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Flow Characteristics around a Circular Cylinder with a Slit*

(2nd Report, Effect of Boundary Layer Suction)

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Experimental investigations on the effect of boundary layer suction for a circular cylinder with a two-dimensional slit placed along a diameter have been carried out.

Flow characteristics around the cylinder for cases of intermittent boundary layer suction (Pattern I), alternate boundary layer suction and blowing (Pattern II) and transition regions were clarified. Particularly, the mechanism of the boundary layer suction, fluid flows in the slit and rear surface of the cylinder and the mechanism of the vortex formation in the wake were clarified.

Key Words : Unsteady Flow, Boundary Layer Suction, Circular Cylinder

1. Introduction

In the previous paper⁽¹⁾ general characteristics of the flow around a circular cylinder with a two-dimensional slit placed along a diameter were clarified. Two types of flow control can be made. One is a wake control by self-injection in which a part of main flow through the slit ejects into the wake as a jet in the range of inclination angles $0^\circ \leq \beta \leq 40^\circ$. The other is a kind of boundary layer control by suction at the slit of the front surface in the range of $60^\circ \leq \beta \leq 90^\circ$. Particularly, in the range of $80^\circ \leq \beta \leq 90^\circ$, suction and blowing are done alternately at both ends of the slit with a period of the vortex shedding.

Concerning the flow control by boundary layer blowing which is one of the basic methods of boundary layer control, both experimental and theoretical investigations on the flow past a circular cylinder with slot-blowing have been carried out by Dunham⁽²⁾, Furuya and Yoshino^{(3), (4)} and Ueda and Tanaka^{(5)~(7)}. On the other hand, reports concerned with boundary layer suction applied to a circular cylinder have apparently not been published to date due to the difficulty in the experiments. From such a standpoint the flow around a circular cylinder with a slit accompanied with boundary layer suction is worth notice. The circular cylinder is characterized by the self-control without artificial external power and periodical unsteady suction. Such a cylinder is used as a Kármán vortex flow meter. The vortex shedding frequency behind the cylinder was the object of the investigations on the vortex flow meter by Tsuchiya et al.⁽⁸⁾ and Yamazaki et al.⁽⁹⁾.

Thus the characteristics of the flow around the cylinder have not been clarified yet. From a standpoint of industrial uses, it is very significant to clarify the fluid flow around a circular cylinder with a slit.

The purpose of this study is confined to the case of the boundary layer suction. The effects of the width of the slit on the pressure distribution on the cylinder, the drag and lift forces acting on the cylinder and the Strouhal number were investigated. The flow patterns including the transition region changing its own pattern were classified in detail. The flow visualization and simultaneous measurements of the velocity fluctuations and the pressure fluctuations were carried out in order to clarify the mechanism of boundary layer suction, the fluid flow in a slit and the mechanism of the formation of a separated vortex adhered on rear surface of the cylinder.

Nomenclature

C_D : drag coefficient
 C_L : lift coefficient
 C_p : pressure coefficient $= (p - p_0) / 0.5 \rho u_0^2$
 d : diameter of circular cylinder
 f : vortex shedding frequency
 p : pressure
 p' : fluctuation pressure
 Re : Reynolds number $= u_0 d / \nu$
 S : Strouhal number $= fd / u_0$
 s : width of slit
 u : velocity
 x : streamwise coordinate from the center of circular cylinder
 y : coordinate perpendicular to x
 α : slit angle $= \sin^{-1}(s/d)$
 β : inclination angle of slit
 δ : distance from peripheral surface
 ν : kinematic viscosity of fluid
 ρ : density of fluid
 ϕ : circumferential angle on the cylinder

Subscript

o : undisturbed flow condition

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2. Experimental apparatus and procedure

