Effectiveness of Corner Modification to Optimize Aerodynamic Responses of Square Cylinder

Md. Naimul Haque
Department of Civil Engineering, East West University, A/2, Aftabnagar, Dhaka-1212
E-mail: naimul@ewubd.edu

Abstract. This study investigates the effectiveness of a new technique to optimize aerodynamic responses of square cylinder by corner modification. The corner of the square cylinder was modified by introducing a small inclined opening which was measured in terms of corner point dislocation. Four specific opening widths (normalized with the depth of the cylinder) viz. 0.02, 0.08, 0.12 and 0.18 were considered. The normalized length of the inclined opening was 0.05 for all cases. The aerodynamic responses of these four modified square cylinders are compared with the unmodified square cylinder. Direct Numerical simulation was utilized to predict the aerodynamic responses and the flow filed. Second order accuracy was maintained both in space and time. The Reynolds number was kept constant at 100. The mean and RMS values of the force coefficients are calculated and compared. The flow filed is analyzed in terms of vorticity filed, mean flow streamlines and after-body wake characteristics.

Due to corner modification, a drag reduction of approximately 5% is achieved for square cylinder with corner opening. Along with the separated flow, the corner opening affected the wake of the cylinder as well. Square cylinder with corner opening had different wake characteristics as compared to the unmodified cylinder.

1. Introduction
Optimization of aerodynamic responses is one of the prime engineering interests in various fields such as civil, mechanical, chemical, naval and aerospace engineering etc. Reduction of force coefficients, especially the drag force, by understanding the flow mechanism has drawn the attention of researchers due to its huge practical application and make the design more economic. Past researchers explored various active and passive control systems to reduce the force coefficients and improve the flow field. Among the passive control systems, the effectiveness for wake control of circular cylinder by attaching a horizontal plate (splitter plate) at the downstream side of the circular cylinder was shown by Roshko [1]. The mechanism of splitter plate for square cylinder was different as the leading edge separated flow goes at the downstream with large side bubbles [2]. Over the time, a number of other effective passive control systems have also been invented for square cylinder and their effectiveness have been investigated at various Reynolds number.

Shiraishi et al. [3] experimentally investigated the influence of corner cut on square cylinder and found that corner modification significantly reduced the drag and fluctuating lift coefficient. The influence of corner cut, recession and roundness was experimentally investigated by Kawai [4]. Among the three methods, the corner roundness was the most effective to suppress the aeroelastic instability. Tamura and Miyagi [5] found that the square cylinder with corner cut and roundness have lower drag both in smooth and turbulent flows. Suppression of fluid force on square cylinder by putting a small bluff
body was achieved by number researchers. By placing a control cylinder at the shear layer for forced reattachment of flow to reduce the drag coefficient was achieved by Igarashi and Tsutsui [6] and Shakamoto et al. [7]. A reduction of both in drag an lift force coefficients was obtained by Dey and Das [8] by attaching a triangular thorn at the upstream face of the square prism. The reduction in drag was obtained mainly due to the weakening pressure and friction drag. By placing multiple small square prisms around the square cylinder the reduction of drag force was obtained by Islam et al. [9-10].

With this background, in the present study the corner of a square cylinder is modified to improve the aerodynamic responses. Figure 1 shows the side view of the square cylinder with corner modification. Four corners of the square cylinder is opened to introduce inclined gap. The details of the corner opening is shown in Figure 1(b). The width of opening is defined in terms of corner point dislocation which is named as $x$. Four different widths of opening viz. 0.02, 0.08, 0.12 and 0.18 were modeled and compared with the unmodified square cylinder. The length of the inclined opening was kept constant at 0.05. The Reynolds number was constant at 100. The z-vorticity, mean streamlines, wake characteristic and force statics were taken s a parameter of interest.

2. Details of numerical methods

The flow around the square cylinder was assumed as two dimensional and simulated by solving the unsteady incompressible Navier-Stokes Equations without any turbulence model as presented below.

