Numerical simulation of two dimensional unsteady flow past two square cylinders

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***Abstract*— This paper presents a numerical investigation of two dimensional unsteady flow past two square cylinders with in-line arrangements in a free stream. The main aim of the study is to systematically investigate the influences on size of the eddy, Monitored velocity, frequency of vortex shedding, pressure coefficient and lift coefficient by varying pitch to perimeter Ratio of two square cylinders. It has been found that the size of the eddy and the monitored velocity in between the square cylinders increases with increase in PPR. Frequency of vortex shedding is found to be same in between the cylinders and in the downstream of the cylinder. The pressure distribution near to the surface of the cylinder, flow momentum is quite low due to viscous effects. The upstream cylinder is found to experience higher lift compared to the downstream cylinder.**

***Index Terms*— Square cylinder; Vortex shedding; Strouhal number; Vorticity; Numerical Simulation**

I. INTRODUCTION

In many mechanical engineering applications, separated flows often appear around any object. Tall buildings, monuments, and towers are permanently exposed to wind. Similarly, piers, bridge pillars, and legs of offshore platforms are continuously subjected to the load produced by maritime or fluvial streams [1]. The motivation for the present study has been taken into account after studying the following available literature.

The open literatures are very limited for flow past square cylinder. A. Roy, G. Bandyopadhyay [2] have simulated flow past a square cylinder placed inside a channel with two different blockage ratios and for different Reynolds numbers. Jerry M et al [3] have carried out experiments on vortex-shedding frequencies and surface pressures of a square cylinder at non-zero angle of incidence. M. Breuer, et al.[4] have studied confined flow around a cylinder with square cross-section mounted inside a plane channel by two entirely different numerical techniques, namely a lattice-Boltzmann automata (LBA) and a finite volume method (FVM). A. Lankadasu, and S. Vengadesan [6] have made study on the incompressible linear shear flow across a square cylinder by solving unsteady 2-D Navier–Stokes equations. M. Cheng et al. [7] have presented in numerical simulation of a two-dimensional (2-D) incompressible linear shear flow over a square cylinder. Numerical simulations are performed, using the lattice Boltzmann method. The effects of the Reynolds number, spacing ratio and rotation angle of the downstream cylinder on flow characteristic modes, drag coefficients and vortex shedding properties were studied by S.C.Yen et al. [10] for the case of two identical square cylinders were installed in tandem in a vertical water tank. Do-Hyeong Kim et al. [12] have numerically investigated the turbulent flow past a square cylinder confined in a channel by large eddy simulation (LES). Yoshiyuki Ono and Tetsuro Tamura [13] employed the application of Large Eddy Simulation (LES) in a curvilinear coordinate system to the flow around a square cylinder. Numerical study is carried out on spatial evolution of vortices and transition to three-dimensionality in the wake of a square cylinder by A.K. Saha et al. [14].

These bodies usually create a large region of separated flow and a massive unsteady wake region in the downstream. Vortex shedding observed in the wake of these bodies generates unsteady (periodic) lift and drag forces. When fluid flows around a Square cylinder, the vortices are alternatively shed and a well known Karman vortex street is formed in the wake of the cylinder. The oscillating wake rolls up into two staggered rows of vortices with opposite senses of rotation. The frequency of vorticity pairs is a function of velocity, square cylinder perimeter, orientation of square cylinder and Reynolds number. One of the main features of this flow configuration is a periodic force loading in streamwise and vertical directions due to the pressure variation on the cylinder surface caused by the periodic vortex shedding.

Oscillation of square cylinder and other structures in transverse flow is essentially due to vortex shedding. An initially smooth and steady flow across a square cylinder may bring about damaging oscillations, in cases where the natural frequency of the obstacle is close to the shedding frequency of the vortices. An alternating deflection influences the fluid flow patterns of the wake region behind the square cylinder. As a result, the induced forces on the square cylinder become periodic and culminate in coupling between the fluid and the structure. This can be detected from the oscillation of the square cylinder. If the resulting excitation frequency synchronizes with the natural frequency of the square cylinder, the phenomenon of resonance is the obvious outcome. Therefore, the simulation of unsteady flow past square cylinder has practical relevance.

In flow past a Square cylinder, the location of flow separation is fixed at upstream sharp corners due to the abrupt geometrical change. This makes the flow diverge further and creates a wide wake. Larger wake means higher form drag and smaller value of vortex shedding frequency or Strouhal number. This feature is utilized in some practical applications in heat and mass transfer, especially in a confined geometry. For example, the flow analysis around a flame-holder in designing of a combustor is very important to improve its performance.