The configuration of a circular cylinder with a slit is shown in Fig. 1, and the dimensions are shown in Table 1. The cylinders were $d = 34$ mm and 50 mm in diameters and the values of the slit ratios were in the range of $0.056 \leq s/d \leq 0.185$ ($\alpha = 3^\circ \sim 11^\circ$). The inclination angle of the slit, β , was varied from 40° to 90° . Tests were carried out in a low speed wind tunnel whose test section was $400 \text{ mm} \times 150 \text{ mm} \times 800 \text{ mm}$. The time-averaged pressure distributions and the distributions of the R.M.S. pressure fluctuations around the cylinder were measured by a manometer and a semi-conductor pressure converter respectively. The velocity fluctuations around the cylinder were measured by using a hot-wire anemometer. And the Strouhal numbers of the vortex shedding from the cylinder were obtained from the frequency analysis of the velocity fluctuations. The flow on the surface of the cylinder was visualized by an oil film method. These experiments above mentioned were made mostly at the free stream velocity $u_0 = 20 \text{ m/s}$. Flow visualizations were performed in a smoke wind tunnel having a working section $600 \text{ mm} \times 150 \text{ mm} \times 800 \text{ mm}$ at $u_0 = 6 \text{ m/s}$. And a flow visualization with an incense stick was carried out in the same wind tunnel at $u_0 = 2 \text{ m/s}$. The Reynolds numbers in these experiments were in the range of $4.4 \times 10^3 \leq Re \leq 6.5 \times 10^4$, and the turbulence intensity of the free stream was 0.5% in this range. It is confirmed that there is no effect of the Reynolds number in the experiments. A correction for the tunnel blockage effect was not made.

Table 1

d mm	s/d	α
34	0.080	$4^\circ 35'$
	0.185	$10^\circ 40'$
50	0.056	$3^\circ 15'$
	0.076	$4^\circ 20'$
	0.100	$5^\circ 40'$
	0.136	$7^\circ 50'$
	0.157	9°

Fig. 1 Coordinate system and symbols

3. Experimental results

3.1 Pressure distribution and drag coefficient

Typical pressure distributions for $s/d = 0.100$ are shown in Fig. 2. There is a similar tendency to that of the former report⁽¹⁾ for $s/d = 0.080$. In the case of $\beta = 40^\circ$ and 50° there is no effect of the slit, which almost agrees with that of the cylinder without a slit. For $\beta = 60^\circ$ and 70° of pattern I, the flow on the upper side of the cylinder becomes a potential flow due to the boundary layer suction at the slit of the front surface. Therefore the pressure coefficients behind the slit decrease remarkably. And the profiles on the rear surface are not symmetric and look like a twin mountain having two peaks. On the contrary, for $\beta = 80^\circ$ and 90° of pattern II, suction and blowing take place alternately

Fig. 2 Pressure distribution

Fig. 3 Pressure distribution for transition region I

at both ends of the slit with a period of the shedding vortex behind the cylinder. The time-averaged flow is, therefore, symmetric with respect to the undisturbed flow. The profiles on the rear surface of the cylinder have symmetry and three peaks. As described above, two typical flow patterns I and II occur according to the inclination angle of the slit. Below and beyond the pattern I, that is, the ranges of the angles $50^\circ < \beta < 60^\circ$ and $75^\circ < \beta < 80^\circ$ are defined as transition regions I and II respectively. Figure 3 shows the pressure distribution for the transition region I. As the inclination angle increases, the profiles on the rear surface of the cylinder become gradually an unsymmetrical twin mountain. In the transition region II, as the angle of β increases, the unsymmetric profile turns gradually symmetric. Figure 4 shows the effect of the slit ratio on the pressure distribution near $\phi = 180^\circ$ for $\beta = 90^\circ$. A unique profile recognized in the former report⁽¹⁾ that the pressure coefficient for about $\phi = 180^\circ$ increases remarkably does not appear for $s/d = 0.056$ and 0.185 , but appears clearly in the range of $0.080 \leq s/d \leq 0.136$. It is concluded that this phenomenon occurs for a specified range of the values of the slit ratio. Examination of the profiles of patterns I and II for about $\phi = 180^\circ$ shows that they have a minimum and a maximum value at the position respectively. This suggests that the flow direction of the time-averaged flow along the rear surface of the cylinder for about $\phi = 180^\circ$ of the pattern I is toward the rear stagnation point, and that of the pattern II is opposite to the pattern I.

