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Wall proximity effects on the flow past cylinder with flexible filament

K. Venkat Narayanan, S. Vengadesan *, K. Murali

Indian Institute of Technology Madras, Chennai, 600036, Tamil Nadu, India

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ABSTRACT

The response of thin, elastic filament attached to a circular cylinder is numerically investigated under uniform flow at different wall proximities, $\frac{G}{D}$ (0.5, 0.6, 0.8, 1, 1.5, 2 and 2.5). The Reynolds number based on the diameter of the cylinder is 200. Numerical simulations were conducted for a range of reduced velocities U_r (3,4,5 and 6), where $U_r = \frac{U_\infty}{f_n D}$ which appropriately captures the synchronization range of vortex-induced vibration(VIV) of the structure. U_r is varied by changing the density of the material. The force coefficients, the frequency of shedding/flapping are observed to be the function of $\frac{G}{D}$ and U_r. The positive vortices diffuses faster as $\frac{G}{D}$ decreases. The skewness in the amplitude attained by the flapping filament on either side of the cylinder causes unsteady shedding of vortices. Filament flaps in frequency that is closer to its natural frequency at higher $\frac{G}{D}$ and at lower $\frac{G}{D}$, the frequency of flaps for all U_r is similar. For lower gap ratios, 0.5 and 0.6, the modulations in flapping amplitude is observed. The modulation is predominant as the U_r increases. During the growth and damping phase of the amplitudes in each modulation cycle, the vortex shedding is observed to be oblique towards the wall. The filament flaps in single mode shape. The frequency of the flapping depends on the U_r and $\frac{G}{D}$. The frequency of the flapping is in resonance with shedding frequency.

1. Introduction

Flow past cylinder has been the area of interest for researchers because of its applications in engineering fields. The alternate shedding of vortices causes the cylinder to excite due to pressure fluctuations. These fluctuations are undesirable in industrial applications such as the pipeline or for the locomotion of insects. They cause the body to vibrate at a particular frequency which causes fatigue. These phenomena are extensively studied by many researchers and are briefly reviewed by Sarpkaya (2004) and Williamson and Govardhan (2008). The methods of controlling the vortex shedding gained importance and have been studied using active and passive means. Splitter plate at the wake of the cylinder is one of the passive methods that efficiently modify the flow field by preventing the shear layer interaction at the trailing edge (Gozmen et al., 2013). Most of the literature that reports the effect of splitter plate on lift and drag coefficients are based on the Reynolds number and the length of the plate. The plate considered is rigid and non-deformable. Under different conditions, drag reduction and vortex suppression phenomena are reported. Sudhakar and Vengadesan (2012) performed numerical studies on oscillating splitter plate, which controls the flow when oscillated at low frequencies. For stationary plate, the length required is of five times the diameter of the cylinder.

Inspired by nature, the effect of the flexible splitter plate which aids locomotion is being studied simultaneously. The effect of flexible fin is found to manipulate the vortex shedding because of its motion induced by the hydrodynamic loads on the plate. The frequency of flapping of the plate depends on the natural frequency of the geometry and Reynolds number of the flow. This motion is studied to harvest energy as shown through experiments (Allen and Smits, 2001).

Numerical studies on flexible geometries are also conducted for a wide variety of parametric variations. Lee and You (2013) concluded that the effect of bending stiffness has a major effect on the hydrodynamic forces and shedding frequency. Wu et al. (2014) reported that compared to rigid splitter plate of the flexible plate with low bending stiffness suppresses the shedding. Biologically, flexible splitter plate or wing, plays a major role in reducing the drag. Lacis et al. (2014) concluded that the plate projection should be sufficiently short giving more area for the flow reversal. Teksin and Yayla (2017) and Teksin and Yayla (2016) conducted experiments to analyse the behaviour of deformable splitter plate of different lengths.

Understanding the effect of wall proximity is necessary for the field of ocean and aerospace industries. Many animals, like fish, swims near the

* Corresponding author.
E-mail addresses: vengades@iitm.ac.in (S. Vengadesan), murali@iitm.ac.in (K. Murali).

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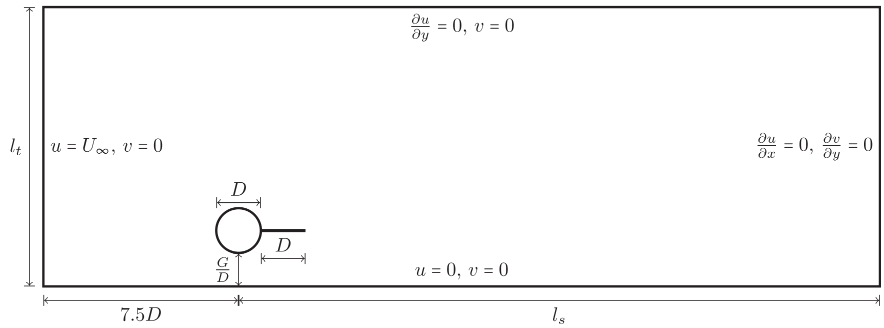

Fig. 1. Schematic diagram of computational domain.

