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# Streaked flow around an oscillating circular cylinder

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When a circular cylinder oscillates transversely in water at rest, a three-dimensional streaming flow streaked with the chains of separated dye sheets is produced over a certain range of amplitude of the oscillation. This paper reports observations of this three-dimensional flow instability.

## 1. Introduction

Streaming flow induced by an oscillating circular cylinder has been investigated by Schlichting (1932), Stuart (1966), Tatsuno (1973), Bertelsen, Svardal & Tjøtta (1973), and others. The flow has a close relationship to the one referred to as acoustic streaming (Batchelor 1970; Lighthill 1978*a*, *b*). This paper reports the results of observations of a three-dimensional instability of the flow induced by a circular cylinder oscillating transversely at relatively large amplitudes in water at rest.

## 2. Experimental methods and flow visualization

Experiments were performed with a glass-sided water tank of 45 × 30 × 23 cm filled with water, in which a circular cylinder positioned vertically was forced to oscillate transversely along a diameter as shown in figure 1. The amplitude ($\frac{1}{2}d_0$) and frequency ($f$) of cylinder oscillation were less than 2·5 cm and 0·65 Hz, respectively. The diameters ($D$) of cylinders made of brass, plastics, and wood were between 2·00 and 3·80 cm, with ratios of length to diameter between 6·40 and 11·6.

In order to reduce effects of the ends of a cylinder, the gap between the bottom of the cylinder and that of the tank and also the gap between the top of the cylinder and the water surface were kept smaller than 0·5 cm. In relation to the end effects, some further experiments were performed using cylinders equipped with upper and lower end-plates, which were 0·5 mm thick circular aluminium plates 16 and 20 cm in diameter, with a ratio of plate diameter to cylinder diameter of about 5·3.

The electrolytic precipitation method described in Taneda, Honji & Tatsuno (1974, 1979) and Honji (1975) was used for flow visualization. White 'smoke' of a metallic compound was produced electrochemically from the surface of a thin strip of solder (0·3 cm wide) put on the surface of two opposite sides of a cylinder along its axis. The smoke or dye covered the whole surface of the cylinder immediately after the onset of cylinder motion. What is visualized with this method of flow visualization is called by Taneda (1978) an 'integrated streaksheet'; this term is used, rather than 'integrated streakline', since in general situations flows are three-dimensional.

The integrated streaksheet is composed of all fluid particles which have come out of the whole surface of a body, and visualizes the successive motion of all the fluid particles

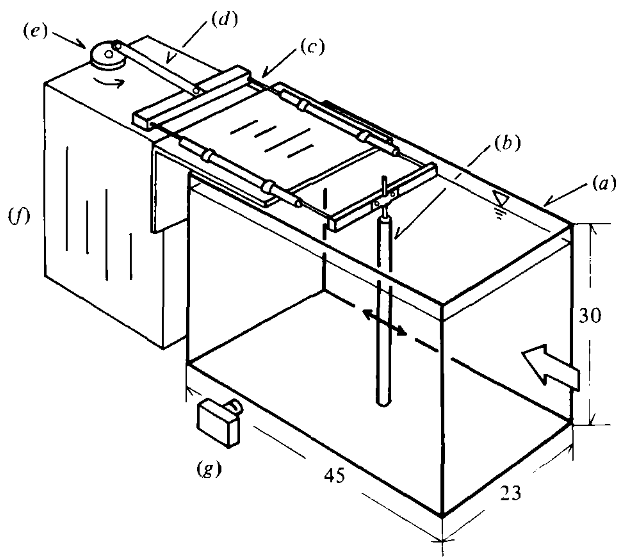



FIGURE 1. Experimental set-up (dimensions in cm). Open arrow indicates one of the directions of illumination, and double arrow the direction of cylinder oscillation. (*a*) Water tank, (*b*) circular cylinder, (*c*) slider rod, (*d*) connecting rod, (*e*) rotor, (*f*) motor and gear box, (*g*) camera (c.p. 1 in figure 2).

