Unsteady Flow Near a Circular Cylinder Oscillating Sinusoidally in a Uniform Flow*

(The Structure of the Boundary Layer and Flows Near the Separation Points)

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The flow past a circular cylinder oscillating transversely in a uniform flow was investigated by flow visualization techniques. The frequency of the oscillating cylinder was set in the synchronized range in which the vortex sheds periodically with the same frequency as the oscillating cylinder. The experimental conditions were $Re=1\ 100$, and $A/D=0.2$, where Re is the Reynolds number based on the diameter D , and A is the amplitude of the oscillation of the cylinder. The characteristic values (the displacement thickness, the shape factor, and the velocity at the outer edge of the boundary layer) were measured using the hydrogen bubble techniques. From the values, the local skin friction on the cylinder was estimated with the oscillating phase angle during a cycle. The characteristics of the unsteady boundary layer near the separation points, where the dye filaments separate from the cylinder, are discussed in comparison with those of a steady one.

Key Words: Unsteady Flow, Boundary Layer, Oscillating Cylinder, Skin Friction, Separation, Flow Visualization

1. Introduction

In the previous paper⁽¹⁾, the mechanism of vortex shedding synchronized with the oscillation of a circular cylinder was elucidated in relation to the transfer of the vorticity generated on the surface of the cylinder oscillating in the transverse direction in a uniform flow. The details of the boundary layer, which separates from the surface of the oscillating cylinder were not described in the previous paper⁽¹⁾.

The unsteady boundary layer with separation has not been elucidated yet. There have been few experimental studies on the phenomenon of separation of the boundary layer on the oscillating cylinder, since the velocity in the boundary layer is difficult to measure.

Recently theoretical studies on the unsteady boundary layer on the starting cylinder has made progress, and the relation between the separation point and the singular point of the boundary layer

equations has been explained^{(2)~(4)}. Since the theoretical results obtained on the basis of the boundary layer equations are valid only when Re assumes an extremely large value, these results must be verified experimentally.

In this paper, the boundary layer on the oscillating cylinder with synchronized shedding of vortices was visualized in detail and the velocity profiles of the boundary layer were measured to elucidate the change of the characteristic values of the boundary layer (the displacement thickness, the shape factor and the velocity at the outer edge of the boundary layer) from the stagnation point to the separation point and behind the separation point. On the basis of these measured values, the phenomena of separation of the unsteady boundary layer were discussed.

Experimental Conditions

Reynolds number: $Re = Ud/\nu = 1\ 100$, Nondimensional frequency of oscillation of the cylinder: $Sc = f_c D/U = 0.20$, Nondimensional amplitude of oscillation of the cylinder: $A/D = 0.20$

Here, U stands for the velocity of the uniform flow (about 20 mm/s), D for the diameter of the cylinder (50 mm), A for the amplitude of the oscillation.

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tion of the cylinder, f_c for the frequency of the oscillation of the cylinder (about 0.08 Hz), and ν for the kinematic viscosity.

In the following sections, we describe the motion of the cylinder under the following conditions: the displacement Y of the cylinder is expressed as $A \sin \omega t$, and the velocity of the cylinder is equal to $\dot{Y}$ (ω : angular frequency of the oscillation of the cylinder, t : time). The cylinder is oscillated in a horizontal plane, and we call the location of the cylinder at the phase of $\omega t = 90^\circ$ the "upper dead point" and that of the cylinder at the phase $\omega t = 270^\circ$ the "lower dead point". We observed the flow near the separation point located on the surface facing the lower dead point and described the location of the surface of the cylinder as the azimuthal angle θ , which is shown in Fig. 1.

2. Experimental Apparatus and Method

2.1 Apparatus

The experiment was carried out by using the apparatus described in the previous paper⁽¹⁾. The test cylinder was attached to the carriage, on which a camera was also set up. The carriage with the cylinder was capable of being driven sinusoidally along the rails in the direction perpendicular to the uniform flow. The flow near the surface of the cylinder was visualized by the electrolysis method and the hydrogen bubble technique in the horizontal plane 40 mm under the free surface of water.

