Effect of gap height and non-linearity of incident Couette-Poiseuille flow on aerodynamic characteristics of a square cylinder near wall

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ABSTRACT

A numerical study on the Couette-Poiseuille based non-uniform flow over a square cylinder of height \( a^* \) placed parallel to the wall at different gap ratios (\( L = H^*/a^* \): 0.1 \( \leq L \leq 2.0 \), where \( H^* \) is the gap between the cylinder and wall) is conducted for different inlet non-dimensional pressure gradients \( P \). The governing equations are solved numerically through finite volume method based on SIMPLE algorithm on a staggered grid system. Both \( P \) and \( L \) have an appreciable effect on the vortex shedding frequency, aerodynamic forces and the flow structure around the cylinder. At \( L \leq 0.25 \) for \( P \leq 3 \) the flow remains steady similar to the linear shear flow (\( P = 0 \)). While increasing the value at \( P = 5 \), unsteadiness developed in the far field propagates towards the cylinder, becoming quasi-steady in nature for \( L = 0.1 \). A further increase in \( L \) results in stretching of the shear layers from the cylinder; for a high \( P \) the flow deflects towards the downstream side with irregular transverse and longitudinal vortices. Collecting all the simulated results obtained, four distinct flow patterns I, II, III and IV are identified based on the vorticity contours, which are steady flow, unsteady single row vortex, two stretched row of vortices and trailing edge separation with complex wake, respectively. The critical gap height for onset of the vortex shedding decreases with increasing the value of \( P \). The intensity of peak in the power spectra of the lift coefficient increases with the increase in \( P \). At large \( L \), the sharp peak changes into broad band and the wake interaction becomes complicated depending on \( P \) and \( L \). An attempt is made to find a universal shedding frequency that is independent of \( L \) for different nonlinear velocity profiles.

NOMENCLATURE

\( a^* \) : height of the cylinder (m)
\( L \) : nondimensional gap height from cylinder to plane wall
\( P \) : nondimensional pressure gradient
\( Re \) : Reynolds number \( (Ua^*/\nu) \)
\( C_D \) : time averaged drag coefficient
\( C_L' \) : rms of lift coefficient
\( St \) : Strouhal number
\( U \) : velocity at distance \( h^* \) from the wall (m/s)
\( V \) : kinematic viscosity of fluid
1. INTRODUCTION

In many practical cases the flow approaching the structures, for example offshore platforms, is not uniform because of the velocity gradients from the incoming flow. Although high Reynolds number flows appear in most practical examples, the flow at low Reynolds number has an application in small heat exchangers and electronic cooling components. The difference between the flow velocities at upper and bottom part of the structure in the wall proximity makes flow somewhat more complex, resulting in different wake flow patterns. Therefore, it is very important to understand the basic flow phenomena from a cylinder under the influence of a non-uniform velocity profile near the wall. This study investigates the effect of the gap height \( L = \frac{H}{a^*} \), where \( H \) is the gap between wall and the cylinder and \( a^* \) is height of the cylinder and non-linearity of approaching velocity profile based on inlet pressure gradient \( P \) on flow characteristics of a square cylinder.

Numerical studies on flow past a square cylinder for different inlet shear parameter \( K \) and at different Reynolds numbers \( Re \) were conducted by Hwang et al. (1997, \( Re=500-1500, K=0-0.25 \)), Cheng et al. (2005, \( Re=100, K=0-0.5 \)), Cheng et al. (2007, \( Re=50-200, K=0-0.5 \)), Lankadasu and Vengadesan (2008, \( Re<100, K=0-0.2 \)). The results showed that the Strouhal number \( (St) \), mean drag \( (C_D) \) and fluctuating forces decreases with increasing \( K \). Cheng et al. (2007) conducted simulation at \( Re=100, 0 \leq K \leq 0.5 \) for flow over a square cylinder and concluded that unlike that for a circular cylinder, the shedding frequency for the square cylinder decreases with increasing \( K \). Lankadasu and Vengadesan (2008) reported that with increasing \( K \), the critical \( Re \), at which flow becomes unsteady, is reduced. Similarly several numerical studies have been conducted on rectangular cylinder of different aspect ratios under uniform and shear flow, e.g. by Sohankar (2008, \( Re=10^5 \)), Islam et al. (2012, \( Re=100-250 \)), Yu et al. (2013, \( Re=10^5 \)) and Cao et al.(2014, \( Re=22000 \)). These studies have shown that \( Re \) effect is less significant compared to other parameters (e.g., incoming velocity profile). Cao et al. (2014) concluded that the linear movement of the stagnation point to the high velocity side with increasing \( K \) is an inherent behavior in shear flow.

