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FLOW CONTROL AROUND A CIRCULAR CYLINDER BY A SMALL CYLINDER

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ABSTRACT

Fundamental studies on the control of the flow around a circular cylinder were conducted by a new method. It was found that a forced reattachment of the shear layer separated from the cylinder was realized by setting up a small cylinder in the shear layer near the main cylinder. The diameters of the cylinders were 40 and 2 mm, respectively, and the Reynolds number ranged from 5.1×10^3 to 5.1×10^4. At the gap of the two cylinders from 3 to 6 mm, the shear layer reattached onto the rear surface of the cylinder and the flow adhered beyond the rear stagnation point. It is very interesting that the drag of the main cylinder decreases by 20 to 30%, and the gain of C_L=1.0 in lift is acheived by the forced reattachment.

NOMENCLATURE

C_D : drag coefficient
C_L : lift coefficient
Cp : pressure coefficient
D : diameter of main circular cylinder
d : diameter of small circular cylinder
G : gap between two circular cylinders
Re : Reynolds number $=UD/\nu$
U : free stream velocity
$\overline{u}$, u' : mean velocity and fluctuating velocity
x : streamwise coordinate from the center of a circular cylinder
y : coordinate perpendicular to x
α : angle of location of small cylinder
δ : distance from wall surface
ν : kinematic viscosity of fluid
ϕ : angle from front stagnation point

Subscripts
o : the case of without a small cylinder
b : in the vicinity of rear stagnation point
s : separation point

INTRODUCTION

One of the authors investigated the fluid flow around the H-2 Rocket (Godai, 1985) composed of a main cylinder and two subcylinders closely arranged in line. It was found (Igarashi et al., 1988, 1989) that the shear layer separated from the main cylinder reattaches and adheres to the rear surface of the main cylinder by a coanda effect at the attack angle of 60~80°. This fact suggests a new method of flow control around a circular cylinder by a small cylinder.

The objective of this studies is the realization of the forced reattachment of the shear layer separated from the main cylinder. The optimum location of the small cylinder was obtained, and the reduction of the drag force and the gain in lift were found.

The flow around a circular cylinder may be controlled in two ways: by boundary layer control (Schlighting, 1968); and by prevention of the regular oscillation of the wake. Several methods of controlling the boundary layer have been developed, such as a rotating cylinder as demonstrated by Prandtl(1925), boundary layer suction (Lachmann, 1961), boundary layer blowing (Dunham, 1968, Ueda and Tanaka, 1976, Waka and Yoshino, 1987), and a tripping wire (Prandtl, 1914). For the latter, a splitter plate (Roshko, 1954) is well known. These methods are necessary to provide external power and external fluid, and to processing the inside or outside of the cylinder.

The present method is different from the conventional methods. This method does not need the external power and fluid, and the processing of the cylinder. Then, this system is simple in processing, and the main and small cylinders are independent each other. Therefore, this method is expected to be widely applied in many fields.

EXPERIMENTAL APPARATUS AND PROCEDURE

The configuration of the model and symbols are shown in Fig. 1. The diameters of the main and small cylinder, D and d, were 40 and 2 mm, respectively, so the ratio d/D was 0.05. The small cylinder set up in the shear layer from the main cylinder. The gap between the two cylinders, G, ranged from 2 to 7 mm. The angle of location of the small cylinder, α, was varied from 100 to 140°. Experiments were carried out in a low speed wind tunnel with working section 400 mm high, 150 mm wide and 800 mm long. The free stream velocity ranged from 2 to 20 m/s, and the turbulence intensity in this range was less than 0.5 %. The Reynolds number was in the range of $5.1\times10^3 \leqq Re \leqq 5.1\times10^4$. In order to confirm the forced reattachment, the mean velocities in the wake and in the vicinity of the rear stagnation point of the

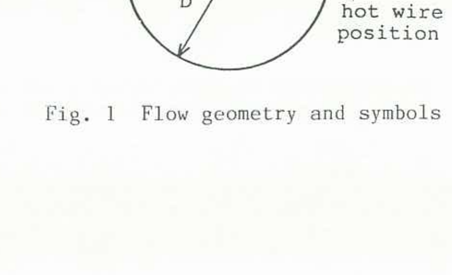


Fig. 1 Flow geometry and symbols

cylinder, u and u_b, were measured by a hot-wire anemometer. The flow around the cylinders was visualized in a smoke tunnel at U=2 and 4 m/s. The visualization of the surface flow of the main cylinder was also made by an oil-film method at U=16 m/s. The pressure distribution around the cylinder was measured by a manometer. And the drag and lift coefficients were obtained by integrating the pressure distributions.