2.2 Measurement of velocity profile of the boundary layer and skin friction

The velocity profiles of the boundary layer were measured by means of the hydrogen bubble technique. As shown in Fig. 2, the wire for generating hydrogen bubbles was set like a short piece of whisker (there was no support needle for the generating wire in the flow), and the end of the wire reached a location a little beyond the outer edge of the boundary layer. The details of the way this wire was set were described in the previous papers^{(5),(6)}. The setting position of the

Fig. 1 Schematic diagram which explain the notation and the direction of movement of the cylinder

wire (shown by θ_w) could be varied in order to measure the velocity profile of the boundary layer in any azimuthal angle of the cylinder. In the case of Fig. 2, the setting positions of the wire are $\theta = \theta_w = 40^\circ$ and 130° in azimuthal angle. The procedure for measuring the velocity profile from the traces of the hydrogen bubbles was the same as in the previous paper⁽¹⁾.

The displacement thickness δ_1 , the momentum thickness δ_2 , and the shape factor H (the ratio δ_1/δ_2) of the boundary layer were determined by integrating numerically the measured velocity profile of the boundary layer. As in the previous paper⁽⁷⁾, the skin friction was estimated through use of Pohlhausen's profile corresponding to the shape factor H obtained by the above-mentioned procedure. The coefficient of skin friction $C_f = \tau_o/\rho U^2$ (τ_o : skin friction of the cylinder, ρ : density) in Pohlhausen's profile is expressed by

$$C_f \sqrt{Re} = \left(2 + \frac{\Lambda}{6}\right) \left(\frac{3}{10} - \frac{\Lambda}{120}\right) \frac{U_\theta}{U} \frac{\delta_1}{D} \sqrt{Re}, \quad (1)$$

where U_θ denotes the velocity at the outer edge of the boundary layer. Since the values of H and Λ are connected uniquely, the coefficient of skin friction C_f can be determined by substituting the measured values of H , U_θ/U and $(\delta_1/D)\sqrt{Re}$.

2.3 Observation of the flow near the separation point

The electrolysis method was used in the same way as described in the previous paper⁽⁸⁾ to observe the flow near the separation point. In this method, the surface of the cylinder coated with an electrically conductive point was used as an electrode for generating a white colloidal dye. The point where this colloidal dye filament departs from the surface of the cylinder was defined as a separation point. This definition of separation point corresponds with the one proposed by Taneda⁽⁹⁾. In the previous paper⁽¹⁾, this point was confirmed as the point from which the vorticity generated on the surface of the cylinder is

Fig. 2 Flow near the surface of the cylinder visualized by the hydrogen bubble technique ($\omega t = 321^\circ$, $\theta_w = 40^\circ$, 130°)

conveyed downstream. The photograph in Fig. 3 shows an example of the flow near the separation point.

3. Experimental Results and Discussion

3.1 Velocity at the outer edge of the boundary layer

Figure 4 shows an example of the circumferential distribution of the velocity U_θ at the outer edge of the boundary layer of the oscillating cylinder. Nondimensional velocity $U_\theta^* = U_\theta/U$ is plotted against the azimuthal angle θ (see Fig. 1).

