

$$\frac{\partial^2}{\partial x^2}(h(x)\varphi(y)) + \frac{\partial^2}{\partial y^2}(h(x)\varphi(y)) = 0$$

$$\varphi(y) \frac{d^2 h}{dx^2} + h(x) \frac{d^2 \varphi}{dy^2} = 0$$

$$\frac{1}{h} \frac{d^2 h}{dx^2} = - \frac{1}{\varphi} \frac{d^2 \varphi}{dy^2}$$

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Mohamed Karim Ettouhami, Abdellah ElGharad, Mohamed Boukalouch, Abdellah Jilbab, Hamid Mounir

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Numerical Simulation of Fluid Flow Around Circular and I-Shape Cylinder in a Tandem Configuration

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Abstract

We consider two-dimensional numerical simulation of a tandem configuration of both *I*-shape cylinder and circular cylinder. Diameter of circular cylinder is D as the bluff body and *I*-shaped cylinder has diameter of d with a cutting angle 53° as passive control, that is located in front of the bluff body. Navier Stokes equations are used to solve this problem and solved with a finite difference method. When we put the Reynolds number of $Re = 7 \times 10^3$, the domain distance between bluff body and passive control is a $0.6 \leq S/D \leq 3.0$ and $X/D = 2.0$ then we obtain profile streamline around the bluff body, pressure distribution, separation point on the top around the 65° and on the bottom around 285° , wake and mathematics models of drag coefficient.

Mathematics Subject Classification: 76D05, 65D05

Keywords: Passive control, drag coefficient, wake, streamline

1 Introduction

Ongoing research will result in sophisticated technology and will change human behavior towards the technology itself. Research can be carried out with either experimental or simulated, with the hope of beneficial results of these studies to the humans. One area of research is the field of fluid dynamics research, the study of fluid flow through the circular cylinder as bluff body and I-shaped cylinder as passive control on the front bluff body. The research is carried out numerical simulations for various purposes such as to determine the effect of a drag force on the bluff body, wake of fluid happened behind the bluff body, the pressure distribution on the bluff body and the separation bubble is also occurred in the bluff body.

The interaction between fluid flow with an object commonly found in reality. Some examples are building offshore piling, structural overpass and other engineering products are often designed in groups. The construction will receive the load from above and also accept the burden of the surrounding. The object is construction usually called the body or bluff body in which geometrical shape varies and is usually on group. The geometry of the object is the main factor that should be taken into account in the design as the flow of fluid through and it will have different characteristics, so that the object is a stand alone or in groups.

Laminar and turbulent flow pass an object surface, the particles around the surface move slowly due to a viscous force, so that the particle velocity is zero relatively close the surface. While other fluid trying to move slowly on the particles are relatively silent as a result of the interaction between a faster fluid motion and a slower fluid. This is a phenomenon that can increase the force or shear stress. Velocity layer is affected by the shear viscosity due to a force called the boundary layer.

Research on the phenomenon of fluid flow across the outer surface of an object growing fast. The concept of the boundary layer manages to uncover some answers to the influence of shear stress plays an important role on the characteristics of a drag around the object[13]. For example, several studies have been done that the fluid flow through a single circular cylinder[12], which is modified into either *D*-shape cylinder or *I*-shape cylinder [8, 10]. In addition, this is also an example, i.e. the fluid flow through more than one cylinder of different sizes and arranged tandem[3, 4, 6, 7].

The fluid flowing across an upright cylinder profile will produce a drag, that is often adverse direction. The size of the drag force is influenced by several

parameters, one of which is the drag coefficient C_D . One way to reduce the drag force on the main cylinder is to add a small cylinder in front of the main cylinder, called the passive control cylinder. The experiment has been done in that way, i.e. it can reduce the drag coefficient of 48% compared with no passive control [3]. It has also done with variation of Reynolds numbers as a result minimum pressure coefficient in which $C_{P_{min}}$ becomes lower [4].

The characteristics of the flow through the D -shape and I -shape cylinder, show that the cutting angle (θ_s) reaches 53° , drag coefficient (C_D) reaches 50% from C_D circular cylinder. If $\theta_s > 60$, then C_D will be greater than C_D when $\theta_s > 60^\circ$ [8]. I -shape cylinder with angle 65° as passive control with $R_e = 3.8 \times 10^4$ provides a drag reduction of 7% smaller than when fully cylinder[6]. I -shape cylinder with cutting angle $\theta_s = 65^\circ$ has a drag coefficient (C_D) is greater than I -shape cylinder with cutting angle $0^\circ \leq \theta_s < 65^\circ$, the wake formed on the passive control cylinder with the cutting angle $\theta_s = 65^\circ$ is greater[2]. All the studies mention above are the experimental results.

