Commun. Comput. Phys. Vol. **38**, No. 2, pp. 491-520
doi: 10.4208/cicp.OA-2024-0304 August 2025

Aerodynamic Performance and Data-Driven Optimization of Flow Past an Inclined Rounded Square Cylinder

Wentian Song[1], Jingrun Chen[2,4,5,*], Wan Cheng[3], Zhouwang Yang[2] and Xisheng Luo[3]

[1] *School of Artificial Intelligence and Data Science, University of Science and Technology of China, Hefei, Anhui, China.*
[2] *SSchool of Mathematical Science, University of Science and Technology of China, Hefei, Anhui, China.*
[3] *School of Engineering Science, University of Science and Technology of China, Hefei, Anhui, China.*
[4] *Suzhou Institute for Advanced Research, University of Science and Technology of China, Suzhou, Jiangsu, China.*
[5] *Suzhou Big Data & AI Research and Engineering Center, Suzhou, Jiangsu, China.*

Received 12 December 2024; Accepted (in revised version) 8 March 2025

Abstract. This study systematically investigates the flow characteristics around an inclined rounded square cylinder in the laminar flow regime, focusing on key influential parameters. The simulations cover a broad parameter space, including incidence angles from 0° to 45°, Reynolds numbers from 45 to 170, and corner radii from 0 to 0.4. Data from direct numerical simulations, including mean force and moment coefficients, root mean square of force fluctuation coefficients, and Strouhal numbers, are meticulously analyzed and divided into two datasets for model training. The developed data-driven model exhibits exceptional predictive accuracy, mirroring a high-fidelity physical model. Based on this model, the optimization strategy also demonstrates notable accuracy. Specifically, the implementation of optimal design using the high-fidelity model allows precise control of output physical parameters, aligning them with targeted optimal conditions. This capability offers significant potential for improving the efficiency of various engineering applications.

AMS subject classifications: 76D55, 76D17, 93C95, 68T07

Key words: Rounded square cylinder, high-fidelity physical model, shape optimization.

*Corresponding author. *Email addresses:* soungwentian@mail.ustc.edu.cn (W. Song), jingrunchen@ustc.edu.cn (J. Chen), wancheng@ustc.edu.cn (W. Cheng), yangzw@ustc.edu.cn (Z. Yang), xluo@ustc.edu.cn (X. Luo)

1 Introduction

Flow around structures has been attracting many researchers' attention for decades [1–7], not only due to its academic significance, but also due to its practical applications, such as skyscrapers, towering structures, long-spanned bridges, and submarine transportation pipeline, to name a few. Among different geometries, circular and square cylinders are widely employed canonical configurations that represent typical flow mechanisms. Transitional configurations between circular and square geometries, combining the flow features of both cylinders, give rise to abundant physical phenomena.

The flow around a square cylinder is highly influenced by the angle of incidence (α) due to the fourth-order rotational symmetry of its cross-sectional shape. Unlike a circular cylinder, which has a finite curvature (inversely proportional to the radius of the surface), a square cylinder exhibits infinite curvature at its corners and zero curvature on its surfaces. Therefore, rounding the corners of a square cylinder from the corner radius ratio $r/b=0-0.5$ leads to the formation of a series of cylinders, where r is the radius of the rounded corners and b is the side width of bounding rectangle of the rounded square cylinder (Fig. 1(a)). Notably, when the ratio r/b equals 0.5, the rounded square cylinder effectively transforms into a circular cylinder. Thus, it is crucial to understand the flow characteristics of a rounded square cylinder with changing α and r/b. Zdravkovich [8] categorized the laminar flow around a circular cylinder into three classical flow regimes with a periodic laminar regime occurring at $30-48<Re<180-200$, where Re denotes the Reynolds number based on the cylinder diameter. In this regime, the flow around a bluff body is particularly sensitive to changes in Re, as noted in previous studies [9, 10].

Prior research has explored the low Reynolds number flow around stationary square sections at angles of incidence experimentally [11, 12] and numerically [7, 13]. These studies have primarily concentrated on the fluid forces, critical angles, and the critical Reynolds number, highlighting the significance of the angle of incidence (α) on the flow characteristics. Specifically, when a rectangular cylinder is inclined relative to the main flow direction, it can cause a shift of the separation points to other edges, resulting in notable changes in flow topology downstream of the cylinder and flow forces [12]. Miran and Sohn [14] performed a numerical investigation for flow past a square cylinder with different corner radii placed at an angle to the incoming flow. At a fixed Reynolds number of 500, the corner radius and angle of incidence were found to significantly influence the flow characteristics around the cylinder. Alam et al. [15] numerically studied the flow topology, heat transfer, and forces for a cylinder with its cross-section varied from square to circular by changing the cylinder corner radius at a fixed Reynolds number of 500 and a Prandtl number of 0.7. The introduction of rounded corners has often the positive effect of reducing the drag and the fluctuation of the transversal force due to vortex shedding [16–20]. Sarioglu et al. [21] experimentally investigated the aerodynamic characteristics of a square cylinder at incidence in the wake to achieve control of flow by using a rod.

Although extensive studies have been carried out on square/cylinder flows, a complete