Numerical investigation of flow over a circular cylinder at different gap ratios

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Abstract. The present paper numerically investigates the three-dimensional fluid flow with emphasis on the cylinder and wall gap effect. The non-dimensional gap ratio (G/D), between the cylinder end and the wall, ranges from 0, 2.5, 5, and 7.5 for the Reynolds number 3.7×10^4. Numerical analysis was done with help of finite volume method, which brings the detailed information of flow at different gap heights. The reduction in the vortex shedding and increase in amplitude of frequency of the lift coefficient is observed with the reduction in the gap ratio. Thus, the drag and lift coefficients exhibit the influence of gap ratio on fluid structure in wake.

Keywords. Circular cylinder; Gap ratio; sub-critical Reynolds number range; Drag coefficients.

1. Introduction

The flow over a circular cylinder placed in adjacent to a wall has been a universal fluid flow problem from many years. Heat exchanger tubes and offshore pipelines are the practical applications of such problems. At unsteady forces, the intervention between cylinder and the wall leads to deviations. These interventions are observed in frequency of vortex shedding and bluff body characteristics. Many of the investigations were done over a cylinder near wall for turbulent flow [Bearman [5]; Ayukawa [6]; Price [7]; Bhattacharyya [8]; Wang [10]; Mahir [11]; Harichandan [12].

Achenbach [1] represented three basic flow regimes depending on the experiment. The pressure force, the drag force and the friction force were calculated with the results of experiment. He has defined three flow regimes: (1) subcritical- where the boundary layer separates in a laminar way; (2) critical- where the separation bubble is followed by turbulent flow; (3) supercritical- transition from laminar to turbulent boundary layer. As the Reynolds number increases, the transition point is shifted in the direction of the stagnation point. Achenbach [2] showed that the surface roughness influences the cross-flow around a circular cylinder. He has carried the experiment for the Aspect ratio 3.3 in the precritical regime. The local pressure and the skin friction near the cylinder was measured which helps in determining the total drag coefficient and percentage of friction as a function of Reynolds number and roughness parameter. In the transcritical regime, higher roughness leads to higher drag coefficient.

Roshko [3] showed that the transition at high Reynolds number (3.7×10^6) will increase the drag coefficient to 0.7 and then becomes constant. He has observed that changes in the drag coefficient will changes the base pressure coefficient. The changes in the drag coefficient, base pressure coefficient and Strouhal number will be dependent on the effect of Reynolds number on the wake mechanism. He has also observed that due to splitter plate used in the experiment the vortex shedding was suppressed.

Schewe [4] showed that due to transition from laminar to turbulent which has occurred only on one side of the cylinder gives unsteady flow and steady lift in the critical range. Transition- A, symmetric to asymmetric flow is accompanied by generation of circulation around the cylinder. Circulation is followed by a starting vortex. Transition- B, asymmetric to symmetric flow is due to second bubble formation on the other side of the cylinder. Due to circulation, the acceleration takes place on the side where the transition has occurred while the deceleration takes place on the side and hence the bubble formation takes place. As the Reynolds number increases, the asymmetric state becomes unstable.

Zdravkovich [5] conducted experiments to investigate flow cross a cylinder in close adjacent to a plane wall for Re=2.5×104 and 4.5×104. He inspected that the boundary layer was formed on the wall. For G/D less than 0.3, a traditional vortex shedding and independent Strouhal number was observed. At G/D less than 0.3, the suppression of vortex shedding was observed. Pressure measurements indicated that the wall effect was observed for G/D<1.0 and for G/D<0.6, there was a sudden decrease in the base pressure coefficient with reduction in the gap height. For small gap heights, the front stagnation point drifted close to the plane wall which leads to the development in steady mean lift force dispersing the cylinder off the wall. Aukawa [6] did numerical simulation of the flow cross a square cylinder. He has recognized that, increase in the shear rate will have an impact on the Strouhal Number which decreases the Strouhal number although there was no strong diversity in the Strouhal Number. C_D, the drag coefficient fluctuated because of the position of the formation of large vortices in the wake. At greater shear rate, the Von-Kármán street was crippled down and the flow arrangement for downstream was identical at any instant. Price [7] had conducted experiment to investigate the flow cross a circular cylinder in adjacent to a wall for range, 1200<Re<4960. He has observed four definite regions for expressing the flow for the suppression of vortex shedding. As the gap ratio increases, the size of the upstream separated region decreases. In this case, the coupling between the shear layer and the boundary layer was observed. The shear layers shed from the cylinder enfold and form an alternating vortex shedding pattern, where the length of the separation bubble is very small. In such case, there is no separation from the cylinder upstream whereas at cylinder downstream, a periodic vortex shedding is observed. As the G/D increases, the coupling between the vortex shedding from the cylinder and the wall boundary layer decreases. This significantly changes the lift and drag forces which are acting on the body and the frequency of vortex shedding.