From the view point aforementioned, the flow on the surface of the cylinder was visualized by an oil film method. In the case of low viscosity of the oil, the separation point and the positions of the maximum and minimum pressures on the rear surface appear clearly as shown in Fig. 5. The direction of the pressure gradient along the rear surface and that of the surface

Fig. 4 Pressure distribution for pattern II

oil flow are the same. For $\beta = 60^\circ$ the two positions of the maximum pressure on the rear surface of $\phi = 140^\circ$ and 220° are not so clear as that for $\beta = 90^\circ$. This indicates that the flow of the pattern I is not regular unlike that of the pattern II. At the boundary layer suction the point of separation moves downstream to $\phi = 110^\circ$. And two flows in opposite directions from the upper and lower surface of the cylinder to the position of $\phi = 175^\circ$ are recognized, showing that the flow from the upper surface is stronger than that of the lower surface. In the case of $\beta = 90^\circ$, the oil flow patterns at about $\phi = 150^\circ$ and 210° which present the minimum pressure on the rear surface of the cylinder show a separation of the flow. The patterns of a reattached flow appear at the positions of the second maximum pressure coefficient; $\phi = 125^\circ$ and 235° beside the rear stagnation point. The flow of suction side on the rear surface is not always attached to the cylinder, it is accompanied by local separation and reattachment of its own flow. In spite of such a non-steady flow field, the time-averaged oil flow pattern corresponds well to the pressure distribution. This indicates that the pressure distribution on the rear surface is dominated by the flow along the rear surface of the suction side. On the other hand, a circular cylinder without a slit ($s/d = 0$) shows the separation of the oil film between $\phi = 155^\circ$ and 205° . The adhered flow from $\phi = 180^\circ$ separates at two points of $\phi = 155^\circ$ and 205° . This indicates that a part of the separated shear layer reattaches intermittently near the rear stagnation point and separates at the above two points. As

Fig. 5 Flow visualizations by oil film method

seen in Fig. 2 the pressure distribution on the rear surface shows a slightly falling gradient toward the rear stagnation point, which is opposite in direction to the flow of the oil film. It can be considered that there is no effect of the intermittent reattachment of the separated shear layer from the cylinder without a slit near the rear stagnation point, on the pressure distribution on the rear surface. The drag and lift coefficients, C_D and C_L , obtained from integration of the pressure distributions are shown in Fig. 6. In the range of $40^\circ \leq \beta \leq 50^\circ$, the drag coefficient is nearly 1.17 and agrees with that of the cylinder without a slit, and a small lift force acts on the cylinder. In the range of $50^\circ < \beta \leq 75^\circ$, the values of C_D increase rapidly to the maximum of 1.80 with a remarkable falling of the pressure coefficient on the upper side of the rear surface, and the values of C_L increase between 0.5 and 0.6 due to an unsymmetric pressure distribution. For the range of the slit ratios $0.080 \leq s/d \leq 0.136$, there is no effect of the inclination angle of the slit on the range of the transition region and the values of the drag and lift coefficients. In the range of $80^\circ \leq \beta \leq 90^\circ$, the lift force disappears and the drag force C_D is nearly 1.5, the effect of the slit ratios being rather complicated.

3.2 Pressure fluctuation

The distributions of the R.M.S. pressure fluctuations on the surface of the cylinder are shown in Fig. 7. In the case of $s/d=0$ without a slit, the profile takes a maximum value near the separation point on the front surface. On the rear surface,

