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Vortex shedding suppression and aerodynamic characteristics of square cylinder due to offsetting of rectangular cylinders towards a plane

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ABSTRACT

Numerically simulated results are presented for shear flow past a square cylinder (of height A) near a wall (at a gap height $0.5A$) in the presence of a family of upstream rectangular cylinders (of different heights a and widths $b \le a$) in an offset tandem arrangement (towards the wall) in order to investigate the physical mechanism for the cessation of vortex shedding from the downstream cylinder due to this arrangement and the dependency of the aerodynamic characteristics of the downstream cylinder on the operational dimensionless parameters, Reynolds number Re, gap height L from the wall, spacing distance between the cylinders S, ratio of heights $r_2 = a/A\ (\le 1)$ and aspect ratio $r_1 = b/a\ (\le 1)$. The governing unsteady Navier–Stokes equations are solved numerically through SIMPLE algorithm with the QUICK scheme for convective terms. The strong dependency of diversion of the flow (away from the narrow passage between the downstream cylinder's lower face and the wall) on the shape (square/rectangular) and the position (with respect to the wall and the downstream cylinder) of the upstream cylinder is explored in this study and is justified physically exhibiting the flow structures and gap flow. The discontinuous jump in the aerodynamic characteristics against the flow parameters is absent in this arrangement since the change in the flow patterns between the cylinders is essentially found to be minimum.

1. Introduction

There have been numerous experimental and numerical studies on unsteady flow past bluff bodies. The flow field and various transport coefficients strongly depend on the shape and configuration of the bodies. A rectangular and/or a square-shaped body and tandem, side-by-side or staggered arrangement of these bodies offer different scenarios altogether. There have been several studies on the behavior of vortex shedding behind obstacles placed parallel to the ground because of their relevance in practical cases. Typical examples are the vibration of pipelines lying on the sea-bottom under the effect of sea-currents; pipelines and bridges under the effect of the wind, flow past heat exchanger tubes near walls, multiple conductor transmission lines, structures in the atmospheric boundary layers or other significant cases. Vortex shedding causes a noticeable erosion of the support of these structures. Such oscillation may cause structural vibration and noise which may lead to structural failure or reduction in performance. Therefore it is essential to control the shedding of vortices in the wake of the bluff bodies in practical engineering flow situation. The presence of a upstream cylinder of rectangular shape may control the undesired flow mixing in the wake of a square cylinder in an offset tandem arrangement. At the same time the presence of the ground modifies the dynamics, with respect to the unbounded conditions, due to essentially three different factors, namely the impermeability of the wall gives an irrotational constraint to the bluff body wake, the velocity profile in front of the body is not uniform, production of the secondary vortex along the ground and the unsteady boundary-layer separation from the wall. *This is the motivation behind this study.*

Studies on the problems of wake development and vortex shedding behind a rectangular cylinder in free-stream flows were investigated both numerically and experimentally by Davis and Moore (1982), Franke et al. (1990), and Patankar and Kelkar (1992). Davis and Moore (1982) studied the vortex shedding from rectangular/square cylinder numerically in uniform flow and they continued their study in channel (Davis et al., 1984). Flows around rectangular cylinder in an unbounded domain were vigorously studied experimentally and numerically by Okajima (1982, 1990). They showed the strong dependency of aerodynamic characteristics on the Reynolds number and the side ratio of the cross-section of a model. Tian et al. (2013) numerically studied the flow normal to

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rectangular cylinders with different aspect ratios ($r_1 \leq 1$) using the k–ω SST turbulence model and observed that the vortex shedding frequencies are not sensitive to the aspect ratio.

When the cylinder is placed in the proximity of a solid wall, the strength of the upper and lower shear layers separated from the surfaces of the cylinder is not equal and the vortex shedding pattern is distorted. The form of the wake and the vortex shedding behind a cylinder in proximity of a wall were studied by several authors namely Bearmen and Zdravkovich (1978), Bosch and Rodi (1996), and Bhattacharyya and Maiti (2004, 2005, 2006). Bhattacharyya and Maiti (2006) observed that the suppression of vortex shedding from a square cylinder near a wall depends on the wall to cylinder gap heights as well as on the Reynolds number. The dependence of flow characteristics of rectangular cylinder near a wall on the incident velocity and on the gap height has been reported in the previous studies (Maiti, 2011, 2012) under incident inlet shear flow. It has been accounted there that the geometry of the rectangular cylinder (and hence the gap flow between the cylinder's lower face and the wall) plays a major role on the onset of vortex shedding from the cylinder placed at lower gap height $L \leq 0.5$. Singha and Sinhamahapatra (2010a,b) confirmed that transition to vortex shedding regime is delayed when the channel walls are close to the cylinder. The mechanism of vortex shedding suppression in the laminar or the turbulent range of the Reynolds number is made for a circular cylinder (Bearmen and Zdravkovich, 1978; Taneda, 1965; Lei et al., 2000; Zovatto and Pedrizzetti, 2001; Price et al., 2002). Wang and Tan (2008) reported experimentally that the averaged and instantaneous flow fields depend on the gap spacing between the cylinder bottom and the wall surface. In another experimental study, Oner et al. (2008) indicated that the changes in the flow structure become very slow when the gap ratio is small, and the wall proximity effect on the flow around the cylinder becomes insignificant when the gap ratio is larger than unity.

