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Computational Study of Fluid Flow Characteristics past Circular Cylinder due to Confining Walls with Local Waviness

R Deepakkumar¹, S Jayavel¹ and Shaligram Tiwari²

¹IIITD&M Kancheepuram, Chennai-600127, Tamilnadu, India

²Department of Mechanical Engineering, IIT Madras, Chennai-600036, India

sjv@iiitdm.ac.in

Abstract. Flow past circular cylinder confined by walls with local waviness near the cylinder has been computed and the vortex shedding characteristics are studied at Reynolds number 200. The governing equations are solved using finite volume based CFD solver, 'Ansys Fluent 15.0'. In the present study, flow fields have been computed with waviness placed at four different locations. The effect of the location of waviness on vortex formation and its shedding frequency has been closely captured and presented. The flow parameters such as drag, lift and Strouhal number are calculated using the field data obtained from computations. It has been observed that the vortex shedding is significantly controlled by changing the location of local waviness. Among the four different locations considered in the present study, the waviness located near the wake region effectively suppresses the shedding. Moreover, the inward projection of the waviness plays a vital role in vortex suppression. It is also observed this method of vortex suppression leads to increase in drag.

1. Introduction

Flow physics in the downstream of flow past an unconfined circular cylinder is an interesting phenomenon. Flows over civil structures and heat exchanger tubes are such examples. Confining walls in the proximity of the cylinder significantly influence the alternate vortex shedding. Further, with high confinement, the shedding gets completely suppressed (Tiwari *et al.* 2006). Confining walls and protrusions in the confining boundaries such as vortex generators can also be effectively utilized to control the flow characteristics (Jayavel and Tiwari 2008; Jayavel and Tiwari 2009). For example, cylinder confined by rigid walls effectively controls the shedding characteristics, Chen *et al.* (1995), Sahin *et al.* (2004), Tiwari *et al.* (2006) and Singhaet *al.* (2010) have studied the effect of wall confinement on vortex shedding and reported increased drag on the cylinder. From the work of Dipankar and Sengupta (2005), it is observed that when the cylinder is exposed to an oncoming shear flow by placing near to a solid wall, that weaken the shed vorticity from the cylinder at Reynolds number 1200. Also they have explained the effect of plane wall on flow around the cylinder in terms of vorticity dynamics and vortex induced instability mechanism. Strykowski and Sreenivasan (1990), Mittal and Raghuvanshi (2001) have used a secondary small control cylinder in the wake of the main cylinder and effectively controlled the shedding. The presence of splitter plate in the wake also effectively controls the shedding, Kwon and Choi (1996); Jayavel and Tiwari (2010); Dehkordi and Jafari (2010) have identified the location and length of the splitter plate to reduce drag and lift acting on the cylinder. From the available literature, it is clear that the effect of wall confinement on vortex



shedding characteristics and especially waviness near the cylinder would be of more interest. The present work is aimed to study the physical phenomena of flow past circular cylinder confined between parallel walls with waviness in selected region close to the cylinder.

2. Problem statement

This numerical study is aimed at the control of vortex shedding on a cross flow past circular cylinder confined between two parallel rigid walls with waviness in the walls near to the cylinder as shown in Figure 1. The Reynolds number taken for the study is 200 (Sahin *et al.* 2004), which ensures the shedding in presence of plain wall confinement. Waviness has been located at different locations in the plain wall as shown in Figure 2 and the shedding characteristics are monitored. The Figure 1 shows the various dimensions of the computational domain using cylinder diameter (D) as the characteristic length scale. The cylinder confinement is $2D$, upstream and downstream lengths are $6D$ and $24D$ respectively. The wavelength and amplitude of waviness are $2D$ and $0.15D$ respectively. The location of waviness is specified in terms of horizontal distance between the cylinder center and the wave center. The four different locations considered in the present study are shown in Figure 2.