In Fig. 4 the solid lines show the velocity distribution for the oscillating cylinder, and the dotted line, the velocity profile for the stationary cylinder. The arrows in the figure indicate the points where the dye filament (visualized by the electrolysis method) departs from the surface of the cylinder. Such measurements as in Fig. 4 were

Fig. 3 Dye filaments shedding from the surface of the cylinder ($Re=1000$, $\omega t=19^\circ$)

Fig. 4 Examples of the velocity at the outer edge of the boundary layer ($Re=1100$, $Sc=0.20$, $A/D=0.20$)

performed for eight phases in a period ($\omega t=7^\circ, 52^\circ, 97^\circ, 142^\circ, 187^\circ, 231^\circ, 236^\circ, 321^\circ$) to elucidate the variation of U_θ^* with phase, ωt . The results are shown in Fig. 5 with azimuthal angle θ as a parameter. The solid curves in Fig. 5 were obtained by fitting the relation $U_\theta^* = \bar{U}_\theta^* + U_\theta^{*'} \cos(\omega t + \phi)$ to the experimental values of velocity. For every azimuthal location θ , it is found that the experimental results can be represented by the curves with a satisfactory degree of approximation.

Figure 6 shows the relations of $\bar{U}_\theta^*$, $U_\theta^{*'}$, and ϕ to θ . From this figure, the average velocity $\bar{U}_\theta^*$ is found to agree fairly well with the velocity U_θ^* at the outer edge of the boundary layer of the stationary cylinder ($Sc=0$), which is shown as a dash-dotted line in the figure. The amplitude of the fluctuating velocity $U_\theta^{*'}$, maintains an approximately constant value over the range of $0^\circ < \theta < 20^\circ$, that is, near the stagnation point ($\theta=0^\circ \sim 20^\circ$), then decreases gradually for $\theta > 30^\circ$, and

Fig. 5 Variation of the velocities at the outer edge of the boundary layer with time

Fig. 6 Mean velocity $\bar{U}_\theta^*$, amplitude of the fluctuating velocity $U_\theta^{*'}$, and the difference of the phase from the cylinder oscillation ϕ at the outer edge of the boundary layer

assumes a value less than half that at the stagnation point at the location of $\theta=85^\circ\sim 110^\circ$, near the separation point. Near the stagnation point, as seen in Fig. 6, a large velocity fluctuation in phase with the oscillation of the cylinder is observed, since the direction of the oscillation of the cylinder coincides with that of the velocity at the outer edge of the boundary layer near the stagnation point. In other words, in the coordinate system attached to the cylinder, nondimensional velocity $2\pi A/D \cdot S_c \cos \omega t \approx 0.25 \cos \omega t$ is superposed on the flow near the stagnation point uniformly in space in a direction opposite to that of the motion of the cylinder. Furthermore, since this superposed velocity causes the stagnation point to move, the amplitude of velocity fluctuation U_θ^* is about 0.4, larger than 0.25. This value of U_θ^* is nearly equal to the value of $\bar{U}_\theta^*$ at the point ($\theta=14.4^\circ$) where the curve of $\bar{U}_\theta^*$ intersects the dashed line in Fig. 6. This location ($\theta=14.4^\circ$) corresponds to the maximum incident angle α for the resultant flow toward the oscillating cylinder. The fact that U_θ^* is about 0.4 indicates that the flow near the stagnation point ($\theta=0^\circ\sim 30^\circ$) is characterized by the movement of the stagnation point with the variation of incident angle α .

On the other hand, near the separation point, the direction of the velocity at the outer edge of the boundary layer is nearly perpendicular to the direction of the motion of the cylinder. The velocity fluctuation U_θ^* , where $\theta \approx 90^\circ$, is smaller than that one near the frontal stagnation point and the phase difference is large. Thus, it can be interpreted that this part of flow is strongly influenced by the location of the separated shear layer relative to the cylinder and the structure of vortices behind the cylinder, as described in the previous paper⁽¹⁾.

Figure 7 shows the variation of U_θ^* vs. $\theta - \theta_{st}$ with the phase angle ωt as a parameter, where $\theta - \theta_{st}$ denotes the azimuthal angle measured from the stagnation point θ_{st} . Figure 7 (a) shows U_θ^* in the case in which the cylinder moves from the lower dead point to the upper dead point ($\omega t = 270^\circ \rightarrow 90^\circ$) and Fig. 7 (b) shows it in the case in which the cylinder moves from the upper dead point to the lower dead point ($\omega t = 90^\circ \rightarrow 270^\circ$). The symbol "P" in the figure indicates the separation point where the dye filament departs from the surface of the cylinder. From Fig. 7, the flows near the stagnation point are found to be almost the same as those of the stationary cylinder ($S_c = 0$) as seen from the coincidence between the dashed line and the solid lines in the figure.

