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# Shedding Vortices from Spheres

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Vortex shedding from spheres was studied experimentally using a flow visualization and a hot film technique in water in the Reynolds number range from 100 to 20000. The mechanism of vortex shedding to the shear layer of the sphere was found, and the co-existence of double vortices was observed in the high Reynolds number region and explained as a collection of small scale vortices.

## § 1. Introduction

Unsteady flow past a sphere has been studied by many researchers during long time. Not only fluid dynamiststs have been interested in this problem, but also people in the fields of chemistry and engineering were interested in this phenomena in the real applications. Möller[1] made an experiment moving a sphere in a water tank vertically. Magavey and Bishop[2] observed a liquid drop falling into the lighter fluid, Mujumdar and Douglas[3] used the hot wire technique for auto-correlation measurements of the velocity behind the sphere in a wind tunnel. There are some discrepancies among these works concerning the relation between the Reynolds number $Re$ and the Strouhal number $S$, where $Re$ is based on the sphere diameter $D$ and the undisturbed velocity $U_0$ of the fluid, and $S$ is given by $fD/U_0$, $f$ being the shedding frequencies from the sphere. For example; $S=2.0$ at $Re=1000$ by Möller, and $S=0.2$ by Mujumdar and Douglas at $Re=5600\sim10000$. Achenbach[4] carried out the experiments over wide range of the Reynolds number both in water and in air, but he could not make the measurement in the region of $Re=3000\sim6000$.

The flow condition around the sphere highly depends on the Reynolds number. At low Reynolds number, $Re<250$, the flow was almost laminar and the laminar wake formed behind the sphere. When $Re$ was over 250, the periodic vortices began to shed into the flow field behind the sphere and the shedding frequencies were increased gradually as $Re$ increased. At higher Reynolds number than that causing the periodic shedding, the fluid of the inner part of the vortices behaved in random motion, and all the flow field behind the sphere became turbulent as Reynolds number increased. Although these general observations by some authors were almost the same, there exist some differences among these works. For example, while some authors observed that Strouhal number $S$ increased as the Reynolds number increased at low Reynolds number region, other authors observed that $S$ remained constant to be about 0.2 at high Reynolds number region. There seemed to be no connection between these two Strouhal numbers in the work of Achenbach. On the other hand, Commeta[5] carried out the experiment under $Re=7400$ and observed the co-existence of the double mechanism of the shedding vortices, that is, $S=0.2$ and $0.8\sim1.4$, but he did not explain the phenomena and he only suggested that a transition occurred in vortex shedding of this region. So it seemed to us that one key to solve the mechanism of the vortices was hidden in this Reynolds number region. To prove the conjecture and to combine the results in reasonable form, we attempted the further measurements of the shedding frequencies from the spheres using the flow visualization and the hot film method. In following sections, experimental results of Reynolds number from 200 to 20000 were reported which were carried out using the water tank, and the co-existence of small and large vortices in the shear layer of separation of the sphere was suggested.

## § 2. Experimental apparatus and method

Experiments were carried out using two water tanks. One was a towing tank with the size of 50 cm width, 40 cm depth and towing distance was 230 cm, and the speed of towing was changeable from 0 to 10 cm/sec by the rotation of shaft gear. The tank was mainly used for flow visualization owing to the low background turbulence, but it was not useful for hot wire measurements because of its short running distance. The other was a circulating tank with the size of cross section of $50\times50$ cm. Figure 1 shows the diagram of the circulating water tank, the water was circulated by pump ① and arrows show the direction of water flow. Glass plates of $80\times20$ cm ② were inserted as the side walls for observation in the test section. Water speeds were changeable continuously from 0 to 12.5 cm/sec by controlling the valve opening ③. The horizontal distribution of the water speed was uniform except narrow regions of side boundaries and the vertical uniformity of the speeds was accomplished by the control of the width of the slotted plates ④ near the suction part