Several studies on effect of wall proximity of a cylinder have also been carried out (Bailey et al., 2002; Lee et al. 2005; Kumar and Vengadesan, 2007; Wang and Tan, 2008; Dhinakaran, 2011; Maiti, 2012; Samani and Bergstorm, 2015). Bailey et al. (2002) conducted an experimental study and examined the vortex shedding from a square cylinder near a wall at \( Re=19000 \) and their results showed that the suppression of vortex shedding occurs for \( L<0.4 \). Lee et al. (2005) studied effect of aspect ratio and \( L(0.3 \leq L \leq 2) \) and introduced simple passive control method to reduce the aerodynamic drag and vortex-induced oscillation. They observed that the vortex begins to shed by the interaction of the separated shear layer on the upper surface of the cylinder with the upwash flow from the gap region. Wang and Tan (2008) experimentally compared the near-wake flow patterns for a circular and a square cylinder for different \( L \) ranging from 0.1 to 1.0. They concluded that the vortex shedding strength in the case of square cylinder is relatively weaker, as compared to that of the circular cylinder at the same \( L \), and the critical \( L \) for vortex shedding are 0.3 and 0.5 for the circular and square
cylinders, respectively. Maiti (2012) reported that aerodynamic characteristics of a square cylinder under uniform shear flow are more sensitive to $L$ for $L>1$ than for $L \leq 1.0$. Dhinkaran (2011) observed an increment in aerodynamic forces with a decrement in $L$ for the flow past a square cylinder placed near a moving wall at $Re=100$. The flow behavior was classified into two-row vortex street ($1 \leq L \leq 4$), single-row vortex street ($0.4 \leq L \leq 1$), quasi-steady vortex street ($L=0.3$) and vortex shedding suppression ($L<0.3$). Recently, Samani and Bergstrom (2015) conducted large eddy simulation to examine the wall proximity effect of a square cylinder for three values of $L=0$, 0.5 and 1.0 at $Re=500$. An increase in $L$ leads to an increase in mean lift force ($C_L$) and a decrease in mean drag ($C_D$) coefficients. As the cylinder approaches the wall, the wake flow becomes increasingly asymmetric with the top recirculation cell displaced significantly upward and further downstream, and a secondary recirculation zone develops on the bottom wall.

The aforementioned studies on the flow around a single cylinder are based on either uniform flow or linear shear flow with and without wall proximity. It is clear from these studies that the inlet velocity profile and the gap flow greatly altered the aerodynamic forces and flow around the cylinder. However, numerical studies on a square cylinder in wall proximity under non-uniform velocity profile are scarce. Therefore, the present study is aimed at understanding the effect of inlet non-linear velocity profile on aerodynamic forces and the wake flow structure of a square cylinder at different $L$.

### 2. PROBLEM DESCRIPTION

With a wall lying along the $x^*$-axis, a cylinder of square cross section of height $a^*$ is placed parallel to the wall at gap height $H^*$ from the wall (Fig.1(a)). The inflow and outlet boundaries lie at a distance $10a^*$ and $20a^*$ from the front and rear face of the cylinder, respectively. The top lateral boundary lies at $10a^*$ from the plan wall. The upstream flow field is taken as Couette-Poiseuille flow based nonlinear velocity profile $u^*(y^*)$. This upstream condition is consistent with the Navier-Stokes equation and viscous effects, because of no-slip requirement at the wall (Schlichting, 2000). In other words, the cylinder is sub-merged into the boundary layer of a plane wall. The following nonlinear velocity profile (with characteristic velocity $U$ at $y^* = 10a^*$) is considered at the inlet:

$$\frac{u^*(y^*)}{U} = \frac{y^*}{h^*} + P \frac{y^*}{h^*} \left(1 - \frac{y^*}{h^*}\right)$$  \hspace{1cm} (1)

where $U$ is the velocity at distance $h^*$ from the wall, and $P$ is the nondimensional pressure gradient, which is defined as

$$P = \frac{h^*}{2\mu U} \left(\frac{dp^*}{dx^*}\right) = \frac{1}{2} h^2 Re \left(\frac{dp}{dx}\right)$$  \hspace{1cm} (2)

where $Re=Ua^*/\nu$, $p^*=p^*(\rho U^2)$ and, $\mu$ and $\nu$ are the viscosity and kinematic viscosity of
the fluid. Different forms of the nondimensional velocity profile $u(y)$ for different values of $P$ with fixed height $h=10$ are presented in Fig. 1(b).

