THE RESPONSE OR VORTICES TO IMPULSIVE MOTIONS OF A CIRCULAR CYLINDER

HONJI, Hiroyuki
Research Institute for Applied Mechanics, Kyushu University : Lecturer

https://doi.org/10.5109/7170851

出版情報：Reports of Research Institute for Applied Mechanics. 18 (61), pp.61-68, 1970. 九州大学応用力学研究所
バージョン：

Reports of Research Institute for Applied Mechanics
Vol. XVIII, No.61, 1970

THE RESPONSE OF VORTICES TO IMPULSIVE MOTIONS OF A CIRCULAR CYLINDER†

By Hiroyuki HONJI*

The unsteady flows induced by the impulsive motions of a circular cylinder were studied experimentally by means of a flow visualization technique at Reynolds numbers below 160.

When the cylinder moving with constant speed in advance was stopped impulsively, it was observed that a back flow took place and an unsteady vortex pair was formed upstream of the cylinder. The form of these vortices was somewhat different from that of ordinary standing vortices formed behind a stationary circular cylinder. The time-dependent development of the length of these vortices was measured from photographs of flow patterns.

The responce of established steady vortices behind the cylinder to a more complicated cylinder motion was also studied; the circular cylinder moving with constant speed in advance was stopped impulsively, and then started impulsively after a given period of time with the same speed that it had initially. When the period of time of stopping was shorter than some critical value, the twin vortices could follow the prescribed unsteady cylinder motion keeping their initial vortex form. On the contrary, when the period of time of stopping exceeded the critical value, the initially established vortices were detached from the body, and entirely new twin vortices began to develop behind the cylinder in a manner similar to that for the case of impulsive start from rest. The Reynolds number dependence of the critical dimensionless time of stopping was found to be approximately $\tau_{oc}=0.004(3/2-R/150)$.

1. Introduction

While numerous experimental and theoretical investigations[1~12] have been made of the unsteady laminar flow past accelerated obstacles of many diverse shapes, few studies have been made of the decelerated flow. To the author's knowledge, no systematic experimental investigation of unsteady laminar flow past decelerated obstacles is to be found in the literature except two recent papers by Tatsuno and Taneda.[13,14] They investigated extensively the wake vortices

† This work was read at the Meeting of the Physical Society of Japan held in Sendai (April 2, 1970).

* Lecturer, Research Institute for Applied Mechanics, Kyushu University.

behind a circular cylinder and a flat plate decelerated uniformly from one steady speed to another by means of a flow visualization technique in a water tank. They found the two different types of the process of transfiguration of the vortex patterns behind the test bodies ; for the case of slow deceleration the twin vortices were elongated slightly immediately after the onset of deceleration, and then shortened gradually with time, and for the case of rapid deceleration the vortex length increased monotonically.

This paper presents the results of an experimental investigation of unsteady flows induced either by impulsive stopping, or by impulsive stopping and subsequent impulsive starting of a circular cylinder. Since the impulsive stopping may be considered as the limiting case of the decelerated motion, it is expected that there is an intimate similarity in the flow patterns for both cases. The motion, impulsive stopping and subsequent impulsive starting, belongs to a somewhat complicated type of body motions. In general the flow configurations around decelerated obstacles are more complex than those around accelerated obstacles. This is interpreted intuitively as due to the following fact (see also Ref. 12) ; while the accelerated body is always in a state of getting free of the vortex wake region, the decelerated body is overtaken by that region and consequently immersed fully in the established eddying wake.

The main purpose of this study is the observation of unsteady flows caused by the impulsive cylinder motions as described above, with particular interest in the formation and interaction of vortices. Many photographs of the flow patterns are included.

2. Methods and Apparatus

Experiments were carried out using a 38 cm $\times$ 40 cm $\times$ 200 cm water tank. Fig. 1 shows the side view of the apparatus used. Test circular cylinders were attached vertically to a carrier which could be moved uniformly. Impulsive starting was achieved by coupling the carrier of the test bodies with a lead screw driven by a motor ; for coupling a pin was dropped impulsively. Impulsive stopping was achieved by pulling up the coupling pin impulsively. The use of the lead screw could shorten the time required for establishing a body motion. The

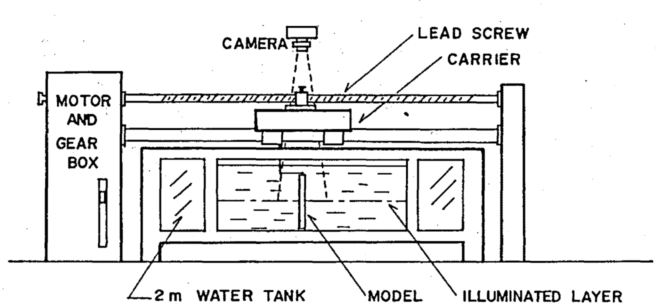


Fig. 1. Schematic view of test equipment.

carrier speed could be varied between about 0.1 cm/s and about 5.0 cm/s.