$$\nabla \cdot \mathbf{u} = 0$$

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

where $\mathbf{u}$ is the velocity vectors and $p$ denotes the pressure. These dimensionless governing equations were integrated in time using second order accurate backward differentiation method. The convective and diffusive terms were discretized with a second-order accurate central differencing scheme. In space, the governing equations were discretized by the finite volume approach in an unstructured grid system. The pressure-velocity coupled discretized equations were solved by pimpleFoam algorithm which combines the conventional PISO (Pressure Implicit with Splitting of Operator) and SIMPLE (Semi-Implicit Method for Pressure Linked Equations) methods. The domain was sufficiently large to avoid domain sensitivity. In the horizontal direction, the domain was stretched up to 61D (where, $D$ is the height of the cylinder) and 25D was stretched in the vertical direction. The square cylinder was placed 20D downstream from the inlet of the domain. Non-slip boundary condition was applied on the cylinders surface. The domain was divided into three parts. In the inner domain, finest mesh and in the outer domains, coarser meshes were utilized. A grid size of 0.005D was used around the square cylinder. The grid system is shown in Figure 2. All simulations were carried out for a minimum period

---

(a) Location of corner opening

(b) Details of corner opening

**Figure 1.** Square cylinder with corner openings.
of 500 sec and statistical analysis was carried out for last 250 sec. Lift history of unmodified square cylinder is shown in Figure 3. A validation study was carried out to examine the reliability of the numerical setup for a square cylinder at Re 100. Force coefficients were compared with past numerical results and very good agreement was found which as shown in Table 1.

3. Results and discussion
The force statistics of the modified and unmodified square cylinders are summarized in Table 2. The mean drag force coefficients of all the square cylinders with corner opening are smaller than the unmodified square cylinder. Specially for a corner opening width ($x/D$) of 0.12, the drag is approximately 5% lesser than the unmodified square cylinder. For a wider opening the drag coefficient increases again. The cases those have been explored, among these the square cylinder with a corner opening of 0.12 has the least mean drag force coefficient. There is no significant influence of corner modification on RMS value of $C_d$. The RMS of lift force coefficient ($C_l'$) decreases for small opening then increases again beyond an opening width of 0.12. For large opening ($x/D=0.18$), $C_l'$ increases around 17%. Increase in $C_l'$ indicates the enhancement of fluctuation in the flow around the bluff.

![Figure 2. Meshing details around the bluff body and within the domain.](image)

![Figure 3. Time history of lift force coefficient ($C_l$).](image)

| Author               | Reynolds Number ($Re$) | Simulation Type | $C_{d \text{mean}}$ | $C_{d \text{rms}}$ | $C_{l \text{rms}}$ | $S_t$ |
|----------------------|------------------------|-----------------|---------------------|---------------------|---------------------|-------|
| Sharma and Eswaran [11] | 100                    | 2D              | 1.494               | 0.0054              | 0.1922              | 0.1488 |
| Zhao et al. [12]     | 100                    | 2D              | 1.452               | 0.0057              | 0.1908              | 0.1447 |
| Present              | 100                    | 2D              | 1.475               | 0.0050              | 0.1817              | 0.1440 |
Table 2. Comparison of force statics among the modified and unmodified square cylinders.

| Case Name | Mean \(Cd\) | RMS \(Cd\)' | RMS \(Cl\)' | RMS \(Cm\)' | Strouhal Number, \(St\) | Change in \(Cd\) w.r.t. \(x/D=0.0\) | Change in \(Cl\)' w.r.t. \(x/D=0.0\) |
|-----------|-------|-------|------|-----|----------------|----------------|----------------|
| \(x/D=0.0\) | 1.475 | 0.005 | 0.1817 | 0.0119 | 0.144 | --- | --- |
| \(x/D=0.02\) | 1.445 | 0.005 | 0.1747 | 0.0105 | 0.148 | -2.03% | -3.85% |
| \(x/D=0.08\) | 1.401 | 0.006 | 0.1736 | 0.0079 | 0.152 | -5.02% | -4.45% |
| \(x/D=0.12\) | 1.396 | 0.005 | 0.1840 | 0.0069 | 0.152 | -5.36% | +1.26% |
| \(x/D=0.18\) | 1.420 | 0.008 | 0.2138 | 0.0057 | 0.156 | -3.72% | +17.66% |

(a) Unmodified square cylinder (\(x/D=0.0\))

(b) Modified square cylinder with corner opening (\(x/D=0.12\))

Figure 4. Comparison of z-vorticity among modified and unmodified square cylinders.

body. Unlike \(Cl\)', the RMS value of moment coefficient \((Cm')\) of the modified square cylinder decreases with the increase in width of opening. Strouhal number \((St)\), which is another important parameter increases with the increase in corner opening and becomes almost constant beyond an opening width \((x/D)\) of 0.02.