In flow over a square cylinder confined in a channel or subjected to a free-stream flow. In such flow, various complex physical phenomena including flow separation, reattachment, recirculation, and vortex shedding occurs, producing a very challenging flow field for both experimentalist and also CFD practitioners.

Understanding the wake behavior and the associated dynamics of flow past square square cylinder helps in the better design of the concerned or desired objectives, where the engineering parameters need to be designed with reasonable precision. A designer, therefore, is required to have a large database available in order to choose an optimal one among the different alternatives. To achieve this objective, extensive established correlations are required for different alternatives. Elaborate experiments were the order of the day. However with the advent of modern digital computers, numerical procedures are complementing with the experiments. This approach has substantially reduced monotony, time and higher labor costs involved with experimentation. In a numerical simulation changing the geometric parameters and fluid flow conditions can be easily accomplished by making suitable modifications in the input parameters.

A. Flow past square cylinder

The problem considered is the flow past a square cylinder in a free stream with Reynolds numbers of 200 and 500. The Geometry and Boundary conditions used for the investigation is same as used by other investigators. Because only a finite computational domain can be employed for the numerical simulation, it is important to locate the inflow and far-field boundaries at sufficient distance such that the boundary conditions applied at these boundaries do not introduce significant effects into the main region of interest, around and behind the square cylinder. The inflow, top and bottom boundaries have been located 6.5 square cylinder with respect to the center of the square cylinder. Similarly, in order to minimize the effects of the outflow boundary condition on the flow in the vicinity of the cylinder, the computational domain has been extended to 30 square cylinder Perimeters in the downstream of the cylinder.

On each of the four boundaries (left, right, top, bottom) of the rectangular computational domain, one of the four boundary conditions may be imposed, namely, free slip, no slip, Continuative and prescribed velocity profile. Finite volume mesh used for the numerical simulation is shown in Fig 1.

In the present investigation, flow past square cylinder has been computed by applying boundary conditions as follows.

(a) Inlet - Uniform flow (U = 1.0, V = 0.0)

(b) Cylinder surface -No slip (U = V = 0.0)

(c) Top and Bottom Boundaries (U =1.0 V = 0.0)

(d) Outlet Boundary -Continuative boundary condition can be expressed as (P = 0.0)

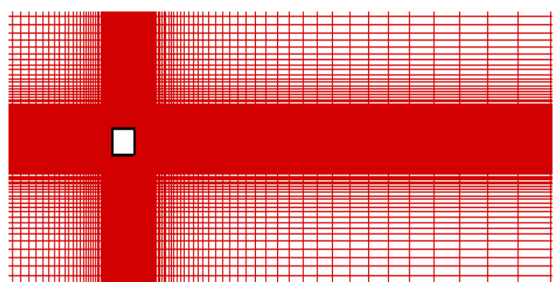

Figure 1: Finite volume mesh

B. Mesh sensitivity analysis

The mesh independence test ensures consistency of results achieved using different mesh sizes. In numerical computations, it becomes essential to perform a grid independence study. In the present work, the grid independence is carried out using three different grid sizes for same computational domain size. Grid sizes of 165x140, 175x140, 210x210 are considered for the investigation. The result in the form of Strouhal number is presented in Table 1 respectively. It can be seen readily that the results are independent of Mesh size. However a 210x210 grid size has been selected to carry out the further computational work.

TABLE 1. STROUHAL NUMBER OBTAINED FROM TIME HISTORIES OF LIFT COEFFICIENT

Grid size	Re=200
165x140	0.13
175x140	0.13
210x210	0.13

C. *Streamlines*

In the case of flow over a single cylinder for Re=200, the flow is uniform and symmetrical in the upstream of the cylinder. The eddies are alternatively formed on either side of the square cylinder in the downstream. As the flow forms a clockwise eddy, it rushes past the top of the square cylinder somewhat faster than the flow across the bottom. When the clockwise eddy breaks away, the opposite pattern develops at the bottom. The eddies grow in size as they move away from the cylinder upto a certain length from the cylinder and then gradually die out and the flow becomes uniform as in the upstream. This is presented in the form of streamlines as shown in Fig. 2(a)-(b) for half shedding cycle. A similar nature of flow has been observed by other investigators. When Reynolds number increased from 200 to 500 a similar flow pattern has been observed except the length of is vortex formation with increasing Reynolds number.