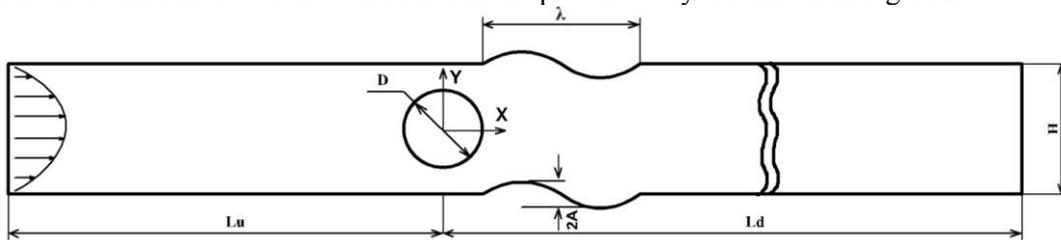


Figure 1. Computational domain.

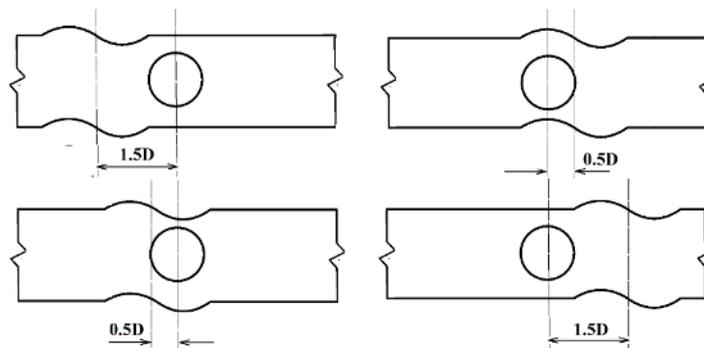


Figure 2. Different location of waviness.

3. Numerical solution methodology

In order to obtain the flow fields in the computational domain, the entire domain has been discretized into finite number of small control volumes as shown in Figure 3 using the Ansys ICEMCFD 15.0. The block structured grid methodology has been used to generate body fitted structured grid, so as to improve convergence of the solution. To capture the steep gradients near the cylinder, 'O' grid has been generated around the cylinder with very fine mesh size. The governing equations are solved using the solver Ansys Fluent 15.0 with appropriate boundary conditions. At the inlet, fully developed flow condition has been imposed using user defined function. Outflow condition with zero-gradient for variables has been assumed at the domain exit. The no-slip boundary condition is used for rigid solid walls such as side walls and cylinder surface. As the Reynolds number ($Re=200$) considered in the present study ensures shedding with plain wall confinement, the entire simulations of wavy wall confinement have been conducted using unsteady solver. The time step taken for the study is 0.002 based on Courant–Friedrichs–Lewy (CFL) condition and the computations are carried out for 5000

time-steps. Second order implicit method is chosen for transient formulation. The numerical scheme, COUPLED algorithm is employed for coupling pressure and velocity while solving the momentum and pressure-based continuity equations. As the grids are aligned with flow direction, the convective terms are discretized using QUICK scheme to improve the solution accuracy. Second order interpolation scheme is used for calculating the pressures at cell face. The gradients of solution variables at cell centers are determined using least-square cell-based approach. The convergence criterion for the residuals of continuity, X-Velocity and Y-Velocity components are taken as 1×10^{-6} .

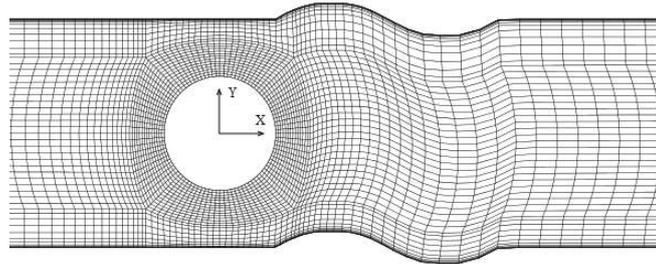


Figure 3. Schematic representation of mesh used in the present study.

4. Results and discussion

The following sections details the grid independent results, validation of the numerical methodology, the importance of waviness in the side wall on vortex shedding and its control. The effects of location of waviness on the shedding characteristics are also presented and discussed.