The studies on the several aspects of the unsteady flow past a tandem circular cylinders arrangement were performed by Alam et al. (2003) and Sharman et al. (2005), and the flow and the heat transfer from other obstacles in tandem arrangements were conducted by Zhu et al. (2006) and Singha and Sinhamahapatra (2010a,b). The flow over two circular cylinders with the large diameter cylinder upstream of the smaller one was experimentally studied by Baxendale and Grant (1986) and Sayers and Saban (1994) at different cylinder spacings, diameter ratios and stagger angles. Flow past single and tandem cylindrical bodies near a plane wall in a two-dimensional incompressible boundary layer flow were studied numerically by Harichandan and Roy (2012). They reported that apart from the Reynolds number, gap ratio has a strong influence on the vortex shedding from the cylinder and the vortex shedding frequency for wall proximity flow was higher than those for corresponding unconfined flows.

The square cylinders were installed in tandem in a vertical water tank and the effects of Reynolds number, spacing ratio and rotation angle of the downstream cylinder on the aerodynamic characteristics were experimentally studied by Yen et al. (2008). Etminan et al. (2011) numerically studied the unconfined flow characteristics around the tandem square cylinders in both steady and unsteady laminar flow regimes at fixed $S=5$. Sohankar (2011) and Malekzadeh and Sohankar (2012) reported three major regimes in the flow patterns depending on spacing distance, height and position of a control plate. The flow of incompressible fluid past a pair of square cylinders in inline tandem arrangement; Lankadasu and Vengadesan (2007) reported the negative drag experienced by the downstream cylinder at some shear rates. In a similar study (when both the square cylinders of same height A placed near a wall at a fixed height $0.5A$), Bhattacharyya and Dhinakaran (2008) observed that the vortex shedding starts for Re beyond 125 for all values of spacing distances. Maiti and Bhatt (unpublished research) extended the above study considering the upstream cylinder as a rectangular shape of different heights a and widths b (at which $b \leq a \leq A$) in an inline tandem arrangement. There it is reported that the transition (from unsteady/steady to steady/unsteady) of flow over the upstream/downstream cylinder strongly depends on the shape and the position of the upstream cylinder, apart from Re, and the dependence of the aerodynamic characteristics of both the cylinders on the aspect ratio b/a and the spacing distance S becomes predominant due to the increasing of height of the upstream cylinder.

To the knowledge of the authors, not a single published paper is available in the literature on the shear flow around a square cylinder near a wall in the presence of a family of upstream cylinders of rectangular shape in an offset tandem arrangement (towards the wall). In contrast to the previous observation the upstream cylinders of rectangular shape with $r_1 \leq 1.0$ generate the developing boundary layers, which swirl, and hence the unsteadiness is generated in the steady flow of a downstream square cylinder in an inline tandem arrangement (Maiti and Bhatt, unpublished research), a cessation of vortex shedding from the downstream cylinder is likely to happen due to the offsetting of the upstream cylinder towards the wall since the downstream cylinder's gap flow is to be largely hampered here. In our previous study (Bhattacharyya and Maiti, 2004), the vortex shedding from a square cylinder placed at a gap height $L=0.5$ under the incident of shear flow was observed for $Re \geq 125$. Therefore, varying the Reynolds number Re from 125, the main objective of this study is to delineate the affected flow of the downstream cylinder (of height A) placed at $L=0.5$ in the presence of a family of upstream rectangular cylinders (of different heights a and widths $b \leq a \leq A$) at different positions (with respect to the wall and the downstream cylinder). An attempt is made to propose some inequalities for $S_{cr}(L, r_2, r_1)$, the critical value of S for which the flow behavior of the downstream cylinder is seen to be unaffected by the upstream cylinder, at each value of Re. The dependency of the aerodynamic characteristics of the downstream cylinder on the operational dimensionless parameters, gap height L, spacing distance S, ratio of heights $r_2 = a/A$ (≤ 1) and aspect ratio $r_1 = b/a$ (≤ 1), is also documented here.

2. Problem formulation and numerical method

2.1. Problem formulation

A wall lying along the x^*-axis and a long cylinder of square cross-section of height A is placed parallel to the wall at a height $0.5A$ from the wall. Another cylinder of rectangular cross-section of aspect ratio b/a – with height a and width b – is placed in the upstream side of the square cylinder at a distance D from the upstream face of square cylinder and parallel to the wall at a height H ($< 0.5A$) from the wall (see Fig. 1). The upstream flow field is taken as a uniform shear flow $u^* = U_0 y^*/A$ where U_0 is the velocity at height A from the wall. The rationale for this choice of linear velocity profile near the wall has been discussed in the

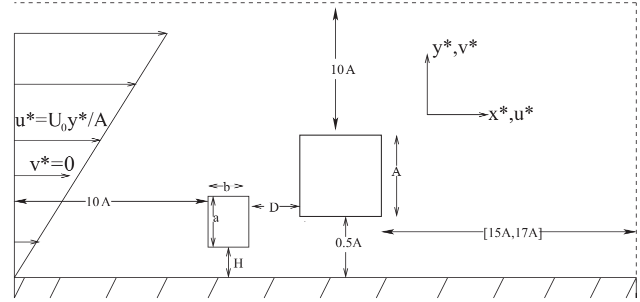

Fig. 1. Schematics of the flow configuration.