	s/d	d mm	Re
△	0.056	50	6.4×10^4
○	0.100		
□	0.136		
●	0.080	34	4.5×10^4
■	0.185		

Fig. 6 Variation of drag and lift coefficients with inclination angle of slit

a minimum value appears at the rear stagnation point for $\phi=180^\circ$ and the second maximum value appears at about $\phi=155^\circ$; these two points are the position of the reattachment of the separated shear layer and that of the separation of the reattachment flow respectively. The R.M.S. values on the front surface of a cylinder with a slit of patterns I and II are smaller than those of one without a slit on the front surface. This is due to the shift of the separation point toward downstream. For the case of pattern I of $\beta=60^\circ$, the R.M.S. value increase drastically behind the slit, indicating that the boundary layer suction has been done intermittently. The R.M.S. value decreases rapidly along the circumference and takes the minimum value at the rear stagnation point. On the lower side of the cylinder, the separated shear layer acts in the same manner as that of a cylinder without a slit, therefore, the profile of the R.M.S. pressure fluctuations makes little difference from that of $s/d=0$. For the case of pattern II of $\beta=90^\circ$, the R.M.S. values on rear surface are remarkably larger than those of pattern I and the values considerably decrease near the rear stagnation point. The profile of the R.M.S. pressure fluctuations is in contrast to the pressure distribution, that is to say, the positions of the maximum and minimum values of the pressure coefficients have one to one correspondence to the positions of the minimum and maximum values of the R.M.S. pressure fluctuations. The patterns I and II differ remarkably from each other in flow pattern. A detailed discussion about this will be done in the next chapter.

Fig. 7 Distributions of R.M.S. pressure fluctuations around a circular cylinder with a slit

Fig. 8 Effect of Reynolds number on Strouhal number

3.3 Strouhal number

The Strouhal numbers for $s/d = 0.080$ are shown in Fig. 8 in the range of $4.4 \times 10^3 \leq Re \leq 6.5 \times 10^4$. The values of the Strouhal numbers of pattern I of $\beta = 60^\circ$ are smaller than those of a cylinder without a slit. On the contrary, those of pattern II of $\beta = 90^\circ$ are larger than those of the cylinder without a slit. It can be considered that there is no effect of the Reynolds number on the Strouhal number in the range of present experiment. The variations of the Strouhal number with the inclination angle of the slit are shown in Fig. 9 for various slit ratios at the free stream velocity $u_0 = 20 \text{ m/s}$. The values of the Strouhal number are larger than those of the cylinder without a slit in the range of $40^\circ \leq \beta < 50^\circ$, decrease rapidly in the transition region I, are nearly constant and smaller than those of the cylinder without a slit in the pattern I and increase gradually between the transition region II and pattern II. Generally speaking, the Strouhal numbers have a tendency to decrease as the slit ratios decrease. As the inclination angle of the slit increase, the Strouhal numbers for $s/d = 0.076$ and 0.080 have the least value 0.182 in the range of pattern I and increase remarkably in the range of pattern II. At $s/d = 0.080$, a peculiar pressure distribution on the rear surface occurs. Therefore, it is considered that the effect of the boundary layer suction appears remarkably at the slit ratio.

3.4 Classification of flow patterns

Examples of hot-wire signal traces of the velocity fluctuations are shown in Fig. 10. The hot-wire positions are $\delta = 1 \text{ mm}$ distance from the peripheral surface on the upper and lower sides of the cylinder $\phi = 90^\circ$ and 236° . For $\beta = 80^\circ$, the two traces give a phase difference of half a period between them. This indicates that boundary layer suction and blowing are done alternately at both ends of the slit with a period of the

Fig. 9 Effect of slit ratio on Strouhal number

vortex shedding. In the case of $\beta = 75^\circ$ and 60° the traces show that intermittent boundary layer suction is done at the upper side of the slit and in consequence the flow around the cylinder is an unsymmetric flow. The traces of $\beta = 76^\circ$ are the transition region II in which the phenomena of patterns I and II occur irregularly. Then there exist two flow patterns in the transition region. If one which is either in pattern I or in pattern II has occurred, the other can never occur at the same time, the frequency varying in proportion to the inclination angle of the slit. The boundary layer suction does not occur for $\beta = 50^\circ$, but it is slightly observed in the region I of $\beta = 55^\circ$. From the results described above, the flow patterns around a circular cylinder with a slit in the case of boundary layer suction can be classified according to the inclination angle of the slit β and the slit angle α as follows:

- (a) $40^\circ \leq \beta + \alpha \leq 55^\circ$: a little effect of the slit,
- (b) $56^\circ \leq \beta + \alpha \leq 62^\circ$: transition region I,
- (c) $62^\circ - \alpha \leq \beta \leq 75^\circ$: pattern I, intermittent boundary layer suction, unsymmetric flow,
- (d) $75^\circ \leq \beta \leq 78^\circ$: transition region II,
- (e) $78^\circ \leq \beta \leq 90^\circ$: pattern II, alternating boundary layer suction and blowing, symmetric flow

Two distinct flows of patterns I and II appears at the slit ratio $s/d = 0.080$.