4.1. Grid independence and validation

In order to obtain an optimum grid size based on reduced computational time and improved solution accuracy, a thorough grid independence study has been conducted with various grid sizes as listed in Table-1 and the study has been extended for various Reynolds numbers. The grids are generated using block structured method, which facilitates the grid refinement around the cylinder and the confining walls. The percentage variation in C_D between (G_1 & G_2) and (G_2 & G_3) are 0.25 and 0.17, respectively at $Re = 20$, whereas at $Re = 200$ the variations are 0.17, 0.07. On the other hand, the percentage variation of C_{pb} between (G_1 & G_2) and (G_2 & G_3) are 6 and 1.76, respectively at $Re = 20$. It is noticed that for a fixed Reynolds number, the percentage variation with change in grid size is more for base pressure co-efficient (C_{pb}) as compared to drag coefficient (C_D). The value of C_{pb} is monitored from a nodal point, whereas C_D is calculated using the force values averaged over the cylinder surface, this averaging process make the value of C_D less sensitive to grid size. Hence a nodal point observation is better choice to conduct grid independence tests. In the present study, the maximum percentage variation of C_{pb} between (G_2 & G_3) is 3.96 at Reynolds number 200. Therefore, the grid size G_2 has been chosen as the optimum grid size for further computations. Moreover, the present computational methodology has been validated with the results of Sahin *et al.* (2004). The drag computed from the present study and those available in the literature shows good agreement with each other and the maximum deviation between the results is 1.82% at $Re = 10$. The results of grid independence study and validation of the results are not presented due to space constraint.

Table 1. Number of nodes and cells used in various grid sizes.

Grid	Total nodes	Total cells
G_1	26053	25550
G_2	43364	42782
G_3	139679	138528

4.2. Significance of local waviness

In order to study the significance of waviness on vortex shedding and its control, simulation has been carried out on trough only confined cylinder and corresponding flow characteristics such as drag and lift-signals are observed and shown in Figures 4(a) & (b), respectively. The drag and lift-signal confirms the presence of shedding, which is also observed from the streamline plots as shown in Figure 5. Hence it is clear that the trough only confinement is not enough to suppress shedding.

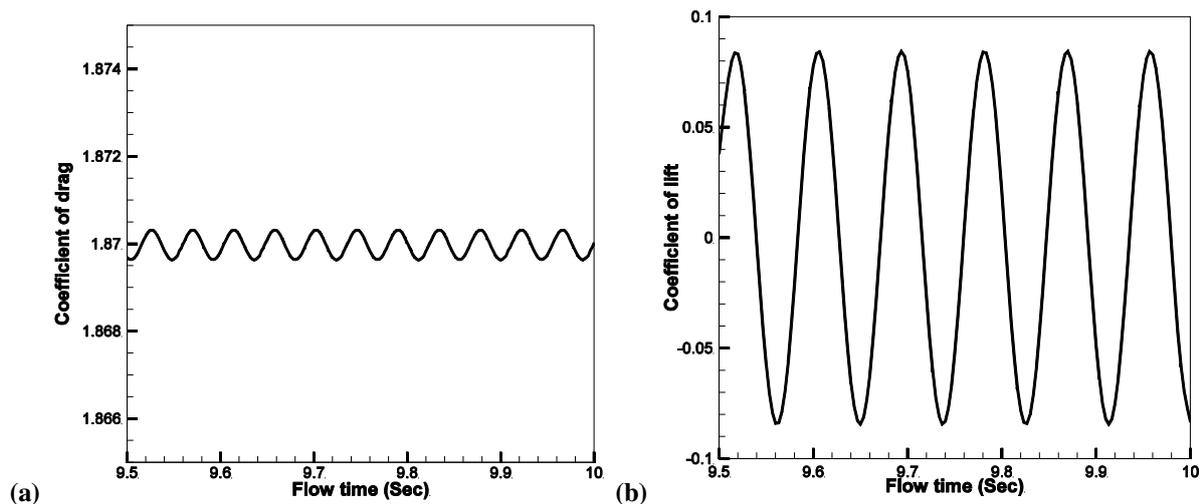


Figure 4. Effect of trough only confinement at $Re = 200$ (a) drag signal and (b) lift signal

