by the direction of the local flow. On the other hand the author tried to see the vortex filament directly. When a cylinder coated with condensed milk is set in motion in water, the milk melts in the wake little by little and forms the vortex filaments. Thus we can clearly observe the structure of the vortex street. This method, however, does not succeed always, and moreover it has two defects: (1) milk does not show the velocity field. (2) milk being heavier than water, the form of the wake is a little deformed. Plates 11 and 12 are the photographs taken by this method.

4. Interpretation of Results. Examining these pictures taken by these alternative methods, the three-dimensional structure of the "Kármán Vortex Street" was concluded as is schematically shown in Fig. 6. That is, Fig. 6a is the stereographic view, b the side view, c the horizontal section X – Y in b, d the birds-eye-view of the bottom, respectively. Immediately behind the cylinder the vortex street is spaced appreciably narrowly in the bottom, but soon each vortex becomes vertical and parallel. At the beginning the bottom of the vortex street has the structure as is shown in Fig. 6, but in the course of time it gradually changes the shape and is finally destroyed (see Fig. 7). Thus the dissipation of the vortex street always begins in the bottom and gradually propagates to the upper portion.

Next, it must be noticed that solid wall or free surface near the vortex street cannot influence the structure of the vortex street sensibly contrary to our first expectation. For instance, when the moving cylinder was completely submerged but held very close to the free surface (1 ~ 2 mm below), the surface itself did not move at all. Similary when the cylinder advanced only about 1 mm above the solid plate, the structure of the vortex street was quite unaltered. These facts suggest us that the system of the vortex street might be self-closed and stable.

5. Summary and Acknowledgement. We have reported on the structure and nature of the three-dimensional vortex wake behind a circular cylinder in general. They are summarized as follows:

1. The vortex tubes interconnect edgewise with each other.

2. The bottom of the vortex street gradually changes its form as time goes on, and is finally destroyed.

3. The structure of the vortex street is not influenced by the presence of boundaries or solid walls fixed relatively to the general flow.

4. The vortex wake spreads sideway but contracts upwards with time.

This experiment has been carried out as a preliminary part of the research project "Studies on Wake Vortices" by Professer H. Yamada under the monetry aid of the Scientific Research Expenditure of the Ministry of Education (Monbushō Kagaku Kenkyū Hi).

The author wishes to express his thanks to Professor H. Yamada for suggesting this problem and for his valuable advices; and to Mr. K. Ushijima for his assistance.

(Received November 15, 1952; Communicated by H. Yamada)