FOSSEE, IIT Bombay
OpenFOAM Research Migration Project
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Low Reynolds Number Flow Over a Square Cylinder with a Detached Flat Plate

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Synopsis

This research migration project aims to do numerical simulations of the alteration of a square cylinder wake using a detached downstream thin flat plate using OpenFOAM . The geometry and mesh were defined using blockMesh utility. A simulation uses a transient incompressible solver, pisoFoam to simulate the flow over a square cylinder with detached flat plate. The wake is created by a uniform flow with a Reynolds number of 150 based on the cylinder's side length, D. By altering the gap distance (G) along the wake centerline in the range $0 \leq G \leq 7D$ for a constant plate length of L = D, the sensitivity of the near wake structure to the downstream position of the plate is explored. A condition where significant unstable total lift reduction can occur is obtained by adjusting the plate length and gap spacing.

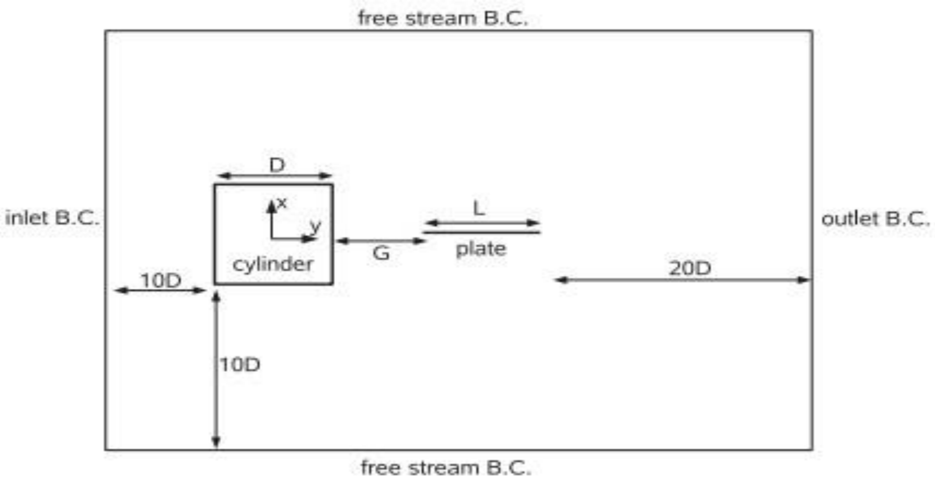

Figure No 1: Flow domain for a square cylinder with a splitter plate [1]

References

[1] Mohamed Sukri Mat Ali , Con J. Doolan, Vincent Wheatley, “Low Reynolds number flow over a square cylinder with a detached flat plate” , International Journal of Heat and Fluid Flow 36 (2012) 133–141, http://dx.doi.org/10.1016/j.ijheatfluidflow.2012.03.011

1.Introduction

Many engineering applications are concerned about vortex shedding behind bluff bodies. It is in charge of high-rise building structural movement and scours development around bridge piers. Channel beds, industrial component vibrations, aircraft landing gear acoustic radiation, and other related issues make it critical to comprehend and control these flow-induced phenomena. So that engineering design and public comfort can be continuously improved.

The current research will look at the impact of a detached flat plate on the flow around a square cylinder in greater depth. This research is part of a larger project to look into employing a rigid thin flat plate as a passive noise reduction device. It follows up on a recent study of the influence of a splitter plate on the flow around a square cylinder [3]. The current research has two goals. First, we'll look at how changes in the gap distance between the two bodies affect the near-wake flow behavior. Second, look at the potential of building a downstream flat plate to neutralize the overall lift force. A considerable reduction in noise and vibration could be accomplished by finding a design where the cylinder and plate provide the same magnitude of lift but are out of phase.

2. Flow specification

A rigid square cylinder with side length D submerged in a steady freestream with velocity U_∞ is the problem under examination. We take into account a Reynolds number based on $\left(Re = \frac{U_\infty D}{\nu} = 150\right)$ cylinder height. The unaltered condition is the name given to this state. Then, a rigid thin flat plate is put downstream along the wake centerline. The plate's chord length is originally fixed to the cylinder's side length (L = D).

