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A fully implicit combined field scheme for freely vibrating square cylinders with sharp and rounded corners

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ABSTRACT

We present a fully implicit combined field scheme based on Petrov–Galerkin formulation for fluid–body interaction problems. The motion of the fluid domain is accounted by an arbitrary Lagrangian–Eulerian (ALE) strategy. The combined field scheme is more efficient than conventional monolithic schemes as it decouples the computation of ALE mesh position from the fluid–body variables. The effect of corner rounding is studied in two-dimensions for stationary as well as freely vibrating square cylinders. The cylinder shapes considered are: square with sharp corners, circle and four intermediate rounded squares generated by varying a single rounding parameter. Rounding of the corners delays the primary separation originating from the cylinder base. The secondary separation, seen solely for the basic square along its lateral edges, initiates at a Reynolds number, *Re* between 95 and 100. Imposition of blockage lowers the critical *Re* marking the onset of secondary separation. For free vibrations without damping, *Re* range is 100–200 and mass ratio, m^* of each cylinder is 10. The rounded cylinders undergo vortex-induced motion alone whereas motion of the basic square is vortex-induced at low *Re* and galloping at high *Re*. The flow is periodic for vortex-induced motion and quasi-periodic for galloping. The lower branch and desynchronization characterize the response of rounded cylinders. For the square cylinder, the components of response are the lower branch, desynchronization and galloping. Removal of the sharp corners of square cylinder drastically alters the flow and vibration characteristics.

1. Introduction

The analysis of flow around a single body or multiple bluff bodies continues to attract the attention of the research community. The primary motivation behind the present work concerning an isolated obstacle stems from the need to optimize multi-column offshore structures subjected to ocean currents. In particular, there is a growing demand to reduce or control the vortex-induced motions of multi-column structures. Motion of such offshore structures can be minimized by suitably altering the spacing between the columns and also by selecting appropriate column shapes such as circular, and square with sharp/rounded corners.

The presence of sharp corners on a square cylinder largely alters the flow characteristics as compared to the ones with circular/elliptical section having smooth contours. Besides the angle of incidence, the sharp corners appear as a major influencing factor in the body geometry, that affect the flow separation. The location of the separation points strongly depends on the body shape which in turn governs the wake dynamics and fluid loading. Removal of the sharp corners of a square cylinder and gradual transition to the circle through intermediate rounded squares generate cross-sections, that might be competitive both for a stationary and vibrating cylinder in various mechanical and civil engineering applications. It is therefore important to study the effect of gradually rounding the corners of a square cylinder at zero incidence on the flow till the circular section is reached.

In correspondence with a steady or time-averaged flow, existence of an even number of zero vorticity points on the surface of a symmetric or asymmetric obstacle was earlier suggested in [1]. For a separated flow, these singular points are alternate points of attachment and separation. In terms of streamlines, the schematics in Fig. 1 (upper row) illustrate various wake configurations of a square cylinder with sharp corners in low to moderate Reynolds number regime ($Re \leqslant 150$). Also shown is the corresponding vorticity, ω distribution along half the circumference of the cylinder. Here, θ is the circumferential angle measured counterclockwise from the forward stagnation point. Points 1, 2, 6, 8 and 9 denote locations of attachment while 3, 4, 5 and 7 denote locations of separation. An attached laminar boundary layer as observed at very low *Re*, is represented by Fig. 1a where formation of wake does not take place. The wake configuration depicted by

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Fig. 1b (four singular points) relates to the steady separated flow or time-averaged unsteady flow at relatively low *Re*. In this case, separation of laminar boundary layer initiates from the base point (point 2) implying separation angle, $\theta_{sr} = 0^\circ$ (measured counter-clockwise from the base point; subscript *sr* suggests 'separation from rear') at separation Reynolds number, Re_s and the separation points finally stagnate to the rear corners ($\theta_{sr} = 45^\circ$) of the trailing edge. The length of closed wake bubble forming out of primary separation from base point or rear corners is denoted by L_r. For a blockage, *B* of 0.05, [2] suggest that this wake configuration with rear corner separation exists till $Re \leqslant 125$. Blockage is the ratio of cross-stream projection of the body to the width of the computational domain.

As the Reynolds number is increased further ($150 \leqslant Re \leqslant 200$, $B = 0.05$ [2]; $Re = 120$, $B = 0.056$ [3]), the time-averaged wake resembles the sketch shown in Fig. 1c. In addition to the trailing edge separation, secondary separation from leading edge (points 5 and 7) and subsequent reattachment on the horizontal surfaces (points 6 and 8) raise the total number of singular points to eight. Using $B = 0.05$, [4] observed the trailing edge separation to exist at $Re = 100$. They presented results for leading edge separation from $Re = 110$ onwards. Thus, a scatter exists in the literature on the onset of secondary separation from the leading edge of a square cylinder. Results are also not available for the locations of separation and reattachment and the effects of *B* and *Re* on the streamwise extent L_f of lateral edge recirculation zone.