![Figure 1](image)

**Fig.1.(a)** Schematics of flow configuration, (b) Couette-Poiseuille flow based nonlinear incident velocity profiles for different $P$, and (c) typical grid distribution for $L=0.5$.

### 2.1 Governing equations and numerical method

The non-dimesionoal Navier-Stokes equations for two-dimensional laminar flow are given by

$$\nabla \cdot V = 0$$

$$\frac{\partial V}{\partial t} + (V \cdot \nabla)V = -\nabla p + \frac{1}{Re} \nabla^2 V$$
The non-dimensional quantities $V=(u, v)$, and $p$ and $t$ denote the velocity, pressure and time, respectively, with characteristic length and velocity are $a^*$ and $U$, respectively.

No-slip condition is used on the cylinder surfaces and on the plane wall. A Dirichlet boundary ($u=u(y)$, $v=0$) is used at the inlet boundary, while the Sommerfeld condition $(\partial \phi / \partial t) + u_c (\partial \phi / \partial x) = 0$, where $\phi$ is any flow variable, and $u_c$ is the local wave speed) is applied at the outlet. A slip boundary condition ($\partial u / \partial y = 0$, $v=0$) is imposed on the top lateral boundary. The numerical treatment to the Sommerfeld condition has been discussed in details in the previous study (Maiti, 2011).

A finite volume method on a staggered grid system and then the pressure correction based iterative algorithm SIMPLE (Patankar, 1980) are applied. A third-order accurate QUICK (Leonard 1995) is employed to discretize the convective terms and central differencing scheme for diffusion terms. A fully implicit second-order scheme is incorporated to discretize the time derivatives. At the initial stage of motion, times step is taken to be 0.0001 which has been subsequently increased to 0.001 after the transient state.

3. GRID INDEPENDENCE AND VALIDATION OF CODE

In this study, a nonuniform grid distribution is considered in the domain, with a uniform grid along the cylinder surface and increasingly enlarged grids away from the cylinder surface. The grid distribution in x-and y-directions is shown in Fig.1(c). The grid distribution in x - and y - directions is similar to that used in our previous study, Maiti (2012). Depending on the size of the distributed grids, the horizontal and vertical lines of the computational domain are divided into five and three, respectively, distinct segments. Along the y-direction, a uniform grid with size 0.005 is considered between wall and top of the cylinder (within the segment ‘Iy’ in Fig.1(c)). With reference to Franke et al. (1990) and Sohankar et al. (1997), the value of the first grid size from the cylinder is kept constant as 0.004 for the present computation.

The grid refinement study on the number of uniform nodes and on the resolution of grid near the cylinder surface and the far-fields was conducted in the previous study (Maiti, 2011, 2012 and Maiti and Bhatt, 2015) for the case of single and inline tandem cylinders. A detailed discussion on the percentage of deviation has been made in these studies. In the present study the grid distribution along the y-direction varied according to the gap height of the cylinder from the wall. The numerical code validated for the case of a square cylinder placed near a wall (Bhattacharyya et al., 2006) has been used in the present study. Thus, the previous published results by the authors also show the validity of the used code for this work.

In the present study the following operational dimensionless parameters affecting the flow are considered:

- $L=0.1, 0.25, 0.5, 1.0, 1.5$ and $2.0$
- Inlet pressure gradient $P = 0, 1, 3, 5$
- Reynolds number ($Re$): 1000 (based on velocity at height $10a^*$ from wall (Maiti and Bhatt (2015))). Davis et al. (1984) found a good agreement between the numerical and experimental results for Re around 1000 for uniform flow.
Bhattacharyya and Maiti (2004) and Maiti (2011, 2012) presented the two-dimensional simulations for different gap heights and Re up to 1400. However, it is assumed that the three-dimensional effect would not severely contaminate the results presented in this study based on the assumptions of two dimensional and laminar flow for the Re=1000 based on the Couette-Poiseuille flow based non linear flow.

