Effects of a Detached Plate on Aerodynamic Characteristics of Linear Shear Flows over a Circular Cylinder

Xiaojie Wang, and Liming Dai

Abstract— The present research investigates the effects of a thin detached plate on the aerodynamic characteristics of linear shear flows over a circular cylinder. The vortex shedding and distribution of aerodynamic forces acting on the circular cylinder, with and without the application of the plate, are studied numerically with considerations of the system parameters such as shear parameter, velocity gradient, upstream mean velocity and cylinder-plate system geometry and separating gap. It is found in the research that a thin plate separated from the cylinder plays an important role on the flow phenomenon in the vicinities of the cylinder and the exertions applying on the cylinder subjected to linear shear flows**.**

Index Terms— Aerodynamic excretion; linear shear flow; cylinder-plate system; vortex shedding**.**

I. Introduction

Fluid flow over bluff bodies has been an interesting topic for researchers and engineers in the fields of aeronautics, aerospace, civil and mechanical engineering, due to their wide range of application in the fields. Though the geometric shapes of the bluff bodies can be simple, the aerodynamic phenomena at the vicinity of the bluff bodies can be rich and complex. Even for a thin plate, the fluid flow passing through it may cause complex aerodynamic phenomena [1]. The vortex shedding is commonly seen at the rear ends of the bluff bodies and the vortex shedding significantly increases the drag force acting on the bluff bodies and triggers an extra oscillating force perpendicular to the direction of the upcoming flow, known as vortex-induced vibration. For the concern of safety and reliability of engineering structures, it is of great importance to have a comprehensive understanding of the flow mechanism.

Great contributions have been made by researchers and engineers on this field, yet most of them are concentrated on bluff bodies associated with uniform approach flows. In many engineering applications, bluff bodies are usually immersed in nonuniform approach flows. Therefore, studies on the aerodynamics of bluff bodies in nonuniform flow are significant in research and industrial applications. Numerous experimental and numerical investigations are found in the literature. For example, considering a circular cylinder placed near a plane wall boundary [2], the non-uniformity of the approach flow was found numerically to have significant influences on the aerodynamic forces acting on the bluff bodies as well as vortex shedding behavior. A cylinder in a linearly varying flow was studied [3]. It was found in their numerical study that the time-averaged lift force varied proportional to a shear parameter. Experimental investigations were also conducted on circular cylinders in linear shear flow, such as the works [4,5]. Based on the results of the researchers, the effects of shear flow on bluff bodies are considerably different from that of uniform flow.

One may notice, from the results of the current research, most of the research works available in the literature are concentrated on the effects of shear parameter and the variation of aerodynamic characteristics of linear shear flow. The control of vortex shedding and flow at the surface of the cylinders, with an additional physical component, has rarely been considered either numerically or experimentally as per the current literatures. Controlling the flow at the vicinity of a cylinder by applying a thin plate is seen for the cases of uniform approach flow [6,7,8], but not for shear flow, which is more close to reality but may cause aerodynamic phenomena of high complexity.

In the present research, the shear flow over a circular cylinder is to be studied numerically with application of a thin plate near the cylinder to control the flow. Various gaps between the plate and cylinder are to be considered. The combined effects of both the shear parameter and the detached plate will also be investigated. The lift and drag forces acting on the cylinder is to be quantified and compared with the scenario where no additional plate is applied. The research is expected to provide some guidance for the design, analysis and manufacturing of structures with bluff components in aeronautic and civil engineering fields.

II. Governing Equations and Numerical Methodology

In this research, the fluid of the flow considered is incompressible and the flow is of low Reynolds number, i.e., $Re < 200$. It is also assumed that there is no heat conduction involved. Therefore, with these considerations, the governing equations for the flow passing over a cylinder can be expressed as:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (i = 1, 2) \qquad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} u_i u_j = -\frac{\partial p}{\partial x_i} + \frac{1}{Re} \frac{\partial^2 u_i}{\partial x_j \partial x_j} \qquad (i, j = 1, 2) \quad (2)$$

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where x_i are the Cartesian coordinates corresponding to the system shown in Fig. 1, u_i are the corresponding velocity components, p represents the pressure, Re the Reynolds number based on the free stream velocity U_c, D is the diameter of the cylinder. The Reynolds number Re is defined as

$$Re = \rho d U_c / \mu \quad (3)$$

where d and μ are the density and viscosity of the fluid.