4. Discussions

In this chapter, the detailed fluid flows of patterns I and II are clarified by the measurements of velocity and pressure fluctuations in a slit and near the rear surface of a cylinder and by the flow visualization around the cylinder.

$s/d = 0.080$, $Re = 4.5 \times 10^4$ 5 ms/div
 $u_0 = 20 \text{ m/s}$, $d = 34 \text{ mm}$, $\delta = 1 \text{ mm}$

Fig. 10 Samples of hot-wire signal trace around a cylinder

4.1 Fluid flow in a slit

Figures 11 and 12 show the velocity and pressure fluctuations in the slit of $s/d=0.080$ for patterns I and II. The hot-wires are located at the center line in the slit and $\delta=-1$ mm inside of the peripheral surface for pattern I, and at $x=0$ and 1 mm and $\delta=-1, -4$, and -10 mm inside of the slit for pattern II. The boundary layer suction of pattern I occurs intermittently at upper side of the slit and the period of the vortex shedding is longer than that of pattern II. And the time required for the suction is shorter than a half of the period. The amplitude of the pressure fluctuation of suction side (p_1) is larger than the magnitude of the dynamic pressure. The amplitude at the center in a slit (p_2) decreases remarkably and the time-averaged pressure coefficient rises. At the blowing side (p_3), the pressure coefficient rises still more, but the amplitude of the pressure fluctuation increases again. For the transition region I of $\beta=50^\circ$, the velocity at inlet of the slit changes sinusoidally, but the periodicity disappears at outlet of the slit. In the case of pattern II, the flow at the section of $x=0$ mm is a separated flow, its turbulent intensity increasing as inside of the cylinder. The signal traces at the section of $x=1$ mm show that boundary layer suction occurs at the corner of the slit, $\phi=\beta+\alpha$, and the fluid comes in along the surface of the slit. When the flow changes its direction by suction and blowing, the fluid near the inlet and outlet of the slit comes to rest momentarily, then its velocity becomes zero. The maximum velocity of suction is 1.4 to 1.7 times as large as the velocity of undisturbed flow u_0 , indicating that the fluid of outer boundary layer flows into the slit. The maximum velocity of blowing is half that of undisturbed flow. The trace of u_3 inside of the slit shows only flow due to suction, the maximum velocity being 1.5 times that of undisturbed flow. In the region forward from the slit, the fluctuation of the pressure decreases as compared with that of the cylinder of $s/d=0$ because of the delay of separation due to suction of boundary layer. On the contrary, a considerable pressure fluctuation is observed at $\phi=110^\circ$ behind the slit. This can be explained as follows: the flow behind the slit becomes a potential flow by suction of boundary layer and becomes a separated flow by blowing. Though the pressure at inlet of the slit, p_1 , fluctuates considerably, that of center of the slit, p_2 , is unchanged. This means that the fluid near center of the slit is stationary. The same statements are true for the pressure fluctuation of the other side of the slit. From the above mentioned results, the flow in a slit is illustrated in Fig. 13. The fluid flowing in a slit by boundary layer suction does not reach the outlet of the slit due to reduction of its velocity. Inside of the slit, there exists a stagnant region enclosed by a dotted line as shown in the figure. The fluid in this region moves through the slit by boundary layer suction and blows the fluid flowing

into the opposite side of the slit just before half a period. In other words, this fluid of the stagnant region moves up and down just as a piston by the boundary layer

Fig. 11 Velocity fluctuation and pressure fluctuation in a slit (pattern I)

Fig. 12 Velocity fluctuation and pressure fluctuation in a slit (pattern II)

Fig. 13 Fluid flow in a slit

suction and blowing with a period of the shed vortices adhered to the rear surface of the cylinder.