4. RESULTS AND DISCUSSION

The effect of L and P on flow and aerodynamic characteristics of a square cylinder is discussed here. The results are presented and discussed in terms of vorticity contours, spectra and pressure distribution.

4.1 Flow structure

Fig. 2 shows the instantaneous vorticity contours for L ≤ 0.5. At L = 0.1, P ≤ 3, the flow remains steady. With increasing P from 3 to 5, unsteadiness is developed in the far field and propagates towards the cylinder, and the flow becomes quasi-steady in nature. Similarly, at L=0.25 for P ≤ 2 the shear layer from upper side of the cylinder emerges almost horizontally and the lower shear layer reattaches the rear face of the cylinder. At P= 3, the shear layer from the upper side of the cylinder tends to roll but due to weaker interaction with the counter rotating vortices the shedding does not occur, generating a steady flow. A more detailed explanation on vortex shedding suppression from a square cylinder at a lower L can be found in Martinuzzi et al. (2003) and Maiti (2012). For P=5, the upper shear layer gets sufficient momentum to shed vortices while the gap flow with a recirculation has a quasi-steady nature. Hence the wake is dominated by the single row of clockwise vortices with a definite peak in the spectra, confirmed by a dominant peak in the spectra of lift coefficient.

Fig. 2. Instantaneous vorticity contours at different gap heights (L ≤ 0.5) for different P.

Upon increasing L to L=0.5, the flow is still steady for P=0. Previous experimental study done by Wang and Tan (2008) reported that the critical L for onset of vortex shedding is 0.5. The steady flow at this P will be explained with the help of the gap flow between the cylinder and wall later. At P=1, the shear layers of different strengths from the upper
and lower sides of the cylinder curl up into an alternating fashion. The vortex from the lower side of the cylinder stretches by the wall vorticity and dissipates faster in the wake. The wake is characterized by a single row of vortices. Analyzing these figures one can see that the interaction takes place in the rear of the cylinder, with a consequent vortex formation and shedding occurring behind the cylinder. Zovatto and Pedrizzetti (2001) reported that interaction of the wall boundary layer and the vortex formation region near wall surface suppresses the positive vortices at the lower side of the cylinder. Therefore, the downstream wake contains a row of negative vortices. Compared to the unsteady case of \( L=0.25 \), \( P=5 \), the streamwise distance between the consecutive vortices is enlarged at this \( L \). The stronger gap flow at \( P=5 \), results stronger coalescence between the cylinder and wall vortices, resulting in more stretched vortices in the wake.

![Image](image1.png)

**Fig. 3.** Instantaneous vorticity contours at different gap heights \( (L \geq 1.0) \) for different \( P \).

The flow for a larger \( L \) will be less influenced by the wall shear, compared to that the smaller \( L \). The vortex shedding commences for \( L=1.0 \), \( P=0 \). The interaction occurs between the counter rotating vortices due to the upwash flow from the gap and a row of negative vortices features the wake. It may be noted that the increase in \( L \) results in an increase in the local Reynolds number that is mechanically similar to the increase in \( P \) since \( -d\Phi/dx = 2P \ (1/h^3 \ (1/Re)) \), where \( h \) is the nondimensional height from wall. The effect of \( L \) at different \( P \) can be observed here. For a given \( P \), with increasing \( L \), the size of negative vortices shrinks. With an increase in \( P \) the interaction of positive and negative vortices, being different in intensity and sizes, leads to an irregular arrangement of vortices in the wake. A dramatic change takes place when \( L \) is increased further to 1.5 for \( P = 1 \). The flow behind the cylinder is quite different from that in the lower \( L \) cases. The regular vortex in the near wake region destroyed and vortices are stretched towards downstream. It delays the roll up process of negative shear layer. For a higher \( P \) the wake is dominated by stronger positive vortices. A further increase in \( L \) results in the stretched shear layers from the cylinder due to a strong interaction of vortices. There is a pronounced separation of the shear layers from the wall at larger \( L \). It triggers the instability in the vortex distribution in the wake and unsteadiness is enhanced. It is clear from the Figs. 2 and 3 that the flow structure strongly depends on \( L \) and \( P \). With the increase in \( L \), the front stagnation point of the
cylinder moves to the higher velocity side and the flow is biased towards the lower velocity side. As reported by Lankadasu and Vengdesan (2008), due to the shifting of the stagnation point, there is separation of shear layers from the bottom face for the higher inlet shear parameters.