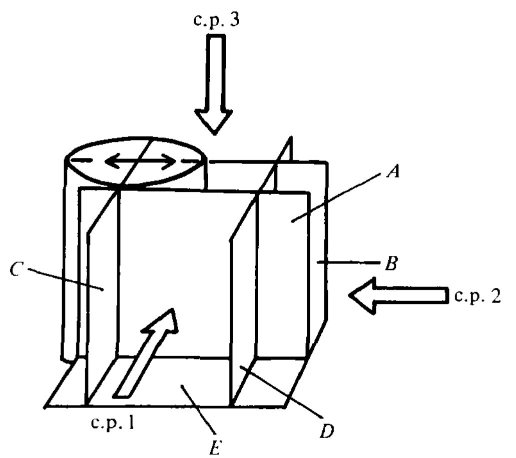



FIGURE 2. Planes of view of flow patterns around a section of cylinder. Double arrow indicates the direction of cylinder oscillation; c.p. 1, 2, and 3 are camera positions.

which have initially constituted the bottom of the boundary layer on the body and later become detached from it. The meaning of integrated streaksheets has been discussed by Taneda (1977, 1978, 1980) and Taneda *et al.* (1979), and in treating unsteady flow separation the concept of integrated streaksheets has been found to be an indispensable complement to the familiar concepts of streamlines, streaklines, and particle paths. In this paper, all the pictures except figure 8 show integrated streaksheet patterns, and the integrated streaksheets are also referred to simply as dye-sheets.

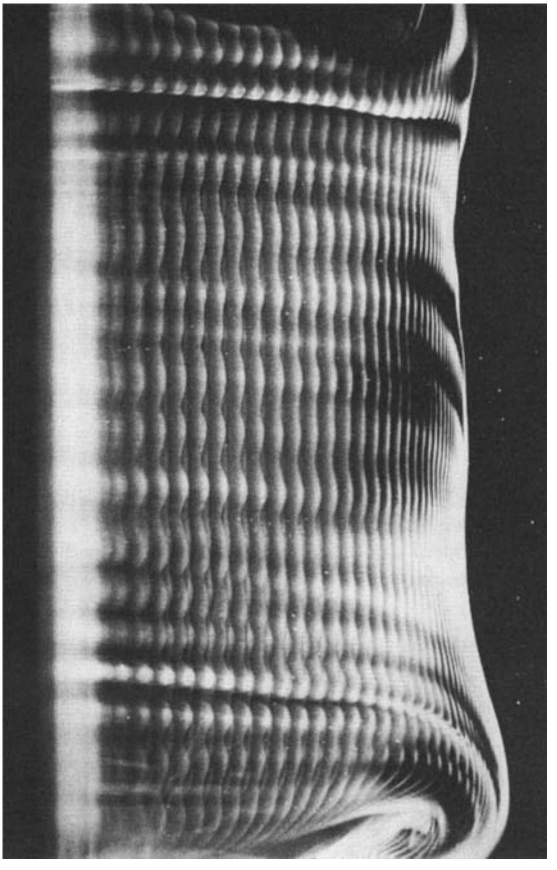


FIGURE 3. Nearly two-dimensional flow in plane $B$. c.p. 1, $f = 0{\cdot}527$ Hz, $D = 3{\cdot}77$ cm, $St = 599$, $d_0/D = 0{\cdot}369$, $T = 0{\cdot}098$.