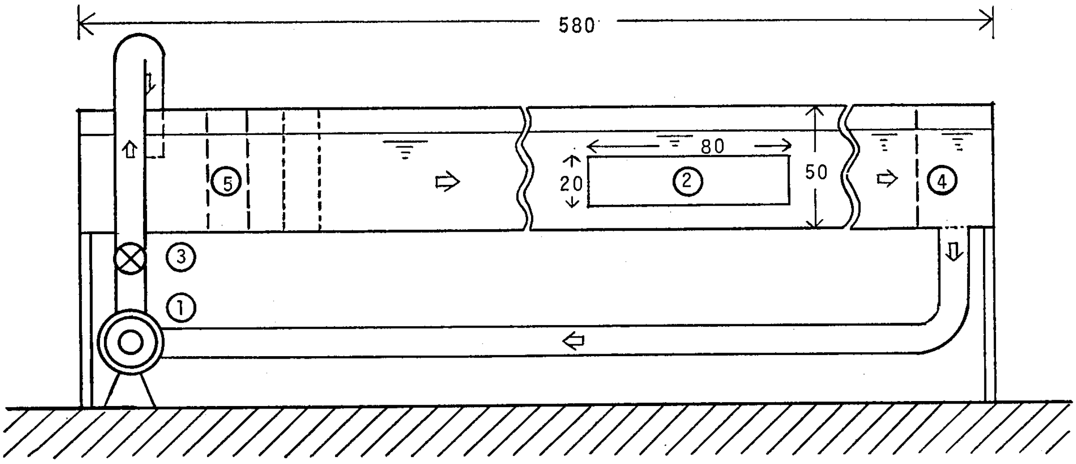



Fig. 1. Circulating water tank, ①: pump, ②: glass plates of test section, ③: controlling valve, ④: slotted plates, ⑤: perforated plates and mesh screens.

except the bottom boundary. Water was passed through two perforated plates and mesh screens ⑤ after the pumping up of water in order to decrease the turbulence of water. Turbulence level of the water flow was 0.5% at $U_0=5.0$ cm/sec but it was increased gradually until 2.0% at $U_0=12.5$ cm/sec. This tank was used both for flow visualization and for hot film measurements. Five spheres of diameter 2.04, 3.75, 4.5, 6.6 and 11.0 cm were used to get the measurements of the wide range of Reynolds number, and they were made of tin for flow visualization by an electrolysis method. When D. C. current was applied between the sphere as an anode and a copper plate as a cathode, fine grains of tin were shedded into the flow field. These grains were visible when they were illuminated by the narrow intense beam of slide projector. Each sphere was supported by the rod of 4 mm$\phi$ in the towing tank as shown in Fig. 2 and the rod was moved with carriage in constant speed. In circulating tank, the sphere was supported tightly by six thin nylon fish lines (0.3 mm$\phi$) to a frame with the size of the test section, as shown in Fig. 3, and the frame with the sphere was inserted into the test section of water path. As the blockage of the cross section by the sphere was not over 5% of the test section, it was considered to have little effect for the

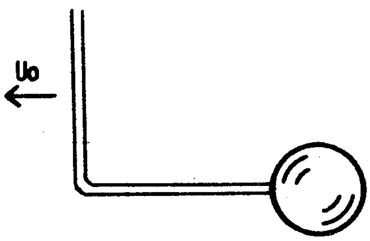



Fig. 2. Sphere supported by rod in towing tank.

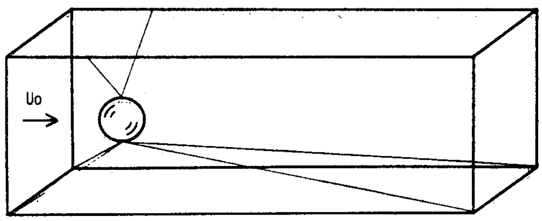


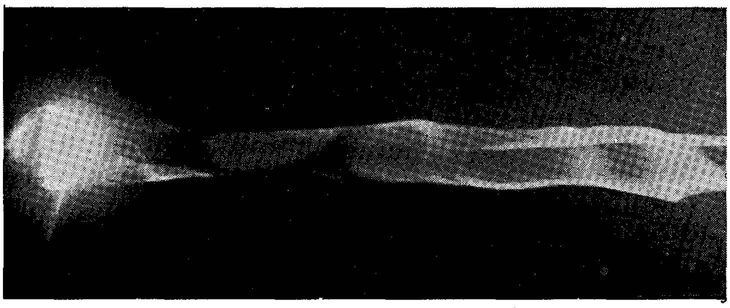

Fig. 3. Sphere fixed to frame by fishing lines.

observation of the flow patterns and the vortex shedding. Hot film coated with the thin quartz film was adopted to pick up the velocities and the velocity fluctuations of the flow field. The hot film was operated in a constant temperature method and fluctuations of the out put of the hot film were recorded by a pen recorder and were analyzed. In order to detect the phase relation of the shedding vortices, two hot films were used at two points simultaneously in the flow field.