Based on the above discussion, four distinct flow patterns can be identified in the broad sense (Fig. 4). Since limited computations were performed, the boundaries of the flow pattern are difficult to assess. Steady flow (pattern-I) noticed when \((0 \leq P \leq 5, L=0.1)\), \((0 \leq P \leq 3, L=0.25)\) and \((P=0, L=0.5)\). Unsteady periodic flow with single row of vortices (pattern-II) is found for \((P=5, L=0.25)\), \((1 \leq P \leq 3, L=0.5)\) and \((0 \leq P \leq 1, L=1.0)\). Pattern-III is found approximately when \((P=5, L=0.5)\), \((P=3, L=1.0)\), \((0 \leq P \leq 1, L=1.5)\) and \((0 \leq P \leq 3, L=2)\); in this range two row of vortices are observed which are stretched in the streamwise direction. Pattern-IV is appears in the range of approximately \((P=5, 1.0 \leq L \leq 2)\) and \((P=3, L=1.5)\). In this range shear layers separated from the trailing edge of the cylinder and are elongated in the transverse direction. Due to the stronger interaction with wall vortices complex wake is formed from the wake.

![Fig. 4. Classification of flow patterns and representative vorticity contours in L-P plane.](image)

### 4.2 Gap flow

It is clear from the discussion made in the previous section that both \(L\) and \(P\) affect the flow structure behind the cylinder. Therefore, it is also instructive to investigate the velocity profile in the gap region for different \(P\) to understand the wake structure. Fig. 5 show the mean velocity profiles for different \(L\) and \(P\). Lee et al. (2005) reported that in the cases where the vortex shedding occurs, the value of velocity is greater than in the cases without vortex shedding. Also, the position at which maximum velocity occurs is closer to the lower surface of the cylinder. For \(L \leq 0.5\) at \(P = 0\), the gap flow is similar to the jet flow along the wall and the velocity profile takes a parabolic form owing to a steady flow. As observed in Fig. 3, the flow becomes unsteady for \(L \geq 1.0\) at \(P = 0\). The gap flow for the unsteady cases biased towards the lower face of the cylinder and the position of the maximum velocity is move closer to the surface of the cylinder. The
interaction between the wake vorticity and vortices attached to the plane wall causes the upward flow near the trailing-edge of the cylinder. At \( P=5 \) (Fig. 5b), an increase in the mean velocity in the gap region prevails and vortex shedding occurs at relatively smaller \( L \) compared to \( P=0 \). The stronger gap flow exists for a higher \( P \) for a large \( L \). Therefore, the mean velocity profile provides some insight into the validity of the wake vortices shown in Fig. 2 and 3. However, the flow decelerates along the lower surface of the cylinder and a small region of reverse flow is observed. The gap velocity phenomena presented here are in a good agreement with those of Lee et al. (2005) for uniform flow and Maiti (2012) for uniform shear flow.

![Fig. 5](image_url)

**Fig. 5.** Mean velocity profile for various \( L \) at the exit position of the gap between the cylinder’s lower face and the wall. (a) \( P = 0 \), (b) \( P = 5 \).

