Effect of Selectively Applied Surface Roughness and Wake Splitter Plate on the Aerodynamic Characteristics of a Circular Cylinder

Shruthi Sivadas, K. Arun Kumar and R. Ajith Kumar

Abstract This paper investigates flow over a stationary circular cylinder (diameter, D) with locally applied roughness height, 'k' applied at certain circumferential locations of the cylinder in the presence of a detached wake splitter plate with varying length, L. The numerical simulations are done by using commercial software ANSYS Fluent. This numerical study is conducted at a Reynolds number value of 25,000, $k/\delta = 1.1$ (δ is the boundary layer thickness at a given circumferential location) and $L/D = 0.5, 1, 1.5, 2.0$ at different roughness locations $\alpha = 0°$, 9°, 31°, 65°, and 75°. The results indicate that lift coefficient, drag coefficient, and Strouhal number are significantly affected as the L/D ratio increases, whereas with the change in the roughness location, the aerodynamic/hydrodynamic characteristics are not notably affected. Longer splitter plate along with roughness application is found to cause two effects: (a) considerable reduction in drag coefficient and Strouhal number and (b) considerable increase in the lift coefficient.

Keywords Drag coefficient · Lift coefficient · Strouhal number

Nomenclature

G	Gap between the cylinder and splitter plate
D	Diameter of cylinder
Cl*	Non-dimensional lift coefficient
Cpb	Base pressure coefficient
θ	Circumferential range of the roughness strip
G/D	Gap-to-diameter ratio
α	Circumferential location of the roughness strip
δ	Boundary layer thickness
L/D	Length of splitter plate to cylinder diameter ratio

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U	Freestream velocity
Cd*	Non-dimensional drag coefficient
k	Roughness height
St^*	Non-dimensional Strouhal number
L	Length of the splitter plate

1 Introduction

Flow over a bluff body is a very common phenomenon that can be seen over various engineering structures like cooling towers, stacks, bridges, high-rise buildings, and aircrafts. Right from 1960s, various researchers report measurements on the lift and drag forces on a circular cylinder at various Reynolds numbers. Gerrard [1] explained the mechanics of the formation region of vortices behind the circular cylinder. Further, Achenbach [2] investigated the effect of surface roughness on the cross flow around a circular cylinder by representing a curve of the drag coefficient as a function of Reynolds number. As the roughness parameter k/D increases ('k' is the surface roughness height), the flow will be modified by increasing the minimum drag coefficient and shifting the critical Reynolds number to lower values. Niemann [3] discussed the sudden drop of the drag and the Strouhal number in the critical regime.

Catalano [4] found that at high Reynolds numbers, the lift (rms) increases rapidly. Bernitsas [5] has proved that the application of roughness at a certain circumferential position of a circular cylinder has shown to bring significant effect on the flow-induced vibration (FIV) of a circular cylinder. But, all the works of Bernitsas's group was on a flexibly mounted cylinder exposed to water flow, wherein the fundamental aspects of lift and drag forces were not dealt with. The present study is aimed at filling this gap.

Apart from the roughness, effect of the splitter plate which is one of the devices (also known as wake stabilizer) attached/detached to the circular cylinder has been studied extensively in the past due to its significant effect on the parameters such as lift and drag forces, and Strouhal number around a circular cylinder. It was reported by Roshko [6] that the vortex shedding was completely eliminated at $L/D \geq 5$ which was supported by Gerrard [1] that as the splitter plate length increases, Strouhal number decreases. Apelt and Isaacs [7] conducted a wind tunnel test which measured a drag reduction of 17 and 32% for different ratios of L/D which was verified by Apelt and Szewczyk [8] by numerical simulation. It has been found that a detached plate behind the cylinder may also change the pattern of vortex shedding and reduce the shedding frequency.

Park et al. [5, 9] reported the effect of roughness, its location and orientation on a circular cylinder, wherein it was noted that the roughness strip location in the range 60°–80° exhibits significant variation in the amplitude trend, whereas 90°–106°

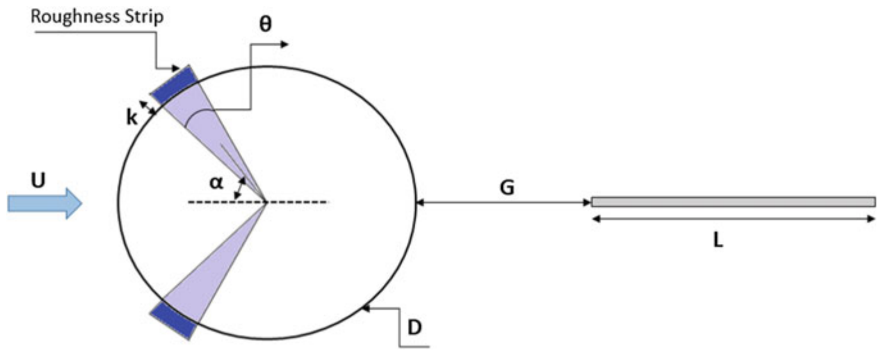

Fig. 1 Model geometry and test configuration

range shows a similar trend to that of smooth circular cylinder. On a further study, Park [10] identified one strong-suppression zone and two weak-suppression zones based on passive turbulence control location (local surface roughness application).