The metallic dust method was used for flow visualization of the vortex patterns; a number of aluminum dusts were suspended in a water, and a sheet of it was illuminated by making use of a 1 kw projector. Many photographs of the flows at different stages in the pattern variation were obtained using a camera equipped with an automatic motor drive device.

The unsteady motions of the test body were observed with the aid of a hot-wire anemometer. The trace of stopping, or starting motion of the test body and the time of exposures for photographing were recorded simultaneously with an electromagnetic oscillograph. A shutter synchronization unit of the camera was put to use to generate an electric signal when the film was set in exposure. Times elapsed since stopping, or starting of the test body were determined by reading the oscillograms obtained. The middle of the time of exposure was adopted as the "time of observation". Smooth ebonite circular cylinders with 23.0 cm length and 1.00 to 5.25 cm diameters were used as the test bodies.

3. Results and discussion

3-1. Case of impulsive stop

Unsteady phenomena in the flows induced by impulsive stopping of a circular cylinder were investigated using the flow visualization method. At time $t = 0$, the circular cylinder moving steadily with constant speed in advance is stopped impulsively, and thereafter maintained in a state of rest, as illustrated in Fig. 2. The Reynolds number R based on the initial velocity U_0 and the cylinder diameter d ranged from about 30 to about 160 in the present experiment. The dimensionless elapsed time τ is here defined as $\tau=\nu t/d^2$, where the elapsed time t is measured from an instant of stopping to the time of observation defined in Sec. 2, and ν is the kinematic viscosity of water.

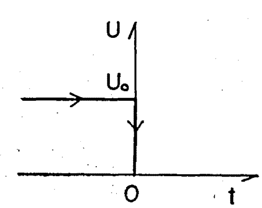


Fig. 2. Cylinder motion, I.

Many photographs of unsteady flow patterns were obtained and some of them are presented in Photoes. 1, 2 and 3, which show the time-dependent variation of the flow patterns at $R=$ 60.0, 92.7 and 127, respectively. In general the established vortices in the wake of a moving obstacle advance upstream with some small velocity. When the obstacle stops impulsively the unsteady back flow past it occurs and consequently the new twin vortex formation begins upstream of the obstacle. This situation will be seen clearly from the illustrated photographs.

It is well known that for a stationary circular cylinder the periodic vortex shedding begins first at about $R=40$. When R is less than about 40, the symmetrical twin vortices attached to the rear of the cylinder are observed. In the present experiment, when the initial steady flow was not periodic one, the symmetrical back flow and accordingly the symmetrical upstream vortices were always observed. The same was also observed when the circular cylinder was stopped before the final flow regime—periodic vortex wake—was not yet reached; the symmetrical twin vortices were formed upstream of the cylinder, as will be seen from Photo. 1. Photo. 1(a) shows the cylinder wake at $R=60.0$; but it was not yet in a steady state. Photo. 1(b) shows the flow pattern immediately after impulsive stopping of the cylinder. The vortex form variation is observed around the cylinder. The remaining photographs of Photo. 1 illustrate the time-dependent development of the twin vortices. As will be seen from these photographs, the upstream vortex form is considerably different from that formed behind the cylinder before its stop. The vortices formed upstream of the body are fattened; the transverse distance between the vortex centers is fairly increased.

Photo. 2 shows the same phenomena as illustrated in Photo. 1 with a different Reynolds number, and in this case the initial flow was completely in a steady state. As will be seen from the photographs, the symmetrical form of twin vortices is broken due to asymmetrical nature of the original back flow. Photo. 3 also shows the same phenomena as already shown in previous two examples, with a further larger value of R, i.e. $R=127$. The symmetry of the new vortex is also broken to a considerable extent. It is interesting to compare the flow pattern presented in Photo. 3(a) with that presented in Photo. 3(g); the former is approximately symmetrical to the latter in the flow direction with respect to the position of the cylinder. The closed vortex wake is seen upstream of the cylinder immersed in the

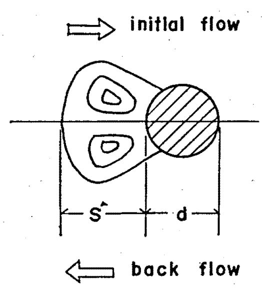


Fig. 3. Vortex length s', and direction of flows relative to test cylinder.