### 4.3 Pressure distribution on the cylinder surface (\( \overline{C_p} \))

The time-averaged surface pressure distribution (\( \overline{C_p} \)) along the periphery of the cylinder for different \( P \) at intermediate and large \( L=0.5 \) and 1.5 is plotted in Fig. 6(a, b). The \( \overline{C_p} \) distribution around the surfaces of the cylinder is not affected for \( P=0 \). This trend is attributed to the steady flow around the cylinder. For \( P \geq 3 \), \( \overline{C_p} \) distribution is affected by increased nonlinearity of the flow at the inlet. Except at the front face, \( \overline{C_p} \) is negative for all surfaces. There is a suction occurring at the front top corner of the cylinder. As \( P \) is increased, \( \overline{C_p} \) is biased towards the front top corner of the cylinder and it is more pronounced for larger \( P \). It should be noted that the difference in \( \overline{C_p} \) between the surfaces of the cylinder results in an enhancement in total average and fluctuating forces on the cylinder with the increase in \( P \). Along the top and bottom faces, more negative \( \overline{C_p} \) is observed with increase in \( P \). The difference in \( \overline{C_p} \) distribution is associated with the wake vorticity structure. It should be noted here that the pressure distribution is affected more on the top surface compared to other surfaces due to the higher nonlinear flow in upper surface. As shown in Fig. 5, for higher \( L \) and \( P \), reverse flow is observed due to the negative mean velocity near the bottom face of the cylinder. It results in more negative pressure distribution on the rear surface (Fig. 6(b)).
Fig. 6 (c) shows $\bar{C}_\rho$ distribution in the gap region of the cylinder, along the lower surface of the cylinder and along the plane wall, at different $L$ for a particular $P=3$. For $L=0.25$, that the difference between $\bar{C}_\rho$ at the cylinder surface and wall is almost zero in the core of the gap region. This implies that the gap flow is unidirectional, and the core flow resembles that of a channel flow. As a result, the interaction between the shear layers of the cylinder is lost (Fig. 2). The $\bar{C}_\rho$ distribution changes with change in $L$ for $L \geq 0.5$. At $L=0.5$ the stagnation point is shifted towards the lower side. For $L=1.5$, the $\bar{C}_\rho$ on the wall is always higher than that along the bottom surface of the cylinder. This indicates that the streamline curvature is positive, and there is strong coupling between the upper and lower shear layers of the cylinder (Fig. 3).

**Fig. 6.** Time-averaged pressure coefficient ($\bar{C}_\rho$) on the cylinder surface: (a) $L=0.5$, (b) $L = 1.5$. (c)Pressure distribution in gap for different $L$ for $P = 3$. Legends are same in (a) and (b).

### 4.4 Time averaged drag coefficient ($C_D$) and fluctuating lift coefficient ($C_{L'}$)

Contours for the time averaged drag coefficient ($C_D$) and rms lift coefficient ($C_{L'}$) of the cylinder on the $L$-$P$ plane are shown in Fig. 7. The boundaries corresponding to the different flow patterns are also marked in the figure. The $C_D$ is always positive on the entire $L$-$P$ plane as expected. In general, $C_D$ shows qualitatively similar behavior for $P \geq 1$, with change in $L$. The variation of $C_D$ consists two regimes: $L \leq 0.5$ for $P \geq 1$ and $P=0$ for all $L$ and second: $P \geq 1$ for $L > 0.5$. For first two regimes corresponding to flow patterns I & II, flow is either steady or fluctuation is very less and the change in $C_D$ is insensitive to $L$. The direction of the drag force on the cylinder was also confirmed by the pressure distribution on the surface of the cylinder (Fig. 6). At lower gap heights the pressure difference between the front and rear faces of the cylinder is very less (Fig. 6), resulting smaller $C_D$. For second regime (pattern-III & IV), $C_D$ increase gradually with gap height. However, this increment for $P=1$ case is less. When the cylinder is placed at the large $L = 1.5$, the flow past cylinder will be influenced less by the plane wall shear layers as compared to the lower $L$. Therefore, it displays larger variation of forces acting on the cylinder at large $L$. As can be seen from Fig. 6 for higher $P$ at a particular $L$, there is large pressure difference which contributes the higher total average drag on the cylinder. For $L \leq 0.5$, $C_D$ for $P=0$ is 0.022, and the value slightly increased up to 0.12 at $L=2$. Corresponding value of $C_D$ for $P=5$ are 0.47 and 3.85, respectively. The rate of
increment in $C_D$ depends on $P$ and it increases monotonically with $P$ at a particular $L$.

![Graph](image)

**Fig. 7.** Contours of (a) time averaged drag coefficients ($C_D$) and (b) rms lift coefficient ($C_{L'}$) at different $L$ and $P$.