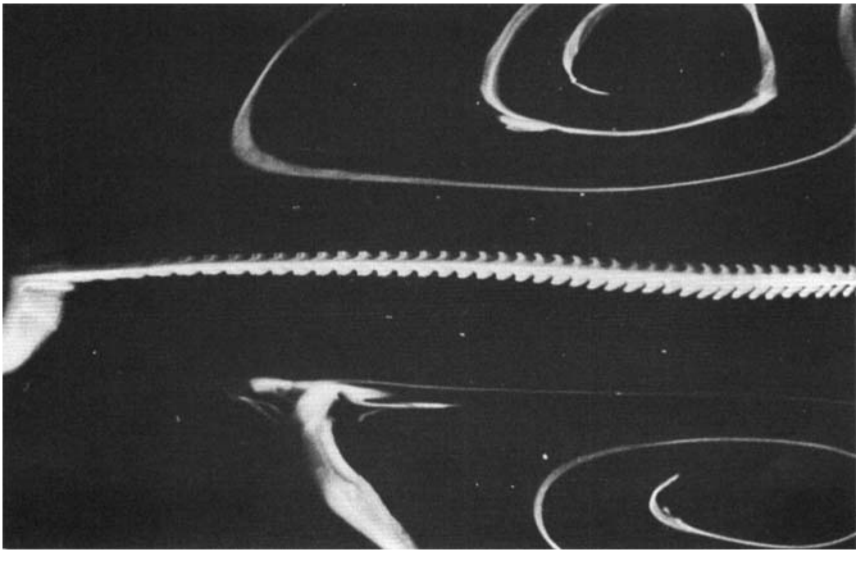


FIGURE 4. Same as figure 3, but in plane $E$, c.p. 3, $T = 0{\cdot}47$.

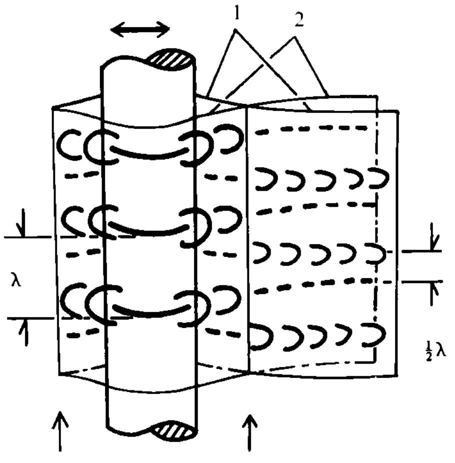



FIGURE 5. Schematic sketch of three-dimensional streaked flow viewed obliquely from above, and definition of streak spacing $\lambda$ on a cylinder. Sheets 1 and 2 indicate those in which the streaks lie alternately with vertical separation of $\frac{1}{2}\lambda$. A double and two single arrows indicate the direction of cylinder oscillation and the intersection of the two sheets, respectively.

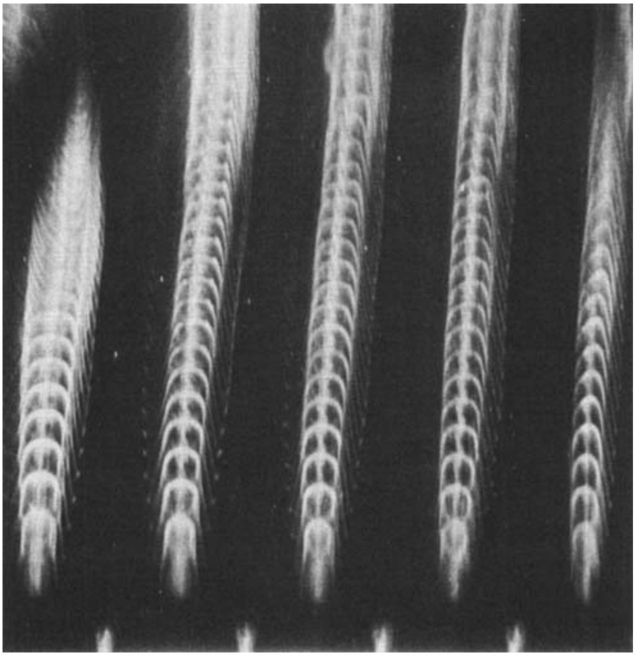
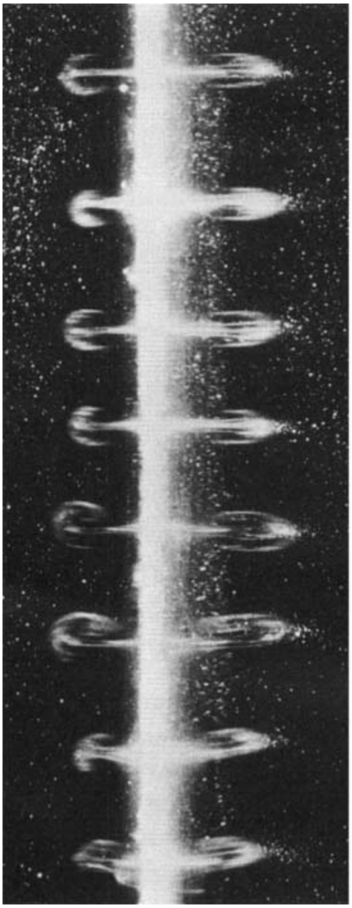


FIGURE 6. Streaked flow in plane $A$. c.p. 1, $f$ = 0·238 Hz, $D$ = 2·00 cm, $St$ = 77·4, $d_0/D$ = 0·900, $T$ = 2·7.