3.2 Virtual pressure gradient

When x stands for the distance and u for the velocity along the surface of the cylinder, in the manner of Dwyer and McCroskey⁽¹⁰⁾, the two-dimen-

sional unsteady boundary layer equations can be rewritten in terms of the physical quantities measured in the coordinate with the origin at the stagnation point on the oscillating cylinder (those quantities with the suffix R) as follows by means of conventional symbols:

$$\frac{\partial u_R}{\partial t} + u_R \frac{\partial u_R}{\partial x_R} + v_R \frac{\partial u_R}{\partial y_R} = \left(\frac{\partial U_R}{\partial t} + U_R \frac{\partial U_R}{\partial x_R} \right) + \nu \frac{\partial^2 u_R}{\partial y_R^2}, \quad (2)$$

When the first term in the right hand side of Eq. (2) is assumed as a virtual pressure term of the oscillating cylinder, the virtual pressure gradient $G \equiv -\partial P_V / \partial x_R$ is expressed as

$$-\frac{1}{\rho} \cdot \frac{\partial p_V}{\partial x_R} = \frac{\partial U_R}{\partial t} + U_R \frac{\partial U_R}{\partial x_R}, \quad (3)$$

The virtual pressure gradient G is calculated by substituting the measured velocities at the outer edge of the boundary layer into Eqs. (2) and (3). We omit suffixes V and R , and in the following sections, we substitute as follows: $p = p_V$, $U = U_R$ and $x = x_R$.

(a) $\omega t = 270^\circ \rightarrow 90^\circ$

(b) $\omega t = 90^\circ \rightarrow 270^\circ$

Fig. 7 Velocity at the outer edge of the boundary layer vs. azimuthal angle measured from the stagnation point

The relations between the nondimensional virtual pressure gradient $G^* = GD/\rho U^2$ and the azimuthal angle θ of the cylinder were plotted in Figs. 8 (a) and (b). Figure 8 (a) shows the relation in the case in which $\omega t = 270^\circ \rightarrow 90^\circ$ (the cylinder moves from the lower dead point to the upper dead point); Fig. 8 (b) shows that in the case in which $\omega t = 90^\circ \rightarrow 270^\circ$. The dash-dotted lines in Fig. 8 indicate the measured values of G^* in the case of the stationary cylinder ($Sc = 0$). In the case of the oscillating cylinder at the location where $\theta = 0^\circ \sim 70^\circ$, the virtual pressure gradients G^* vary considerably both with time and space in comparison with the stationary cylinder. Especially when ωt is from 90° to 270° , as seen in Fig. 8 (b), a rapid decrease in the preferable pressure gradient is observed at $\theta = 60^\circ \sim 75^\circ$.

Figures 9(a) and (b) show the virtual pressure gradient due to the unsteady term $\partial U_R/\partial t$. The non-dimensional values of this pressure gradient $G_t^* = (\partial U_\theta/\partial t)D/U^2$ are plotted against the azimuthal angle θ with the phase angle ωt as a parameter. As seen in Fig. 9, the contribution of the unsteady terms to the pressure gradient G_t^* is large near the stagnation point and becomes smaller as θ increases. When Fig. 9 is compared with Fig. 8, the contribution of the

unsteady terms G_t^* to the pressure gradients G^* is found to be small; i. e., the ratio G_t^*/G^* is about 1/6. This value ($G_t^*/G^* \approx 1/6$) is of the same order as the value of $Sc = 0.20$, since the value of Sc corresponds to the ratio of the local acceleration to the convective acceleration. The contribution of the unsteady term $\partial U/\partial t$ is not negligibly small, and the value of the convective term $U\partial U/\partial x$ also changes with time; the unsteadiness of the flow in this experiment is considered to be sizable. The problem of how the characteristics of the boundary layer are affected by this type of unsteady flow is interesting.