The variation of RMS lift coefficient ($C_{L'}$) in $L$-$P$ plane also consists of two regimes: lower fluctuation regime (for pattern I and II), and quickly increasing regime (for pattern III and IV). $C_{L'}$ is relatively low for $P=0$ case compared to the higher values of $P$. Similar to the $C_D$ coefficient, $C_{L'}$ attributes either suppression of vortex shedding or very small fluctuation at lower $L$ and $P$. Quick increasing regime is corresponds to the onset of vortex shedding regime for all $L$ and $P$. Higher fluctuation at higher $P$ indicates fluctuation of lift is stronger. At $L=2$ the fluctuation of the lift coefficient enhanced approximately 100% for $P=5$ case compared to $P=0$. As it can be seen from the flow structures in Figs.2 and 3, with the increase in $L$ the stagnation point is shifted into the higher velocity region. Lei et al. (1999) and Dipankar and Sengupta (2005) reported that the variation in the force coefficients is associated with the movement of the front stagnation point of the cylinder. Maiti (2012) observed the similar trend of increase in $C_D$ and $C_{L'}$ values with increase in $L$ for the uniform shear flow.

### 4.5 Vortex shedding frequency and spectra

The spectra of lift coefficients of the cylinder as functions of $L$ and $P$ are presented in Fig. 8. For $L \leq 0.1$, $P \leq 5$ and $L = 0.25$, $P \leq 3$ and $L = 0.5$, $P = 0$, the flow was steady, and there was no peak the power spectra. For higher values of $L$ and $P$, a definite peak is observed in the spectra. For $P = 0$, one single dominant peak is identified (Fig. 8a), the peak height boosting with increasing $L$. For higher values of $P$ and $L$, the wake and wall vortex interaction results in a complicated wake (Fig. 3) and multiple and/or broadbanded peaks. These multiples peaks correspond to the cylinder own shedding frequency and the interaction of the wake with wall vortices.
Fig. 8. The power spectra of fluctuating lift coefficient at different $P$ and $L$.

Fig. 9. Contours of Strouhal number ($St$) at different $L$ and $P$.

Fig. 9 presents the contour plots of Strouhal number ($St$) of the vortex shedding of the cylinder for different $L$ and $P$. The dominant peak in Fast Fourier transform (FFT) is considered as the $St$. As demonstrated in Figs. 2 & 3, the wake topology of the cylinder placed in nonuniform flow crucially depends on $P$ and $L$. The Strouhal number increases when $P$ is further increased from 0 to 5. The increase in $St$ for present study is contrary to the finding of Saha et al. (1999) and Lankadasu & Vengadesan (2008).
who reported that $St$ either remain constant or decreases with increase in the incoming shear rates. The maximum $St$ ($=0.18$) is identified in pattern-II for $L=0.25$, $P=5$, where the wake consists of a single row of regular vortices. $St$ of the dominant peak is sensitive to $P$. In general for pattern-III and IV, $St$ decreases with increase in $L$ for $P \geq 1$. At large $L$, the effective Reynolds number increases and vortices are stretched, it results smaller value of $St$. These observations are consistent with Maiti (2012) who reported drop in $St$ at higher $L$ for a uniform shear flow past square cylinder.

It has been observed here that significant changes occur in $St$ with change in $L$ particularly for higher values of $P$. For $P \leq 3$ variation in $St$ is less with variation in $L$, compared to the higher value of $P \geq 3$. The variation in $St$ is corresponding to change in wake flow pattern. Roshko (1954) define a universal Strouhal number ($St^*$) based on the hypothesis that the wake of different bluff bodies are similar in structure, as

$$St^* = \frac{f}{U} \frac{w}{u_b} = St \frac{U}{u_b} \frac{w}{a}$$  \hspace{1cm} (5)

Where $f$ is the shedding frequency, $w$ is the lateral distance between the two free shear layers and $\overline{u_b}$ is the time mean velocity at the boundary layer separation defined as

$$\overline{u_b} = \sqrt{1-C_P}$$  \hspace{1cm} (6)