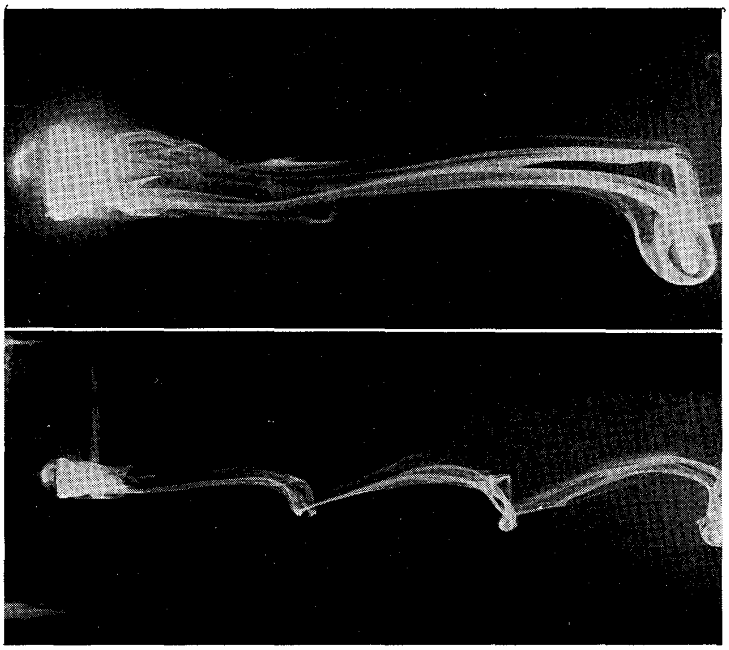
## § 3. Results and discussions

In Fig. 4, the examples of pictures by the flow visualization at some Reynolds number are shown. The rolling up from the sphere began to shed periodically at $Re=250$ although the thin film of tin grains shedded continuously behind the sphere when $Re<250$, (a). Due to the support or fish lines which caused a little velocity defect behind them, the vortex shedding was not discrete, and its vortex filaments were continued partially to the next stage of vortex shedding (b). Schematic diagram of the configuration of the vortex is shown in Fig. 5 from two directions perpendicular to each other on the basis of our observation at $Re=500$. This configuration was almost similar to the observation by Achenbach at $Re=1000$ except the connection of vortices. In his observation, loops of the vortex twined around the elongated part of the vortex separation. One filament was not able to divide into two parts in our observation and a part of one loop of the filament was elongated and was delayed to shed due to the velocity defect of the support. With increasing Reynolds number, the distances to the next stage of the shedding decreased as the intervals of the vortex decreased, and finally the vortex loops lost their individual character. Figure 6 shows the picture of the cross section of the shedding vortices at $Re=1300$ illuminated by the slit beam of light. As is shown, the distance to the next stage became shorter but shedding vortices still kept their individual character.

Hot film was inserted into the wake of the sphere and was moved vertically at each point across the wake. The periodic wave patterns



(a)



(b)

Fig. 4(a) Photograph of the beginning of the vortex shedding.
$D=2.04$ cm, $U_0=1.4$ cm/sec, $Re=245$.
(b) Photographs of the vortex shedding.
$D=2.04$ cm, $U_0=1.6$ cm/sec, $Re=290$.

