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Aerodynamic forces on square cylinder due to secondary flow by rectangular vortex generator in offset tandem: Comparison with inline

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ABSTRACT

A numerical study is made of the shear flow past a square cylinder (of height A^*) near a wall (at a gap height $0.5A^*$) in presence of a vortex generating upstream rectangular cylinder (of different heights a^* and widths b^*) placed at a fixed height $1.25A^*$ in an offset tandem arrangement. Influence of fluctuating aerodynamic forces of the vortex generator (VG) on the downstream cylinder (DSC) is investigated based on parameters : spacing between the cylinders $S(=D^*/A^*)$, ratio of heights $r_2 = a^*/A^*$ (≤ 1), aspect ratio $r_1 = b^*/a^*$ (≤ 1) and Reynolds number Re (based on A^*). A formula is derived for local $Re_l = Re \times (L + \frac{r_2}{2}) \times r_2$ to calculate the effective Re for the VG placed at height L. The critical Reynolds number $Re_{r_1-1.25}$ (at which the VG of $r_1 = 0.1, 0.5$ and 1.0 starts to shed the vortices) is predicted (using the formula for Re_l and the Lagrange interpolation based on the previous data for single cylinder) and validated in the present study of tandem arrangement. A linear relation between $Re_{r_1-1.25}$ and r_1 is established to predict $Re_{r_1-1.25}$ and finally a region of finite volume in the r_1ReS-space (for the values of r_1, $Re_{r_1-1.25}$ and critical spacing S_{cr} for fixed value of r_2) is proposed in order to generate the unsteadiness in the steady flow of the DSC at lower Re. The governing unsteady Navier–Stokes equations are solved numerically through a finite volume method on a staggered grid system using QUICK scheme for convective terms. The results for the present case of offset arrangement are compared with that for the case of inline arrangement highlighting some of the major issues : generating the vortices by the VG, the appearance of multiple peaks in the spectra of fluctuating lift coefficient, and the deviation of the aerodynamic characteristics of the DSC from that of the isolated square cylinder.

1. Introduction

The flow around cylinders is encountered in many engineering applications such as compact heat exchangers, cooling of glass, plastics and industrial devices, tall buildings, groups of free-standing cooling towers, electronic systems especially in a computer equipment and so on. There have been numerous experimental and numerical studies on unsteady flow past bluff bodies. The objective of the most studies has been devoted to examining the unsteady nature of the flow behind the bluff bodies and the effects on heat transfer and flow-induced vibrations. 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. As it can be found from the previous literature (e.g., Yang and Fu [1]; Sharma and Eswaran [2]), the heat flux for the case of flow with vortex shedding is higher than that without vortex shedding. An enhancement of heat transfer from heated cylinder/flat tube bank fin due to the interaction of vortices generated by a vortex generator was reported in some of the previous studies (Devarkonda and Humphery [3]; Zhu et al. [4]). An upstream cylinder of rectangular shape can generate the vortices and enhance the heat transfer from a heated square downstream cylinder in tandem arrangement. The Reynolds number considered in these studies lies in the laminar flow regime.

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 [5], Franke et al. [6] and Okajima et al. [7,8]. The form of the wake and the vortex shedding behind a cylinder in proximity of a wall were studied by several authors namely, Bearman and Zdravkovich [9] and Bhattacharyya and Maiti [10]. 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

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Nomenclature

A^*	height of the square cylinder [m]
a^*	height of upstream cylinder [m]
b^*	width of upstream cylinder [m]
S	non-dimensional distance between two cylinders, $\frac{D^*}{A^*}$
L	non-dimensional gap height from cylinder's lower face to the plane wall, $\frac{H^*}{A^*}$
r_2	ratio of heights of cylinders, $\frac{a^*}{A^*}$
r_1	aspect ratio of upstream cylinder, $\frac{b^*}{a^*}$
C_D	drag coefficient, $\frac{F_D}{\frac{1}{2}\rho U_0^2 A^*}$
C_L	lift coefficient, $\frac{F_L}{\frac{1}{2}\rho U_0^2 A^*}$
F_D	the integrated drag force experienced by the cylinder
F_L	the integrated lift force experienced by the cylinder
S_{cr}	critical S at which the unsteadiness is generated in the steady flow of downstream cylinder
St	Strouhal number, $\frac{fA^*}{U_0}$
f	frequency of vortex shedding, $\frac{1}{T}$
Re	Reynolds number, $\frac{U_0 A^*}{\nu}$
Re_l	local Reynolds number based on a^* and u^*
Re_{r_1-L}	critical Re at which isolated cylinder of r_1 placed at L starts to shed vortices
C_{Lrms}	rms of lift coefficient, $\sqrt{\frac{1}{N}\sum_{i=1}^{N}(C_L(i)-\bar{C}_L)^2}$
C_{Drms}	rms of drag coefficient, $\sqrt{\frac{1}{N}\sum_{i=1}^{N}(C_D(i)-\bar{C}_D)^2}$
$C_L(i)$	lift coefficient of a single point in time
$C_D(i)$	drag coefficient of a single point in time
N	number of samples used to calculate RMS coefficients
T	period of vortex shedding
t	non-dimensional time, $\frac{t^* U_0}{A^*}$
U_0	reference horizontal velocity [m s^{-1}]
u^*	x-component of velocity [m s^{-1}]
$v*$	y-component of velocity [m s^{-1}]
x^*	horizontal distance [m]
y^*	vertical distance [m]
Greek	
ν	kinematic viscosity coefficient [m^2 s^{-1}]
ρ	fluid density [kg m^{-3}]
Superscript	
$*$	dimensional quantity
-	time average quantity