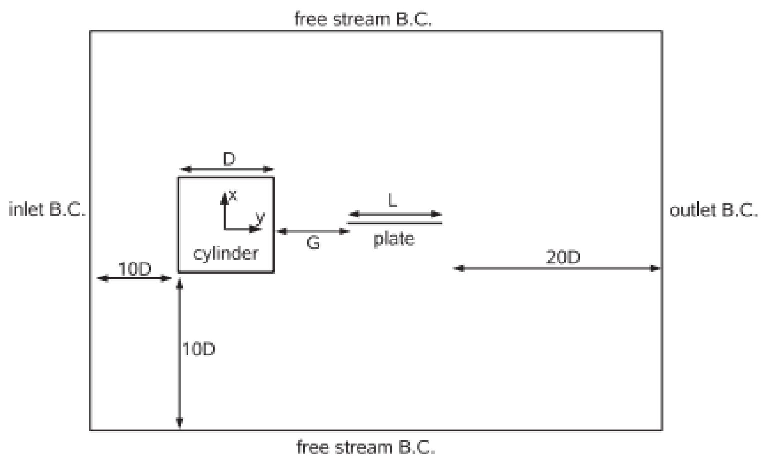

Figure No 1: Flow domain for a square cylinder with a splitter plate [1]

The separation distance (G) is measured from the cylinder's rear surface to the plate's leading edge and ranges from 0 to 7.0 D. The plate's thickness is set to h = 0.02D. A schematic illustration of the problem geometry is shown in Figure 1. A second simulation is shown in which the plate length is lowered to L = 0.26D, and the G = 5.6D position is used. The length and spacing are selected so that the lift on the plate is the same as the lift on the square cylinder but in reverse order.

3. Simulation Procedure

3.1 Geometry and Mesh

Figure. 1 shows the computational domain used in this study. The plate has 36 cells along the edges. A uniform mesh with cells being spaced equally at 36 cells for every cylinder side length (D) is constructed within the gap. The grid domain is extended downstream according to the corresponding gap, so the streamwise distance between the trailing edge and the downstream computational domain is always 20D.

