EFFECTS OF A THIN PLATE ON AERODYNAMIC CHARACTERISTICS OF LINEAR SHEAR FLOWS OVER A BLUFF STRUCTURE

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Abstract - A study on the effects of a thin detached plate on the aerodynamic characteristics of linear shear flows over a circular cylinder is conducted in the present research. The vortex shedding and behavior of aerodynamic forces acting on the circular cylinder, with and without the application of the plate, are studied numerically. System parameters such as the shear parameter, velocity gradient, cylinder-plate system geometry and separating gap between the plate and the circular cylinder are all taken into consideration. It is found in the research that a thin plate separated from the cylinder plays an important role in the flow phenomenon including the vortex shedding pattern in the vicinities of the cylinder and in the exertions applied on the cylinder subjected to linear shear flows.

Keywords - Vortex control; Linear shear flow; Bluff structures; Vortex shedding.

I. SCOPE AND BACKGROUND

Bluff structures are widely seen in aeronautics, aerospace, civil engineering and mechanical engineering fields [1]. The aerodynamic phenomena at the vicinity of bluff bodies are rich and complex. Even for a thin plate, fluid flow passing through the plate may cause complex aerodynamic phenomena [2]. Most of the archived documents are concentrated on bluff bodies associated with uniform approach flows. However, in many engineering applications, bluff bodies are usually immersed in non uniform approach flows [3]. Therefore, studies on the aerodynamics of bluff bodies in non uniform flows are significant for aerodynamics research and industrial applications. Additionally, the control of vortex shedding and flow at the surface of cylinders, with an additional physical component, has rarely been considered either numerically or experimentally. At the vicinity of a cylinder, controlling the flow by applying a thin plate was studied for the cases of uniform approach flow [4,5]. Kwon and Choi [6] numerically investigated the effects of splitter plates with various lengths attached to a circular cylinder at low Reynolds numbers. The critical length of the splitter plate, beyond which the vortex shedding behind the circular cylinder disappears, was found to be proportional to the Reynolds number. The present research aims to study the shear flow over a circular cylinder with the application of a thin plate near the cylinder to control the flow and the vortex shedding of the flow. Various gaps between the plate and cylinder are considered. The combined effects of both the shear parameter and the detached plate are also investigated. The lift and drag forces acting on the cylinder is quantified and compared with the scenario where no additional plate is applied. This research is expected to provide useful guidance for the design, analysis and manufacturing of the structures consisting of bluff components in aeronautic and civil engineering fields.

II. THEORETICAL MODEL DEVELOPMENT

The governing equations for a flow passing over a cylinder can be expressed as:

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

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

Where, x_i are the Cartesian coordinates corresponding to a cylindrical structure over which air flows, u_i in the equation are the corresponding velocity components, pis the pressure, Reis the Reynolds number based on the free stream velocity U_c and D is the diameter of the cylinder.

The Reynolds number Re is defined as

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

where ρ and $\mu$are are the density and viscosity of the fluid, respectively.
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,
Let G_u represents the velocity gradient along the y direction. The velocity of a linearly distributed flow applying on the cylinder is defined as

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

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

Let G_s be 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.

III. SEMI-IMPLICIT METHOD FOR PRESSURE-LINKED EQUATIONS

The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) is employed in solving the governing equations presented in Eq. (1) and Eq. (2). 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 [7], which allows the vortices to pass away from the outlet smoothly.

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

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 [6], corresponding to $CFL \approx 4$, which is defined as

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

where u_x and u_y are the velocity magnitudes along x and y directions, respectively, Δt is the time step andΔx and Δy represent the length interval along x and y directions respectively. The whole computational domain in this research is divided into three sections according to the variation of the flow field, for assuring accurate and reliable numerical results without excessive computational cost. , an appropriate mesh of the model is crucial.

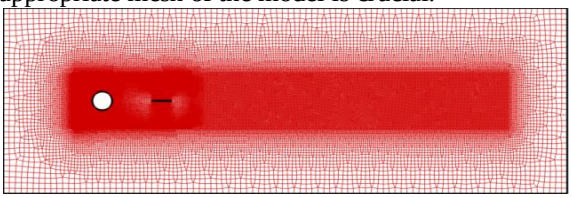


Fig. 1 Mesh for $G_s/D = 2.0, L = D$ (Total nodes: 79998; Total elements: 83192)

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

A. Vortex shedding with shear separating distance

In analyzing vortex and vortex shedding, the Strouhal number is an important factor. For the system the Strouhal number is found to vary with the position of the splitter plate. Fig. 2 shows the variation of Strouhal number S_t, defined as $S_t = fD/U_c$, with separating distance corresponding to different shear parameter and different Reynolds number. f in the expression represents the vortex shedding frequency.