RESULTS AND DISCUSSION

Wake Flow

It is important to know the optimum location of the small cylinder. Because the separated shear layer from the main cylinder is forced to reattach to the cylinder surface by the small cylinder. The reattachment flow adheres beyond the rear stagnation point of the cylinder. Then, the mean velocity at the near wake of the main cylinder is chosen as the most simple criterion for judgement of the reattachment.

An example of the distributions of the mean velocity, $\bar{u}$, and the turbulence intensity, $\sqrt{\overline{u'^2}}$, behind the cylinder at y/D=0, is shown in Fig. 2 for the gap of G=6 mm and various angle of α. For $\alpha=121^\circ$, the mean velocity has a maximum in the vicinity of the rear surface of the cylinder, and the value exceeds the free stream velocity. This fact indicates the reattachment. As an increase in x/D, the value of $\bar{u}/U$ decreases suddenly and has a minimum 0.1 at between x/D= 0.80 and 0.90, then increases again to 0.4. The turbulence intensity of $\alpha=121^\circ$ has a maximum 0.3 near the rear surface, and a minimum 0.08 at x/D=0.85, then increases to 0.2. On the contrary, the mean velocity of the case of without a small cylinder increases monotonusely from 0.3 to 0.86 with x/D, and the turbulence intensity is nearly constant 0.3 for $x/D \leqq 3$, and a maximum 0.4 at x/D=1.5.

As above mentioned, it becomes clear that when the reattachment takes place, both of the mean velocity and turbulence intensity in near wake of x/D=0.8 to 2.5 decrease about a quarter comparing to that of without a small cylinder. The vortex formation occurs at x/D=3. This fact suggests the reduction of the drag force acting to the cylinder is induced by the reattachment. For $\alpha=124^\circ$, the both curves have a minimum at x/D=0.8, and show qualitatively similar to the case of $\alpha=121^\circ$. In the range of x/D>0.7, the both curves are in the region between the cases of with and without the reattachment. In the case of $\alpha=118^\circ$, there is no effects of the small cylinder on the flow around the main cylinder.

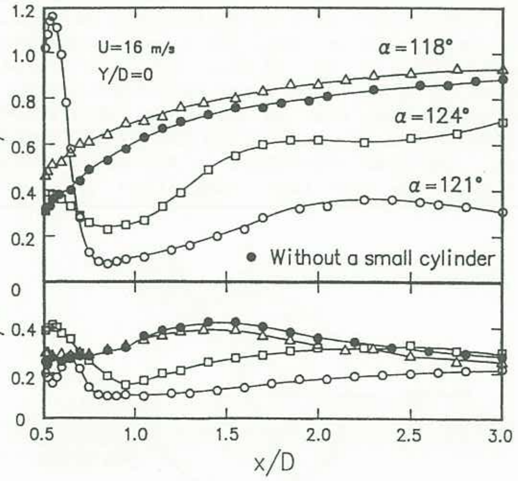


Fig. 2 Distributions of mean velocity and the r.m.s. velocity fluctuations in the wake

Flow Near the Rear Stagnation Point

In the previous session, it was clear that in the case of the forced reattachment, the mean velocity near the rear surface of the cylinder exceeded the free stream velocity. Then, the mean velocity at δ=1 mm from the rear stagnation point, u_b, was measured for various location of the small cylinder. The mean velocities for various α and G are shown in Fig. 3. At the gap of G=2 and 7 mm, the reattachment can never occured. Namely, the reattachment occurs under the gap of G=3 to 6 mm, and the angle α increases with G and become narrow range about 1 to 2° for a given G. When the small cylinder is setting up slightly inside of the separated shear layer, the value of $\bar{u}_b/U$ decreases to about 0.1∿0.2. This fact is worth notice, and indicates the reduction of the drag force. In the two cases mentioned above, that is to say, the maximum value of u_b/U are about 1.0 and 0.2, the two cases denote the patterns A and B, respectively. From the correlation between $\bar{u}_b/U$ and α, the forced reattachment can be called a unique phenomenon, which occurs under a specified condition.