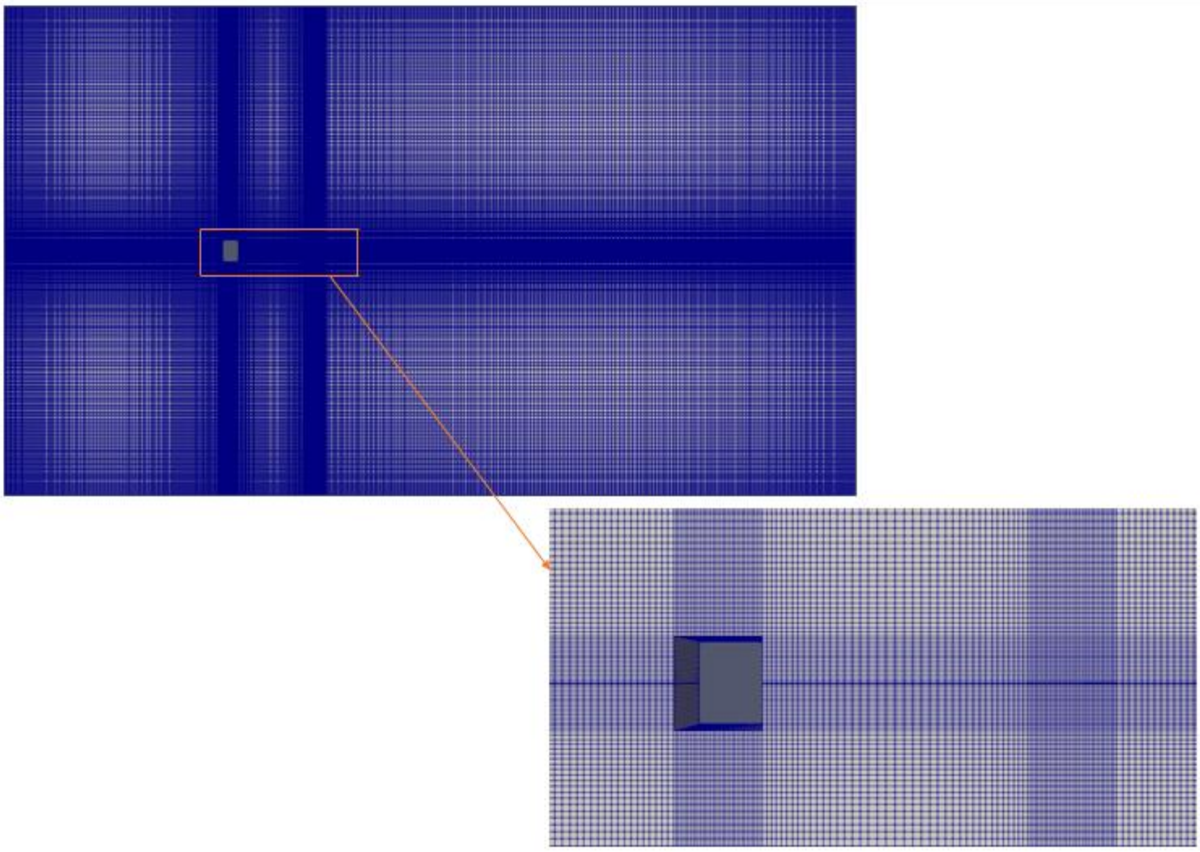

Figure No 2: Mesh used for the simulations.

3.2 Initial and Boundary Conditions

There are four boundaries that require boundary conditions: An inlet, outlet, Top Wall, and Bottom Wall. The other two boundaries are front and back; that set as empty boundaries. The inlet velocity is specified using the Reynolds number and other flow parameters, and the pressure is given as a zero gradient. The Top wall and Bottom wall are provided with the free stream boundary conditions for both velocity and pressure. The outlet condition for the velocity is given as the inlet-outlet boundary condition and the pressure uniform 0 as the condition. The square cylinder and the detached plate are provided with a no-slip boundary condition for velocity and zero gradient for the pressure.

3.3 Solver

The two-dimensional unstable incompressible Navier-Stokes and continuity equations are used to compute the primitive variables of the flow fields numerically. These governing equations are solved using the OpenFOAM (Weller et al.; 1998) numerical simulation system. These transient issues are solved using the pressure implicit split operator (PISO) solution algorithm (Barton, 1998), which includes two corrective phases for pressure-velocity coupling. The 2nd-order backward scheme of Jasak (1996) is used for temporal discretization. The convection term is discretized using the 2nd-order Upwind scheme. The 2nd-order unbounded Gauss linear differencing scheme is used for the viscous term. For pressure and velocity solutions, the convergence criterion is defined so that the residual falls below the tolerance of 10^{-6} and 10^{-5} at each step.

Table No 1: Comparison of the Present Study results with other previous studies (unmodified square cylinder).

Previous studies	C_{Lrms}	C_{Dmean}	St
Experiments (Okajima, 1982; Sohankar et al., 1999)	—	1.40	0.148-0.155
Doola (2009)	0.296	1.44	0.156
Sohanker et.al (1998)	0.230	1.44	0.165
Inoue et.al (2006)	0.40	1.40	0.151
Ali et.al (2009)	0.285	1.47	0.160
Present Study	0.282	1.45	0.150

4 Results and Discussions

4.1. Integral Properties

4.1.1 Strouhal Number

The fluctuation of the Strouhal number $St = \frac{f_s D}{U_\infty}$ where f_s is the fundamental vortex shedding frequency as a function of gap distance is seen in Fig. St decreases with gap distance for gaps in the range of (i.e., 0.5D ≤ G ≤ 2.3D). The connection between the shear layers decreases as the plate approaches the centre of the expanding vortex, and the shear layers interact heavily with the plate. When the gap distance is extended, these effects delay the vortex generation process, lowering the Strouhal number.

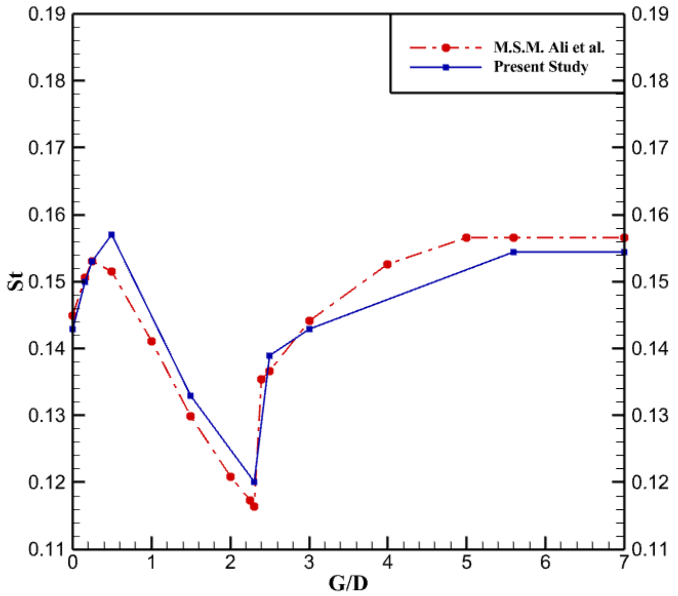

Fig 3: Variation of Strouhal number with gap for the square cylinder test cases of the current study