The flow over the cylinder a linear shear flow as shown in Fig. 1, where the coordinates and the arrangement of the cylinder and plate are illustrated. It should be noticed that the direction of the approach flow is parallel to the thin plate.

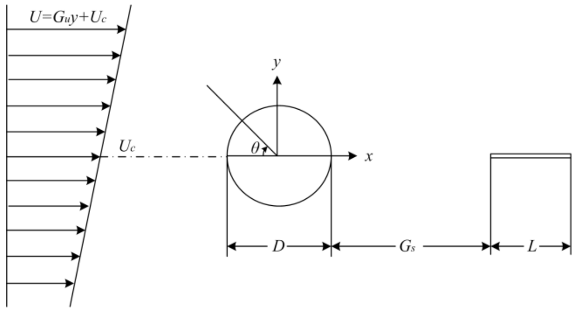


Fig. 1 Model of a cylinder-plate system in a linear shear flow with geometries in a Cartesian coordinate system

In Fig. 1, G_u represents the velocity gradient along the y direction. The velocity of the flow applying on the cylinder is thus defined as

$$U = G_u y + U_c \quad (4)$$

where U_c is a constant designating the average velocity of the approach flow, i.e., the velocity as y = 0.

In Fig. 1, G_s is the separating gap between the rear surface of the cylinder and the front frontier of the detached plate. L in the figure represents the length of the detached plate. The center of the cylinder is located at $x = 0$ and $y = 0$ with its axial perpendicular to the direction of the shear flow.

In the research, the detached plate is with a thickness of h=0.02D. The plate is considered as thin in comparing with the diameter of the cylinder. The plate is placed horizontally downstream along the centerline of the computational domain, which passes precisely through the center of the cylinder.

With the two dimensional cylinder-plate system modeled, for the sake of clarity in numerical calculations and analyses, the length of the plate is set as L=D, and the computational domain is selected as $-6D \leq x \leq 16D$ and $-5D \leq y \leq 5D$ such that it would prevent the inlet and outlet boundaries from affecting the core flow quantities. The flow in the computational domain is triggered by the linear shear approach flow shown in Fig. 1. Both the cylinder and the detached plate are considered rigid and the nonslip boundary conditions are applied on their surface.

The numerical solutions of the flow field, including the pressure field and velocity field, are obtained via the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) in solving for the two dimensional incompressible Navier-Stokes equations presented in Eq. (1) and Eq. (2). In order to perform the transient numerical calculations, the first order implicit scheme is applies for temporal discretization. The convection term is discretized by using the second order upwind scheme. A Dirichlet boundary condition is applied at the inlet position; where $u_1 = U$, and $u_2 = 0$. The outlet boundary is handled with utilization of a convective boundary condition [9], which allows the vortices to pass away from the outlet smoothly.

$$\frac{\partial u_i}{\partial t} + c\frac{\partial u_i}{\partial x} = 0 \qquad (i = 1, 2) \quad (5)$$

where c is the average exit velocity. The top and bottom boundaries are no-slip moving walls with the same velocity as that at the inlet. The time step selected for the calculations is $\Delta t U_C / D = 0.06$ as per the suggestions made by [10], corresponding to $CFL \approx 4$, which is defined as.

$$CFL = \frac{u_x \Delta t}{\Delta x} + \frac{u_y \Delta t}{\Delta y} \quad (6)$$

where u_x and u_y are the velocity magnitudes along x and y directions respectively, Δt is the time step, and Δx and Δy represent the linear intervals along the x and y directions respectively.

III. Results and Numerical Analyses

Based on the cylinder-plate model established with the conditions and parameters determined in the previous section, numerous numerical simulations are performed in investigating the dynamical behavior around the cylinder, the development and stabilization of the vortex shedding at the vicinity of the system, and the exertions applied on the cylinder. In performing the numerical simulations, besides the Re number, another important nondimensional number used for the analyses is the shear parameter, which measures the non-uniformity of the shear flow and is defined as

$$\beta = G_u D / U_c \quad (6)$$

The analyses based on the numerical simulation results lead to the following findings.

1. Effects of shear parameter and detached plates on the variations of the stagnation point.

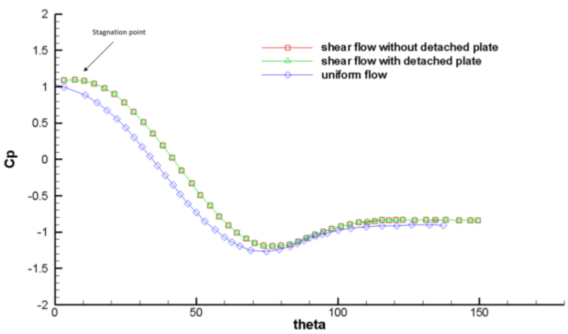


Fig. 2 Comparison of the pressure distributions in uniform flow and shear flow with and without detached plate (Re=150, $\beta = 0.1$)

Stagnation point is critical in analyzing the fluid flow over the surface of a bluff body. The distribution of the pressure coefficient along the cylinder surface is determined and plotted in Fig. 2. In the figure, the pressure coefficient is defined as

$$C_p = {p - p_\infty}/{q_\infty} \quad (7)$$

where p is the static pressure, p_∞ is the freestream static pressure and q_∞ is the freestream dynamic pressure. In the figure, the angle theta is measured from the negative x axis (theta equals zero) to the positive x axis (theta equals 180 degrees).

It can be seen from the figure, the linear shear flow does vary the distribution of the relative pressure along the cylinder surface. The relative pressure becomes higher especially on the windward surface of the cylinder in the linear shear flow as shown in Fig. 1, in comparing with that of the uniform flow. When the shear flow is considered, as shown in Fig. 2, the stagnation point is also moved to a higher position, with the shear parameter considered. One may also conclude from the numerical results showing in Fig. 2 that the application of a detached plate makes no noticeably change on the distribution of the relative pressure and the value of C_p , nor the change of stagnation point position, in comparison with the case without applying a detached plate.

2. Effects of shear parameter and detached plate on aerodynamic forces

The aerodynamic forces, including the lift and drag forces, are investigated and compared for the cases with and without detached plate. In the following figure, the stabilization of the lift forces with time is demonstrated for the cases with and without applying the thin detached plate.

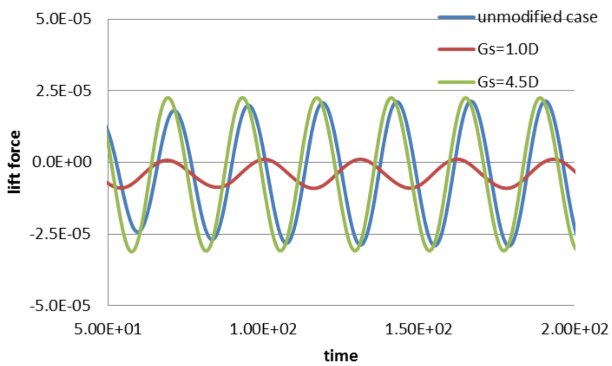


Fig. 3 Stabilization of lift forces with time (Re=150, $\beta = 0.1, L = D$) for the cases with and without detached plate

It can be seen from the Fig. 3 that, with the application of a detached plate in the flow region, the lift force can be drastically reduced by about 80%. This is mainly because that the vortex formation behind the cylinder is suppressed by the detached plate such that the vortex will shed behind the rear end of the plate instead of the cylinder. However, when the detached plate is placed too far away from the cylinder, as illustrated in Fig. 3 for $G_s = 4.5D$, the magnitude of the lift force almost remain unchanged, which means the detached plate plays no roles in modifying the upstream flow in this case. This can be simply understood by the vorticity contour presented below. It should be noted that due to the shear flow, the time-average lift force will not remain zero like that of uniform flow, because the time averaged pressure distribution on the high velocity side and low velocity side is no long symmetrical. Instead, the time averaged lift force will go toward to the lower velocity side. The variation of the drag force after applying the detached plate is also obvious. As demonstrated in Fig. 4, when the detached plate is placed at a proper position, as shown in the Fig. 3 for $G_s = 1.0D$, the drag force can be reduced by approximately 13%. However, when the plate is further placed downstream from the cylinder, the magnitude of the drag force may vary little.