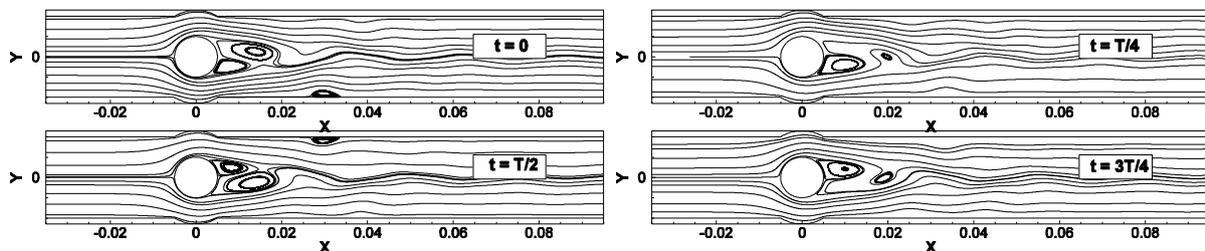


Figure 5. Streamlines at various flow time with trough only confinement at $Re = 200$

4.3. Effect of local waviness on shedding characteristics

The Figures 6(a) & (b) are plotted to observe the variation of C_D and C_L with flow time for various locations of waviness for a time period of 0.5 second and compared with the similar results corresponding to Pw confinement (reference case). The drag force on the cylinder is higher with waviness in all cases except Case-1. In case-1, the approaching flow striking the cylinder is slightly inclined with respect to the main flow direction. Thus, the total force on the cylinder is reinforced by lift force, hence drag reduced. With Case-1, the time-averaged flow past the cylinder is one-sided *i.e.*, increased flow rate in the gap between bottom wall and cylinder creates more pressure and leads to the shift of fluctuating lift-signal towards positive y -direction as shown in Figure 6(b) as compared to alternating lift of Pw configuration. The increased drag in case-2 and case-3 is due to the presence of wavy-crest near the cylinder which reduces flow passage and creates local acceleration of flow near the cylinder surface. The suppression of shedding and no fluctuation in lift is observed for the Cases 3

and 4 (Figure 6b) but offers more drag on the cylinder as compared to Pw configuration. In case-3, the maximum drag experienced is due to partially attached flow, that leads to increase in separation angle thus more shear on the cylinder surface. On the other hand, the more flow passage between cylinder and confining wall the drag is lesser in case-4 as compared with case-3. In presence of wavy confinement, the percentage increase in drag force is 17.28 and 2.64 for the Cases 3 and 4, respectively. It is also identified that with Cases 1 and case 2, fluctuating lift-signal is shifted either towards positive or negative y-direction depending on the direction of the approaching flow. With Case-1, drag is slightly reduced (0.7%) due to inclined approaching flow. But, with Case-2 drag increases (12.21%) due to increase in local confinement of cylinder. The percentage increase in maximum lift is 32.18 and 205.5%, respectively with Cases 1 & 2. This drastic rise in lift force with Case-2 is due to unequal confinement of the cylinder and approaching flow direction. It is also noticed that with Case-3, the crest of the waviness suppresses the shedding effectively and results in no fluctuation in lift. The quantitative results such as coefficient of drag, coefficient of lift and Strouhal number are computed for all the four cases are presented in the Table-2. The streamlines as shown in Figure 7 indicates the presence of vortex shedding for the Cases 1 & 2, and complete suppression of vortex shedding for the Cases 3 & 4. Finally, it is observed that the suppression of shedding is achieved by some penalty in increased drag or lift force on the cylinder. Hence, to reduce or nullify this effect the study can be extended to impose the waviness in out-phase configuration (OPC). With this OPC configuration the reduced flow passage between confining wall and cylinder surface can be avoided.