The magnitude of St steadily increases to a constant value that is close to the unmodified situation in regime II (G P 2.4D for the square cylinder). The process of vortex generation complete occurs inside the gap in this phase. The plate's blocking effect causes the progressive increase in St. The convective speed of the shear layers is reduced due to the obstruction effect. However, when the gap distance grows, the effect gradually fades.

4.1.2 Mean Drag

The cylinder mean drag increases with gap distance for gaps in the range of $G \leq 0.25D$. When $G \leq 0.25$, a jet flow is formed in the gap. This jet flow lowers the cylinder's base pressure, increasing drag. When the distance is raised further, in the region of $0.5D \leq G \leq 2.3D$, the mean drag continues to decrease. This was attributed to the plate's prevention of vortex shedding. Then, when G = 2.4D, there is a step increase in C_{Dmean}.

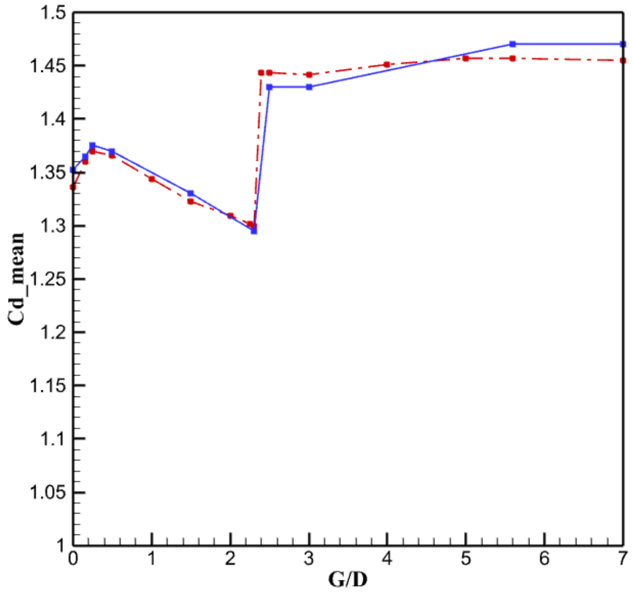

Fig 4: Variation of Mean Drag with gap for the square cylinder test cases of the current study

There are two other areas with high Reynold's stress concentrations near the plate. This is because the vortex plate interaction in that region magnifies the velocity fluctuations. The downstream pair of Reynolds stress maxima, on the other hand, is too far downstream to have any effect on the cylinder's mean drag. As a result, the cylinder's mean drag for regime II is insensitive to the gap distance, with a nearly constant magnitude comparable to that of the unmodified cylinder case.

4.1.3 Root Mean Square Lift

The influence of gap distance on C_{Lrmsc} and C_{Lrmsp} in regime I is sensitive to gap distance. C_{Lrmsc} continues to decrease as gap distance rises, whereas C_{Lrmsp} increases in magnitude. This is primarily due to the plate's distance from the expanding vortex's core.As the plate approaches the developing vortex's core, velocity variations near the plate become more pronounced, but the plate also dampens the shear layers' transverse oscillations.

As a result, surface pressure fluctuations on the plate continue to rise, but they decrease with gap distance on the cylinder. The effect of gap distance on C_{Lrmsc} and C_{Lrmsp} grows increasingly weaker in regime II before becoming constant at G ≥ 5.6D. This is because the wake blockage is severe for short gaps. As the separation distance reaches sufficiently large, the effect progressively fades. The weakening influence of the intense pressure field near the plate (due to the vortex-plate interaction) on the pressure field near the cylinder causes C_{Lrmsc} to decrease with gap. The increase in C_{Lrmsp}, on the other hand, is attributed to the formation of more organized large-scale vortices that interact with the plate.