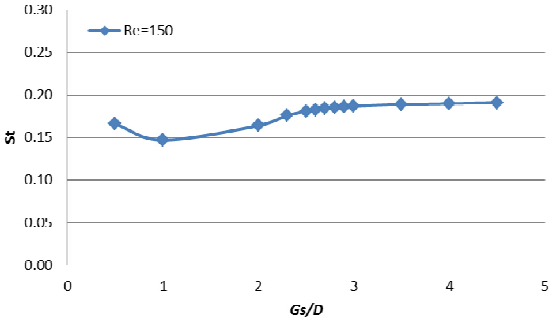


Fig. 2 Variation of Strouhal number with shear separating distance (β=0.1)

As can be seen from Fig. 2, for the case of $Re = 150$ and $\beta = 0.1$, the Strouhal number decreases first as the detached plate is moving apart from the cylinder. At the position where $G_s/D \approx 1.0$, the Strouhal number reaches a local minimum or a critical point and then increases slowly as the plate is placed further from the cylinder. After $G_s/D \approx 3.0$, the Strouhal number remains a stable state and possesses a value which is more or less the same as that without a plate applied.

With the results obtained, one may concluded that the application of the detached splitter plate may significantly reduce the Strouhal numbercompared with the unmodified condition in which no detached plates are considered and *St*=0.183, or reduce the frequency of the vortex shedding, so long as the separation distance represented by *G/d* is below the critical value.

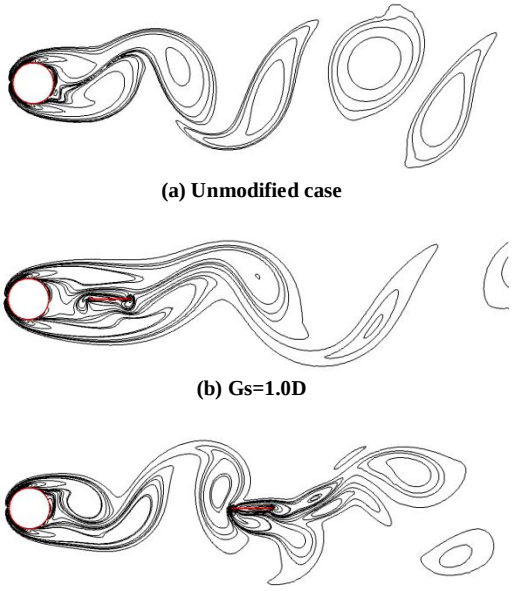
B. Effects of shear parameter and detached plate on vortex shedding pattern

The vortex shedding and vortex shedding pattern of the systems considered are also affected by the application of the detached splitter plate. Fig. 3shows the vortex shedding pattern of the system with and without the detached plate.

As can be seen from Fig. 3(b), where the detached plate is applied,

- the vortex is shedding from the detached plate, instead of from the cylinder directly as shown in the case of Fig. 3(a) where no plate it applied;
- the vortex experiences longer time to shed, when the detached plate is applied;
- the shedding frequency decrease significantly, when the detached plate is applied;
- as shown in Fig. 3(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=1.0D

(c) Gs=4.5D

Fig. 3 Transient vorticity contour for the cases with and without a detached plate (Re=150,β=0.1,L=D)

There is, however, a limit for lift force reduction and flow stabilization with the application of the detached plate. When the separation distance becomes too large, referring to Fig. 3(c), the vortex will start to shed directly from the cylinder instead of from the detached plate, and the forces acting on the cylinder turn back to the larger values as in the case where no detached plate is applied.

Based on the results obtained in this research, when a detached plate is inserted in the flow, the plate directly interferes with the vortex if the separation distance is smaller than the length of the vortex. The vortex generated from the cylinder interacts with each other in the downstream and sheds from the detached plate instead of directly from the cylinder, as shown in Fig. 3.

CONCLUSION

Effects of a detached thin flat plate on the vortex shedding and aerodynamic behavior at the vicinity of a cylinder in linear shear flow are studied quantitatively in this research. It is evidently shown by the findings of this research that a detached splitter plate applied behind the cylinder can be used to control the vortex and vortex shedding induced by the linear shear flow passing through a bluff structure. The following conclusions can be drawn with the findings of the research:

- Linear shear flow may significantly vary the distribution and magnitude of the aerodynamic forces acting on the cylinder, in contrast with the case of uniform flow. The time averaged lift force on the cylinder is no longer zero but pointing to the lower velocity side.
- Due to the asymmetry of linear shear flow, the critical distance (with which the forces on the cylinder are reduced) is reduced.
- 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.
- Addition of a detached plate behind the cylinder may also change the pattern of vortex shedding and reduce the shedding frequency.

The investigation carried out in this research may be enlightening and of great significance to engineering applications. Considering that the engineering structures widely seen in practice are subject to shear flows and nonlinear flows, the findings in this research are significant for engineering design and research of structures consisting of bluff bodies.

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