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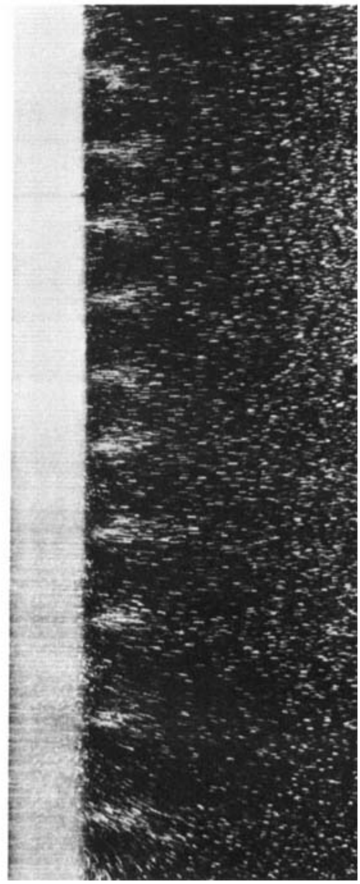

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FIGURE 7. Streaked flow in plane $A$. c.p. 1, $f$ = 0·210 Hz, $D$ = 2·93 cm, $St$ = 197, $d_0/D$ = 0·659, $T$ = 0·036.

FIGURE 8. Streaked flow in plane $A$ visualized with aluminium flakes. c.p. 1, $f$ = 0·318 Hz, $D$ = 2·93 cm, $St$ = 204, $d_0/D$ = 0·580, $T$ = 0·61.

Five slices of water around a cylinder, illustrated schematically as different planes $A$–$E$ in figure 2, were illuminated through a slit, and flow patterns in these planes were photographed with a camera at rest with respect to the tank. The position of the camera, denoted as c.p. in figure 2, was changed according to the direction of illumination; a case of c.p. 1 is shown in figure 1. Unless otherwise stated, the direction of cylinder oscillation is right and left in the pictures.

## 3. Results and discussion

When a circular cylinder oscillates transversely at small amplitudes, two-dimensional streaming flow is induced around it. Typical patterns of such a flow are shown in Schlichting (1932, 1979). Figure 3 shows an induced flow in plane $B$ at a relatively

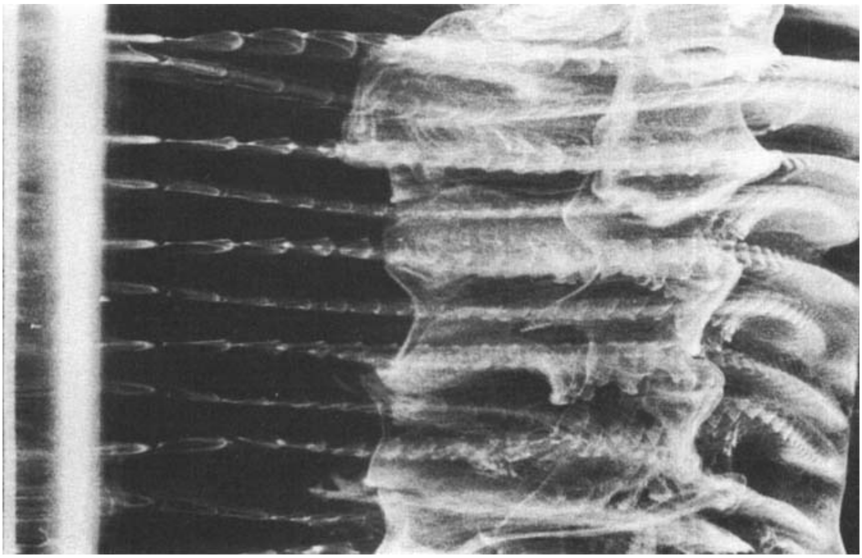


FIGURE 9. Streaked flow in plane $B$. c.p. 1, $f$ = 0·240 Hz, $D$ = 3·77 cm, $St$ = 276, $d_0/D$ = 0·584, $T$ = 0·21.