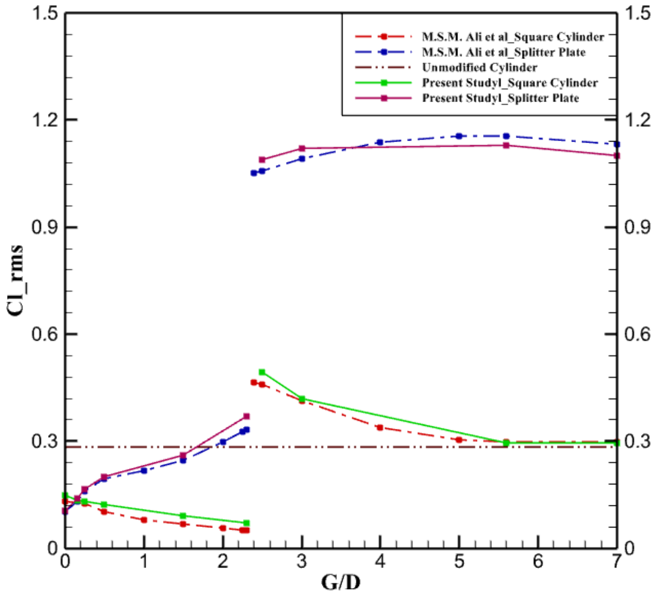

Fig 5: Variation of root mean square lift fluctuation with gap distance.

4.2 Flow structure

4.2.1 Pre-vortex formation regime

Compared to the unmodified cylinder instance, the increasing vortices cannot entrain fluid from the opposing shear layer until further downstream. When the developing vortex travelled around the trailing edge of the plate, entrainment did not happen right away. Instead, some of the fluid in the expanding vortex was lost to the opposite shear layer. This happened when the developing vortex swept some of its fluid onto the plate's trailing edge. The space between the cylinder and the plate allows the expanding vortex to entrain fluid from the other side of the cylinder through the gap when the plate is separated from the cylinder.

The fluid entrainment process observed for the unmodified cylinder begins to be re-established for close-proximity gap distances (i.e., 0.15D ≤ G ≤ 0.5D), except that there is no direct fluid entrainment into the core the expanding vortex since the plate prevents it. The fluid entrainment process via the gap produces additional vortices in this area. The flow at the trailing edge of the plate is roughly in the direction of the y-axis for G < D and when the lift fluctuation on the cylinder is at its peak

When the top shear layer begins to roll up over the plate for intermediate gaps (i.e., 1.5D ≤ G ≤ 2.3D), a stagnation point arises on the top plate surface. Part of the vorticity associated with the shear layer is swept past the trailing edge, and some are convected back towards the gap due to the stagnation point flow field. There is no evidence of fluid entrainment from the lowest shear layer into the rising vortex. As a result, the entrainment process is comparable to Ali et al. (2011)'s connected plate case, in which the developing vortex exclusively entrains fluids from the irrotational free streamflow.