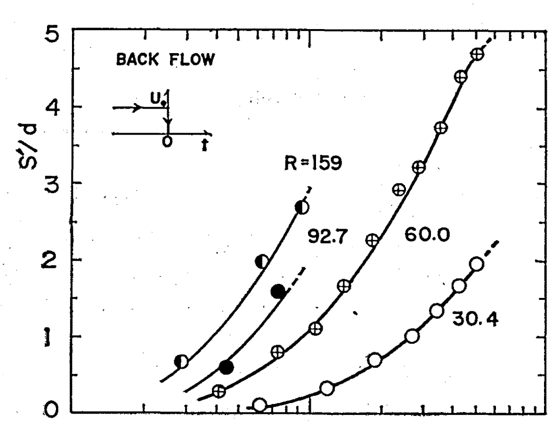


Fig. 4. Development of the length of unsteady twin vortices formed upstream of a circular cylinder after its impulsive stopping.

back flow. The length of time-dependent twin vortices formed upstream of cylinders was measured from the photographs of flow patterns, and the result is presented in Fig. 4.

3-2. Case of impulsive stop and subsequent impulsive start

Flow pattern variations were observed for a circular cylinder, when it was stopped and then started impulsively. The prescribed motion of the test circular cylinder is illustrated in Fig. 5; the cylinder initially moving with constant speed U_0 is stopped impulsively at $t=0$, and then started at $t=t_0$ impulsively. The time interval t_0, which was varied over a wide range of values in the experiment, is non-dimensionalized to give τ_0, which is here defined as $\tau_0=\nu t_0/d^2$.

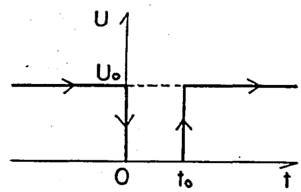


Fig. 5. Cylinder motion, II.

When the parameter τ_0 prescribed was larger than some critical value, the

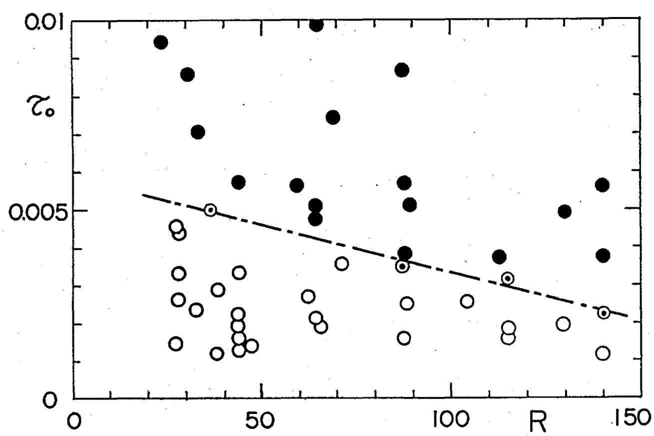


Fig. 6. Responce of twin vortices to unsteady cylinder motion: persistence (○), or no persistence (●) of the initially established vortex form for a cylinder making a motion as illustrated in Fig. 5; the ordinate is the non-dimensionalized period of time of suspension of uniform motion, and the abscissa is the Reynolds number. The circles (⊙) show that no sharp distinction can be made at the corresponding points.

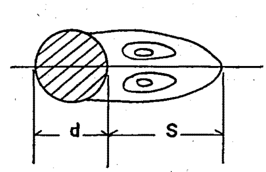


Fig. 7. Vortex length s.

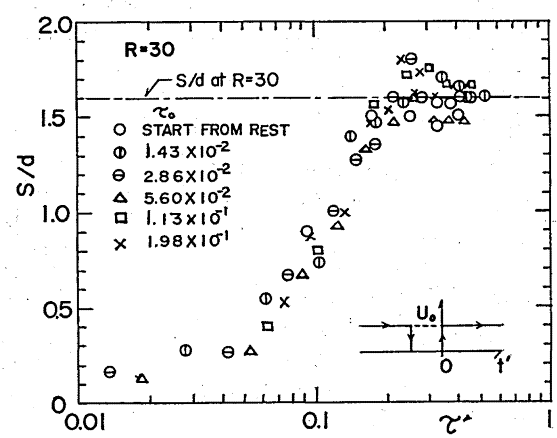


Fig. 8. Development of the length of newly formed vortices behind a test cylinder at a Reynolds number of 30.0. The elapsed time t′ is measured from the instant of an impulsive start after suspention of cylinder motion, as pictured in the corner of the figure. A dimensionless parameter τ' is here defined as $\tau'=\nu t'/d^2$. The horizontal dotted line indicates the dimensionless vortex length for a stationary cylinder.