The vorticity in the Z-direction of \(x/D=0.0\) and 0.12 cases are compared in Figure 4. In both cases, clear after-body vortex shedding can be seen. However, in case of \(x/D=0.12\), the intensity of vortex seem little bit dimmer. The time averaged velocity streamlines around the same square cylinders are compared in Figure 5. No significant variation in the shear layer flow is observed, however, the square cylinder with corner opening has smaller wake as compared to the unmodified square cylinder. The normalized velocity distribution at the vertical plane at 1D downstream of the square cylinders are plotted in Figure 6. The figure depicts, the square cylinder with a corner opening of 0.12 has little bit smaller wake. The decrease in wake size, literally indicates the enhancement of flow reattachment which is not clear yet.
4. Conclusions
This paper summarizes the results obtained from DNS simulation run for unmodified and modified square cylinders with corner opening. Four widths \((x/D)\) of corner opening i.e., 0.02, 0.08, 0.12 and 0.18 were explored as a benchmark work to see the effect of corner openings on aerodynamics of square cylinder at low Reynolds number. The obtained results showed that corner modification of square cylinder with inclined opening has noticeable influence on aerodynamic responses. For a corner opening width \((x/D)\) of 0.12, the drag coefficient reduced approximately 5%. The RMS of lift force coefficient and Strouhal number also showed sensitivity to the small corner openings. The modified square cylinder had a smaller wake both in terms of width and length. The reason for different responses in case of square cylinder with corner openings is not completely understood. The reduction of wake size literally indicates, the enhancement of flow reattachment at the side face of the cylinder could be an influence cause. However, further detailed flow analysis such as pressure distribution and boundary layer flow around the cylinder is required to better understand the flow field which is under consideration. Further, more simulations will be carried out for square cylinder with other values of corner openings to find the optimum width of corner opening.

Acknowledgments
All simulations were performed by using the high performance computer provided by the East West University, Bangladesh. This support of the university is gratefully acknowledged. The author also would like to thank Dr. Zhang Kai in University of California, Los Angles for his supports.
References

[1] Roshko, A. (1954) On the drag and shedding frequency of two-dimensional bluff bodies. NACA Technical Note, No. 3169.

[2] Doolan, C.J. (2009) Flat-plate interaction with the near wake of a square cylinder. AIAA J., 47, 475.

[3] Shiraishi, M., Matsumoto, M., Shirato, H., Ishizaki, H. Nagata, H., Matsui, T. (1986) "On aerodynamic stability effects for bluff rectangular cylinders by their corners cut." Proc. 9th National Symp. on Wind Engineering, 193-198 (in Japanese).

[4] Kawai, H. (1998) Effect of corner medications on aeroelastic instabilities of tall buildings. Journal of Wind Engineering and Industrial Aerodynamics, 74-76, 719-729.

[5] Tamura, T. and Miyagi, T. (1999) The effect of turbulence on aerodynamic forces on a square cylinder with various corner shapes. Journal of Wind Engineering and Industrial Aerodynamics, 83, 135.

[6] Igarashi, T., Tsutsui, T. (1989) Flow control around a circular cylinder by a new method, 1st Report, Forced reattachment of the separated shear layer. Transactions of JSME, 55 (511), 701–706.

[7] Sakamoto, H., Tan, K., Haniu, H. (1991) An optimum suppression of fluid forces by controlling a shear layer separated from a square prism. ASME Journal of Fluids Engineering, 113 (2), 183-189.

[8] Dey, P. and Das, A.K. (2015) Numerical analysis of drag and lift reduction of square cylinder, Engineering Science and Technology, an International Journal, 18(4), 758-768.

[9] Islam, S., Manzoor, R., Islam, Z., Kalsoom, S. & Ying, Z.C. (2017) A computational study of drag reduction and vortex shedding suppression of flow past a square cylinder in presence of small control cylinders. AIP ADVANCES, 7, 045119.

[10] Islam, S. Manzoor, R. Khan, U., Nazeer, G. & Hassan, S. (2018) Drag Reduction on a Square Cylinder using Multiple Detached Control Cylinders. KSCE Journal of Civil Engineering, 22(5):2023-2034.

[11] Sharma, A. and Eswaran, V. (2004) Heat and fluid flow across a square cylinder in the two-dimensional laminar flow regime. Numer. Heat Transfer, Part A 45, 247–269.

[12] Zhao, M., Cheng, L. and Zhou, T. (2013) Numerical Simulation of vortex-induced vibration of a square cylinder at a low Reynolds number. Physics of Fluids, 25, 1-25.