4.2 Flow along rear surface of the cylinder

Let us examine the relationship between vortex formation and pressure distributions on the rear surface of the cylinder. A typical flow visualization using an incense stick at $Re = 4.4 \times 10^3$ is shown in Fig. 14.

Fig. 14 Flow visualizations by smoke wind tunnel and by incense stick smoke

The Reynolds number is considerably low, so the case at $Re = 1.3 \times 10^4$ is given for reference. For $s/d = 0$, as the Reynolds number decreases, the vortex formation region moves considerably toward downstream. On the other hand, there is no effect of the Reynolds number for $s/d = 0.080$. In the case of pattern I of $\beta = 60^\circ$, the vortex adhered to the upper surface of the cylinder grows enough, the separated shear layer from the lower side rolls up inside of the vortex (photo 1), and then a new vortex generates on the lower side of the cylinder (photo 2). On the upper side, the vortex is shed and the boundary layer suction occurs. The separation point of the flow moves toward downstream (photo 3) and the separated shear layer rolls up into the vortex of the lower side (photo 4). When this vortex is shed, the flow of upper side separates at the slit and a new vortex generates and grows on the upper side of the cylinder (photo 5). At the same time, the separated shear layer from the upper surface rolls up to the one from the lower side and reattaches upward to the rear surface of $\phi = 220^\circ$, that is to say, the position of the maximum pressure coefficient, then the flow attaches to the rear surface at $\phi = 175^\circ$. The behavior of the shear layer of the lower side of the cylinder looks like that of the one without a slit, $s/d = 0$. In the case of pattern II of $\beta = 90^\circ$, a vortex adhered to the surface behind the slit of blowing side forms and grows (photo 1), and the flow of suction side moves along the rear surface (photo 2). Detailed examination reveals that the flow separates locally near $\phi = 150^\circ$ and reattaches near $\phi = 180^\circ$ to the surface of the cylinder due to pull in by the adhered vortex of blowing side (photo 3). At upper side suction (photo 5), the separated flow reattaches again downward at $\phi = 180^\circ$ and at lower side suction (photos 2, 3), the separated flow reattaches upward at $\phi = 180^\circ$.

Fig. 15 Velocity fluctuation and fluctuation pressure on the rear surface of a cylinder for pattern II

These reattachment flows join the adhered vortices at blowing side near $\phi = 210^\circ$ and 150° respectively. These two points are the positions of the minimum values in pressure and correspond to the oil-flow pattern of separation of flow. The velocity fluctuations, u , on the rear surface of the cylinder at $\delta \sim 0.5$ mm are shown together with the fluctuation pressure, p' , in Fig. 15. In upper side suction, the traces of u at $\phi = 150^\circ$ and 165° show separation of flow and that of u at $\phi = 180^\circ$ shows reattachment of the flow. When the boundary layer blowing occurs on the upper side of the cylinder, an adhered vortex form there and the velocity u at $\phi = 110^\circ$ is small. As the vortex grows, u at $\phi = 150^\circ$ increases remarkably due to the shear layer from the upper side of the cylinder. At this time, the traces of u show the reattachment of the flow from $\phi = 180^\circ$ to 165° caused by the boundary layer suction at the lower side of the slit, the value of u being considerably large.

Close investigation of the flow in the wake of pattern II ($\beta = 90^\circ$) as shown in Fig. 14 shows that the vortex streets are identical to that of an oscillating aerofoil. (10), (11) In pattern II, though the flow of suction side separates locally, it seems to be a potential flow on the whole up to the position of the adhered vortex of blowing side. It is considered that the position corresponds to the trailing edge of the oscillating aerofoil, namely, the distance between the two adhered vortices on the upper and lower sides of the rear surface of the cylinder corresponds to the amplitude of the aerofoil. According to the discussions done so far, the mechanism of vortex formation of a cylinder with a slit is basically different from that of a circular cylinder without a slit (bluff bodies). In the case of a bluff body, the separated shear layer develops, rolls up and then forms a vortex in a wake. On the contrary in the case of an oscillating aerofoil, there is no separation of the flow at the trailing edge, circulations are produced by the discontinuity of the velocity at the tip, then a pair of two vortices appear which have a positive and a negative circulation shed periodically with every vibration. It is concluded that the alternation of boundary layer suction and blowing at both ends of the slit in a circular cylinder with a slit has the same effect as an oscillation of the aerofoil.