I -shape cylinder with cutting angle $\theta_s = 53^\circ$ has most width wake than the other cylinders. The shear layer formed is also suspected to be more wider width and stronger disturbing flow on walls of bluff body. Therefore, the transition from laminar into a turbulent boundary layer will occur more quickly, so the momentum of the turbulent flow are better able to resist the adverse pressure gradient and friction along the walls of the bluff body, the result of those will delay separation flow. When the separation flow delay, then the wake formed on a bluff body becomes narrower. This is obtained in a reduction in drag on a bluff body.

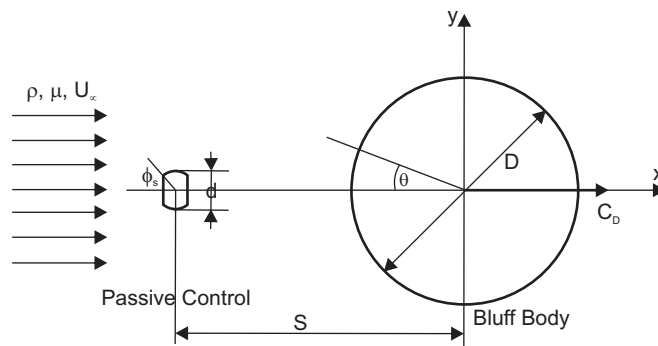


Figure 1: Schematic of passive control and bluff body

Based on the above results, and the passive control is a I -shape cylinder with $\theta_s = 53^\circ$ and Reynolds number $R_e = 7.0 \times 10^3$ which causes a turbulent flow [1] and the tandem arrangement can be seen in Figure 1. Rasio S/D varies from 0.6 to 3, which is S is distance center of bluff body and center of passive control, and D is diameter of bluff body. By using these parameters

it will be sought from the mathematical model of drag coefficient of the bluff body, in which the wake behind the bluff body and the location of separation point are also take consider.

2 Numerical Method

Let see Navier-Stokes equations for unsteady incompressible fluid,

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot \mathbf{u}\mathbf{u} = -\nabla P + \frac{1}{Re} \nabla^2 \mathbf{u} \quad (1)$$

$$\nabla \cdot \mathbf{u} = 0. \quad (2)$$

where \mathbf{u} is the velocity, P is the pressure, and Re is the Reynolds number. To solve the above equations using numerical solution technique, it needs to do the following steps. The first step to ignore the pressure, so equation becomes

$$\frac{\partial \mathbf{u}}{\partial t} = -\nabla \cdot \mathbf{u}\mathbf{u} + \frac{1}{Re} \nabla^2 \mathbf{u} \quad (3)$$

This equation further is solved and it is obtained \mathbf{u} , then

$$\frac{\partial \mathbf{u}}{\partial t} = \frac{\mathbf{u}^{**} - \mathbf{u}^*}{\Delta t} = -\nabla P \quad (4)$$

We now put divergence on both sides, the result

$$\frac{\nabla \mathbf{u}^{**} - \nabla \mathbf{u}^*}{\Delta t} = -\Delta P \quad (5)$$

and since $\nabla \mathbf{u}^{**} = 0$, then the equation turns into

$$\frac{\nabla \cdot \mathbf{u}^*}{\Delta t} = -\Delta P \quad (6)$$

This equation is called the Poisson equation and we will obtain the P . The last step is a correction velocity, ie.:

$$\frac{\partial \mathbf{u}}{\partial t} = -\nabla P \quad (7)$$

3 Result and Discussion

The numerical simulation of the Navier-Stokes performed by the following conditions, i.e., the Reynolds number of 7×10^3 , velocity of $U = 1.0$ in the horizontal direction and $V = 0.0$ in the vertical direction. In addition, grid

used is 400×800 , the diameter of the bluff body D and the diameter of the passive control is d . To obtain the data, we make five variations of S/D are 0.6, 1.6, 2.2, 2.6 and 3.0. Pressure distribution seen on the walls of the bluff body with a distance of 10° , starting from the front of the bluff body and rotates clockwise. Numerical simulation played is run of at most 99999 iterations and each 1000 iterations the numerical result are stored in a file. Since $Re = 7 \times 10^3$, then the flow is turbulent flow, resulting in a vortex[1]. Therefore, the flow through the bluff body will be unbalanced. Data of the wake behind a bluff body is taken to the distance $X/D = 2.0$ from the center of the bluff body.

The comparison of the drag coefficient (C_D) with some previous studies in Tabel 1.