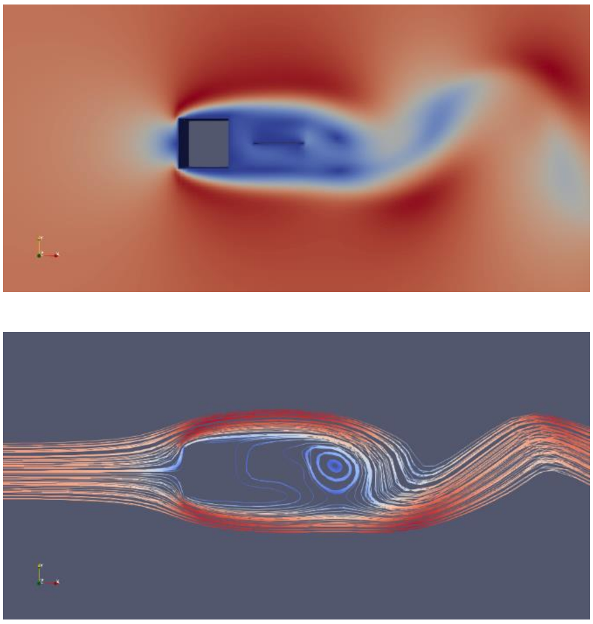

Fig 6: Streamline contour in case of G= 0.5D

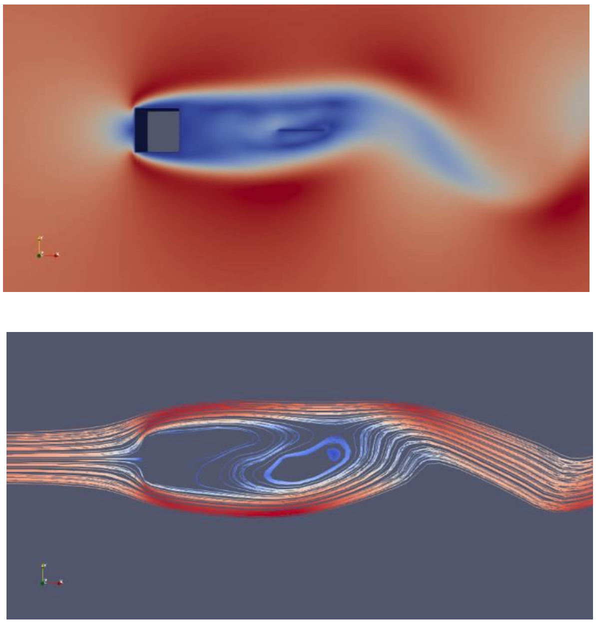

Fig 7: Streamline contour in case of G= 2.3D

The increased shear layer-plate interaction, on the other hand, causes the shear layers to oscillate significantly within the gap, reducing the energy of the expanding vortex via viscous diffusion. The formation of secondary vortices at the plate's leading and trailing edges is observed mostly due to the fluid being swept downward over the leading and trailing edges by the expanding vortex above the plate. This is in contrast to close-proximity gaps, where the secondary vortex at the leading edge is formed by fluid moving through the gap from the bottom shear layer. Thus, for gaps in the close-proximity range (i.e., 0.15D ≤ G ≤ D) and the intermediate gap range, opposite sign secondary vortices are formed at the time of maximum lift (i.e., 1.5D ≤ G ≤ 2.3D).

4.1.2 Post-vortex formation regime

When G ≥ 2.4D, a noticeable change in flow structure occurs. The unstable shear layer on the cylinder's upper side extends downstream of the gap at G = 2.3D. The shear layer predominantly interacts with the plate, and a stagnation point near the trailing edge may be seen on the top surface. Then, a large-scale vortex forms inside the gap, which convects downstream and hits the plate. In the vicinity of the plate, the vortex-plate interaction creates a complicated flow configuration.