4.3 Mechanism of boundary layer suction

According to the comparison of the pressure coefficients at both sides of the slit as shown in Fig. 2, as the inclination angle of the slit increases from $\beta = 40^\circ$ to 50° (transition region I) and 60° (pattern I), the inequality of the pressure coefficients between at inlet and outlet of the slit is reversed from positive to negative values. This suggests that the boundary layer suction is closely related to the pressure fluctuations accompanied with a periodical reversal of the pressure between

both ends of the slit. From such a viewpoint, the velocity fluctuations in a slit and the pressure fluctuations behind the slit on the circumference of the cylinder were measured, the results being shown in Fig. 16. Figure (a) shows the traces of the pressure fluctuations of a circular cylinder without a slit, which supports the above inference that the inequality is reversed in pressure on both ends of the slit at the inclination angle $\beta = 50^\circ$, but such a reversal does not occur at $\beta = 40^\circ$. Figures (b) and (c) are simultaneous records of pressure fluctuations and velocity fluctuations for patterns I and II respectively, where u_1 is the same as that in Figs. 11 and 12. In either case the pressure of suction side is higher than that of blowing

Fig. 16 Velocity fluctuation and pressure fluctuation in boundary layer suction

side in boundary layer suction. For pattern I of figure (b), the boundary layer suction does not occur in spite of the pressure of the lower side of the slit being higher than that of the upper side, because the flow around the cylinder separates far ahead of the slit. From the fact described above, we may conclude that the boundary layer suction is caused by the pressure fluctuations accompanied with a periodical reversal of the pressure between both ends of the slit, the boundary layer suction occurring at the high pressure side.

5. Conclusions

Experimental investigations on the effect of boundary layer suction for a circular cylinder with a two-dimensional slit placed along a diameter have been carried out. The following conclusions are obtained.

(1) The flow patterns can be classified according to the inclination angle of the slit β and the slit angle α as follows: Pattern I is a case of intermittent boundary layer suction at the slit of front surface of the cylinder ($62^\circ - \alpha \leq \beta \leq 75^\circ$), pattern II is a case of alternating boundary layer suction and blowing at both ends of the slit ($78^\circ \leq \beta \leq 90^\circ$), and transition regions I and II toward the patterns I and II respectively.

(2) The boundary layer suction is caused by the pressure fluctuations accompanied with a periodical reversal of the pressure between both ends of the slit.

(3) In boundary layer suction, the fluid of outer boundary layer flows into the slit and the maximum velocity at inlet of the slit is 1.4 to 1.7 times as large as the velocity of undisturbed flow, but the velocity at outlet of the slit is half that of undisturbed flow.

(4) The fluid flowing into the slit does not reach the outlet of the slit due to reduction of its velocity at the center part of the slit. The fluid of the center part moves up and down like a piston by the boundary layer suction with a period of the shed vortices adhered to the rear surface of the cylinder.

(5) In pattern II, the mechanism of the vortex formation is basically different from that of bluff bodies and is the same as that of an oscillating aerofoil. The

flow of suction side does not separate on the whole up to the position of the adhered vortex of blowing side, the position corresponding to the trailing edge of an oscillating aerofoil.

(6) There is a remarkable effect of the boundary layer suction at $s/d = 0.080$. In the case of pattern I, the Strouhal number is nearly constant $S = 0.182$, the drag coefficient is considerably large, $C_D = 1.80$ and a large lift acts such as $C_L = 0.5 \sim 0.6$. In the case of pattern II, the values of S increases to $0.208 \sim 0.218$ and C_D decreases to 1.5.

(7) Peculiar pressure distributions on the rear surface of the cylinder, patterns I and II, are caused by the adhered vortex on the rear surface and the flow of suction side. In pattern II, the profile is produced by the temporary separation ($C_{p \min}$) and the reattachment ($C_{p \max}$) of the flow along the rear surface of the cylinder.

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