Based on computations at $Re = 250$ and 1000, the authors in [5] demonstrated that rounding the corners of square and diamond cylinders reduce the drag and lift forces. [6] reported a detailed experimental results for flow around a square cylinder with sharp corners (corner radius = 0), a circle (corner radius = maximum radius = radius of circle) and two rounded square cylinders. For $Re = 2600$ and 6000, they found that increasing the corner radius is associated with increase in shedding frequency, width of the wake and decrease in time-averaged wake length, longitudinal and lateral intervortex spacing. By employing immersed boundary method, [7] recently investigated the effect of varying corner radius on $Re = 100$ flow characteristics of two side by side identical squares. For single cylinder, the study was conducted at $Re = 150$.

Only a handful of studies are available [8–10] that explore the free vibrations of a rigid square cylinder with sharp corners. [10] proposed a modified formulation of combined interface boundary condition (CIBC) method where the uncorrected structural traction was discarded when establishing the CIBC terms explicitly into the differential system [11,12]. [10] validated their methodology through detailed comparison of various flow-induced vibration cases at low *Re*. They also reported some interesting results related to vortex-induced motion and galloping. Galloping is a self-excited non-linear instability associated with large amplitude and low-frequency oscillations and is undesirable to avoid structural failure. Therefore, it is interesting to investigate the effect of rounding the corners of the basic square cylinder on the occurrence of galloping.

Branching of cylinder response for vortex-induced vibrations (VIV) has its genesis in two-dimensional low *Re* flow. In [13], the VIV regimes of cylinder response were captured via simulations at low *Re*, similar in nature to the upper and lower branches seen at higher *Re*. Therefore, the present study is relevant in identifying the key features of flow-induced vibrations of offshore structures at higher *Re*.

For stationary or vibrating cylinders, the authors are not aware of studies that investigate at low *Re*, the effect of gradual transition of cross-section from square to circle, on the flow. In order to generate the rounded shapes, the earlier studies used varying locations for center of curvature such that the corner radius increases as the shape approaches a circle from a basic square. In contrast to this, the rounded cylinders in the present work are generated such that the center of curvature in all cases is fixed at the geometric center of the cylinder and a single parameter, i.e. angle, ϕ or radius, $R_c = \frac{D}{2}\sec\phi$ controls the amount of rounding at the corner (see Section 4).

Flow around six different cross-sections including circle and square, is explored. The characteristic dimension, *D* of all the cross-sections is identical where *D* is the maximum dimension of the cylinder normal to the flow. For the steady flow, the blockage used is 0.01 and upper limit of Reynolds number is 40. Results for the unsteady flow for each cylinder shape are presented at $Re = 80 - 150$ using a blockage of 0.05. For the square with sharp corners and circle, unsteady computations are performed also using $B = 0.01$. Besides analyzing the leading edge separation of a stationary square cylinder with sharp corners, the present study also explores the effect of gradual smoothening of corners on the onset of separation and characteristic flow quantities, such as, wake length, separation angle, surface pressure, fluid loading, shedding frequency and primary wavelength of shed vortices in a row. The rigid body motion of cylinders, excited by the fluid flow, is restricted by the elastic and damping properties of the supports. For the two-degrees-of-freedom (in-line and transverse) free vibra-

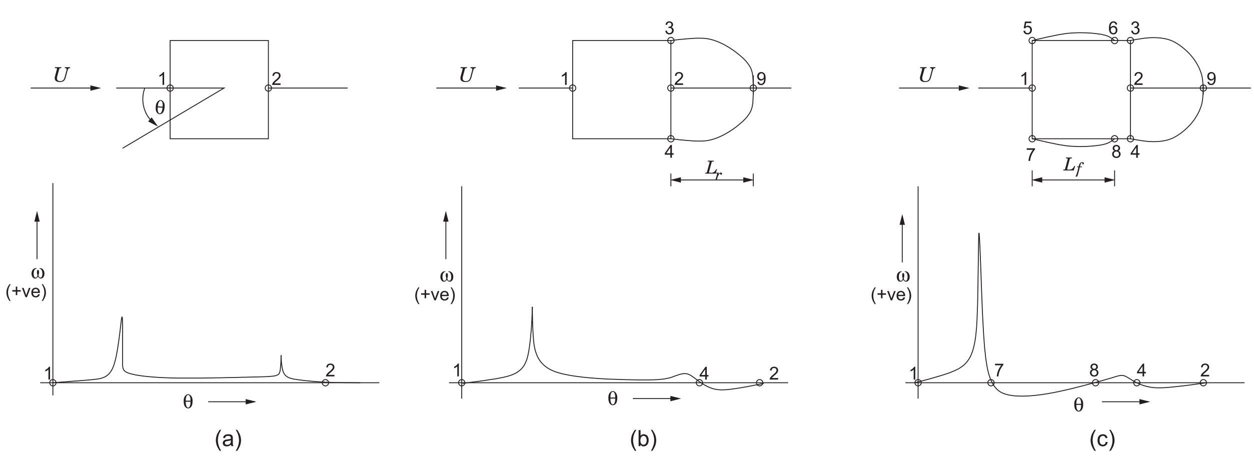

Fig. 1. Steady and time-averaged wake of a square cylinder with sharp corners: (a) attached flow with two singular points on the cylinder, (b) steady separated and unsteady low Re flow with four singular points and (c) unsteady flow at moderate *Re* with eight singular points. Also shown is the $\omega - \theta$ distribution between the stagnation points 1 and 2. *U* is the free-stream speed.