Flow Visualization

Figure 4 shows the visualization of the behavior of the shear layer separated from the main cylinder by the incense stick buried in the front face of the cylinder. Figures 4 (a) and (b) are obtained under long and instantaneous exposures, respectively. For $\alpha=120^\circ$, vortex streets is shown behind the small cylinder. At $\alpha=121^\circ$, the reattachment occurs, the shear layer from the main cylinder impinges on the front face of the small cylinder, then reattaches on the rear face of the main cylinder. The jet through the gap between the two cylinders adheres beyond the rear stagnation point on the cylinder. This flow is similar to the two-dimensional wall jet induced by the Coanda effect along a circular cylinder. For $\alpha=123^\circ$, the small cylinder locates inside of the shear layer, then the position of the vortex formation region moves downstream as compared with that of without a small cylinder.

Figures 5(a) and (b) show the smoke wind photographs at U=4 m/s. On the photographs under long exposure, the region of vortex formation is the part of slightly ahead of the point intersected by the upper and lower sides smoke lines of the cylinder. The reattachment does not occur at $\alpha=120^\circ$ as shown in Fig. 4, but occurs at $\alpha=119$ and 120° in Fig. 5. This fact was caused by the hysterisis of the reattachment of the shear layer on the main flow velocity. For $\alpha=119$∿121°, the

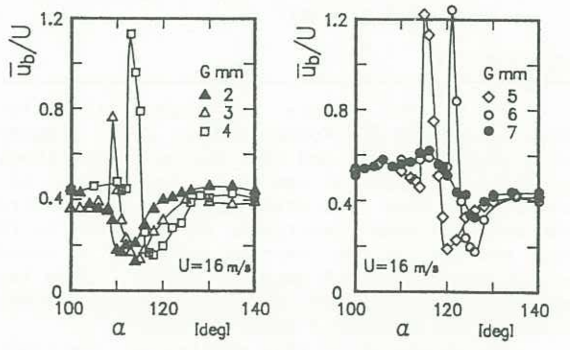
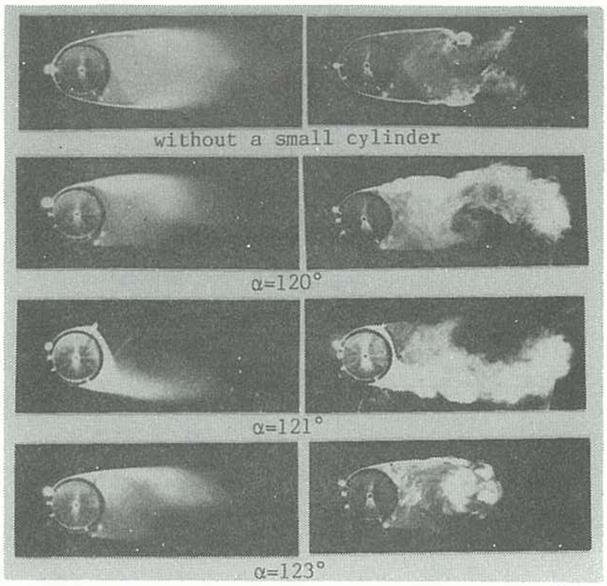


Fig. 3 Variations of mean velocity near the rear stagnation point with the angle α.

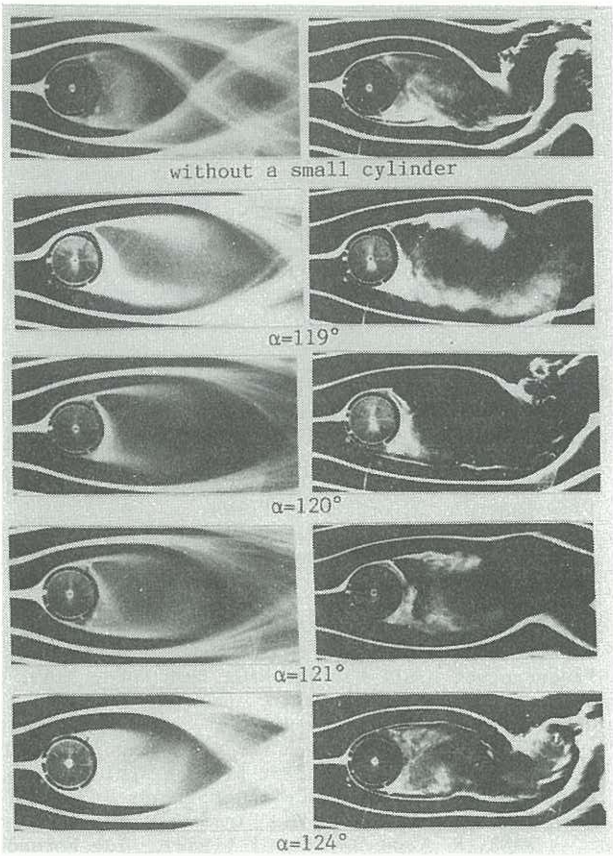
shear layer is divided by the small cylinder, and the spread angle of the wake behind the small cylinder is 70°. A separation bubble was observed between the separation and reattachment points. Moreover, the vortex formation region goes downstream. For $\alpha=124°$, the shear layer becomes longer, it corresponds to the reduction in the mean velocity near wake of the cylinder.