3.3 Skin friction

Figure 10 shows the plot of the coefficient of skin friction $C_f\sqrt{Re}$ vs. the azimuthal angle θ with the phase angle ωt as a parameter. Figure 10 (a) shows the relation in the case in which $\omega t = 270^\circ \rightarrow 90^\circ$ (the cylinder moves from the lower dead point to the upper dead point), and Fig. 10 (b) shows that in the case in which $\omega t = 90^\circ \rightarrow 270^\circ$. The dotted lines in Fig. 10 represent the variation of $C_f\sqrt{Re}$ of the stationary cylinder ($Sc = 0$). The solid circles plotted on the axis $C_f\sqrt{Re} = 0$ indicate the separation points where the dye filament departs from the cylinder. The skin friction on the oscillating cylinder was found to change considerably with θ and ωt . As seen in Fig. 10, the variation of the

(a) $\omega t = 270^\circ \rightarrow 90^\circ$

(b) $\omega t = 90^\circ \rightarrow 270^\circ$

Fig. 8 Virtual pressure gradients

(a) $\omega t = 270^\circ \rightarrow 90^\circ$

(b) $\omega t = 90^\circ \rightarrow 270^\circ$

Fig. 9 Virtual pressure gradients due to the local acceleration term

Fig. 10 Variation of the skin friction of the cylinder

skin friction of the oscillating cylinder with θ shown by the solid curves is considerably different from that of the skin friction of the stationary cylinder shown by the dotted lines in the figure, $Sc=0$, at any phase angle $\omega t=0^\circ \sim 360^\circ$.

Now let us keep our eye on the following two sets of points: the points where the skin friction of the oscillating cylinder is considered to vanish, or the solid curves in the figure intersect the θ axis ($C_f\sqrt{Re}=0$), and the points where the dye filament departs from the surface of the cylinder, which are plotted by the solid circles in the figure.

When the cylinder moves from the lower dead point to the upper dead point ($\omega t=270^\circ \rightarrow 90^\circ$, see Fig. 10 (a)), the two sets of points mentioned above almost coincide with each other. On the other hand, when $\omega t=90^\circ \rightarrow 270^\circ$ (see in Fig. 10 (b)), the dye separation points (solid circles in the figure) are found to be located further upstream than the vanishing points of skin friction.

In order to clarify the relation between the separation point and the skin friction, the skin friction lines which are inspired by the mathematical similarity of unsteady two-dimensional and steady three-dimensional flow proposed by Wang⁽¹¹⁾, are drawn in Fig. 11. In the ωt - θ plane, the skin friction lines of the oscillating cylinder can be defined as the curves with the tangent

$$\frac{d\theta}{d(\omega t)} \sim C_f\sqrt{Re}. \quad (4)$$

Figure 11 shows the skin friction lines in the ωt - θ plane. The inclination angle of the arrow in the

Fig. 11 Group of skin friction lines (limited streamlines for two-dimensional unsteady flows)

figure represents the value of $\beta = \tan^{-1}(C_f\sqrt{Re})$ at a point. The skin friction lines are drawn by a group of solid curves which connect these arrows smoothly, and they have a tangent which should coincide with β at any point on them. The dotted line in the figure shows the location of the separation point (dye) θ_{si} , and dash-dotted vertical lines crossing the dotted line for $\omega t=90^\circ$ and 210° indicate the beginning and the end of the period, respectively, during which the reverse flow does not occur behind the separation point (dye) in the boundary layer. The existence of this duration was reported in the previous paper⁽¹¹⁾ as a remarkable feature of the boundary layer of the