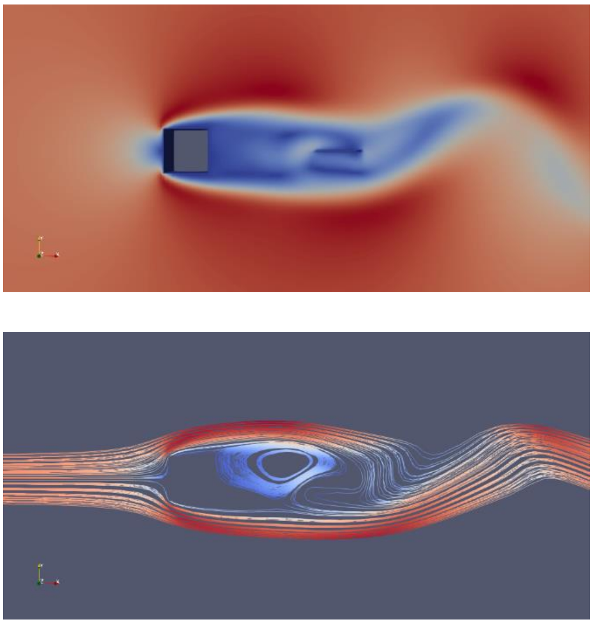

Fig 8: Streamline contour in case of G= 2.5D

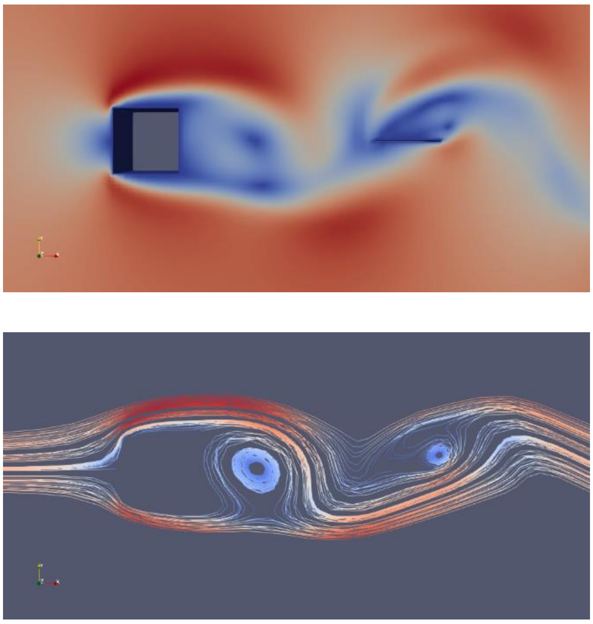

Fig 9: Streamline contour in case of G= 3D

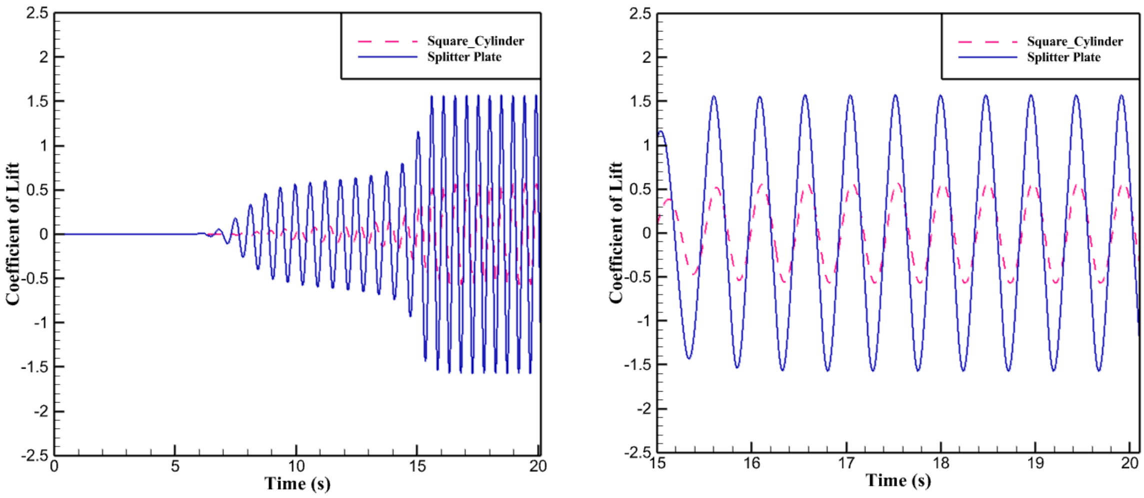

Fig 10: Coefficient of Lift of Cylinder and Plate for G/D=3 which is on phase with each other

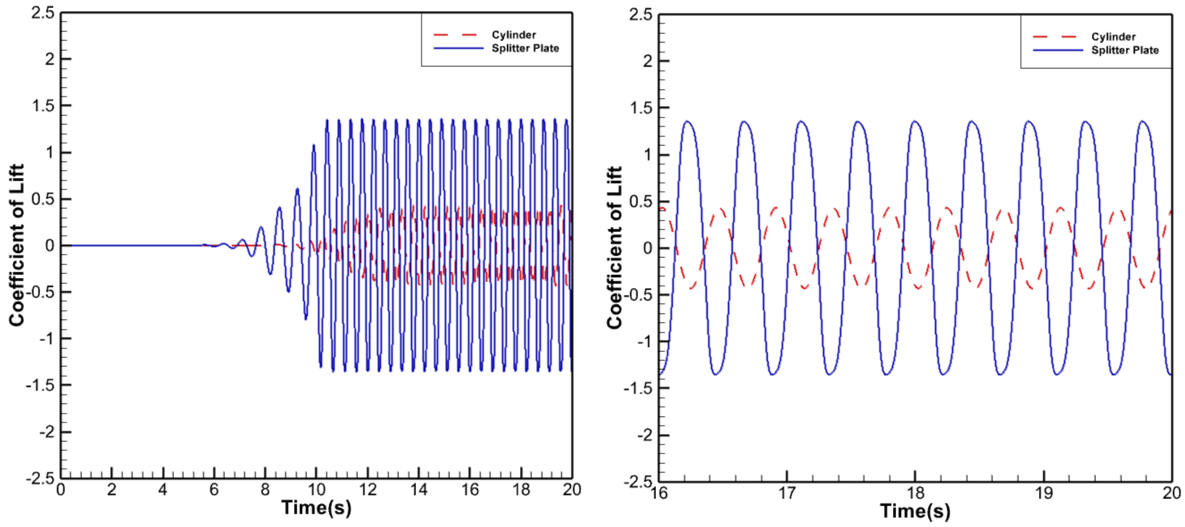

Fig 11: Coefficient of Lift of Cylinder and Plate for G/D=5.6 which is out of phase with each other

4.3. Modified plate for lift cancellation

The plate length and the gap distance are the two key factors that can be changed in the current study to achieve lift cancellation between the cylinder and the plate. The fluctuating lift created by the cylinder and the plate must be equal in amplitude but out of phase to achieve lift cancellation. The situation is out of phase when the gap distance is 5.6D for a plate of length D. The magnitude of the lift on the plate, on the other hand, is significantly greater than that on the cylinder.