(a) long exposure (1s) (b) instantaneous

G=6 mm, U=2 m/s (Re=5.1×10³)

Fig. 4 Flow visualization by incense stick smoke



(a) long exposure (1s) (b) instantaneous

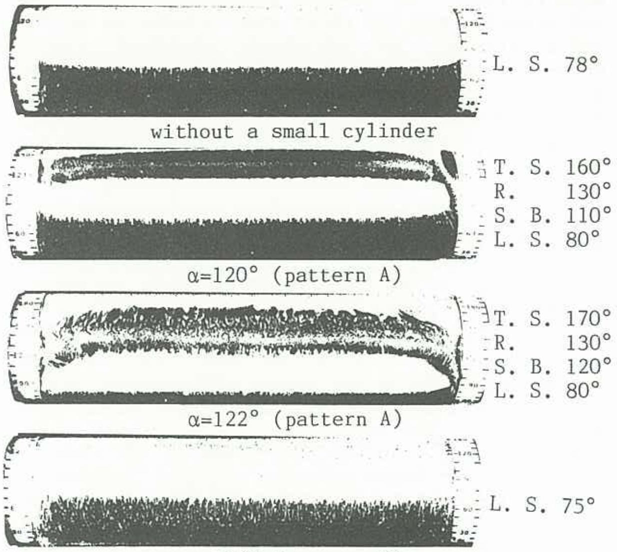
G=6 mm, U=4 m/s (Re=10⁴)

Fig. 5 Flow visualization by smoke tunnel

Figure 6 represents the surface oil-flow patterns on the cylinder at U=16 m/s. In the case of without small cylinder, the laminar separation occurs at the point of $\phi_S=78°$. On the contrary, for $\alpha=120$ and 122°, the shear layer separates at $\phi_S=80°$ and reattaches at $\phi=130°$, then the transition from laminar to turbulent occurs. And the turbulent separation takes place at about $\phi=160\sim170°$. In the separation bubble formed between the laminar saparation and reattachment points, the pattern of reverse flow appears. In the case of $\alpha=124°$, the laminar separation point is $\phi_S=75°$.

Drag and Lift Coefficients

Figure 7 shows the pressure distributions around the main cylinder for various angle of the small cylinder; the constant gap of G=6 mm. At $\alpha=118°$, the pressure coefficient decreases on the upper side comparing to that of without a small cylinder. At $\alpha=121°$ occuring the reattachment,



L. S. : laminar separation
T. S. : turbulent separation
R. : reattachment
S. B. : separation bubble

G=6 mm, U=16 m/s (Re=4.1×10⁴)

Fig. 6 Surface oil flow patterns

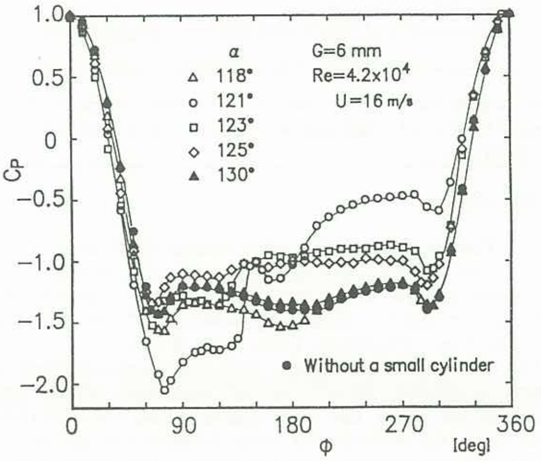


Fig. 7 Pressure Distribution

the pressure coefficient decreases remarkably near the separation point on the small cylinder side, then increase suddenly and has a maximum at $\phi=145\sim150°$. The position of the maximun value corresponding to the reattachment point is downstream compared with that obtained by surface oil-flow pattern, $\phi=120\sim125°$. On the separated flow region of the lower side of the cylinder, the pressure coefficient rises remarkably due to the blowing of the reattachment flow, as is shown in Figs. 4 and 5. At $\alpha=130°$ the small cylinder locates inside of the shear layer, the pressure distribution indicates that there is no effect of the small cylinder.