All the previous studies show that both local surface application and splitter plate have the individual impact on the aerodynamics/hydrodynamics of a circular cylinder. This has generated a curiosity in the authors as to how the aerodynamics of a cylinder would change if both are simultaneously applied on a cylinder. Being motivated thus, this paper is basically intended to investigate the combined effect of both splitter plate and roughness applied selectively on a circular cylinder in water flow, having a roughness strip with width '*b*' (circumferential coverage = 10°) and roughness height (*k*) applied selectively (locally) at five different angles and a detached splitter plate of different length introduced into the body wake at a Reynolds number value of 25,000. The study configuration is shown in Fig. 1.

2 Computational Model and Validation

This investigation is studied using numerical simulation tool ANSYS Fluent, in order to clarify the flow physics related to the gradual reduction of the flow-induced forces on a circular cylinder, wherein finite volume method is used to solve the Navier–Stokes equations, and the coupling of pressure and velocity field is done, and therefore, coupled scheme is used. The SST $k-\omega$ turbulence model is used due to its efficiency in predicting the flow separation under adverse pressure gradient and recirculation which was stated by Vu [11] and Pang [12]. The incompressible continuity and momentum equations are used as the governing equations,

$$\text{Continuity equation: } \partial\rho/\partial t + \nabla\cdot(\rho V) = 0 \tag{1}$$

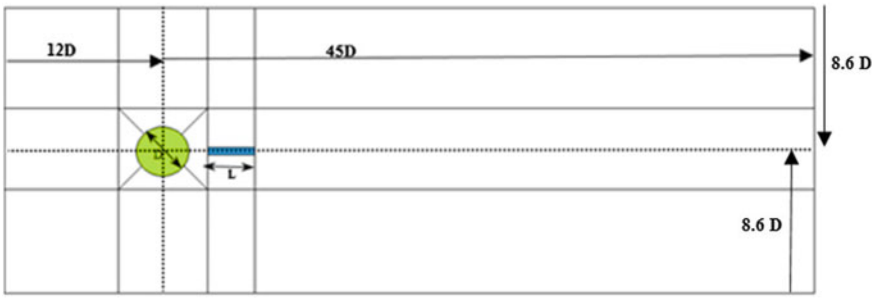

Fig. 2 Domain

Table 1 Validation result of simulation data with experimental results for a smooth cylinder, the cylinder with roughness and cylinder with splitter plate

Reynolds number	k/D	Achenbach [2]		Present study		Ozono [13]	
		Cd	St	Cd	St		
2.5×10^4	Smooth cylinder	1.48	0.22	1.45	0.223		
17,000	75×10^{-5}	1.48	0.23	1.45	0.228		
17,000	3000×10^{-5}	1.48	0.157	1.479	0.15		
2.5×10^4	75×10^{-5}	1.385	0.155	1.4	0.1558		
3×10^5	75×10^{-5}	0.63	0.22	0.625	0.226		
2.5×10^4	Only splitter plate			Cpb = 0.77	0.15	Cpb = 0.8	0.148

$$\text{Momentum equation: } \rho(\partial V/\partial t) + \rho V\nabla \cdot V = -\nabla P + \mu\nabla^2 V + \rho g \tag{2}$$

The computational domain is selected, where the inlet and outlet boundaries are located at 12D and 48D from the center of the cylinder. In Fig. 2, the length of splitter plate varies from 0.029 to 0.058 m. No-slip boundary condition is used for the cylinder wall and the splitter plate. The fluid medium considered is water. The freestream turbulence intensity is 1%. Second-order upwind scheme is used for pressure, momentum, turbulent kinetic energy, and dissipation. Velocity is 0.8662 m/s which is calculated for the given Reynolds number (based on *D*). A mesh size of 700,000 cells is found to be sufficient for a grid-independent solution with mesh quality of 0.989. In order to check the domain and mesh size of the circular cylinder at the selected diameter, the coefficient of drag at the same Reynolds number is validated with Achenbach [2] with roughness applied over the cylinder. Similarly, the coefficient of base pressure and Strouhal number for the case with splitter plate is validated with Ozono [13] (Table 1).