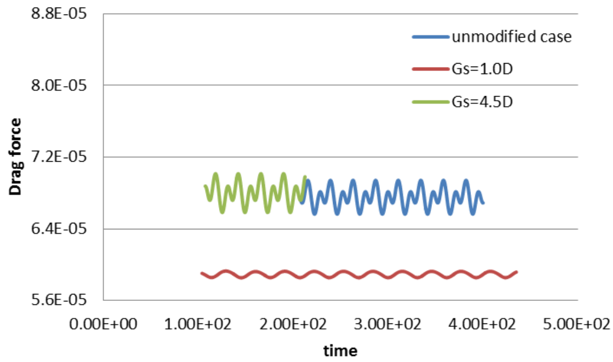
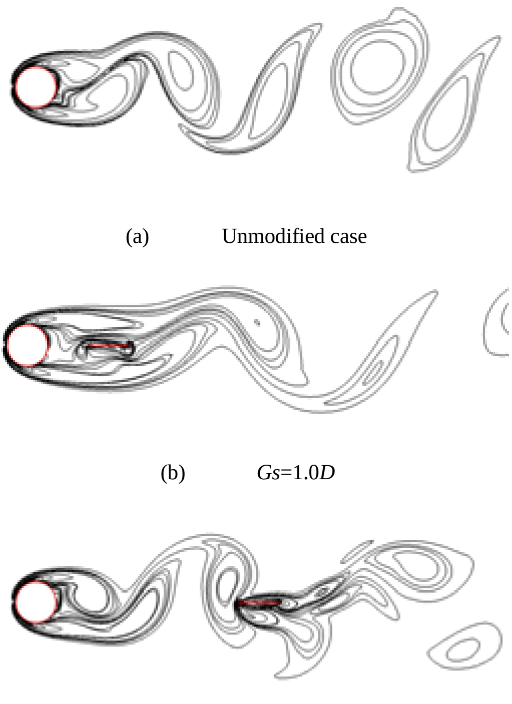


Fig. 4 Stabilization of drag forces with time (Re=150, $\beta = 0.1, L = D$) for the cases with and without detached plate

3. Effects of shear parameter and detached plate on vortex shedding pattern

The vortex shedding pattern of the systems considered is also affected by the application of the detached splitter plate. Fig. 4 shows the vortex shedding pattern of the systems with and without the detached plate applied.

As can be seen from Fig. 5(b), the vortex is shedding from the detached plate, in comparing with the case shown in Fig. 5(a) where no plate it applied. Also, the vortex experiences larger time period to shed and the shedding frequency decrease significantly. Moreover, as shown in Fig. 5(b), the fluid flow between the cylinder and the detached plate becomes more stable which leads to a rapid decrease of the forces acting on the cylinder.



(a) Unmodified case

(b) *Gs*=1.0*D*

(c) *Gs*=4.5*D*

Fig. 5 Transient vorticity contour for the cases with and without a detached plate (Re=150, $\beta = 0.1, L = D$)

There is a limit for the lift force reduction and the flow stabilization with the application of the detached plated. When the separation distance is too large, referring to Fig. 5(c), the vortex will start to shed directly from the cylinder instead of from the detached plate.

Based on the results obtained in this research, when a detached plate is inserted in the flow, the plate would directly interfere with the vortex if the separation distance is smaller than the length of vortex. The vortex generated from the cylinder interacts with each other further downstream and sheds from the detached plate instead of directly from the cylinder, as shown in Fig. 5.

IV. Conclusion

A quantitative investigation of the effects of a detached thin flat plate on the vortex shedding and aerodynamic behavior near a cylinder in linear shear flow is conducted in this research. A detached splitter plate can be used to control the vortex shedding induced by linear shear flow passing through a bluff structure. Based on the findings of the research, the following conclusions can be drawn.

1. Linear shear flow may increase the relative pressure and move the location of the stagnation point in comparing with that of uniform flow.
2. Effect of the applied plate on the distribution of relative pressure and location of stagnation point on the surface of the cylinder is negligible.
3. Addition of a detached plate behind the cylinder with a proper separating distance between the plate and cylinder may significantly reduce the lift and drag forces acting on the cylinder.
4. Addition of a detached plate behind the cylinder may also change the pattern of vortex shedding and reduce the shedding frequency.

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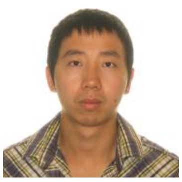

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