D. *Monitored velocity*

The temporal histories for the cross-stream component of velocity (Uy), along the axis of symmetry (in the downstream region), are monitored at several nodal points (X=8.5, X=9and X=9.5) for Re=200 and Re=500. It can be seen from the plots that Strouhal number remains same even if Reynolds number is increased while monitoring the velocity behind the square cylinder. A typical plot of the monitored velocity is shown in Fig. 3.

Figure 2(a): Streamlines for =200

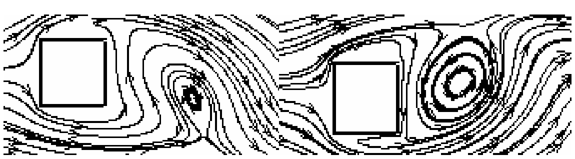

Figure 2(b): Streamlines for Re = 500

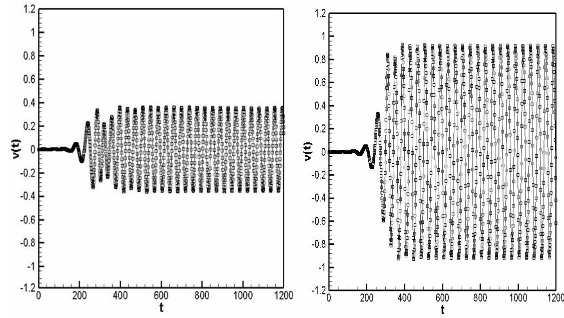

Figure.3 (a): Monitored Velocity in the downstream of single cylinder at X=8 and Y=6.5 for Re=200 and Re=500

E. *Pressure distribution around a square cylinder*

Pressure changes accordingly with the vortices motion in the vicinity of the bodies. Flow separates alternately around symmetrical bodies with sharp corners such as the leading edge of a square section to form vortices around the cylinder. This usually introduces periodic forces on the body due to the pressure changes. This situation is particularly significant in flow involving fluid and structure interaction such as the flow around a tall building or suspension bridge. Although pressure induced force does not affect the simulation on a fixed square cylinder very much. Vortex formation and progression induce forces on the bodies enveloped in the flow. A vortex creates a negative pressure suction area adjacent to the surface where it progresses. Thus the study of pressure distribution is important in the analysis of the aerodynamic forces around a structure. The pressure distribution near to the surface of the cylinder, flow momentum is quite low due to viscous effects and thus is sensitive to the changes of the pressure gradient. Figure 4 shows a typical pressure distribution plot for the flow around a square cylinder for Re = 200.

F. *Lift coefficient*

Fig.5 shows the time history of Lift coefficient of square cylinder for Re=200. Strouhal number for time history of lift coefficient of Re=200 is 0.13.

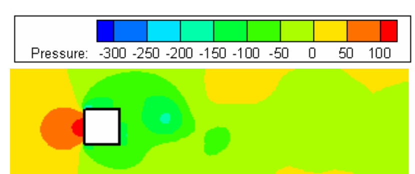

Figure 4: Pressure distribution for Re = 200.

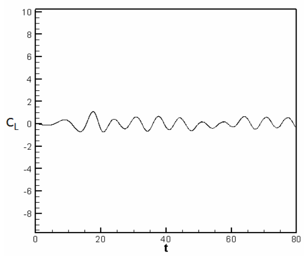

Figure 5: Time History of Lift coefficient of Re=200

Table II. Comparison of strouhal number with Experimental and Numerical investigation of other investigators.

Reynolds number	Contributors	Year	St
Re=200 And Re=500	Ahmad Sohankar ,C. Norberg and L. Davidson	1999	0.160 0.122
Re=200	Sohankar ,Norberg and Davidson	1996	0.168
Re=500	Okajima	1982	0.130
Re=500	Kai Fan Liaw	2005	0.130
Re=200	Ahmad Sohankar, Davidson and Christoffer Norberg	1995	0.165
Re=200 Re=500	Present	2010	0.13 0.12

Strouhal number obtained from the present investigation have been compared with Experimental and Numerical results of other investigators in Table 2.A good agreement has been seen with other investigators.

G. *Flow past two cylinders*

Geometry and Finite volume mesh used for the numerical simulation is shown in Fig.6.Boundary conditions considered are same as that of single cylinder analysis.