oscillating cylinder. As seen from Fig. 11, the inclination angles of the arrows near the separation point (dotted line in the figure) have positive values in the period of no reversed flow mentioned above; that is, the skin friction is positive, $\tau_0 > 0$; and for other phase angles, the inclination angles of arrows are almost zero; that is, the skin friction is zero, $\tau_0 = 0$. Smooth curves can be drawn to have inclinations corresponding to the arrows indicating the value of the skin friction coefficient. These curves are the skin friction lines, and they are represented as solid lines in Fig. 11. This means that the duration of no reversed flow can exist and that the continuity of the skin friction lines can be satisfied in the whole $\omega t - \theta$ plane.

3.4 Characteristics of the boundary layer near the separation point

3.4.1 Outline of the velocity profile of the boundary layer Figure 12 shows the velocity profiles of the boundary layer near the separation point in the $\omega t - \theta$ plane. Each velocity profile is drawn with $y^* = y/D\sqrt{Re}$ as the ordinate and $u^* = u/U$ as the abscissa, where y stands for the distance from the surface of the cylinder, and D for the diameter of the cylinder. The dotted lines in the figure indicate the nondimensional velocity of the movement of the separation point $U_{ss}^* = U_{ss}/U$ (see the previous paper⁽¹⁾). The velocity profile which is measured in the coordinate system with the origin moving with the separation point can be seen when U_{ss}^* is added to u^* . The

moving velocity of the separation point is found to be at most $0.1U$, as seen in Fig. 12. The dash-dotted lines with arrows indicate the location of the separation point θ_{s1} and the direction (arrows) of the movement of the separation point.

When the cylinder moves from the lower dead point to the upper dead point, the velocity profiles of the boundary layer near the separation point are very similar to those in the steady flow in that the velocity gradient is nearly equal to zero and the reverse flow follows, as seen in Fig. 12 (a). On the other hand, when the cylinder moves from the upper dead point to the lower dead point, the velocity profile near the separation point is considerably different from that in the steady flow, as seen in Fig. 12 (b). In the latter case, the formation of a new boundary layer is observed very near the surface of the cylinder (see the velocity profile at the right side of the dash-dotted line at $\omega t = 142^\circ$ and 187°), and the reversed flow is not observed downstream behind the separation point. As mentioned in the previous paper, the reversed flow vanishes near the surface of the cylinder since the relative velocity opposite to the motion of the cylinder is superposed on the flow in the boundary layer behind the cylinder.

3.4.2 Displacement thickness and Shape factor

Figure 13 shows the relation between the displacement thickness δ_1 and the azimuthal angle $\theta - \theta_{s1}$ measured from the separation point θ_{s1} . As seen in the figure, the displacement thickness δ_1 near the separa-

Fig. 12 Variation of the velocity profiles near the separation point

tion point shows almost the same variation as those of the stationary cylinder ($Sc=0$), as shown by the solid lines in the figure, and singular behaviors such as an abrupt increase in the thickness of the boundary layer at the separation point are not observed clearly.

Figure 14 shows the relation between the shape factor H of the boundary layer and the azimuthal angle $\theta - \theta_{s1}$. When the cylinder moves from the lower dead point to the upper dead point, the values of H near the separation point are almost the same as those in the case of the stationary cylinder ($Sc=0$, the solid line in the figure). The measured values of H near the separation point are nearly equal to 3.5.

On the other hand, when the cylinder moves toward the lower dead point ($\omega t = 90^\circ \rightarrow 270^\circ$), as shown in Fig. 14 (b), the values of H near the separation point are smaller than those in the case of the stationary cylinder ($Sc=0$, the solid line in the figure) and the value of H at the separation point ($\theta = \theta_{s1}$) is smaller than 3.5. From the above measurements, the flow near the separation point occurring when the cylinder moves toward the upper dead point is found to be greatly different from that occurring when the cylinder moves toward the lower dead point.

Table 1 shows the characteristics of the boundary layer near the separation point in the cases of the oscillating cylinder ($Sc=0.20$) and the stationary cyl-

inder ($Sc=0$).

As seen at the bottom of Table 1, when the cylinder moves toward the upper dead point ($\omega t = 270^\circ \rightarrow 90^\circ$), the direction of the movement of the surface of the cylinder is the same as the direction of U_θ and so the vorticity generated on the surface of the cylinder has a sign that is the reverse of that of the vorticity in the boundary layer. Therefore, separation of the boundary layer is promoted, and the separation point moves upstream. The pattern of the dye filament at the separation point is considerably different from that in the case of the stationary cylinder, as shown in the sketch in Table 1, though the values of the shape factor H and skin friction τ_o are almost the same as

Table 1 Characteristics of the boundary layer near the separation point

Re=1000	Sc=0 (Stationary)	Sc=0.20	
		$\omega t = 270^\circ \rightarrow 90^\circ$	$\omega t = 90^\circ \rightarrow 270^\circ$
Shape Factor	$H=3.5$	$H=3.5$	$H < 3.5$
Skinfriction	$\tau_o=0$	$\tau_o=0$	$\tau_o > 0$
Dye Filament from the Cyl.	$U_c=0$	$\uparrow U_c$	$\downarrow U_c$
Vel. Prof. & Movement of the Surface

(a) $\omega t = 270^\circ \rightarrow 90^\circ$

(b) $\omega t = 90^\circ \rightarrow 270^\circ$

Fig. 13 Displacement thicknesses near the separation point

(a) $\omega t = 270^\circ \rightarrow 90^\circ$

(b) $\omega t = 90^\circ \rightarrow 270^\circ$

Fig. 14 Shape factors near the separation point

those in the case of the stationary cylinder.

When the cylinder moves toward the lower dead point, the sign of the vorticity generated on the surface of the cylinder is the same as the sign of the vorticity in the boundary layer (see the sketches in Table 1). The vorticity generated on the cylinder forms a new boundary layer which prevents generation of the reversed flow near the surface of the cylinder. The characteristics of the boundary layer of the oscillating cylinder near the separation point are considerably different from those in the case of the stationary cylinder. As seen in Figs. 11 to 14, the skin friction does not vanish and the value of the shape factor H is smaller than 3.5, but the location of the separation point does not change remarkably, because new boundary layer is thin. Therefore, the mechanism of the convective transfer of the vorticity generated on the surface of the cylinder does not change considerably and so, as made clear in the previous paper⁽¹⁾, the vorticity is considered to be transferred downstream through the separation point.

4. Conclusions

The flow near the surface of a cylinder oscillating sinusoidally in the direction perpendicular to a uniform flow was studied in detail by means of visualization techniques. The main results of the study are summarized as follows.

(1) The characteristics of the boundary layer and the skin friction of the oscillating cylinder were discussed in relation to the flow of the stationary cylinder.

(2) The skin friction lines of the oscillating cylinder in the $\omega t - \theta$ plane were obtained. The skin friction lines are very useful for illustrating the variation of the skin friction in time and space. From the continuity of the group of these skin friction lines, the existence of the period of no reversed flow behind the separation point is confirmed experimentally as a reasonable feature.

(3) The characteristics of the boundary layer near the separation point were elucidated. When the cylinder moves toward the upper dead point, the boundary layer on the surface facing the lower dead point has almost the same characteristics as those in the case of the stationary cylinder, and the layer facing the upper dead point has characteristics that are considerably different from those in the case of the stationary cylinder. A new boundary layer is developed in the ordinary boundary layer and the point of vanishing skin friction does not coincide with the

separation point (dye).

(4) The formation of the new boundary layer in the ordinary boundary layer does not remarkably affect the mechanism of the vorticity transfer. The vorticity generated on the surface of the oscillating cylinder can be considered to be transferred through the separation point (dye) in all phases of the oscillating cylinder.

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