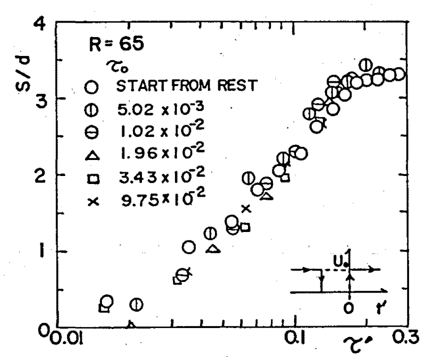


Fig. 9. Same as Fig. 8, with a Reynolds number of 65.0.

initially established vortices attached to the rear of the cylinder was cut off from the body, and left downstream of it as will be seen from Photo. 4. Then the entirely new twin vortices began to grow immediately behind the test body. Photo. 4(a) shows the vortex wake behind the stationary test cylinder. When the cylinder was stopped impulsively, the vortex pattern similar to that for a rapidly decelerated cylinder appeared (see Ref. 13), as illustrated in Photo. 4(b). Shortly after impulsive starting of the cylinder, the new twin vortex formation began at the rear end of the body. The newly formed vortices grew in length with time as shown in the remaining pictures of Photo. 4.

When τ_0 prescribed was smaller than the critical value, however, the initially established twin vortices continued to attach to the rear of the test body. The situation will be seen from Photo. 5. Fig. 6 shows the responce of the twin vortices to the prescribed unsteady motion of the test cylinder at various Reynolds numbers examined in the present investigation. As is evident from this figure, the critical value of $\tau_0(\equiv\tau_{oc})$ decreases with the Reynolds number approximately linearly. The R dependence of τ_{oc} is approximately $\tau_{oc}=0.004$ $(3/2-R/150)$ at least in the range of R examined.

As stated before, the new twin vortices were formed and developed at the rear end of the cylinder, when the stopped cylinder was again set in motion impulsively. The vortex-length variations with time were measured and the obtained results are presented in Figs. 8 and 9 at R=30.0 and 65.0, respectively. In both figures the development of vortices behind the circular cylinder started from rest impulsively is also shown for comparison. The differences are not great as will be seen from the figures. This fact means that when τ_o is larger than τ_{oc} the new vortex formation and development do not depend upon the preceding history of the fluid motion. The flow patterns were also photographed of the impulsively stopped cylinder with varying speed relative to the camera. An example of them is illustrated in Photo. 6.

4. Conclusions

The flow pattern variations were observed using the aluminum dust method in the water tank for an impulsively stopped circular cylinder. It was observed that shortly after stopping of the cylinder the back flow occurred around it, and that flow caused the new twin vortex formation upstream of the body. The flow patterns for the impulsively stopped circular cylinder were similar to those for the rapidly decelerated cylinder.

The flow pattern variations were also observed when a cylinder initially moving steadily was stopped impulsively and then started impulsively with the same speed that it had initially. When the period of time of stopping was larger than the critical value depending on the Reynolds number, the twin vortices established immediately behind the body initially was detached from it, and left downstream in the wake. At subsequent times, the entirely new twin vortices began to develop at the rear of the cylinder in a manner similar to that for the case of impulsive start from rest. For the periods of time of stopping shorter than the critical value, the initially established vortices could follow the unsteady cylinder motion, and consequently keep their initial vortex forms. The upper limit of the dimensionless critical period of time of stopping required for keeping the initial vortex form decreased with the Reynolds number approximately linearly in the range of that number examined.

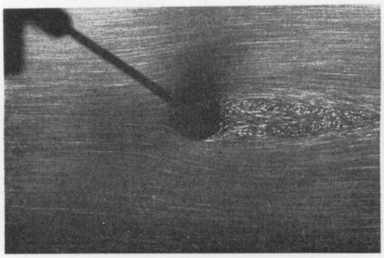
Acknowledgements

The author is indebted to Professor S. Taneda for his continual guidance and interest in this work. Thanks are also due to the staff of Fluid Research Division of the Institute.