Fig. 7 shows the streamlines for the case of two square cylinders of same size with PPR of 6 and with a Reynolds number of 200. The flow is uniform and symmetric in the upstream and the pattern is similar to the case of single cylinder. Alternate eddies are formed in between the cylinders and in the downstream of the second cylinder. The size of the eddy in between the cylinder is smaller when compared to the downstream of the second cylinder for PPR=2. This is due to the fact that the second cylinder is suppressing the eddy formation in between the square cylinders. Also the frequency of formation of eddies in between the cylinders is less when compared to the downstream of the second cylinder because the distance between the two cylinders is very small. When compared with the single cylinder, the size of the eddy in between the cylinder and also in the downstream of the second cylinder is small. But when PPR=6 the size of the eddy in between the square cylinders is elongated. A similar flow pattern has been observed with the increase in Reynolds number to 500.

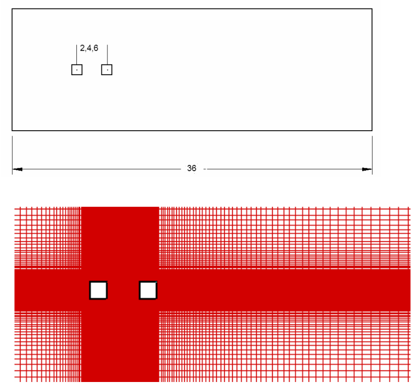

Figure 6: Geometry and Finite Volume Mesh for two cylinders

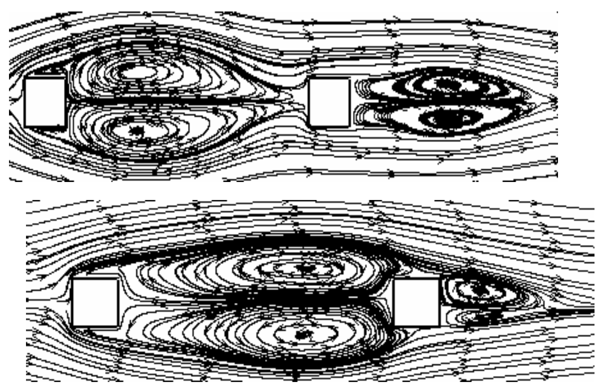

Figure. 7: Stream lines for Re=200 when PPR=6

G. *Monitored velocity*

Figures 8 (a)-(d) shows the monitored velocities for Re=200 and 500 in between the square cylinders as well as for downstream of the second cylinder with a PPR of 2, 4 and 6. Velocities have been monitored at X=8 measured from the inlet section and Y=6.5 which is the centre line of the geometry under investigation. With the increase of Reynolds number the oscillations are found to ascend because of the domination of inertia forces. It can be seen from the plots that the monitored velocities in between the square cylinders are less compared to the downstream of the second square cylinder for both Reynolds number under investigation. But these velocities are less when compared with that of single cylinder. The frequency of vortex shedding in between the square cylinders and also in the downstream of the second cylinder is found to be nearly same. But when compared with that of single cylinder frequency of vortex shedding can be seen decreasing.

When PPR is increased to 4.0 similar to the case of PPR=2 the oscillations in between the cylinders are less when compared with the downstream of the second cylinder. But these velocities are more when compared with PPR=2.0.The frequency of vortex shedding in between the square cylinders is more when compared to the downstream of the second cylinder. It is found to be less when compared with that of the single cylinder.

Further increase in PPR to 6 monitored velocity in between the square cylinders is more compared to the downstream of the second cylinder. But these velocities are more when compared with that of single cylinder, PPR=2.0, PPR=4.0. The frequency of vortex shedding in between the square cylinders and in the downstream of the second cylinder is found to be nearly the same. It is found to be same when compared with that of the single cylinder.

In view of the above discussions we may conclude that the frequency of vortex shedding can be decreased with the introduction a square cylinder in the downstream of the second cylinder. Further with increase in PPR to 6 shedding frequency is found to approach that of the single cylinder.

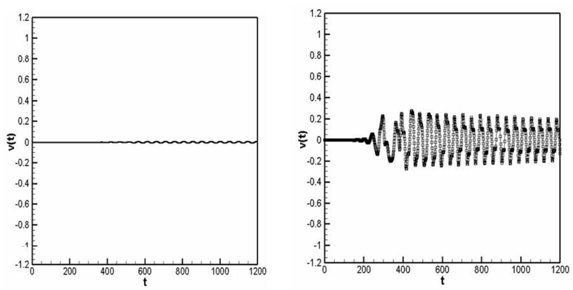

Figure.8 (a): Monitored Velocity in between square cylinders at X=8 and Y=6.5 when PPR=2 for Re=200 and Re=500