small amplitude; here $St = fD^2/\nu$ is the Stokes number as introduced by Gerrard (1978) and $T = \nu t/D^2$, where $\nu$ is the kinematic viscosity of water and $t$ is the time passed from the start of cylinder oscillation. In figure 3, the separated dye sheet growing in the direction of cylinder oscillation is nearly two-dimensional, though it is slightly distorted wavily, possibly due to an instability of the flow along a curved path near the cylinder.

As the dye sheet grew outwards from the cylinder, its leading edge rolled up into a vortex pair and reached the tank wall. Then the expanding roll vortices turned back and the tank was eventually occupied by four symmetrical vortices as shown in figure 4 (plan view), where two of them are seen. Such a dye sheet continued to coil without limit, and no steady state of a pattern of the dye sheet was reached as a whole. However, a flat 'near' dye sheet, extending from the cylinder before rolling up, remained, forming at the same position in the mean flow field. Figures in Schlichting (1979) and figure 4 may indicate the pattern of basic mean flow, free from instabilities, which will occur in the flow as it develops.

When the oscillation amplitude was increased further, the induced flow visualized by the dye sheet came to exhibit a marked three-dimensional structure due to an instability of the flow. Because of the complexity of the flow structure, a rough view of the flow is first presented in figure 5. The flow is composed of equally spaced horizontal streaks of chains of separated dye sheets, each in a form like a mushroom; hence the flow may be called 'streaked flow'. It may be considered that at large amplitudes the flat 'near' dye sheet is broken up into the streaks of mushroom vortex chains, extending in the direction of cylinder oscillation.

The horizontal streaks lie in two imaginary sheets indicated as 1 and 2 in figure 5, where the streak spacing $\lambda$ is defined. Partitions of these sheets in harmony with the

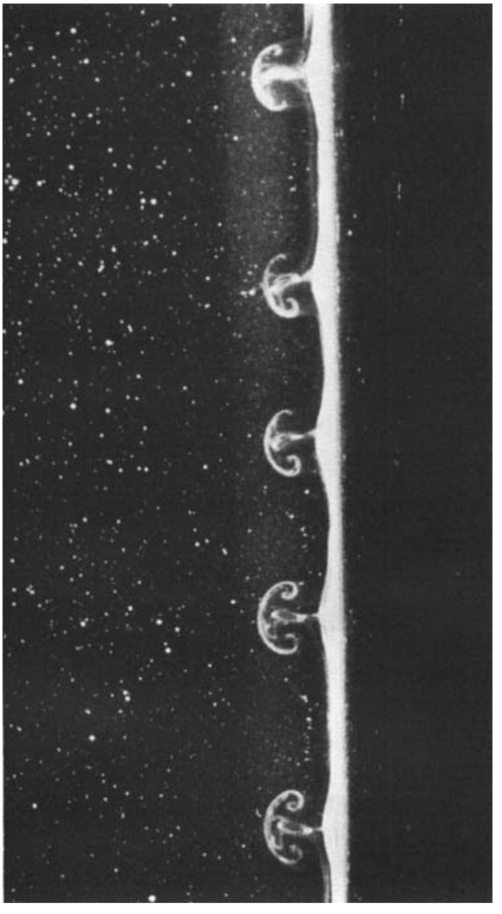


FIGURE 10. Close-up view of streaked flow on cylinder (to the right) in plane $C$. Direction of cylinder oscillation is perpendicular to this page. c.p. 2, $f$ = 0·210 Hz, $D$ = 2·93 cm, $St$ = 197, $d_0/D$ = 0·659, $T$ = 0·043.

streaks indicate the mean flow in the direction of cylinder oscillation. As shown in the figure, the streaks form alternately, in such a way that the vertical distance between a streak lying in one sheet and its neighbouring streaks lying in the other sheet is $\frac{1}{2}\lambda$. The instability seems to be a kind of centrifugal one, and the streaked flow may have a relation to some other types of flows observed by Chen & Christensen (1967), Kirchner & Chen (1970), Taneda, Amamoto & Ishi-i (1972) and Seminara & Hall (1976).