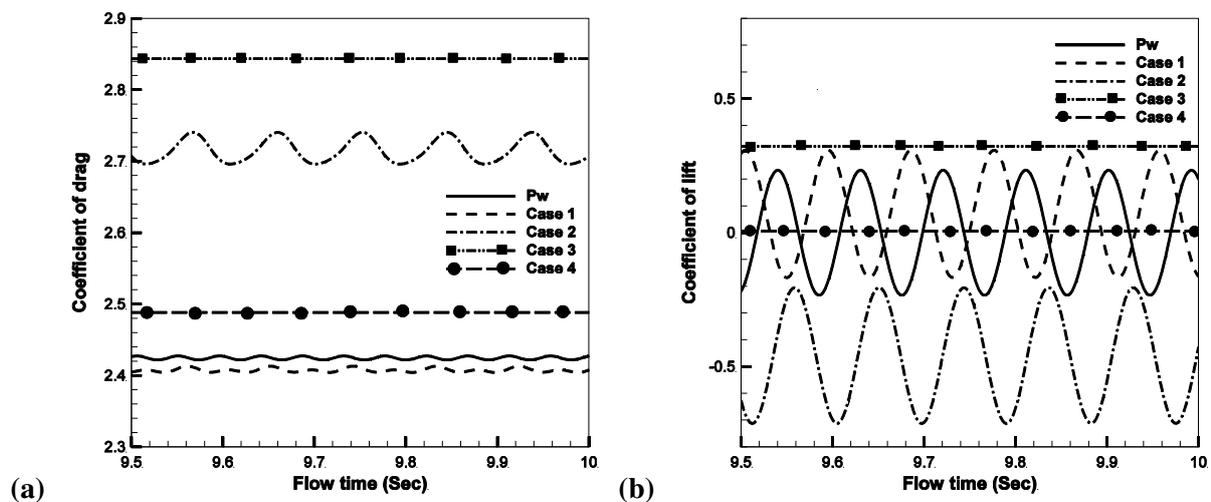


Figure 6. Effect of location of waviness on (a) C_D and (b) C_L

Table 2. Effect of placement of waviness on C_D , C_L and St

Config.	Mean C_D	Peak to Peak C_L	RMS C_L	Mean C_L	St
Pw	2.424	-0.233 to 0.233	0.165	0	0.355
Case 1	2.407	-0.167 to 0.308	0.181	0.032	0.347
Case 2	2.72	-0.205 to -0.712	0.493	-0.458	0.339
Case 3	2.843	No fluctuation	0.322	0.322	No shedding
Case 4	2.488	No fluctuation	0.005	0.005	No shedding

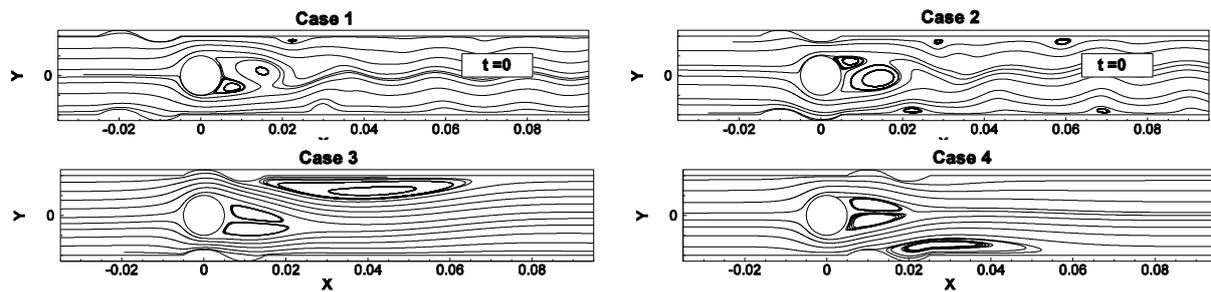


Figure 7. Streamline plots for various cases

5. Conclusion

The significance of local waviness in the confining side walls on vortex shedding from the cylinder surface has been studied using two dimensional numerical simulations at Reynolds number 200. Local waviness in the confining walls has been placed at four different locations with reference to cylinder center. In general, waviness located in upstream controls the shedding. Whereas, waviness in downstream completely suppresses the shedding. The flow direction approaching the cylinder, the gaps between the cylinder and the confining walls and the location of the crest region are the three major parameters that control the shedding characteristics. In the present work, the local waviness in the confining walls are in same phase, the study could be extended with waviness in different phase.

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