Figure 8 represents the the drag and lift coefficients of the main cylinder for various angle of the small cylinder. At $\alpha=120$ and 121°, the drag decreases by 20 to 25% compared with that of without small cylinder, and the lift of $C_L=1.0$ is produced by the reattachment. At $\alpha=123°$ the intermittent reattachment occurs, and the shear layer blowing into the near wake of the main cylinder. At $\alpha=125°$ the reattachment does not occured, and the shear layer elongates by the small cylinder, so the vortex formation region moves downstream. In this case, the lift is not generated, but the drag coefficient decreases by 20 to 30% comparing to that of without small cylinder. The decrease in the total drag force of the main and small cylinders is about 25%.

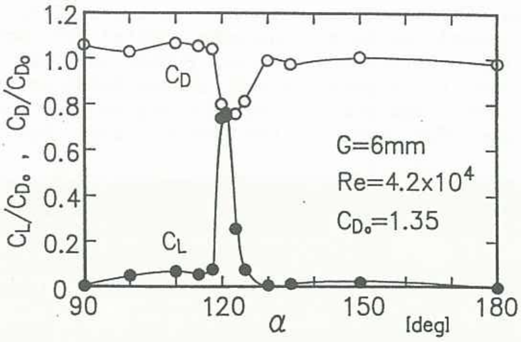


Fig. 8 Drag and lift coefficients

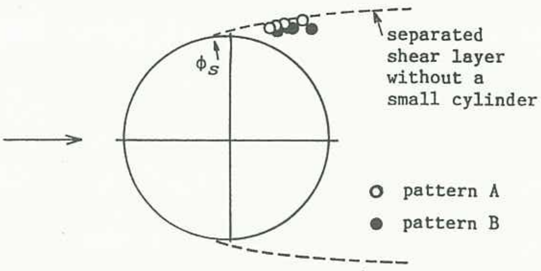


Fig. 9 Classification of flow patterns by mean of the location of the small cylinder

Correlation Between Location of Small Cylinder and Flow Patterns

Figure 9 shows the correlation between the location of the small cylinder and flow patterns. In the figure the position of the symbols corresponds to the location of the small cylinder. The open circle represents the pattern A occuring the forced reattachment and the closed circle shows the pattern B which is the elongation of the shear layer. The dotted line indicates the shear layer obtained from the photograph of the visualization of the main circular cylinder without a small cylinder. In the case of pattern A, the location of the small cylinder is on the divided line. In this case, the gap G is from 3 to 6 mm, and the divided line looks like the tangent at the separation point on the main cylinder. The separation point ϕ_S obtained from the oil-flow pattern was 78°. In the case of pattern B, the location of the small cylinder is in contact with the divided line. Thus, the locations corresponding to the patterns A and B are represented by formulas as a function of the gap, G, and the angle, α, as follows:

$$\alpha=\phi_S+\beta,\quad \phi_S=78° \qquad (1)$$

$$\cos\beta=(D/2)/((D/2+G+d/2) \quad :\text{pattern A} \qquad (2)$$

$$\cos\beta=(D/2-d/2)/((D/2+G+d/2) \quad :\text{pattern B} \qquad (3)$$

The location of the small cylinder expected from eqs.(1) to (3) agrees well with that of observed within ±1°

CONCLUSIONS

The main results were summarized as follows:

(1) The forced reattachment of the shear layer occured at the location of the small cylinder in the shear layer, that is, about 120° and the gap of the two cylinders from 3 to 6 mm.

(2) The spread angle of the wake behind the small cylinder is up to 70° and the shear layer reattaches onto the rear surface of the cylinder, and adheres beyond the rear stagnation point.

(3) At the forced reattachment, the drag coefficient of the cylinder decreased by 20 to 30%, and the gain of the lift is $C_L=1.0$.

(4) In the case of setting up the small cylinder slightly inside of the shear layer, the reattachment disappears. But the shear layer elongates, and the drag coefficient decreases by 25 to 30%.

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