Flow patterns in planes $A$–$E$ (figure 2) show up directly the more detailed structure of streaked flow. Figure 6 shows a typical fully developed streaked flow in plane $A$ near a cylinder, where the long horizontal streaks of mushroom vortex chains lying in sheet 1 (figure 5) are seen clearly. Similar streaks form also on the left-hand side of the cylinder, symmetrically. The mushroom vortices making up each streak are separated from the cylinder one by one in every oscillation of the cylinder, and move away from it in the direction of its oscillation.

Figure 7 shows a view of horizontal streaks aligned on a vertical cylinder in plane A.

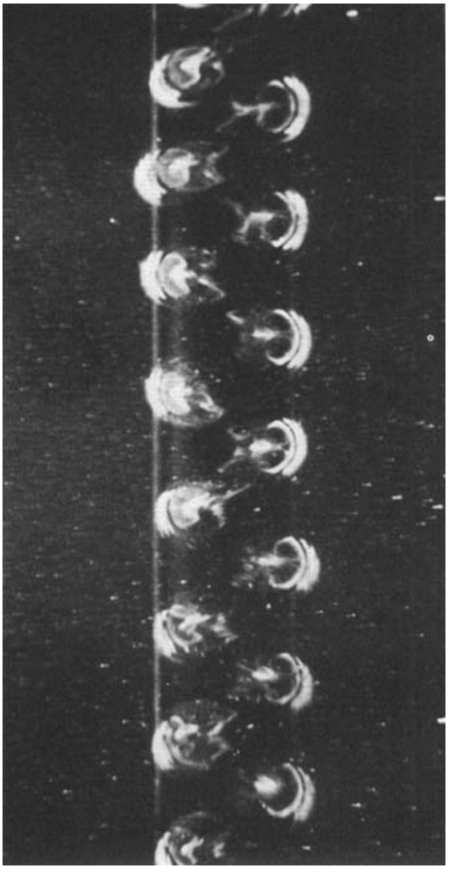
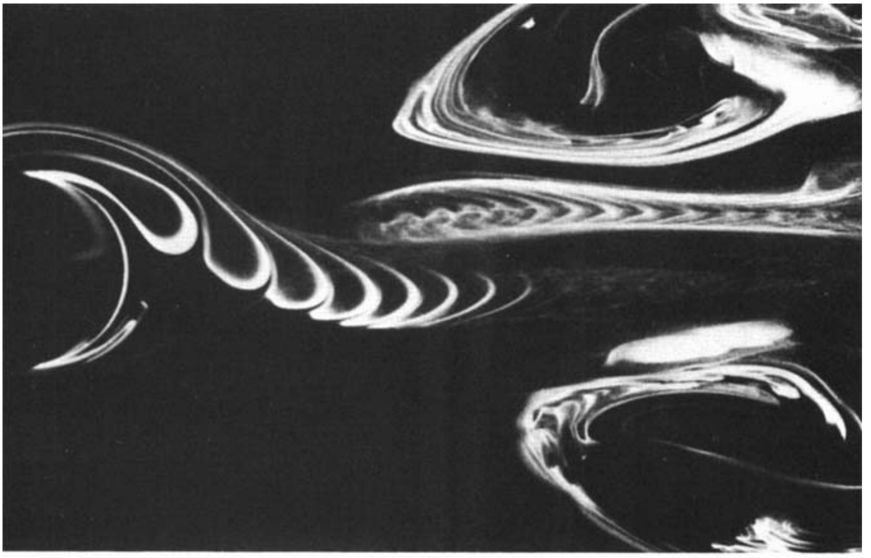


FIGURE 11. Streaked flow in plane $D$ about 5 cm distant from the mean cylinder position; the same oscillation direction as in figure 10. c.p. 2, $f$ = 0·457 Hz, $D$ = 2·00 cm, $St$ = 148, $d_0/D$ = 0·725, $T$ = 0·89.