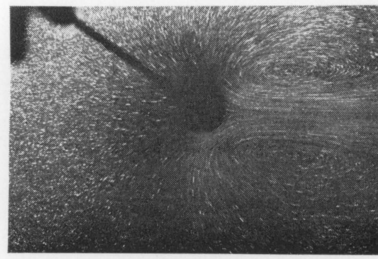
References

1) Von Kármán, Th., Accelerated flow of an incompressible fluid with wake formation, Annali di Matematica pura ed applicata, Ser. **IV**, Vol. **29**, 1949, pp. 247-249.
2) Payne, R. B., Calculations of unsteady viscous flow past a circular cylinder, J. Fluid Mech., Vol. **4**, 1958, pp. 81-86.
3) Sarpkaya, T. and Garrison, C. J., Vortex formation and resistance in unsteady flow, Trans. ASME., Ser. **E**, Mar., 1963, pp. 16-24.
4) Wang, C. Y., The flow past a circular cylinder which is started impulsively from rest, J. Math. Phys., **XLVI**, Vol. **2**, 1967, pp. 195-202.
5) Presz, W. M. Jr. and Heiser, W. H., Unsteady boundary layer analysis for two-dimensional laminar flow, Z. Flugwiss., Vol. **16**, 1968, pp. 33-39.
6) Ingham, D. B., Note on the numerical solution for unsteady viscous flow past a circular cylinder, J. Fluid Mech., Vol. **31**, 1968, pp. 815-818.
7) Son, J. S. and Hanratty, T. J., Numerical solution of the flow around a cylinder at Reynolds numbers of 40, 200 and 500, J. Fluid Mech. Vol. **35**, 1969, pp. 369-386.
8) Honji, H. and Taneda, S., Unsteady flow past a circular cylinder, J. Phys. Soc. Japan, Vol. **27**, No. 6, 1969, pp. 1668-1677.
9) Wang, C. Y., The impulsive starting of a sphere, Quart. Appl. Math., **XXVII**, No. 2, 1969, pp. 273-277.
10) A wide variety of papers concerned with unsteady flows was collected recently as a result of the increasing importance mainly from the point of view of engineering in Transactions of the ASME -*Symposium on unsteady flow*-, 1968, and from the theoretical point of view in Physics of Fluids Supplement -*High-Speed Computing in Fluid Dynamics*-, 1969.
11) Taneda, S. and Honji, H., Unsteady twin-vortices behind a flat plate normal to the flow, Presented at the 24th Annual Meeting of the Physical Society of Japan held in Tokyo (March, 1969); Unsteady flow past a flat plate normal to the direction of motion, (to be published).
12) Honji, H. and Taneda, S., Time-dependent flow around a circular cylinder accelerated uniformly from one steady speed to another, Rep. Res. Inst. Appl. Mech., Vol. **17**, No. 59, 1969, pp. 187-193.
13) Tatsuno, M. and Taneda, S., Flow patterns around a uniformly decelerated circular cylinder, Bull. Res. Inst. Appl. Mech., No. 33, 1969, pp. 1-15, (in Japanese).
14) Tatsuno, M. and Taneda, S., Flow patterns around a circular cylinder and a flat plate normal to the uniformly decelerated flow, (to be published).

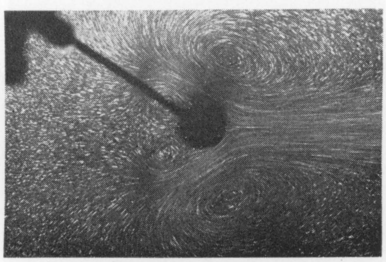
(Received July 9, 1970)



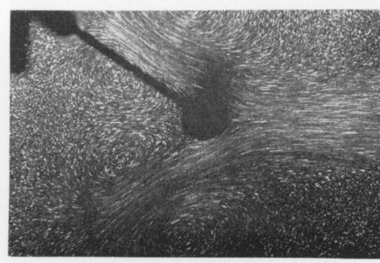
(a) Growing vortices before stopping of cylinder at $R=60.0$



(b) Flow pattern immediately after stopping ; $t=1.89$ s, $\tau=9.66\times10^{-3}$



(c) Formation of upstream twin vortices ; $t=20.9$ s, $\tau=1.07\times10^{-1}$

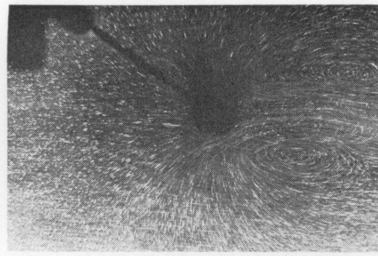


(d) Development of twin vortices ; $t=57.5$ s, $\tau=2.94\times10^{-1}$

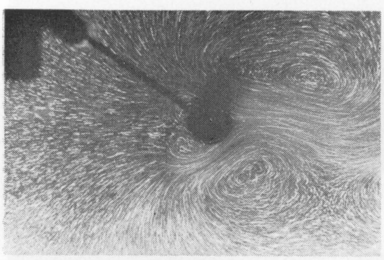
Photo. 1. Different stages of induced flow around a circular cylinder which was stopped impulsively (All photographs in the paper were taken by the camera which was at rest with respect to the test body unless otherwise mentioned.) ; $U_0=0.460$ cm/s, $d=1.50$ cm, t_e (time of exposure)$\simeq$5 s, $R=60.0$.