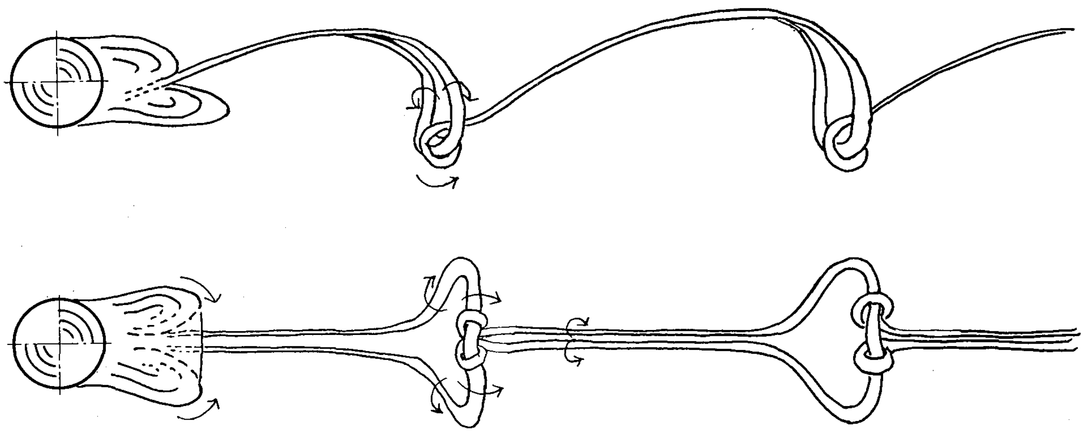


Fig. 5. Schematic representation of the vortex shedding behind the sphere at $Re=500$, flow direction is from left to right.

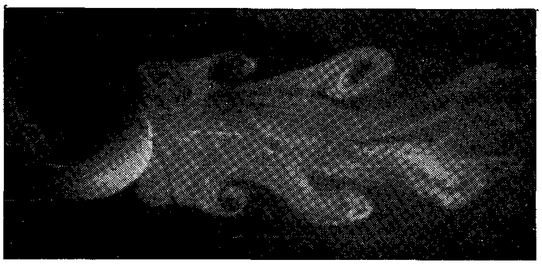


Fig. 6. Photograph of the vortices behind the sphere at $Re=1300$.

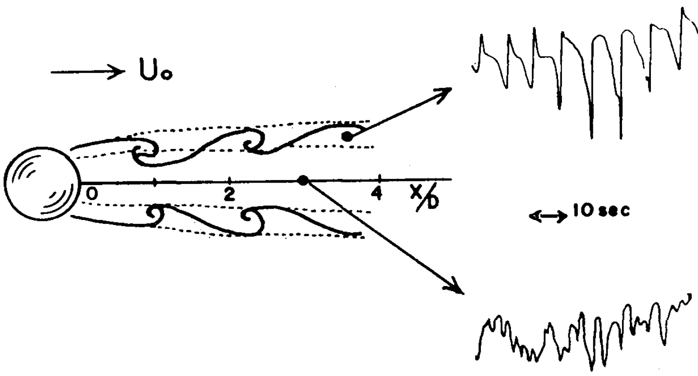



Fig. 7. Flow patterns in the wake of the sphere.

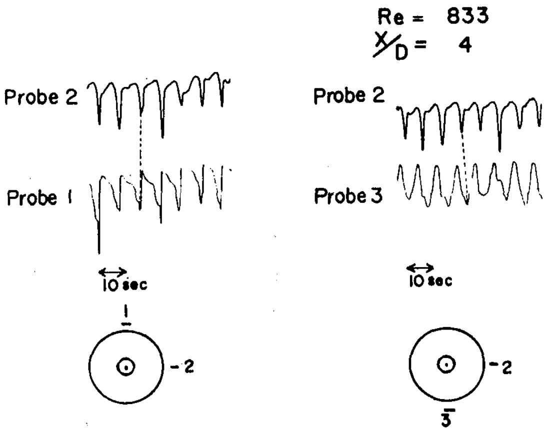



Fig. 8. Flow patterns at different points behind the sphere at the same moment.

were observed at the narrow region of the shear layer between the wake and the free stream where the vortex filaments passed. On the other hand, the irregular wave patterns were observed at the wide range of the center part of the wake. Figure 7 shows the example of wave patterns at $Re=833$ at two points illustrated in the figure, one is the regular pattern at shear layer and the other is irregular at the center part. As is shown in Fig. 8, the wave patterns at two points in the shear layer of the sphere were observed simultaneously. Although the phase of the wave patterns are the same in position 1 and 2, it is observed that the pattern of position

3 was delayed comparing with that of the other positions. It seems to us that the delayed position of the wave was the effect of the velocity defect due to the supporting rod or lines. In order to detect the effect of the velocity defect, a little bump was attached artificially at the surface of the sphere near the separation point. Then the velocity defect happened at the rear part of the bump, and the vortex loops were elongated at this part although the vortices were shedded almost at the same time from the other part. So the vortices flow vertically behind the sphere in the water except the rear part of the bump. If we could fix the sphere freely in the water without any support, vortex shedding would occur discontinuously forming the circular vortex rings behind the sphere. With increasing Reynolds number, the number of vortex shedding increased monotonically as we observed the wave form by the hot film. When the Reynolds number was over 3500, vortices of larger scale were made by the collection of small vortices which were shedded periodically from the sphere. Typical patterns of this wave form is shown in Fig. 9. It seemed that the wave patterns were not so obvious to identify the vortices of larger scale but the wave patterns of the other part were more irregular as we could not recognize the main frequency of both small and large vortices. The Strouhal number based on the large vortices, $S_L$, were distributed in the range from 0.13 to 0.22, and it connected with the value of 0.2 by Cometta. The relation between the Strouhal number and the Reynolds number is shown in Fig. 10 together with the results of Achenbach and others. These results show the measurements of both flow visualization and hot film methods for several spherse. It is shown in this figure that the present result fitted with the results of the Achenbach over the low Reycolds number region. And also the result in the figure shows that the measurements of the co-existence of double vortices have the same tendency with that of Cometta at higher Reynolds number region, although it had wide scattering comparing with the measurements of the low Reynolds number region.

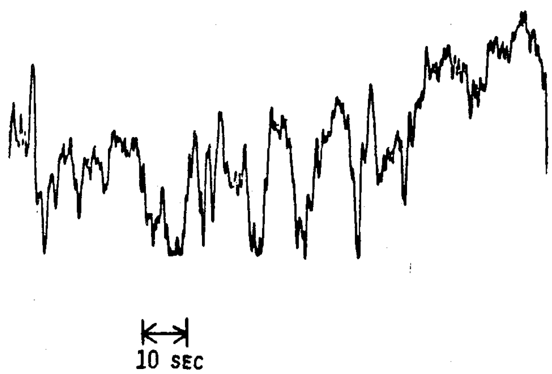



Fig. 9. Flow pattern at $Re$=3680, $S$=1.5, $S_L$=0.13.

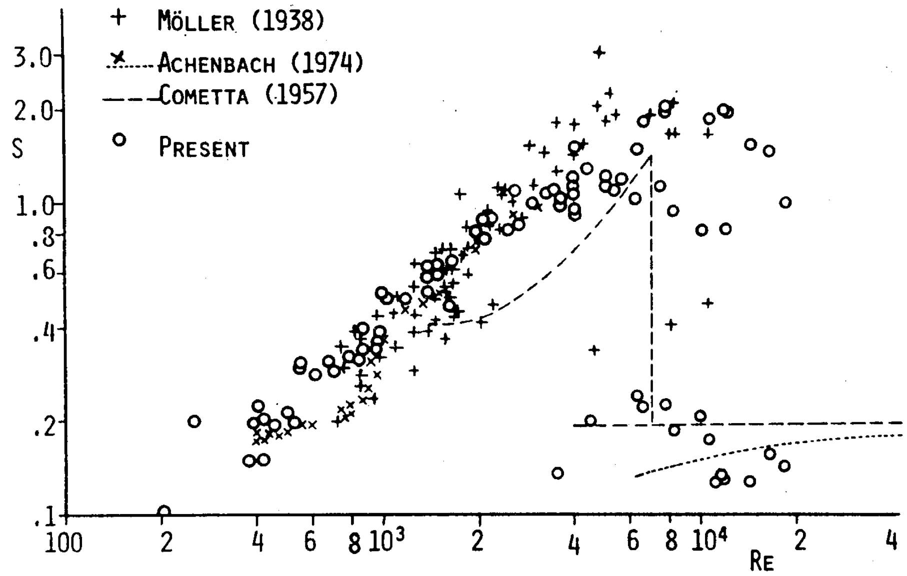



Fig. 10. Relations between Reynolds number $Re$ and Strouhal number $S$.

## § 4. Concluding Remarks

Measurements of the vortex shedding from spheres were made in wide range of the Reynolds number in water and following results were given.

1) Shedding frequencies of the vortices from spheres were increased as the Reynolds number increased in low Reynolds number region.

2) Co-existence of double vortices was explained as that the large vortices were collections of the small vortices from spheres.

3) Strouhal number based on the large scale vortices remained to be constant about 0.2 in high Reynolds number region.

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