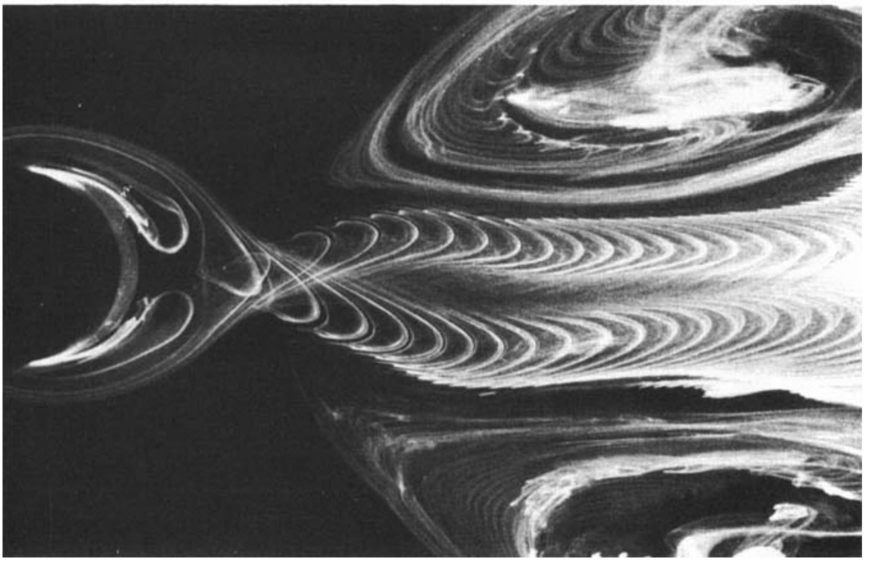
Figure 8 shows similar streaks but visualized with suspended aluminium flakes; on the left is seen the cylinder.

A streaked flow in plane $B$ is shown in figure 9; this view plane is slightly 'thick' in that all the streaks lying in sheets 1 and 2 (figure 5) are seen. The streaks rolled up at their ends, as seen on the right-hand side in the picture. The tank was later occupied by a mean circulatory flow with four symmetrical vortices, just as in the case of the non-streaked two-dimensional flow at small amplitudes. Attention is, however, focused on almost straight 'near' streaks close to a cylinder rather than on the symmetrical outer vortices, which have no appreciable influence on the streak formation in the vicinity of the cylinder.

After the onset of cylinder oscillation, each streak came to stay at the same position, and at the same time $\lambda$ became constant before $T$ reached a value between about 0·03 and 0·05, depending on $St$. At later times, the configuration of the near streaks and $\lambda$ remained steady, in spite of extending motion of the streaks due to continual separation of mushroom dye sheets from the cylinder; in all the pictures the near streak configuration is steady in this sense.



(a)



(b)

FIGURE 12. Plan view of streaked flow in plane $E$. c.p. 3, $f = 0{\cdot}236$ Hz, $D = 3{\cdot}77$ cm, $St = 270$, $d_0/D = 0{\cdot}584$. (a) Flow in a thin view plane; $T = 0{\cdot}28$. (b) Flow in a thick view plane; $T = 0{\cdot}47$.

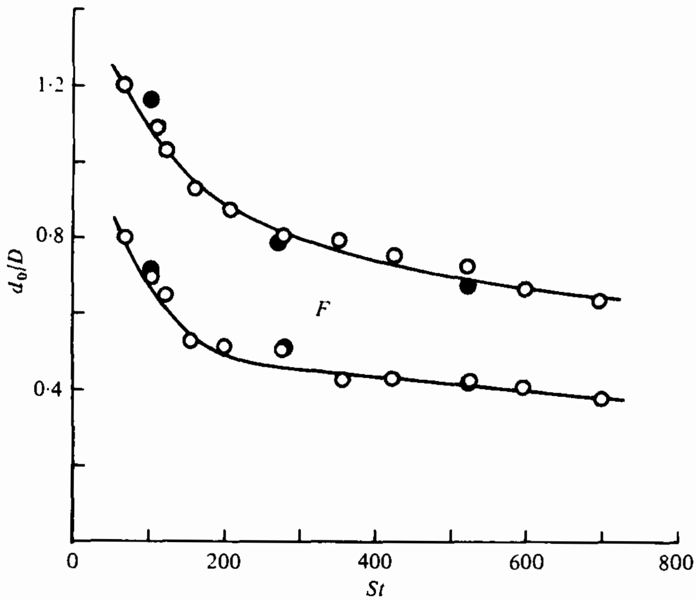



FIGURE 13. Formation region (indicated by $F$) of streaked flow. ○, without end-plates; ●, with end-plates.