Where $C_P$ is the base pressure. The concept of a universal Strouhal number has been used by many researchers with different definition of wake widths (Griffin & Ramberg 1974, Roshko 1954, Alam & Zhou 2007 and Alam et al. 2011). All these studies are based on higher Reynolds number uniform flow. So far, nobody has used this theory for the single cylinder with nonuniform inlet flow in wall proximity. An interesting question arises is : for a nonlinear inlet flow, is it possible to find the universal Strouhal number that is independent of $L$ ? It is clear from the flow structures that the presence of incoming nonlinear flow and the wall confinement produce an asymmetry in the two separated shear layers emerging from the upper and lower surfaces of the cylinder. Therefore, it is difficult to measure the wake width for the present case. For the $St^*$ calculation we have considered cylinder height ($a^*$) as the characteristic length instead of the wake width $w$. The values of $St^*$ are calculated as, $St^* = St / \overline{u_b}$ and plotted along with $St$ in Fig. 10. It is clear from Fig.10, $St$ and $St^*$ curves are qualitatively similar. For linear shear flow case ($P=0$), the values of $St^*$ collapsed to fairly constant value with less variation ($0.037 \pm 0.003$) with $L$. However, there is large variation in $St^*$ for $P=5$ ($St^* = 0.085 \pm 0.03$). The higher variation in $St^*$ for larger $P$ can be explained based on that increase in $P$ is similar to increase in $Re$. Richter and Naudascher (1976) observed variation in $St^*$ ($0.1560-0.2800$) with change in $Re$ from $2 \times 10^4$ to $1.0 \times 10^5$ to $2 \times 10^5$ to $4 \times 10^5$. Here also for $P \geq 3$, we observe large variation in $St^*$ ($0.036 - 0.04$) & ($0.04 - 0.058$) for $P = 0$ & 1, respectively. Large variation at lower $L(\leq 1.0)$ is attributed the wall proximity effect, which insinuates that the defining of universal Strouhal number $St^*$
does not fit for the flow past square cylinder in wall proximity. As it is evident from the Fig. 10 that for \( L \geq 1.0 \), variation in \( St^* \) is less particularly for small values of \( P \). It shows that Roshko theory for finding \( St^* \) based on \( \tau_h \), provides better approximation at lower \( P \) for \( L \geq 1.0 \).

![Graph showing variations in Strouhal number (St) and modified Strouhal number (St*) with L for different P.](image)

**Fig. 10.** Variations in Strouhal number (\( St \)) and modified Strouhal number (\( St^* \)) with \( L \) for different \( P \).

### 5. CONCLUSIONS

The effect of gap height and inlet-flow nonlinearity on the characteristics of flow around a square cylinder has been investigated numerically. We found that the pressure gradient (\( P \)) and gap height (\( L \)) have an appreciable effect on the dependence on the flow structure, forces and shedding frequency. Four distinct flow patterns are classified based on the contours of spanwise vorticity. The flow is steady for \( P \leq 3 \), \( L \leq 0.25 \) and \( P=0 \), \( L=0.5 \) in pattern-I. The unsteadiness is generated for \( L=0.1 \) at far downstream and it converts into complete vortex shedding at \( L=0.25 \) by introducing nonlinearity in the incoming flow at \( P=5 \). Unsteady periodic flow with a single row of vortices is observed in pattern-II. In pattern-III shear layers from the bottom of the cylinder remain attached and two row of vortices stretched in the streamwise direction. For \( L \geq 1.0 \) unsteady flow is observed from the cylinder for all the cases. The gap flow changes appreciably with change in either \( P \) or \( L \) which play a measure role in the formation of wake vortices. At large \( L \) and \( P \) in pattern-IV, trailing edge separation occurs and the wake interaction becomes complicated, which results Strouhal peak becomes broad banded in the power spectra. The critical gap height for onset or suppression of the vortex shedding depends on \( P \). The shedding frequency of the cylinder decreases with increase in the \( L \) for \( P \geq 3 \) compared to \( P=0 \) case. The \( St^* \) variation shows that Roshko’s theory of
universal Strouhal number does not fit for higher $P \geq 3$ and lower $L \leq 1.0$. The values of $C_D$ and $C_L'$ are insensitive to change in $L$ for $P=0$ and upto $L=0.5$ for $P \geq 1$. For $L>0.5$, $C_D$ increases almost linearly with $L$. The average pressure coefficient $\overline{C_P}$ shows significant change along the surface of the cylinder with increase in $L$ and $P$ that result in an increase in the value of $C_D$.

ACKNOWLEDGMENTS

Alam wishes to acknowledge the support given to them from National Natural Science Foundation of China through Grants 11672096 and from Research Grant Council of Shenzhen Government through grant JCYJ20160531191442288.

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