Reducing the drag on a circular cylinder by upstream installation of an I-type bluff body as passive control

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The manuscript was received on 28 January 2009 and was accepted after revision for publication on 8 April 2009.
DOI: 10.1243/09544062JMES1543

Abstract: The bluff body cut from a small circular cylinder that is cut at both sides parallel to the y-axis was used as passive control to reduce the drag of a larger circular cylinder. The small bluff body cut is called an I-type bluff body, which interacts with a larger one downstream. I-type bluff bodies with different cutting angles of $\theta_s = 0^\circ$ (circular), 10$^\circ$, 20$^\circ$, 30$^\circ$, 45$^\circ$, 53$^\circ$, and 65$^\circ$ were located in front and at the line axis of the circular cylinder at a spacing $S/d = 1.375$, where their cutting surfaces are perpendicular to the free stream velocity vector. The tandem arrangement was tested in a subsonic wind tunnel at a Reynolds number (based on the diameter $d$ of the circular cylinder and free stream velocity) of $Re = 5.3 \times 10^4$. The results show that installing the bluff bodies (circular or sliced) as a passive control in front of the large circular cylinder effectively reduces the drag of the large cylinder. The passive control with cutting angle $\theta_s = 65^\circ$ gives the highest drag reduction on the large circular cylinder situated downstream. It gives about 0.52 times the drag of a single cylinder.

Keywords: passive control, I-type bluff body, drag, cutting angle

1 INTRODUCTION

Flow around a circular cylinder has been subjected to extensive research efforts in a wide range of engineering disciplines. Different studies show that this flow configuration has many engineering applications and still presents one of the major challenges in fluid mechanics; for example, bridge piles, tubes in heat exchangers, and supporting columns for offshore constructions. In the last example, one often places a zinc rod as anodic protection close to the column, where the zinc rod has a diameter smaller than that of the column. In this case, at least two aspects can be discussed: material protection and fluid mechanics. In terms of fluid mechanics, the interaction between the two cylinders is very interesting to study. Hence, it is still important to continue studying circular cylinder arrangements as a research subject, as reported in this article.

A circular cylinder has large dynamic drag resulting from the separation of flow over the cylinder. To reduce the drag coefficient of a circular cylinder, some methods have been studied, such as a cylinder with roughened surface, and so on. However, it is not easy to obtain a roughened surface and contaminations in the flow accumulate on the cylinder surface \cite{1}. Flow control around bluff bodies is of importance and of interest for wind engineering. The authors investigated this flow control and proposed two new flow control methods. The first method controls shear layers separated from the bluff body, and the second controls surface flow around bluff bodies by setting up a small rod upstream of the bluff body \cite{2}.

For the second method, the authors \cite{2} stated that the flow pattern changes, depending on rod diameter $d_s$, its position, and Reynolds number. For Reynolds numbers $Re$ ranging from $1.5 \times 10^4$ to $6.2 \times 10^4$ and the
ratio of rod diameter relative to downstream cylinder diameter \((d_s/d)\) being 0.25, with the longitudinal distance between the axis of the downstream cylinder to the rod relative to downstream cylinder diameter \((S/d)\) being 1.75–2.0, the total drag including the drag of the rod decreased by 63 per cent compared with that of a single cylinder \([2]\). Other authors \([3, 4]\) claimed that the reduction of mean drag coefficient is about 32 per cent less than the value obtained for the single cylinder. This result has been obtained at \(Re\) values ranging from \(1.5 \times 10^4\) to \(4.0 \times 10^4\), \(S/d = 2.55\), and \(d_s/d = 1.25\).

The authors \([5, 6]\) studied the flow characteristics of a bluff body cut from a circular cylinder. Two types of test models were employed in their study. The first one is an I-type, which was produced by cutting both sides of the circular cylinder parallel to the \(y\)-axis, and the second one is a D-type, in which only the front side of the circular cylinder was cut. The authors \([5]\) used two values of cylinder diameter \(d\), 20 and 30 mm. The test model with \(d = 20\) mm was used for the measurement of base pressure coefficient \((-C_{pb}\)) and that with \(d = 30\) mm for \(C_D\). They used cutting angles \(\theta_s\) of \(0^\circ < \theta_s < 72.5^\circ\) for each type. Their results show that flow characteristics are singular in the vicinity of \(\theta_s = 53^\circ\), and \(-C_{pb}\) is a minimum of 0.5–0.55 in the two cylinders, when \(\theta_s = 53^\circ\) and \(Re > 2.5 \times 10^4\). In the vicinity of \(\theta_s = 53^\circ\), the value of \(C_D\) for each model is minimum and about 50 per cent that for the circular cylinder. Their experimental results also show that for \(Re = 3.1 \times 10^4\) and \(\theta_s > 60^\circ\), the values of \(-C_{pb}\) and \(C_D\) are higher than that of the circular cylinder for the D-type. They also stated that when the curvature of shear flow from the normal surface to uniform air flow equals that of the circular cylinder, the shear layer separated from the normal surface attaches to the circular surface and changes to a turbulent boundary layer along the circular surface.