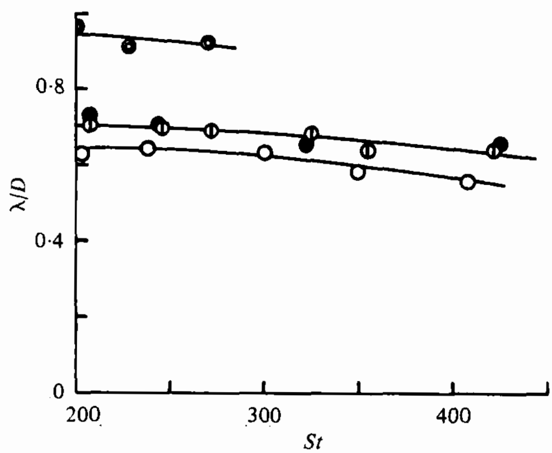



FIGURE 14. Stokes-number dependence of streak spacing along one side of a circular cylinder with $D$ = 2·93 cm and 23·0 cm long. ○, $d_0/D$ = 0·580; ⦶, 0·683; ●, 0·683 (with end-plates); **O**, 0·785.

A flow pattern in plane $C$ is shown in figure 10, where each streak on the cylinder is also of a mushroom vortex form. Figure 11 shows a flow pattern in plane $D$, where the streaks arrange themselves alternately in a vertical double row; the cylinder is seen behind the row.

Figure 12 shows two plan views of a streaked flow in plane $E$. Figure 12($a$) shows the flow in a thin view plane, and the streak is separated only from the upper side of a cylinder. Figure 12($b$) shows the flow when a view plane is thick enough to cover two adjacent streaks. In this picture, the two streaks are seen to cross each other after their separation from the cylinder, but their actual heights along the long axis of the cylinder are different by $\frac{1}{2}\lambda$, as is expected from figure 5.

In figure 13 the smallest and largest values of $d_0/D$ at which streaked flow formed clearly are plotted at 14 values of $St$ between 70 and 700. The symbol $F$ indicates the formation region of streaked flow bounded by upper and lower curves drawn through the plotted data. The values of $d_0/D$ for the formation region decrease with $St$. The open and closed circles show the data for cylinders without and with the end-plates, respectively. There is no marked difference between the two sets of data.

In figure 13, no clear streaked flow forms below the lower curve, possibly because $d_0/D$ is too small for the effect of curvature of flow paths to manifest itself. Above the upper curve also no clear streaked flow forms, because the flow becomes turbulent due to long-standing flow separation. The range of $St$ examined is limited and streaked flow may form outside this range as well.

In figure 14 average values of $\lambda/D$ for the streaks at $T > 0{\cdot}09$ are plotted against $St$ at three different values of $d_0/D$. The closed circles show the data for a cylinder with the end-plates at $d_0/D = 0{\cdot}683$. The other circles show the data for the same cylinder without the end-plates. There is again no marked difference between the two sets of data. Blockage effects of the tank on the formation region and the streak spacing were examined preliminarily by setting the tank broadside to the direction of cylinder oscillation, but no appreciable effects were observed. No further experiments were made on these effects.

The values of $\lambda/D$ decrease with $St$ and increase with $d_0/D$ in the range

$$200 < St < 400.$$

The thickness of the oscillatory boundary layer on a cylinder is of order $(\nu/f)^{\frac{1}{2}}$, with which $\lambda$ may increase, and this would explain the decrease of $\lambda/D$ with the increase of $St$. The increase of $\lambda/D$ with that of $d_0/D$ may possibly be due to the appreciable stretching of separating dye sheets near the cylinder at larger amplitudes.

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