Modifying the length of the plate is a simple approach to adjusting the magnitude of lift. The plate length is lowered in this case to match the cylinder, and plate root mean square lift values. Assuming the lift coefficients of the cylinder and plate remain constant. Equal lift on each object is assumed to occur if the length of the plate is reduced so $L/D = CL_{rmsc} / CL_{rmsp}$. An examination of the lift coefficients shows that L = 0.26D is a suitable plate length to achieve this purpose.

$$Lift\ \ Force\ Fluctuation = C_L * \frac{1}{2}\rho U_{\infty}{}^{2} * area$$

Here the density and velocity values are constant for both plate and cylinder. Hence the product of fluctuation of lift coefficient and area is taken for plotting of the Lift force fluctuation. Consequently, a slight drop in the lift force is observed, where there is a loss in the sinusoidal wave-form of the fluctuating lift.

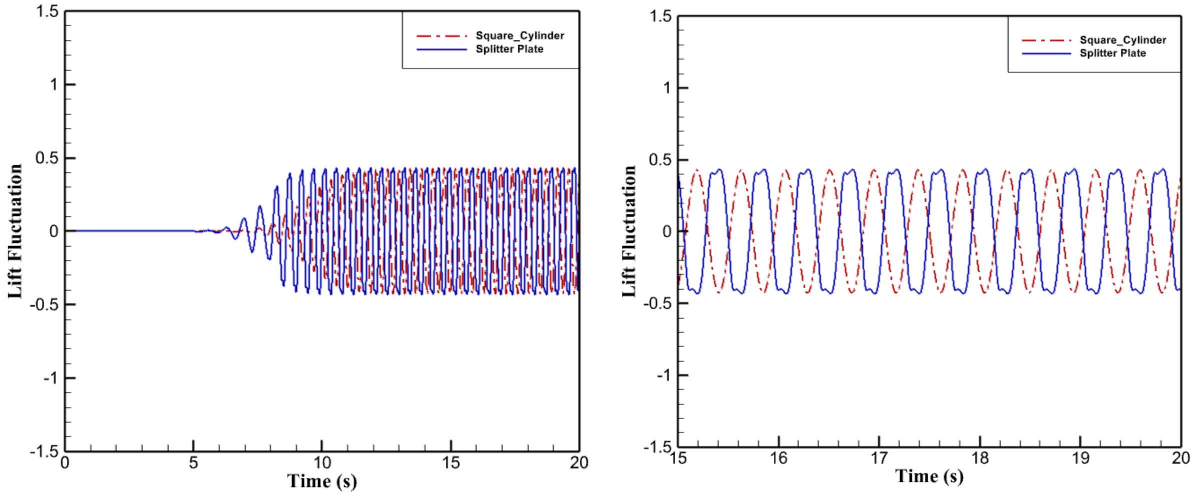

Fig 12: Time histories of Lift Fluctuation for the modified plate and cylinder.

5.Conclusion

At a Reynolds number of 150, the effects of a detachable downstream plate on the wake of a square cylinder were numerically examined. Two flow regimes were found with the transition at the critical gap distance of $G_C = 2.3$. The conclusion of vortex formation downstream of the gap defined the first regime. The conclusion of vortex formation inside the gap defined the second regime. Between regimes I and II, there were abrupt changes in integral properties. When the gap is greater than 5.6D, the plate does not affect the production of the von Kármán vortex. In regime II, the phase difference between the cylinder and the plate lift was linear. When the gap distance is 5.6D, a π radian phase difference in lift fluctuations was detected.

The plate length was lowered using the data from the flow simulations to achieve total lift cancellation. At G = 5.6D downstream of the cylinder, the plate length was estimated to be L = 0.26D. Although no complete lift cancellation was seen, the system's lift fluctuation was significantly reduced. Total cancellation could not be achieved due to the loss of the sinusoidal form of the fluctuating lift signal of the plate due to plate stall.

6. References

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