Based on previous works, the purpose of this article is to present a bluff body cut from a circular cylinder (I-type) as a passive control to reduce the aerodynamic forces on a circular cylinder. The aim of the study is to investigate the problem of controlling or manipulating unsteady loads induced on a circular cylinder of diameter \(d = 60\) mm. Passive flow control is performed by means of the wake of a bluff body cut from a circular cylinder (it is a small circular cylinder of diameter \(d_s\) cut at both sides parallel to the \(y\)-axis called I-type) and the larger one. The idea is to influence the pressure distribution around the larger cylinder with shear layers, coming from the upstream bluff body, in such a way that the separation process is dramatically altered. Using a bluff body cut from a circular cylinder as a passive control is intended to enhance a large wake region emanating from it. This means a strong shear layer affects the downstream cylinder and the separation process is altered so that the aerodynamic forces are reduced.

Fig. 1 Schematic of the two-cylinder experimental set-up in the wind tunnel

2 EXPERIMENTAL SET-UP

Figure 1 shows a schematic diagram of the cylinder configurations and the different parameters under investigation. The diameter \(d\) of the large circular cylinder was 60 mm. Seven bluff bodies cut from small circular cylinders of diameter \(d_s = 7.5\) mm (corresponding to 0.125\(d\)) with cutting angles of \(\theta_s = 0^\circ, 10^\circ, 20^\circ, 30^\circ, 45^\circ, 53^\circ\), and \(65^\circ\) were used. As a passive control, small cylinders were placed with their cutting surfaces perpendicular to the free stream velocity vector. Surfaces of the cylinders were carefully smoothed to guarantee that they are aerodynamically smooth, and hence the surface roughness effect can be neglected in this study. The centre-to-centre spacing between the two cylinders was constantly maintained at \(S/d = 1.375\). A mechanism allowed the stagger angle \(\alpha\) to be adjusted from \(0^\circ\) to \(90^\circ\) relative to the free stream velocity vector.

The experiments were carried out in a subsonic open circuit wind tunnel. This facility is 2980 mm long, with a test section of 300 mm (orthogonal) \(\times\) 450 mm. It is as used by the author \([7]\). The free stream turbulence intensity, defined as the ratio of the root mean square of velocity fluctuation to the mean velocity at the centre of the test section, is \(\sim 0.8\) per cent of all experiments. The free stream velocities in the wind tunnel were constantly maintained at 14 m/s, corresponding to a Reynolds number of \(Re = 5.3 \times 10^4\) (based on diameter \(d\) and the free stream velocity). Interaction between the tunnel wall boundary layer and the cylinder boundary layer is assumed to be negligibly
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Seventy-two pressure taps with interval 5° were installed on the wall of the circular cylinder and connected to an inclined kerosene manometer, which makes it possible to measure the pressure distribution around the circular cylinder. The velocity profile behind the circular cylinder was measured using a pitot-static tube connected to the inclined manometer. The pitot-static tube was placed at 18 cm at the rear of the axis of the cylinder or corresponding to \( x/d = 3 \).

The drag coefficient on cylinder configuration (tandem arrangement of I-type and circular cylinder) was measured using aerodynamic force balance with an uncertainty of 2.0 per cent at a measured drag force of 0.25 N and of 3.3 per cent at a measured drag force of 0.15 N. This balance is as used by the author [7], that is armfield low speed wind tunnel balance – type C2-10. The balance consists of a pair of beam balances supported on a knife edge on mutually perpendicular axes parallel to and normal to the axial centreline of the tunnel. Lift and drag components of forces exerted on the model under test balanced by sliding weights along the arms of the balance until a state of null deflection is reached. The balance arms were graduated in units of force so that lift and drag could be read directly. Room temperature was measured using a thermometer, and this temperature was used to calculate the fluid density.

Surface oil-film techniques were used to investigate the flow patterns on a circular cylinder. A mixture composed of kerosene, titanium dioxide, silicone oil, and coconut oil in a ratio of 2:3:6:40 in weight was used for surface oil-flow visualization. A circular cylinder wrapped in a black paper of 0.03 mm in thickness was uniformly smeared with the mixture, and then cylinders in configuration were placed inside the wind tunnel to obtain a surface oil-flow pattern. Finally, the paper was carefully unwrapped from the cylinder, and a photograph was taken with a digital camera.