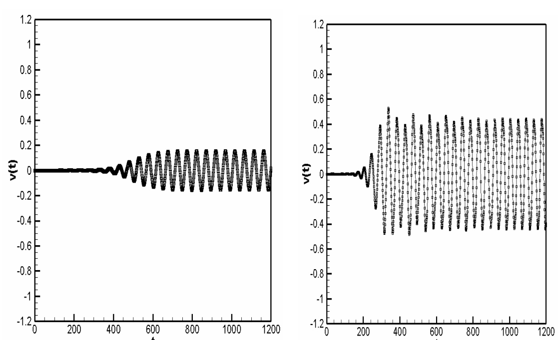

Figure.8 (b): Monitored Velocity in the downstream of a second square cylinder at X=11 and Y=6.5 when PPR=2 for Re=200 and Re=500.

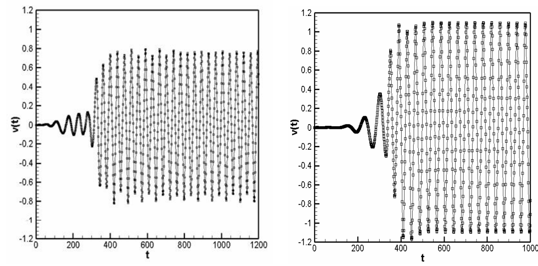

Figure 8 (c): Monitored Velocity in between square cylinders at X=8 and Y=6.5 when PPR=4 for Re=200 and Re=500

G. *Pressure coefficient*

Figure 10 shows Pressure distribution around square cylinders of same perimeter for Reynolds number 200 and PPR=6. It can be seen from the diagram that front portion of the cylinder is experiencing highest pressure compared to the second cylinder. A similar pressure distribution has been observed in all the cases under investigation and also with the increase in Reynolds no to 500.

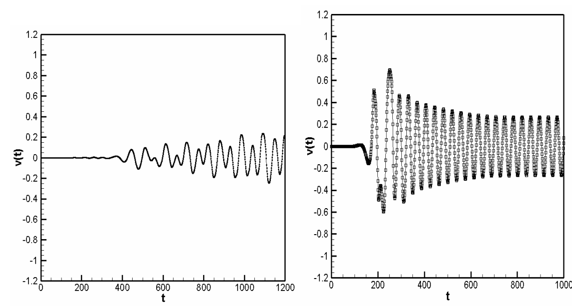

Figure 8(d): Monitored Velocity in the downstream of a second square cylinder at X=17 and Y=6.5 when PPR=6 for Re=200 and Re=500

H. *Lift Coefficient*

Figure 11 shows the time history of lift coefficient for upstream and downstream square cylinder of Re=200 when PPR=2. The frequency of vortex shedding is 0.1. But when compared with that of single cylinder the value is found to be lower than the present case.

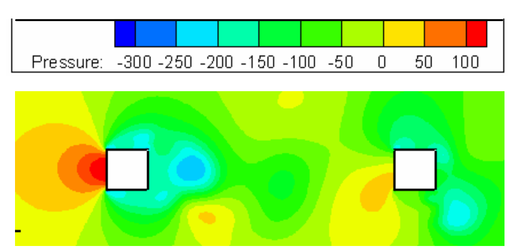

Figure 10: Pressure distribution around square cylinders for Re = 200 when PPR=6

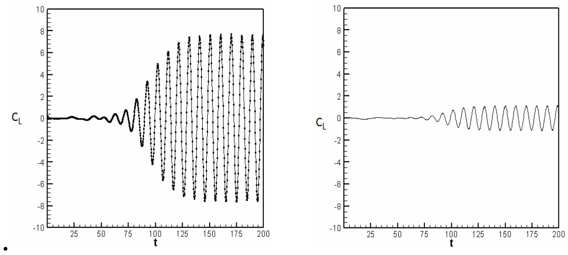

Figure11 : Time History of lift coefficient of upstream and downstream square cylinder for Re=200

II. CONCLUSIONS

The Present numerical results agree well with the available results of other investigators. For the square cylinders of same perimeters, the size of the eddy and the monitored velocity in between the square cylinders increases with increase in PPR. Further with increase in PPR to 6, the flow over each cylinder is almost similar to that of single square cylinder. Frequency of vortex shedding is found to decrease with the introduction of second cylinder either in the upstream or downstream of the first cylinder. As PPR is increase to 6 the behavior of the flow almost approaches that of single cylinder. This has been observed by the other investigators. The upstream cylinder is found to experience higher lift compared to the downstream cylinder.

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