Table 1: The Comparison of Average Drag Coefficient of $Re = 100$

Authors	Present Study	Lima[5]	Zulhidayat[9]	Sintu[11]
C_D	1.358	1.39	1.4	1.431

3.1 Pressure distribution

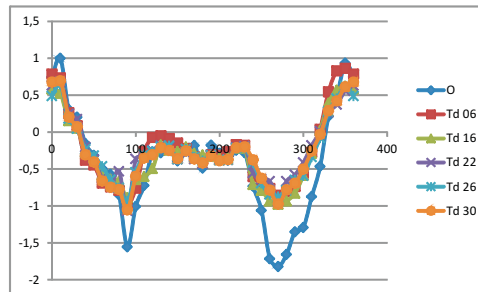


Figure 2: Pressure Distribution on Bluff Body

The pressure coefficient C_p distribution around the bluff body at $Re = 7 \times 10^3$ for five different ratio of distance of two cylinder with a diameter of bluff body (S/D) are shown in Figure 2. Reynolds number large enough of 7×10^3 , then we obtain a vortex behind cylinder so that the saved data is not symmetric. Value C_p on the front area of the bluff body with passive control is always smaller than the bluff body without passive control. It is caused by an obstruction of the passive control flow when the master cylinder. This occasions has been explained by Tsutsui and Igarashi[4]. Pressure distribution on the bluff body informs the pressure coefficient C_p wether max or min by ignoring the pressure coefficient at the rear areas as shown in Table 2. Pressure coefficient when pressure distribution main cylinder S/D of 0.6 has a maximum

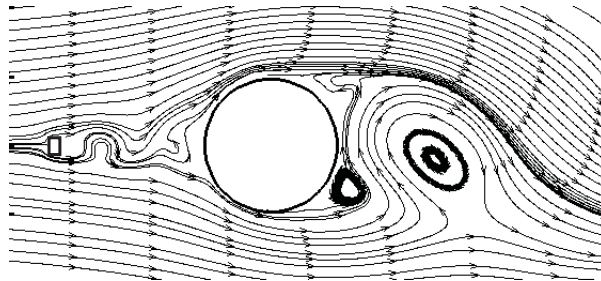
pressure coefficient of 0.8637 location at position of 350° and minimum pressure coefficient of upper area of -0.9833 locates at position 90° , and lower area of -0.8556 locates at position 270° . Upper separation point occurs at the angle of approximately 63.7° and bottom separation point at the angle of about 285.6° .

Table 2: Pressure Distribution

S/D	0.6	1.6	2.2	2.6	3.0
C_{pmax}	0.8637	0.6222	0.68	0.64	0.6933
$C_{pmin} - upp$	-0.9833	-0.89	-1.0667	-0.9333	-1.0533
θ	90°	90°	90°	90°	90°
$C_{pmin} - low$	-0.8556	-0.9778	-0.9378	-0.8756	-0.9756
θ	270°	270°	270°	270°	270°
Separation point up	63.7°	50°	75.7°	79.7°	75°
Separation point low	285.6°	270°	282°	282.7°	297.4°

The pressure coefficient C_{p-max} of bluff body without passive control is 1.0, and minimum pressure coefficient of upper area of -1.5556 locates at position 90° , and lower area of -1.8222 locates at position 270° . Upper separation point occurs at the angle of approximately 52.5° and bottom separation point at the angle of about 297.5°

3.2 Streamline dan Wake

Figure 3: Profile Streamline of $S/D = 1.6$

The results of numerical simulations of the Navier-Stokes equations to produce a streamlined bluff body with a passive control in front of main cylinder are depicted, in Figure 3 and 4. In accordance with the above explanation, the $Re = 7 \times 10^3$, the flow hits an object and produces, vortex behind the object. The vortex behind objects occur periodically. Vortex away from the object, it will be smaller and finally disappears into the surging stream at a slower rate. Flow velocity behind the passive control depends on the distance between the passive control and the bluff body.

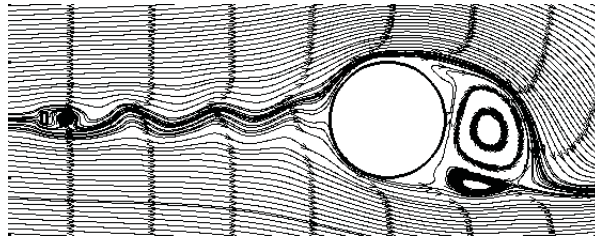


Figure 4: Profile Streamline of $S/D = 3.0$

Behind the passive flow control in which lower speed will hit the front of the bluff body, the flow moves to the top of all, down all, or part of the upper portion of the bluff body down and meets with the free flow. If the velocity of the flow at the top and the bottom respectively has the same speed and the vortex that occurred just behind the bluff body, the wake formed symmetric. However, if the flow rate is not balanced, and the vortex is formed behind the main cylinder is not directly, then behind the main cylinder wake formed is nearly symmetric.