Table 2 Boundary layer thickness at various locations

α	δ (m)
0°	0.000299215
9°	0.000300321
31°	0.000313966
65°	0.000370096
75°	0.000401496

Different geometries are made with roughness strip located at α = 0°, 9°, 31°, 65°, and 75° from which boundary layer thickness δ is calculated which is referred from Khan et al. [14] by using modified Pohlhausen method. For the given α, the boundary layer thickness (δ) is calculated and substituted to calculate the roughness height, k, for $k/\delta = 1.1$ which is fixed at all strip locations tested in this study. From the table, it can be noted that the boundary layer thickness value is maximum at 75°. Hence, the roughness height, $k = 1.1 * \delta$ (m) (at 75°), is used as constant throughout all the circumferential locations coverage of the roughness strip 10°. The simulation is conducted for various cases over a circular cylinder with roughness strip located at selected test angles and a detached splitter plate at L/D = 0.5, 1, 1.5, and 2 for constant ratio of G/D = 1 (Table 2).

3 Results and Discussion

In this section, results are presented with non-dimensionalized values of Strouhal number, coefficients of drag and lift with respect to the circumferential location of the roughness strip. The aerodynamic/hydrodynamic parameters are non-dimensionalized using the respective values for a smooth cylinder at the same

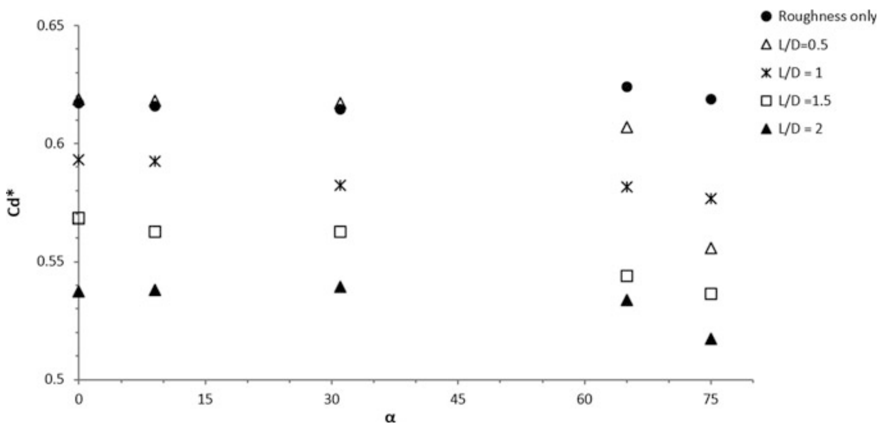

Fig. 3 Variation of non-dimensional drag coefficient with roughness location

Reynolds number. Figure 3 shows the variation of dimensionless drag coefficient for roughness alone cases and cases with roughness and splitter plate simultaneously applied.

It is noted that at *L*/*D* = 2 and roughness location $\alpha = 75°$, there is 48.2% drag reduction when compared with smooth cylinder. As the splitter plate length to cylinder diameter ratio varies from 0.5 to 2, it is observed that there is a significant reduction in drag coefficient from which complies with the results of Kawai [15] for *G*/*D* = 1.0 which is a critical gap as the rolling-up vortices is prevented until this gap ratio. It could also be noted that, till $\alpha = 65°$, drag remains nearly invariant further to which it notably drops (Fig. 3).

Variation of non-dimensional lift coefficient with roughness location is shown in Fig. 4. For cases such as roughness only, splitter plate only and with *L*/*D* = 0.5, 1, and 1.5, there is 50–80% reduction in rms lift coefficient as compared to smooth cylinder. But again, the interesting fact observed is that when the splitter plate length to cylinder diameter ratio is 2.0, the lift coefficient is higher as compared to the other ratios. It is interesting to note that the selective application of roughness tends to subdue drag similar to a splitter tends at *G*/*D* = 1.0. It is to be noted that, due to roughness alone, drag coefficient is the higher than other cases of combined roughness and splitter plate, whereas a roughness alone configuration brings down the lift coefficient to significantly lower values compared to the lift values of smooth cylinder and also compared to configurations with combined roughness and splitter plate. Further, it could be seen that, at a particular roughness location, lift variation is not following a trend w.r.t *L*/*D*. Drop in lift at $\alpha = 65$ could also be seen in Fig. 4 similar to that of drag. Therefore, it could be inferred that by applying both roughness and splitter together at certain locations of the cylinder, both the aerodynamic characteristics can be significantly controlled. More specifically, the