studies (Maiti [11,12]) under the incident of shear flow. It has been reported there that the vortex shedding from a rectangular cylinder of lower aspect ratio occurs at comparatively lower *Re*. In an unsteady flow past a finite square cylinder mounted on a wall at low Reynolds number, Saha [13] observed that the cylinder aspect ratio has a significant effect on the instantaneous as well time-averaged flow characteristics.

Fluctuating forces and flow structures around the bluff bodies due to interaction of vortices from another body can be controlled by several methods like modification in the shape of the bodies or by changing their respective positions (e.g., Alam et al. [14,15]). For a pair of two identical square cylinders in staggered arrangement, Niu and Zhu [16] observed that the gap flow near the upstream cylinder suppresses the oscillation of the drag and lift as well as the generation of the secondary structure in the near wake of the cylinder. Sohankar and Etminan [17] found that the level of the force coefficient on the downstream cylinder is larger than the corresponding value of upstream cylinder due to flow interaction of the upstream cylinder with the downstream cylinder. Ali et al. [18] investigated that the length of the downstream plate introduces a strong interaction to the near wake of the cylinder and the length of the plate affects the flow structure significantly. For a pair of square cylinders at various gap spacings, Chatterjee and Mondal [19] reported that the critical spacing decreases with the increase in *Re*. A discontinuous jump observed for the force coefficients of the downstream cylinder at critical spacing beyond which the coefficients approach the single cylinder values. Huang et al. [20] numerically studied the flow around tandem square cylinders in a channel for fixed a gap ratio. Their results show that the time-averaged drag coefficient of both cylinders increases with the increase in Re while lift coefficient decreases. Alam and Zhou [21] experimentally examined the flow structure around two cylinders and observed that the fluctuating forces dropped because vortices impinging upon the downstream cylinder decreased in scale with decreasing in the diameter ratio of the cylinders. In an experimental study, Wang et al. [22] studied the effect of cylinder to wall gap height ratio and the inter-cylinder spacing ratio of tandem square cylinders on the wall proximity, and the mutual interference between the cylinders. They observed that the wall proximity leads to a longer vortex formation length, broadening of vortex shedding peaks in the spectra and the positive mean lift on the downstream cylinder. For the flow around a row of five square cylinders placed in a side-by-side arrangement at higher separation ratio Chatterjee et al. [23] observed that the secondary frequencies almost disappear and the resulting flow becomes more synchronized dominated by the primary frequency.

Rosales et al. [24] compared the inline and offset tandem pairs of square cylinders at the fixed spacing $S = 2$. Their study revealed pronounced differences in the unsteady behavior of an inline tandem pair of cylinders when compared to that of an offset tandem arrangement. Devarakonda [25] calculated the case of an offset tandem pair of square cylinders exposed to a uniform inlet velocity profile at fixed $S = 3$ and observed that the Strouhal number was larger for an inline pair of cylinders. The effect of placing a control plate upstream of a square cylinder and of two square cylinders was studied by Malekzadeh and Sohankar [26] and Alam et al. [27] to reduce the fluid forces acting on the cylinder.

Investigating the flow of incompressible fluid past a pair of square cylinders in inline tandem arrangement, Lankadasu and Vengadesan [28] reported the negative drag experienced by the downstream cylinder at some shear rates. In a similar study, Bhattacharyya and Dhinakaran [29] observed that the vortex shedding starts for *Re* beyond 125 for all values of spacings. Maiti and Bhatt [30] extended the above study by considering the upstream cylinder as rectangular shape of different widths b^* (at which $b^* \leq A^*$) in an inline tandem arrangement. 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.

From the above literature discussion, it is well understood that there are many reported work on the flow past inline tandem cylinder, the corresponding studies for lower Reynolds number on offset arrangements are almost unavailable. It is proposed in our previous study (Maiti and Bhatt [30]) that the upstream cylinder of rectangular shape ($r_1 < 1$) can be used as a vortex generator in generating the vortices (passively) to dominate the state of the wake of a downstream square cylinder. As a follow-up study, the present study investigates the effects of fluctuating fluid forces of the upstream cylinder (vortex generator) on the downstream cylinder in an offset tandem arrangement. The main issues for driving the present study are: