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Large eddy simulations of flow interference between two unequal sized square cylinders

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A uniform flow past two unequal sized square cylinders arranged in a side-by-side pattern and at a Reynolds number of 50,000 has been investigated using large eddy simulation (LES) technique. The modelling of sub-grid scales of turbulence is done using the Smagorinsky model. The effect of the transverse gap ratio \((T/D)\) on the flow characteristics has been studied. Numerical simulations are carried out for five different transverse gap ratios \((T/D)\), namely 1.120, 1.250, 1.375, 1.750 and 2.500. Results in terms of the aerodynamic forces, Strouhal number, mean base pressure coefficient, streamlines, vorticity, surface pressure distribution, normal and shear stresses are presented. A shift in the stagnation point for the small square cylinder from the centre of its front face towards its gap side is seen at smaller \(T/D\) ratios. The presence of a jet-like flow seen in the gap side is more pronounced at \(T/D = 1.12\). A biased gap side flow towards the near wake of the small square cylinder is seen at smaller \(T/D\) ratios. No interference effect is seen at \(T/D = 2.5\). The flow behaviour is similar to that of the isolated square cylinder at this gap ratio.

Keywords: large eddy simulation; tandem cylinders; square cylinder; wake; vortex shedding; turbulence; bluff bodies

1. Introduction

The phenomenon of flow around two bluff bodies in tandem or in side-by-side arrangement is one of the interesting fluid-structure interaction problems in engineering. As defined by Zdravkovich (1987), the interference brought about by the former arrangement is called wake interference and by the latter arrangement is called proximity interference. Cylinder-like structures find many technological applications both in air and water flows.

The interference effect brought about by the bluff bodies placed side-by-side gives rise to a very complex flow pattern. The complexity lies in the interaction of four separated free shear layers, two Karman vortex formation and shedding processes and interactions between two Karman vortex streets. The lift and drag forces acting on the two structures are quite different from those acting on a single structure. The flow behaviour and parameters like the Strouhal number \((St)\), mean base pressure coefficient, coefficient of lift and drag strongly depend on many factors. Some of the parameters are the spacing between the centres of the two cylinders, blockage ratio, the approaching flow and the aspect ratio of the bluff bodies.

Wong et al. (1995) presented the experimental results for flow past two side-by-side square cylinders of unequal sizes at sub-critical flow regime. They found that the gap side shear layer of the large cylinder reattaches to its inner surface for smaller separation. For larger separation, reattachment of the gap side shear layer was found in the inner surface of the small cylinder. It was shown that only skewed flow towards the small cylinder exists and no bistable flow was observed. As the separation increases, the skewness of the vortex streets towards the small cylinder decreases. Kolar et al. (1997) studied the unsteady flow around two identical square cylinders placed side-by-side using laser-Doppler velocimetry and ensemble averaging. They found a coupled vortex street with in-antiphase mode existing along with the flow being symmetric about the centreline. In addition, they found a jet-like flow in the gap using the time averaged velocity field.

Sumner et al. (1999) reported the dynamics of flow past two and three circular cylinders of equal size arranged side-by-side using flow visualisation, hot-film anemometry and particle image velocimetry. They found that the fluid dynamics of the side-by-side arrangement of cylinders is quite insensitive for \(500 < \text{Reynolds number (Re)} < 1,11,000\). They also found that at small gap ratios, the higher momentum fluid through the gap increases the base pressure, reduces the drag of both cylinders and also increases the stream-wise extent of the vortex formation region in case of two side-by-side cylinders. Sumner et al. (2000) investigated the flow around two equal sized cylinders.
circular cylinders arranged in a staggered pattern using flow visualisation and particle image velocimetry. They identified nine different flow patterns and the processes of shear layer reattachment, induced separation, vortex pairing and synchronisation and vortex impingement were clearly presented. Their study revealed that the vortex shedding frequencies are more properly associated with individual shear layers than with the individual cylinders.

Kondo (2004) showed numerically that when the distance between the two rectangular cylinders located in a uniform flow was short, a very complicated flow pattern arises. Kondo and Matsukuma (2005) numerically obtained the phenomena of biased gap flow that appeared when the two circular cylinders placed side-by-side are at a small separation distance. In addition, they found the flow pattern changing from the biased gap flow to a coupled flow, when the two cylinders are at a larger spacing.

Agrawal et al. (2006) carried out low Re flow around two identical square cylinders placed side-by-side using lattice Boltzmann method. They proved the existence of both synchronised and flip-flop regimes. In addition, they found that the merging of wakes was gradual in the synchronised regime and rapid in the case of the flip-flop regime. They also observed the occurrence of vortex shedding in both regimes to be either in-phase or in-antiphase. Liu and Cui (2006) numerically studied three-dimensional flow over two side-by-side circular cylinders at Re = 200. They found that the wake patterns depend not only on Re and gap spacing but also on the end-flow conditions. They found biasing of the gap flow intermittently towards one cylinder or the other.

Niu and Zhu (2006) presented numerical results for flow past two identical square cylinders in staggered arrangement at Re = 250. They examined the influence of the cylinder spacing on the flow induced forces and vortex shedding frequencies and the effect of primary wake interference on the secondary flow structure. They reported that the momentum of the gap flow which was transferred into the near wake of one cylinder not only suppresses the oscillations of the drag and lift of that cylinder but also suppresses the generation of the secondary organised structures in the near wake of that cylinder. Several experimental and numerical investigations have been made for square/circular cylinder in isolated condition and circular cylinders in side-by-side arrangement. To the best of our knowledge, numerical studies of two unequal sized square cylinders in side-by-side arrangement at high Re have not been reported in literature.

In this article, our focus is to investigate numerically the effect of transverse spacing \((T/D)\) on the flow characteristics past two square cylinders arranged in a side-by-side pattern. The two square cylinders are considered to be infinitely very long. The size of small square cylinder (\(d\)) is half that of the large square cylinder (\(D\)). The Re based on the large square cylinder diameter (\(D\)) and the free stream velocity \(U_\infty\) is 50,000. The transverse gap ratio \((T/D)\) is defined as the ratio between the centre-to-centre distance \((T)\) in the cross-stream-wise direction to the large cylinder diameter \((D)\). The simulations are carried out for five different \(T/D\) ratios, namely 1.120, 1.250, 1.375, 1.750 and 2.500.

As the flow is unsteady and three-dimensional at high Re, large eddy simulation (LES) technique is employed for carrying out the study.

2. Mathematical formulation

Here, a uniform, viscous and incompressible fluid flow with constant fluid properties is considered for carrying out the simulations. The two square cylinders of unequal size are placed in a side-by-side pattern in such a way that the axis of the two cylinders is perpendicular to the direction of the free stream fluid flow. In LES, the contribution of large, energy-carrying eddies to momentum or energy transfer is computed exactly, and only the effect of the smallest scales is modelled. To separate the contribution of large scales from the small scales, LES makes use of the filtering operation. Here, the grid itself acts as a low-pass filter, which is the popularly known implicit filtering approach. Application of a filtering operation to the continuity and Navier–Stokes equations results in the respective filtered governing equations. These equations in non-dimensional tensor form are given by Equations (1) and (2), respectively as,

\[
\frac{\partial \langle u_i \rangle}{\partial t} + \frac{\partial \langle u_i \rangle \langle u_j \rangle}{\partial x_j} = - \frac{\partial \langle p \rangle}{\partial x_i} + \frac{1}{Re} \frac{\partial^2 \langle u_i \rangle}{\partial x_i \partial x_j} + \tau_{ij}
\]

Here, \(\langle u_i \rangle\) and \(\langle p \rangle\) represent the filtered velocity and pressure, respectively, \(\tau_{ij} = -\langle u_i u_j \rangle + \langle u_i \rangle \langle u_j \rangle\) represents the sub-grid turbulence stress and \(\langle \quad \rangle\) indicates spatial filtering. The indices \(i\) and \(j = 1, 2, 3\) represent the three Cartesian coordinates \((x, y, z)\) which in turn represent the stream-wise, span-wise and cross-stream-wise directions, respectively. All geometrical lengths are normalised with \(D\), velocities with \(U_\infty\), physical time with \(D/U_\infty\), and the pressure with \(\rho U_\infty^2\).

The turbulent fluctuations are accounted in the filtered equations. In order to close the equations,
sub-grid turbulence stress modelling is required. The role of the sub-grid-scale model should be to remove energy from the resolved motion and dissipate it at the appropriate rate by the unresolved motion.

In this model, the sub-grid turbulence stress takes the Boussinesq eddy viscosity form which is given by,

\[ \tau_{ij} = -\left( \frac{1}{2} k_s \delta_{ij} \right) + (2u_G S_{ij}) \]

is the rate of strain tensor of the filtered velocity, \( u_G \) is the sub-grid eddy-viscosity coefficient, \( k_s \) is the sub-grid turbulence kinetic energy and \( \delta_{ij} \) is the Kronecker delta. For \( u_G \) and \( k_s \), we use the Smagorinsky (1963) sub-grid-scale model as shown in Equations (3) and (4).

\[ u_G = 2(C_s \Delta)^2 \sqrt{S_{ij}S_{ij}} \]  
\[ k_s = (u_G)^2 / (C_k \Delta)^2 \]

In order to resolve the viscous sub-layer and to apply the no-slip boundary condition on the wall, the first grid point next to the wall in the normal direction should be set close to the wall in terms of non-dimensional wall distance, which should be less than 20. This point becomes physically closer and closer to the wall, as the Re increases. But it is found from approximate calculation for the grid used in this study that the first point was far away from this region. So, Van-Driest type near-wall damping for eddy viscosity is not used. Thus, Smagorinsky constants – \( C_s \) and \( C_k \) are being set to the constant values of 0.13 and 0.094, respectively. \( \Delta \) is the filter width (grid size) which is the characteristic length scale of the largest sub-grid-scale eddies and is taken to be the geometrical average of the grid spacing in the three directions, i.e.

\[ \Delta = (\Delta x_1 \Delta x_2 \Delta x_3)^{1/3} \]  

A typical computational domain along with the boundary conditions used for a transverse spacing of 1.250 is shown in Figure 1. The flow is from left to right and the origin is positioned at the centre of the large square cylinder. The various boundary conditions employed for the simulations are as follows. At the inlet, a constant stream-wise velocity \( (u = 1) \) is specified with the other two velocities set to zero. On the surface of the two square cylinders, the standard boundary condition of no-slip \( (u = v = w = 0) \) has been employed. On the top and bottom boundaries, free-slip or symmetry boundary condition \( (\partial u / \partial y = \partial w / \partial y = v = 0) \) is used. At the exit, the convective boundary condition \( \partial u / \partial t + u_c(\partial u / \partial x) = 0 \) is used.

The simulations for the \( T/D \) ratios 1.120, 1.250, 1.375, 1.750 and 2.500 have been carried out using structured grids of size 208 \( \times \) 41 \( \times \) 206, 208 \( \times \) 41 \( \times \) 219, 208 \( \times \) 41 \( \times \) 226, 208 \( \times \) 41 \( \times \) 257 and 208 \( \times \) 41 \( \times \) 298, respectively, each having a blockage ratio of about 8%. A typical grid generated for \( T/D = 1.250 \) is shown in Figure 2a and a closer view of the grid near the two square cylinders is shown in Figure 2b. In all the cases, the first grid point is at a distance of 0.01 D from the surface of the cylinder and the aspect ratio of the grid used is kept at 40. The total number of grid points in \( x \) and \( y \) directions has been

![Figure 1](image_url)
maintained constant for all $T/D$ ratios. As the cylinders are moved apart in the $z$ direction, the grid points in this direction only are varied. In the stream-wise and cross-stream-wise directions they are stretched gradually going away from the cylinders, on the surface of which grids of non-uniform spacing are generated. The grid points are uniformly distributed in the span-wise direction.

3. Numerical details
A numerical code employing finite difference scheme with staggered grid arrangement is used to discretise the governing equations. The velocity components are defined at the midpoint of the cell face to which they are normal and the pressure at the cell centre. The viscous and sub-grid stress terms are discretised using second-order accurate central differencing scheme. The convective terms are discretised by third-order upwind biased scheme. The time integration is done by using a second-order accurate explicit Adams–Bashforth scheme in two stages. In stage one, the velocity components are found using the previous velocity and pressure values at all cells. These velocities, however, do not satisfy the divergence free condition for incompressible flow. In order to ensure the mass conservation, adjustments must be made in stage two. This is achieved by using the highly simplified marker and cell (HSMAC) algorithm developed by Hirt and Cook (1972). The non-dimensional time step ($dt$) to be used, in order to take care of the stability criteria is determined from the Courant–Friedrichs–Lewy condition. A time step of 0.0005 was employed for all cases. In this study, a convergence limit of 0.0015 was used in all the simulations.

The basic validation of our computational code has already been carried out for laminar and turbulent flow over an isolated square cylinder. These can be found in Lankadasu and Vengadesan (2008a, 2008b, 2009a) for laminar flows and in Nakayama and Vengadesan (2002), Lankadasu and Vengadesan (2009b) for turbulent flows. In addition, for the sake of the present study, we have carried out a separate validation study. We considered two cases: (i) laminar flow past two equal sized square cylinders at $Re = 250$ in staggered arrangement and (ii) turbulent flow past isolated cylinder at $Re = 21,400$. The results are compared respectively with Niu and Zhu (2006) and Lyn et al. (1995). The results in terms of the bulk parameters are shown in Table 1. It should be noted that the work of Niu and Zhu (2006) is a numerical study. The discrepancy found could be due to the difference in the numerical schemes such as mesh size, discretisation, etc. used. Figure 3a shows the instantaneous span-wise vorticity, which are found to be almost in good agreement. The solid lines in the present instantaneous span-wise vorticity plot denote negative vorticity and dashed lines the positive vorticity, with a vorticity increment of 0.2. The flow pattern consists of the primary vortex pairing, splitting and enveloping pattern similar to those identified by Sumner et al. (2000). The mean stream-wise velocity plotted along the geometric centreline in comparison with Lyn et al. (1995) is shown in Figure 3b. They are also found to be in good agreement.

4. Results and discussions
The simulations are started with the fluid at rest and then allowed to progress for sufficient time till the flow gets stabilised. The non-dimensional time corresponding to this condition is around 120. Next, the time averaging was performed for over 20 vortex shedding cycles, which corresponds to approximately the non-dimensional time of 240 for
Table 1. Comparison of bulk parameters at Re = 250 for flow past two equal sized square cylinders in staggered arrangement.

<table>
<thead>
<tr>
<th>H/D = 0.5</th>
<th>C_{LU}</th>
<th>C_{LD}</th>
<th>C_{DU}</th>
<th>C_{DD}</th>
<th>C_{rms,LU}</th>
<th>C_{rms,LD}</th>
<th>C_{rms,DU}</th>
<th>C_{rms,DD}</th>
<th>St_{LU}</th>
<th>St_{LD}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present simulation</td>
<td>-0.425</td>
<td>-0.066</td>
<td>1.839</td>
<td>2.135</td>
<td>0.198</td>
<td>0.751</td>
<td>0.157</td>
<td>0.291</td>
<td>0.045</td>
<td>0.091</td>
</tr>
<tr>
<td>Niu and Zhu (2006)</td>
<td>-0.475</td>
<td>-0.076</td>
<td>1.834</td>
<td>2.061</td>
<td>0.177</td>
<td>0.631</td>
<td>0.136</td>
<td>0.292</td>
<td>0.081</td>
<td>0.081</td>
</tr>
</tbody>
</table>

Subscripts U and D represent upstream and downstream square cylinder, respectively.

Table 2. Comparison of bulk parameters at Re = 50,000 for flow past two unequal sized square cylinders in side-by-side arrangement.

<table>
<thead>
<tr>
<th>T/D</th>
<th>C_{LI}</th>
<th>C_{LI,II}</th>
<th>C_{rms,LI}</th>
<th>C_{rms,LI,II}</th>
<th>C_{DI}</th>
<th>C_{DI,II}</th>
<th>C_{rms,DI}</th>
<th>C_{rms,DI,II}</th>
<th>St_{I}</th>
<th>St_{II}</th>
<th>C_{pbl}</th>
<th>C_{pbl,II}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.120</td>
<td>0.106</td>
<td>-0.004</td>
<td>0.085</td>
<td>0.156</td>
<td>1.739</td>
<td>2.090</td>
<td>0.051</td>
<td>0.125</td>
<td>0.092</td>
<td>0.275</td>
<td>-1.042</td>
<td>-1.536</td>
</tr>
<tr>
<td>1.250</td>
<td>0.341</td>
<td>-0.095</td>
<td>0.163</td>
<td>0.299</td>
<td>1.693</td>
<td>2.204</td>
<td>0.087</td>
<td>0.134</td>
<td>0.015</td>
<td>0.290</td>
<td>-0.977</td>
<td>-1.625</td>
</tr>
<tr>
<td>1.375</td>
<td>0.224</td>
<td>-0.229</td>
<td>0.146</td>
<td>0.209</td>
<td>1.706</td>
<td>2.161</td>
<td>0.068</td>
<td>0.107</td>
<td>0.015</td>
<td>0.015</td>
<td>-0.998</td>
<td>-1.570</td>
</tr>
<tr>
<td>1.750</td>
<td>0.092</td>
<td>0.155</td>
<td>0.074</td>
<td>0.602</td>
<td>1.699</td>
<td>2.770</td>
<td>0.052</td>
<td>0.532</td>
<td>0.031</td>
<td>0.397</td>
<td>-0.998</td>
<td>-2.207</td>
</tr>
<tr>
<td>2.500</td>
<td>0.398</td>
<td>-0.285</td>
<td>1.587</td>
<td>1.259</td>
<td>2.665</td>
<td>2.734</td>
<td>0.354</td>
<td>0.495</td>
<td>0.137</td>
<td>0.290</td>
<td>-2.136</td>
<td>-2.260</td>
</tr>
</tbody>
</table>

Subscripts I and II represent large and small square cylinder, respectively, and overbars represent the mean qualities.

Figure 3. (a) Instantaneous span-wise vorticity at t = 82 for flow past two equal sized square cylinders in staggered arrangement; (ω_{min}, ω_{max}, Δω) = (-1, 1, 0.2). (b) Mean stream-wise velocity plotted along the geometric centreline for flow past in an isolated square cylinder at Re = 21,400.
all gap ratios. The bulk parameters, namely the mean and root mean square (RMS) values of lift and drag coefficients, St and the mean base pressure coefficient for all $T/D$ ratios are presented in Table 2. The suffix I and II for the above parameters represent the large and small square cylinders,

![Figure 4](source_url). Time history of the lift, draft and moment signals for all $T/D$ ratios. (a) Lift signal; (b) Drag signal; (c) Moment signal.
respectively. The instantaneous lift, drag and moment coefficients are determined using the following expressions.

\[
C_L = \frac{2F_L}{\rho AU_\infty^2} \quad (6)
\]

\[
C_D = \frac{2F_D}{\rho AU_\infty^2} \quad (7)
\]

\[
C_M = 2(YF_D - XF_L)/(\rho DAU_\infty^2) \quad (8)
\]

Here, \(F_L\) and \(F_D\) represent the lift and drag forces, \(A\) the frontal area of the corresponding cylinders and \(X, Y\) represent the distances from the centre of gravity up to the surface of the cylinder in \(x\)-\(z\) plane. The variation of \(C_L\) and \(C_D\) from their mean values is represented by the RMS values. It is found using \(\sqrt{\sum_{i=1}^{n} (C_L(i) - \overline{C_L})^2 / n}\). Here, \(n\) is the total number of discrete points over which time averaging has been carried out. \(C_L\) and \(\overline{C_L}\) represent the instantaneous and the mean lift coefficients, respectively. The time history of the lift (Figure 4a), drag (Figure 4b) and moment (Figure 4c) coefficients for all \(T/D\) ratios shows high unsteadiness due to the turbulent nature of the flow. The small square cylinder has the largest moment coefficient for all the gap ratios. Also, both the cylinders have positive moment coefficients. It is clear that the lift force acting on the large square cylinder is more in comparison with that of the small square cylinder for all \(T/D\) ratios except for \(T/D = 1.75\).

Figure 4. (Continued).
According to Shao and Zhang (2008), in case of two equal sized circular cylinders in side-by-side arrangement, the cylinder to which the gap side flow deflects has a higher drag coefficient. The shear layer separated from the large cylinder in the gap side is biased towards the small cylinder and
transfers more momentum through the small-scale instabilities. This alters the near wake of the small cylinder which results in a higher drag force. The smaller amplitude of oscillations seen in the lift signals for smaller $T/D$ ratios (1.12, 1.25, 1.375 and 1.75) could be due to the interference effect. The larger amplitude of oscillations seen in the lift and drag signals for $T/D = 2.5$ is similar to that for the isolated square cylinder flow. This confirms that the effect of interference is almost negligible for this gap ratio.

The vortex shedding process is primarily characterised by the Strouhal number, $St = (fD)/U_\infty$, where $f$ is the vortex shedding frequency. These are identified based on the dominating frequency in Figure 5, which is obtained by performing the Fast Fourier Transform (FFT) of the time variation of lift signals. The small cylinder has a larger $St$ in comparison with the large cylinder for all $T/D$ ratios except for $T/D = 1.375$. In this case, both the cylinders have identical values of $St$. The multiple peaks seen for smaller $T/D$ ratios is due to the interaction of the inner shear layers separated

![Figure 5. Fast Fourier Transform of the lift signals for all $T/D$ ratios.](image-url)
from both cylinders. For $T/D = 2.5$, we can see only a single dominating peak which resembles that for an isolated cylinder.

The mean streamline plot for all $T/D$ ratios is shown in Figure 6. The presence of a wider wake behind the large cylinder and a narrow wake behind the small cylinder is clearly seen. For $T/D = 1.12, 1.25$ and $1.375$, the flow from the gap side consists of a central jet surrounded by two shear layers separated from the sharp corner of the two cylinders. The jet-like nature of the gap side flow is mainly due to the acceleration of the flow to maintain a constant flow rate. This jet-like flow in the gap side is similar to the base bleed flow pattern present in side-by-side circular cylinders [Sumner et al. (1999, 2000)] at smaller spacing. This causes the stream-wise lengthening of the near wake region of both cylinders. Because of this, the recirculation length increases when compared with that of the isolated square cylinder.

The gap side flow is biased more towards the near wake of the small cylinder for smaller $T/D$ ratios. For $T/D = 1.12$, the reattachment of the separated shear layer from the gap side leading corner of the large square cylinder to its inner surface is seen. For $T/D = 1.75$, the reattachment of the separated shear layer from the gap side leading corner of the small cylinder to its inner surface is also seen.

As $T/D$ ratio increases, one can notice the decrease in the wake width for both the cylinders, in the transverse direction. However, in comparison with the large cylinder, the decrease in wake width is not seen clearly for the small cylinder. Because of the interference effect, the wake of both the cylinders is unsymmetrical in nature for $T/D = 1.12, 1.25, 1.375$.
for the smallest $T/D$ ratio. The maximum velocity defect point at $z/D = 1.5$ near the small cylinder is at a distance of 0.38 from its centre for $T/D = 1.120$. This distance is 0.45, 0.43, 0.25 and 0.1 for $T/D = 1.25$, 1.375, 1.75 and 2.5, respectively. This decrease in the distance as $T/D$ increases is very similar to what is reported by Wong et al. (1995). The plot also shows the existence of weaker mean velocity gradient on the small cylinder side and a stronger gradient on the large cylinder side, for all $T/D$ ratios.

The mean base pressure coefficient, $C_{pb}$ (Table 2) is defined as the pressure at the centre point of the rear surface of the cylinder. It is less for the small cylinder in comparison with that for the large cylinder. From the table, it is very clear that the small square cylinder has a lower $C_{pb}$, higher vortex shedding frequency and larger drag values. Moreover, from the mean streamlines (Figure 6), one can see a narrow wake behind the small cylinder. These results confirm with the findings of Roshko (1955).

The mean stream-wise velocity plotted along the geometric centreline for $T/D = 1.25$ is shown in Figure 8a for both large and small square cylinders. In the upstream side of both cylinders, the velocity is positive but decreases steadily as it approaches the cylinder. In the downstream side of the large cylinder, the velocity profile first decreases due to backflow and then starts to increase. The separation of flow over the cylinder causes a pressure drop across its surface and leads to a pressure drag which results in a loss of momentum of the fluid in the wake. This is the reason for the time averaged stream-wise velocity at any point in the near wake, to be smaller than that in the free stream.
After this, the recovery of velocity takes place due to the entrainment of the free-stream fluid. The recovery rate is directly related to the wake width. The narrower the wake, the faster is the velocity recovery and vice versa. In case of the small cylinder, velocity profile just downstream of the cylinder decreases due to loss of momentum of the fluid in the wake. A sudden increase in the velocity profile is

Figure 9. Time averaged pressure coefficient over the cylinder surface for all T/D ratios.
seen after this due to more momentum transferred from the gap side into the near wake of the small cylinder. After this, again a drop in velocity profile is seen as the fluid now moves through the wake of the large square cylinder. The velocity profile again starts to increase as normal recovery due to entrainment of the free-stream fluid taking place. The above discussions are true for all $T/D$ ratios except for $T/D = 2.5$ (Figure 8b). In this case, the cylinders behave like isolated cylinders. The wake centreline coincides

![Figure 10](image_url)

Figure 10. (a) Mean span-wise vorticity for all $T/D$ ratios, $(\omega_y^\text{min}, \omega_y^\text{max}, \Delta\omega_y) = (-1, 1, 0.2)$; (b) Zoomed view of the mean span-wise vorticity, $(\omega_y^\text{min}, \omega_y^\text{max}, \Delta\omega_y) = (-4, 4, 0.3)$. Available in colour online.
with the geometric centreline and the velocity recovery is similar to that observed in the isolated cylinder case.

The surface pressure distribution around the large and small square cylinders for all $T/D$ ratios is shown in Figure 9. In the front portion of both the cylinders, the pressure is maximum at one point which is due to the occurrence of the stagnation point. For the large cylinder, this point occurs exactly at the centre of the front face of the cylinder. No shift in stagnation point for the large square cylinder is seen for all the $T/D$ ratios. In case of the small cylinder, it is shifted towards its gap side from the centre of the front face for $T/D = 1.12, 1.25$ and $1.375$. This is because of the low pressure prevailing in its gap side. For $T/D = 1.75$ and 2.5, the stagnation point starts to move back to the centre of the front face of the small cylinder. Similar inferences can be drawn by observing the mean streamline plots (Figure 6) as well.

Because of the acceleration of flow, the pressure is lower in the gap side of both the cylinders for $T/D = 1.12, 1.25$ and $1.375$. Because of a very low pressure in the gap side when compared to outside, both cylinders are under attraction for $T/D = 1.12, 1.25$ and $1.375$. For $T/D = 1.75$ and 2.5, there is a negligible difference in pressure between the flow in gap side and outside of both the cylinders. Similar results are reported by Wong et al. (1995). For $T/D = 1.12$, another peak is seen on the gap side of the large cylinder which is due to the reattachment of the separated shear layer from the gap side leading corner. For $T/D = 1.75$, the peak is found on the small cylinder side. No additional peak is found for $T/D = 1.25, 1.375$ and 2.5. In the rear side, the pressure is small due to the presence of wake.

The mean span-wise vorticity plot for all the $T/D$ ratios is shown in Figure 10a. The merging of shear layers separated from the small cylinder and that from the top corner of the large cylinder, in the near wake of the small cylinder is seen for $T/D = 1.12, 1.25$ and $1.375$. This leads to a very strong interference effect for these gap ratios. Also, at these gap ratios the flow pattern resembles that of a single bluff body. The effect of interference is less felt in case of $T/D = 1.75$. The interference effect is absent for $T/D = 2.5$ as there is no merging taking place between the shear layers separated from the two cylinders. The zoomed view of the vorticity plot near the two cylinders is shown in Figure 10b for few gap ratios. These show the flow structures in the vicinity of the gap side, details of flow separation, wake formation and deflections very clearly.

The time averaged normal and shear stress profiles at $x/D = 1.0$ location is shown for all $T/D$ ratios in Figures 11 and 12, respectively. For all gap ratios, the
normal stress is high in the regions of peak vorticity. This is similar to that reported by Lyn et al. (1995). It is low at places of zero vorticity. This place is generally along the gap side or geometric centreline of both the cylinders. The shear stress profile at this gap ratio is very similar to that of an isolated square cylinder. At smaller $T/D$ ratios, we see only a single maximum at the place where merging of shear layers in the gap side takes place. This nature is due to the gap side flow being deflected towards the near wake of the small cylinder.

5. Conclusions
The effect of gap ratio on the flow characteristics past two unequal sized square cylinders in side-by-side arrangement has been carried out at $Re = 50,000$ using LES. The coefficient of lift is high for the large cylinder in all gap ratios except for $T/D = 1.75$. The coefficient of drag is high for the small cylinder in all the gap ratios. The vortex shedding is found to be more in small cylinder when compared to that of the large cylinder, for all gap ratios. The mean base pressure coefficient for the small cylinder is low when compared to that of the large cylinder for all gap ratios. At smaller gap ratios, the presence of a jet-like flow is more pronounced in the gap side. The reattachment of the shear layer separated from the gap side leading corner of the large cylinder to its inner surface is seen only for $T/D = 1.12$. For $T/D = 1.75$, the reattachment of the separated shear layer from the gap side leading corner of the small cylinder to its inner surface is seen. Because of the presence of a very low pressure in the gap side than that in the outside, the two cylinders are under attraction mode for $T/D = 1.12$, 1.25 and 1.375. There is only a negligible difference in pressure between the gap side and outside of the two cylinders in case of $T/D = 2.5$. From the mean spanwise vorticity plots, it is clear that the interference effect is present for $T/D = 1.12$, 1.25 and 1.375 ratios. Moreover, the gap side flow is biased towards the near wake of the small cylinder for the above gap ratios. The interference effect is less felt in case of $T/D = 1.75$ and absent in case of $T/D = 2.5$. The flow behaviour at $T/D = 2.5$ is very similar to that of the flow past two isolated square cylinder.

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