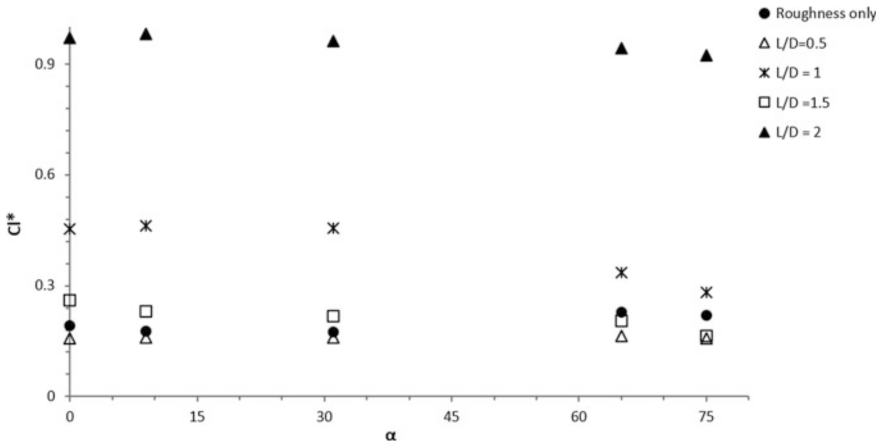

Fig. 4 Variation of non-dimensional lift coefficient with roughness location

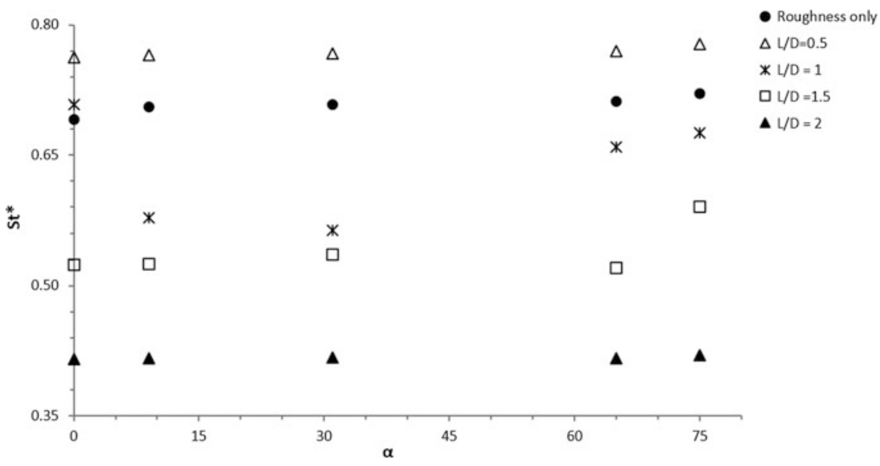

Fig. 5 Variation of Strouhal number with roughness location

present results clearly demonstrate that both local roughness and splitter plate are very good wake flow stabilizers.

Figure 5 shows that non-dimensional Strouhal number variation with respect to local roughness application alone and also with respect to roughness with splitter plate combined configurations. Strouhal number appears to be nearly invariant with respect to the roughness location till $\alpha = 65°$ further to which it slightly increases. With roughness alone, non-dimensional Strouhal number reduces to about 30% as seen in Fig. 5. But, with splitter plate addition, this shedding frequency parameter greatly modifies too much lower values (as low as 0.38) and much higher values (as high as 0.75) depending on *L*/*D* ratio. The highest Strouhal number value is for *L*/*D* = 0.5 (short splitter plate) case. This could be attributed to the amplification of flapping of free shear layers at this configuration as revealed by Kawai [15] and Vu [11]. It could also be seen that, as *L*/*D* increases, Strouhal number decreases for a given particular roughness location, whereas this parameter does not seem to vary significantly with respect to change in roughness location as evident from Fig. 5. The observed trends of the aerodynamic characteristics depicted in Figs. 3, 4, and 5 could be attributed to the changes in the flow field particularly the modifications in the characteristics of the shear layers, their subsequent roll-up the process, and the vortex formation region downstream. All these could very much affect the surface pressure distribution of the cylinder, thereby influencing the lift and drag forces as well as the vortex shedding frequency.

4 Conclusions

The flow around a circular cylinder is numerically simulated using ANSYS Fluent with a detached splitter plate and varying roughness at a subcritical Reynolds number value of 25,000. The aerodynamic characteristics such as the Strouhal number, and drag and lift force coefficients are investigated with respect to the splitter plate length and roughness location, and the following conclusions are obtained:

1. When both splitter plate and roughness are applied together, the aerodynamic characteristics such as the drag coefficient have shown the maximum reduction of about 48.2% compared to smooth cylinder.
2. For all the L/D ratios, Strouhal number remains nearly constant till $\alpha = 65°$ further to which it registers a slight increase.
3. The present study has given more clarity to the fact that even if the critical gap is set constant, the effect of splitter plate length and roughness location is very much critical to control the aerodynamic characteristics as both these passive flow controllers are found to bring in more stability to the cylinder.

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