(Facing p. 68)

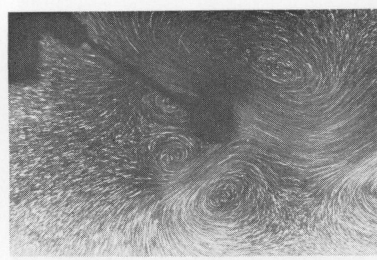
(a) Kármán vortex street at $R=92.7$



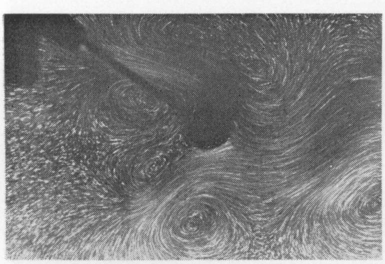
(b) $t=1.00$ s, $\tau=5.64\times10^{-3}$



(c) $t=7.88$ s, $\tau=4.44\times10^{-2}$



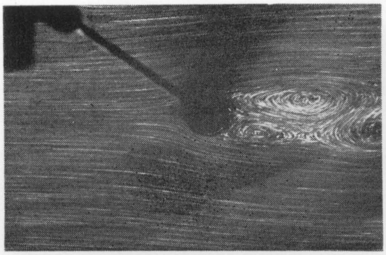
(d) $t=12.9$ s, $\tau=7.28\times10^{-2}$



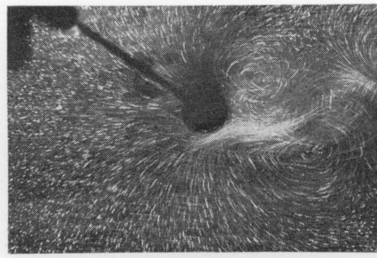
(e) $t=19.3$ s, $\tau=1.09\times10^{-1}$

(f) $t=26.1$ s, $\tau=1.47\times10^{-1}$

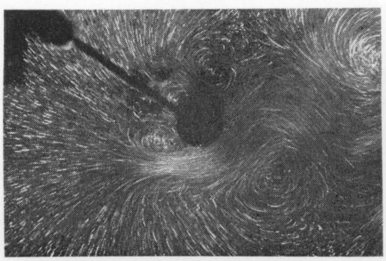
Photo. 2. Same as Photo. 1, with a Reynolds number of 92.7; $U_0=0.785$ cm/s, $d=1.50$ cm, $t_e\simeq 5$ s.



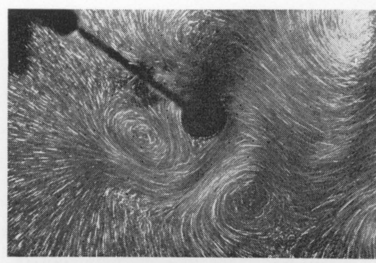
(a) Kármán vortex street at $R=127$



(b) $t=1.00$ s, $\tau=5.64\times10^{-3}$

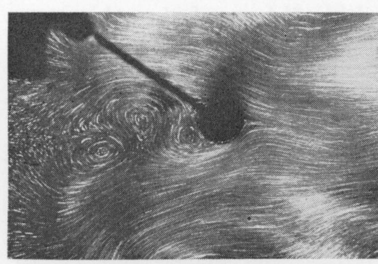


(c) $t=7.38$ s, $\tau=4.16\times10^{-2}$

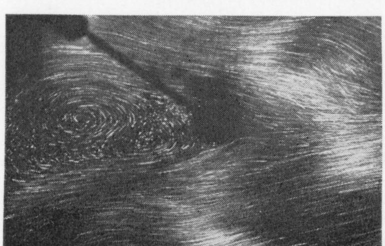


(d) $t=14.4$ s, $\tau=8.12\times10^{-2}$

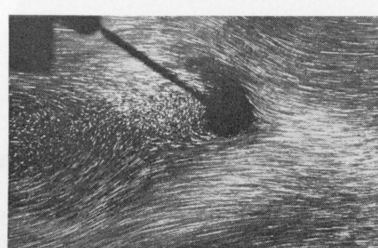
(e) $t=27.0$ s, $\tau=1.52\times10^{-1}$



(f) $t=40.4$ s, $\tau=2.29\times10^{-1}$

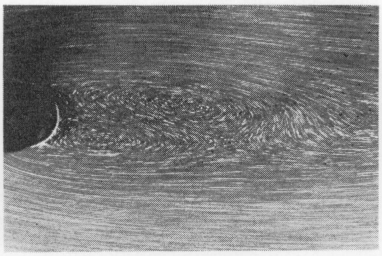


(g) $t=56.3$ s, $\tau=3.18\times10^{-1}$

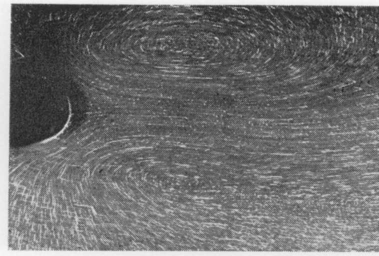


(h) $t=97.8$ s, $\tau=5.51\times10^{-1}$

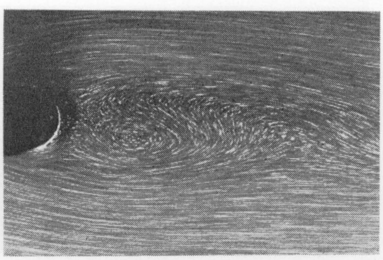
Photo. 3. Same as Photo. 1, with a Reynolds number of 127 ; $U_0=1.07$ cm/s, $d=1.50$ cm, $t_e\simeq5$ s.



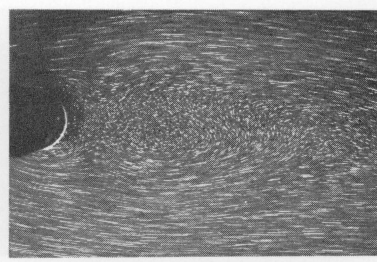
(a) Vortex wake at $R=64.8$



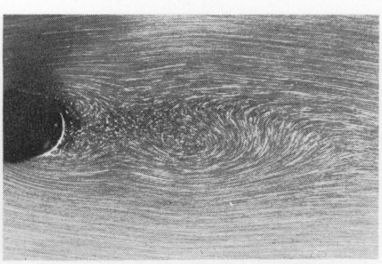
(b) $t=1.23$ s, $\tau=3.80\times10^{-3}$



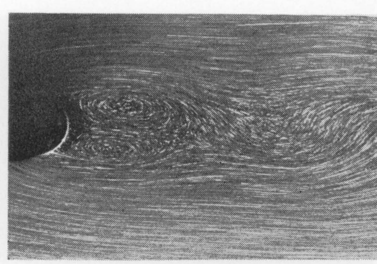
(c) $t=6.25$ s, $\tau=1.93\times10^{-2}$



(d) $t=10.3$ s, $\tau=3.18\times10^{-2}$

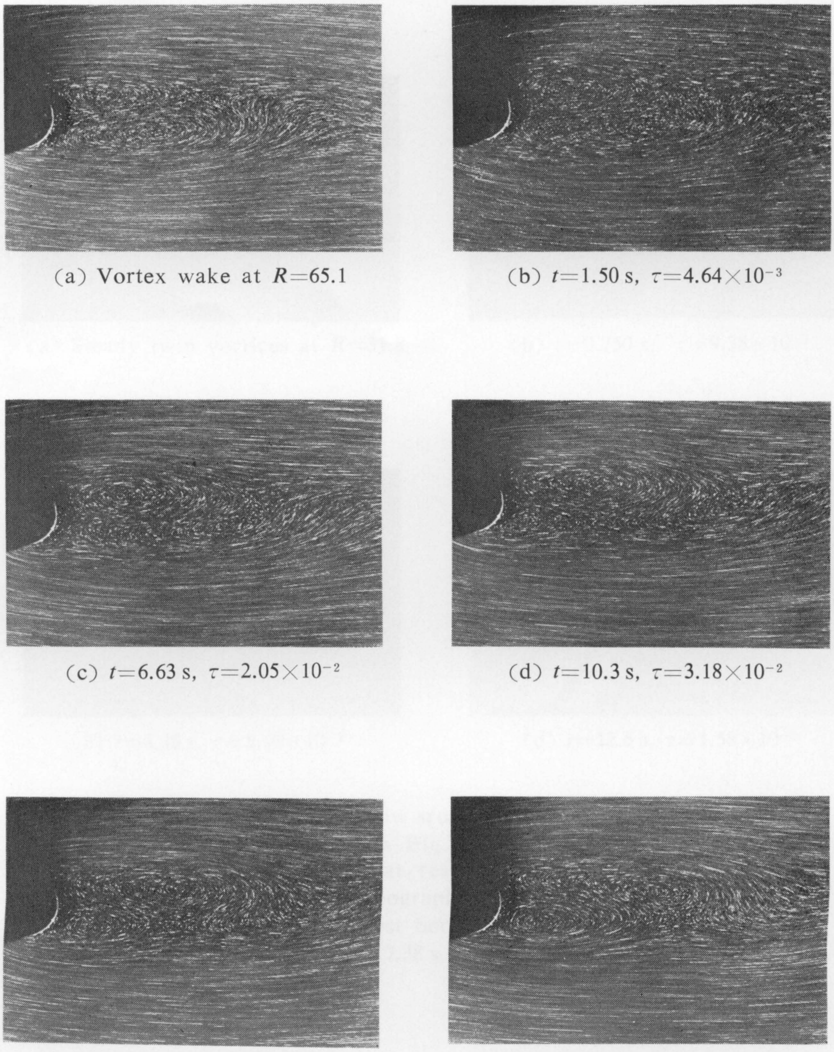


(e) $t=14.3$ s, $\tau=4.42\times10^{-2}$



(f) $t=28.1$ s, $\tau=8.68\times10^{-2}$

Photo. 4. Different stages of flow showing detachment of the initially established vortices from a test cylinder, when the cylinder (a) moving steadily initially (b) was stopped impulsively, and then (c) started impulsively after a certain lapse of time. Photographs (d-f) show the subsequent flow patterns in different delay times ; $U_0=0.404$ cm/s, $d=2.02$ cm, $t_0=3.31$ s, $t_e\simeq5$ s, $R=64.8$, $\tau_0=1.02\times10^{-2}$.



(a) Vortex wake at R=65.1

(b) t=1.50 s, τ=4.64×10^{-3}

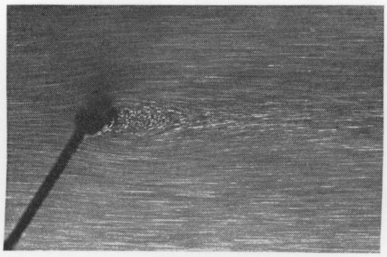
(c) t=6.63 s, τ=2.05×10^{-2}

(d) t=10.3 s, τ=3.18×10^{-2}

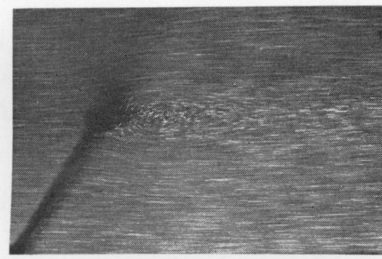
(e) t=16.3 s, τ=5.04×10^{-2}

(f) t=22.5 s, τ=6.95×10^{-2}

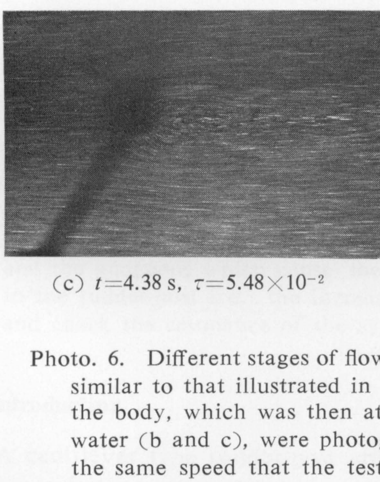
Photo. 5. Different stages of flow showing persistence of the initial vortex form, when a test cylinder (a) moving steadily initially (b) was stopped impulsively, and then (c) started impulsively after a certain lapse of time. Photographs (d-f) show the subsequent flow patterns in different delay times; U_0=0.406 cm/s, d=2.02 cm, t_0=0.625 s, $t_e \simeq 5$ s, R=65.1, τ_0=1.92×10^{-3}.



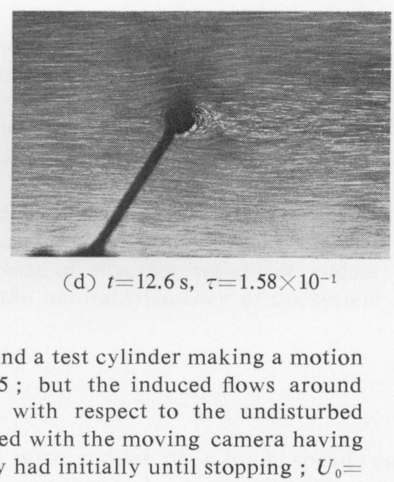
(a) Steady twin vortices at $R=31.8$



(b) $t=0.750$ s, $\tau=9.38\times10^{-3}$



(c) $t=4.38$ s, $\tau=5.48\times10^{-2}$



(d) $t=12.6$ s, $\tau=1.58\times10^{-1}$

Photo. 6. Different stages of flow around a test cylinder making a motion similar to that illustrated in Fig. 5 ; but the induced flows around the body, which was then at rest with respect to the undisturbed water (b and c), were photographed with the moving camera having the same speed that the test body had initially until stopping ; $U_0=0.398$ cm/s, $d=1.00$ cm, $t_0=7.38$ s, $t_e\simeq3$ s, $R=31.8$, $\tau_0=9.22\times10^{-2}$.