3 RESULTS AND DISCUSSION

3.1 Pressure distribution

The pressure coefficient \( C_p \) distributions around the circular cylinder at \( Re = 5.3 \times 10^4 \) are shown in Fig. 2 for seven different cutting angles of small cylinders (\( \theta_s = 0°, 10°, 20°, 30°, 45°, 53°, \) and 65°), and the centre–centre spacing between the two cylinders was kept constant at \( S/d = 1.375 \). The results show that the distributions of \( C_p \) are practically symmetric for all the small cylinders tested (circular or sliced). The value of \( C_p \) at the front region was close to zero or a negative value. This is because a quasi-static vortex is formed between the I-type small cylinder and large cylinder as stated by Tsutsui and Igarashi [8], and \( C_p \) has a maximum of 0.1–0.2 at the reattachment region of the shear layer separated from the small cylinder. The positions of the reattachment region were noted at about \( \theta = 30° \) (upper side) and 330° (lower side). For cutting angle \( \theta_s = 53° \), the value of \( C_p = -2.14 \) is the smallest one and its position is at \( \theta = 80° \) (upper side) and 280° (lower side), aft of the other cutting angles and single cylinder. Relative to the single cylinder, placing the I-type small cylinder, circular or sliced (\( \theta_s = 0°\text{–}65° \)), in front of the large circular cylinder tends to delay the separation points on the upper and lower sides of the circular cylinder. It seems that, as a passive

![Fig. 2](image-url) Pressure coefficient distribution around the circular cylinder for various cutting angles (\( \theta_s \)) at \( Re = 5.3 \times 10^4 \)
control, the I-type small cylinder ($\theta_s = 0^\circ - 65^\circ$) accelerates the transition from the laminar to the turbulent boundary layer.

### 3.2 Drag Coefficient

Figure 3 shows the variation of the drag coefficient of tandem arrangement relative to the value of the single cylinder ($C_D/C_{D0}$) with cutting angle of the small cylinder $\theta_s$, for $Re = 5.3 \times 10^4$. The results show that the drag coefficient of cylinders in tandem arrangement $C_D$, for all the small cylinders tested (circular or sliced), are smaller than the value of the single cylinder $C_{D0}$ or $C_D/C_{D0} < 1$. It tends to decrease as the cutting angle $\theta_s$ increases, except for $\theta_s = 30^\circ$ and $45^\circ$. This means that placing the small cylinder in front of the circular cylinder is more effective in reducing the drag force when compared with the single circular cylinder without passive control. The lowest of $C_D$ is reached at a cutting angle of about $\theta_s = 65^\circ$ of I-type small cylinder and is about 52 per cent of the drag coefficient of the single cylinder $C_{D0}$. It is also important to note that in general, for $Re = 5.3 \times 10^4$, a cutting angle of $\theta_s = 45^\circ$ of the small cylinder is less effective in reducing the drag coefficient when compared with $\theta_s = 65^\circ$ or $\theta_s = 0^\circ$. This is because the I-type cylinder with a cutting angle of $\theta_s = 45^\circ$ gives a smaller $C_D$ than $\theta_s = 0^\circ$ or $\theta_s = 65^\circ$, as stated by reference [5]. As it is known that the smaller $C_D$ is due to the smaller wake region behind the bluff body, the shear layer of the small cylinder with cutting angle $\theta_s = 45^\circ$ is less effective in affecting the downstream cylinder than the other two small cylinders ($0^\circ$ and $65^\circ$). The results also show that the small cylinder with cutting angle $\theta_s = 65^\circ$ gives more reduction in drag relative to that of the small circular cylinder ($\theta_s = 0^\circ$), with the maximum difference in $C_D$ being about 14 per cent.

#### 3.3 Velocity profiles

The velocity profiles behind the large circular cylinder are shown in Fig. 4. The profiles are obtained by placing a pitot-static tube at 18 cm at the rear of the axis of the large circular cylinder or corresponding to $x/d = 3$. Figure 4 shows the variations of velocity profiles behind the large circular cylinder with cutting angle of the small cylinder $\theta_s$, for $Re = 5.3 \times 10^4$. The profiles of velocity are symmetric; this indicates that the wakes are also symmetric, and only drag forces are observed. The results show that the wake region of the tandem arrangement is smaller than the single cylinder. Therefore, its $C_D$ is decreased, as confirmed by Fig. 3. This is because the wake of the small cylinder is interacting with the larger one, where the pressure distribution around the larger cylinder is disturbed by the shear layer coming off the upstream cylinder in such a way that the separation process is dramatically altered.