wall to reduce the energy spent in moving. Wing in ground effect has already attracted many researchers because of the aerodynamic benefits gained when flying near the ground. The ground effects on the isolated cylinder are reported by various literature. Lei et al. (2000) concluded at higher gap ratio $\frac{G}{D} > 1$, the lift coefficient does not change significantly. The lift coefficient increases as the distance from the wall decreases. Zhang and Shi (2016) observed the same behaviour from cylinder with splitter plate near the moving wall. Akilli et al. (Ozkan et al., 2017), Miau et al. (1993), He et al. (2017), and Fu and Rockwell (2005), have studied the flow control of circular cylinder near wall. Vortex induced vibration of cylinder vibrating near the wall are analysed by Tham et al. (2015). Shaafi et al. (2017) analysed the vortex phenomenon by numerically studying the behaviour of rotating cylinder near the ground.

Recently, flow past flexible plunging plate near the ground had been numerically studied by Park et al. (2017) and reported that the observed hydrodynamic benefits or penalties are not only due to ground effects but also due to the flexibility of the plate. It is seen that deformable material has a significant impact on the flow parameters and flow structures. But none of the literature has conducted studies on varying density.

The objective of the present study is to examine the effect of density of the deformable filament in the wake of the cylinder on the flow field. The cylinder is kept at different wall proximities to observe the dynamic response of the plate and force coefficient.

The paper is arranged in the following manner. The governing equations and numerical methodology are explained. Validation tests are carried out. Problem description and the results for different domain and grids independence tests are reported. It is followed by results and discussion in Section 6 and the concluding remarks.

2. Problem description

The cylinder with a flexible filament attached at the wake is placed near the ground. Fig. 1 shows the schematic diagram of the geometry concerned with computational domain and boundary conditions. The leading edge of the filament is attached to the cylinder and trailing edge is free to flap (cantilever). To study the flow behaviour, the governing equations for fluid and solid are solved numerically using commercial software STAR-CCM + V11.04. The rectangular domain is used for computation and the cylinder center is placed at 7.5D from the inlet. Symmetric boundary condition is used on the top wall. No-slip boundary condition is specified on the cylinder, filament and the bottom wall.

3. Governing equations and numerical strategies

3.1. Computational fluid dynamics (CFD)

The incompressible Navier-Stokes equations are solved numerically using PISO algorithm for fluid domain for laminar conditions. The governing equations are as follows:

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i}{\partial x_i} - S_t = 0, \quad (1)$$

$$\frac{\partial (u_i)}{\partial t} + u_j \cdot \Delta u_i = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \eta \Delta^2 u_i + f_b, \quad (2)$$

where $i, j = 1$ and 2. p is the pressure, η is the dynamic viscosity, fb is the body force term and S_t is the source term. u_1 is the velocity component in x - direction. The equations are discretized in finite volume scheme. The convective term is discretized by Hybrid MUSCL 3rd-Order/Central-Differencing. 2nd-order temporal scheme is used to discretize unsteady term.

3.2. Computational structural dynamics (CSD)

The solid domain is governed by conservation of momentum which is as follows,

$$\rho \ddot{Q} - \Delta \cdot \sigma - b = 0, \quad (3)$$

where ρ, σ, b and Q are density, stress tensor, body force and displacement. Using principle of virtual work method,

$$\int_{V_o} \delta Q \cdot \rho_o \ddot{Q} dV - \int_{V_o} \delta Q \cdot b dV + \int_{V_o} \delta E : S dV - \int_{\Gamma} \delta Q \cdot \bar{\tau} d\Gamma = 0, \quad (4)$$

where Q, b, δE: S are displacement, body force per unit volume and variation of Green-Lagrange strain per unit volume. The Green-Lagrange strain is discretized into

$$\delta E = B_M \delta u_M, \quad (5)$$

where B_M is strain-displacement matrix. Equation (4) can be rewritten as

$$\int_{V_o} B_M^T S dV + M_{MN} \ddot{u}_N = \int_V \mathscr{N}_M b dV + \int_\Gamma \mathscr{N}_M \bar{\tau} d\Gamma, \quad (6)$$

$$M_{mn} = \int_{V_o} \mathscr{N}_M I \mathscr{N}_N \rho_o dV, \quad (7)$$

These equations satisfy $Q = \mathscr{N}_M Q_M$ where $\mathscr{N}_M$ is Lagrangian shape function.

Once $\ddot{Q}$ is estimated from Equation (6), the displacement Q and velocity $\dot{Q}$ is calculated from II order difference Newmark scheme.

$$\dot{Q}_N^n = \dot{Q}_N^{n-1} + \left(\delta \ddot{Q}_N^n + (1-\delta)\delta \ddot{Q}_N^{n-1}\right)\Delta t, \quad (8)$$

$$Q_N^n = Q_N^{n-1} + \dot{Q}_N^{n-1}\delta t + \left(\gamma \ddot{Q}_N^n + \left(\frac{1}{2} - \gamma\right)\delta \ddot{Q}_N^{n-1}\right)\Delta t^2. \quad (9)$$

3.3. Fluid-structure integration

The fluid and solid forces are two-way coupled through the boundary condition called interface. The forces are exchanged through the