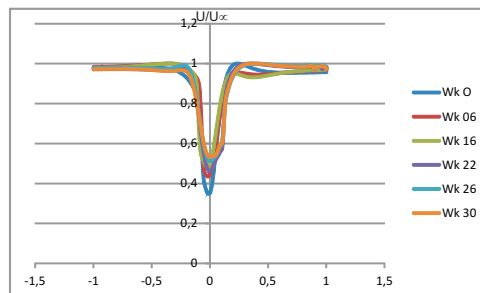


Figure 5: The Variation of Wake at position $X/D = 2.0$

Data of the wake behind a bluff body is taken to the distance $X/D = 2.0$ from the center of the bluff body. The wake when S/D of 1.6 is nearly symmetrical, the lowest velocity compared to free-flow velocity is 0.5259 on position -0.0648 . The flow velocity at the bottom is higher than the top, vortex occurs closer to the bluff body of lines of data, so the flow rate is still higher. The wake when $S/D = 2.6$ is also nearly symmetrical. The lowest velocity compared to free-flow velocity is 0.55 on location of -0.0349 . The flow velocity at the top is higher than the bottom, closer to the line vortex occurs retrieval of data from the bluff body, so the flow rate is lower.

3.3 Mathematical Modeling of Drag Coefficient

Numerical simulation results will be obtained when the pressure distribution on the wall of the bluff body. Five numerical calculations have been conducted

Table 3: Minimum Velocity of the Wake on the Variation S/D

S/D	0.6	1.6	2.2	2.6	3.0
Position	-0.0499	-0.0648	-0.0299	-0.0349	-0.0349
U/U_∞	0.4703	0.5259	0.4898	0.55	0.5644

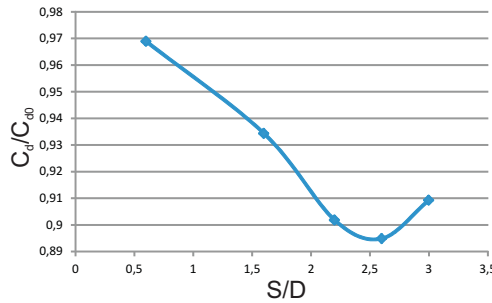


Figure 6: Variation of C_D/C_{D0} towards S/D

when $S/D = 0.6, 1.6, 2.2, 2.6, 3.0$. It is therefore obtained drag coefficient, see Table 4.

Table 4: The Value of Drag Coefficient when Variates

S/D	0.6	1.6	2.2	2.6	3.0
C_D	1.449	1.397	1.348	1.338	1.359

With five drag coefficient data from the Table 4 and by using an approximation, in which the drag coefficient is a function of S/D , we obtain equation, i.e.

$$y = 0.0019 x^4 + 0.0501 x^3 - 0.2128 x^2 + 0.2343 x + 1.3741 \tag{8}$$

We obtain minimum drag coefficient of the bluff body is 1.338223 when $S/D = 2.5483$. This equation is obtain by assuming

$$y = a_0x^4 + a_1x^3 + a_2x^2 + a_3x + a_4 \tag{9}$$

by letting y as the drag coefficient C_D and x as S/D . We further put the five data, it is obtained

$$\begin{aligned}
 1.449 &= 0.1296 a_0 + 0.216 a_1 + 0.36 a_2 + 0.6 a_3 + a_4 \\
 1.397 &= 6.5536 a_0 + 4.096 a_1 + 2.56 a_2 + 1.6 a_3 + a_4 \\
 1.348 &= 23.4256 a_0 + 10.648 a_1 + 4.84 a_2 + 2.2 a_3 + a_4 \\
 1.338 &= 45.6976 a_0 + 17.576 a_1 + 6.76 a_2 + 2.6 a_3 + a_4 \\
 1.359 &= 81.0 a_0 + 27.0 a_1 + 9.0 a_2 + 3.0 a_3 + a_4
 \end{aligned} \tag{10}$$

The equations system has five equations and five unknowns, namely a_i with $i = 0, \dots, 4$. Solve the Equation 10 by using the Gauss-Jordan method, it is obtained a polynomial equation, i.e. Equation 8.

4 Conclusion

Pressure coefficient on the bluff body with passive control is better than without passive control $S/D < 3.0$, the upper separation point around 50° and lower separation point around 270° .

Streamline is happened around the bluff body, vortex will occur behind the bluff body on upstream rounds from upper or lower, then moving to the rear vortex that moves up and down. Therefore, the wake is happened allowing near balanced. When domain $0.6 \leq S/D \leq 3.0$, the ratio of U/U_∞ decreasing with the position around 0.

Mathematical models of the drag coefficient of a bluff body with the passive control type-I, is

$$y = 0.0019 x^4 + 0.0501 x^3 - 0.2128 x^2 + 0.2343 x + 1.3741$$

From this equation, it can be found that the smallest drag coefficient obtained when $S/D = 2.5483$ and $C_D = 1.338223$.

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