The results also show that using an I-type cylinder, for a certain cutting angle, as passive control enhances a large wake region coming off it. This means that a strong shear layer affects the downstream cylinder and the separation process is altered; hence the aerodynamic forces are relatively reduced, as confirmed by Fig. 3.

### 3.4 Flow visualization

Figures 5 and 6 show the results of flow visualization at the wall of the large cylinder using the surface oil-flow pattern method for $Re = 5.3 \times 10^4$, respectively, for single cylinder and tandem arrangement with a cutting angle of 65° of the upstream cylinder.

Figure 5 shows that the single cylinder stagnation point is at $\theta = 0^\circ$, and the separation point is at about $\theta = 85^\circ$ and $275^\circ$ for the upper and lower sides, respectively. This means that the streamlines around the single cylinder are symmetric, which also gives the symmetric wake region behind the cylinder. These angular positions of the separation points obtained from the surface oil-flow pattern conform to the position of the separation point obtained from pressure distributions as indicated in Fig. 2. If the I-type small cylinder is placed upstream of the large cylinder as passive control, as indicated in Fig. 6, the flow characteristics around the large cylinder are changed relative to the single cylinder (without passive control). In general, placing the small cylinder upstream gives symmetric streamlines around the large cylinder and makes the stagnation point of the large cylinder disappear downstream. It seems that the shear layer separated from the I-type small cylinder reattaches to the surface of the large cylinder downstream and bifurcates into two shear layers at the reattachment point, at an angular position of about $\theta = 30^\circ$ (upper side) and $330^\circ$ (lower side). One shear layer flows continuously in the downstream direction and the other

![Fig. 3](image-url) Variation of the drag coefficient of cylinders relative to the single cylinder ($C_D/C_{D0}$) with cutting angle of the small cylinder, for $Re = 5.3 \times 10^4$.
Fig. 4  Variation of the velocity profile behind the large cylinder with cutting angle of the small cylinder, for \( Re = 5.3 \times 10^4 \)

Fig. 5  Flow visualization using surface oil-flow pattern method at the wall of the single large cylinder, for \( Re = 5.3 \times 10^4 \)

shear layer flows in the upstream direction, which Mahbub Alam et al. [9] called the backward and the forward shear layer, respectively. The backward shear layer separates at \( \theta = 115^\circ \) (upper side) and \( 245^\circ \) (lower side); these separation points are more delayed than the separation positions of the single cylinder (without passive control). The forward shear layer also separates in the front region of the large cylinder and becomes a vortex between the I-type small cylinder and the large cylinder, which Tsutsui and Igarashi [8] called a quasi-static vortex. These phenomena are also investigated by measuring the pressure distribution directly on the surface of the large cylinder, as has been discussed in section 3.1.
4 CONCLUSIONS

The installation of bluff bodies (circular or sliced) as passive control in front of the circular cylinder effectively reduced the drag of the circular cylinder. Moreover, the I-type bluff body as passive control is more effective than the circular one in reducing the drag. As a passive control, the I-type small cylinder with cutting angle $\theta_s = 65^\circ$ gives the highest reduction of drag among the small cylinders used in this investigation, where the drag of the tandem arrangement using a small cylinder with cutting angle $\theta_s = 65^\circ$ is about 0.52 times the drag of a single cylinder. This means that use of the I-type small cylinder with a cutting angle of $\theta_s = 65^\circ$ as passive control at a stagger angle of $\alpha = 0^\circ$ is most effective in reducing the drag of the large circular cylinder, among the passive control cylinders used in this investigation.

REFERENCES


APPENDIX

Notation

\[ A \quad \text{cross-sectional area of the main cylinder} = (d \times L) \quad (m^2) \]
\[ C_p \quad \text{coefficient of pressure} = p - p_\infty / 0.5 \rho U_\infty^2 \]
\[ C_D \quad \text{coefficient of drag} = F_D / 0.5 \rho U_\infty^2 A \]
\[ d \quad \text{diameter of the main cylinder (m)} \]
\[ F_D \quad \text{drag force measured by aerodynamic balance (N)} \]
\[ L \quad \text{length of the cylinder (m)} \]
\[ p \quad \text{surface pressure of the main cylinder (N/m}^2) \]
\[ p_\infty \quad \text{free stream pressure (N/m}^2) \]
\[ U_\infty \quad \text{free stream velocity (m/s)} \]
\[ \rho \quad \text{free stream density (kg/m}^3) \]