Bhattacharyya [8] investigated numerically the square cylinder wake placed parallel to a wall for Re=1400 and gap ratio 0.5 to 0.25 times the height of the cylinder. The wall causes difference in strength between two vortex rows. He has inspected that there is gradual reduction in the mean lift coefficient and increase in the drag coefficient as the Reynolds number increases. Bhattacharyya [9] has observed that there was a difference in the strength of two vortex rows for a square cylinder at Re=1400. He also observed that with the reduction in the gap height, the strength of the secondary vortices reduces. Wang [10] has observed that the flow patterns depend on the gap ratio. Strouhal number is unresponsive to gap ratio if the vortex shedding starts. Mahir [11] investigated numerically the effect on the structure of flow in the square cylinder for Re=175,185 and 250 at gap ratios 0.2 to 4. At Re=185, for gap ratios larger than G/D=1.2, vortex structures of mode A (mode A type refers to the usual streamwise vortices which appear in the wake with spanwise length of three cylinder diameter and mode B type refers to the one or more irregular streamwise vortices with mean spanwise length of one cylinder diameter.) type were formed whereas at G/D=0.8, vortex structures of mode B type were observed. Below G/D=0.5, no more mode A type and mode B type was observed. At Re=250, for larger gap heights, vortex structures of mode B type were observed. Harichandan [12] has observed that the vortex structures formed over a wall in the boundary layer interacts with the vortex structures formed in the shear layer emerging from the stagnation point on the surface of the cylinder. Rao [13] has investigated numerically the flow over a cylinder for Re<200. He has observed that a single recirculation was formed in the wake at small gap heights and the cylinder wake becomes symmetrical due to formation of the secondary recirculation zones as the gap height increases. He has shown a linear increase in the Strouhal number.

Jaiman [14] has observed that the early transition takes place at Re=200 for tandem cylinders in close proximity to a moving wall. The existence of a moving wall accelerates the commencement of the shedding for a tandem cylinder and the also reflects the fluctuations in the drag and lift values. The literature review revealed that the flow past circular cylinder with different gap ratio for sub-critical Reynolds number is not done systematically. The present work represents the three-dimensional numerical simulations for a cylinder in adjacent to a wall at contrasting gap ratios for the sub-critical Reynolds number range to determine the wall effects on the flow structure in the wake. Apart from this, the dynamics of flow is explained in term of frequency spectrum.

2. Problem Definition

Figure exhibits the simplified diagram of cylinder with a wall. A cylinder of 'D' diameter is moving at G gap height from the wall. The two controlling parameters are: the Reynolds number, Re=UD/ ν, where ν is the kinematic viscosity of the fluid and the gap ratio, G/D. In this paper, the gap ratio ranges between (0<G/D<7.5) for Reynolds number (Re=3.7x 10^4).

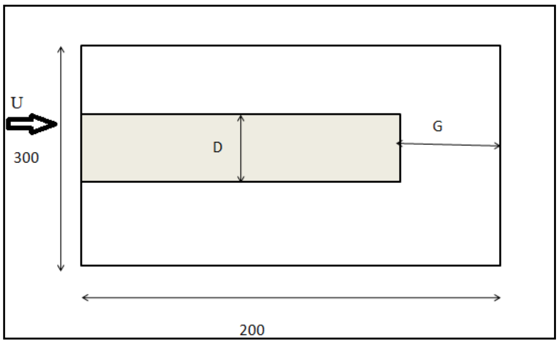

Figure 1. Schematic diagram of a cylinder with gap

The continuity and the momentum equations for incompressible viscous flow are given as (Navier-Stokes equations):

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{\partial p}{\partial y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (2)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (3)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

Where u, v and w are velocity components in x, y and z coordinates respectively;

'p' is the pressure;

't' is the dimensionless time.

3. Computation

The geometry of actual size half-section with the test model was generated using ANSYS-18.1, a commercially available software package. An unstructured mesh was generated for the modeled geometry such that the mesh is fine near the cylinder and coarse in the rectangular domain maintaining a quality of mesh of 0.59. During the computation at inlet, free-stream velocity of 30m/s and

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turbulence level of 5% were defined as input boundary conditions. Remaining walls of the domain were defined as a wall with no-slip condition. For all the computation, the reference pressure was 50,000 Pa was used.

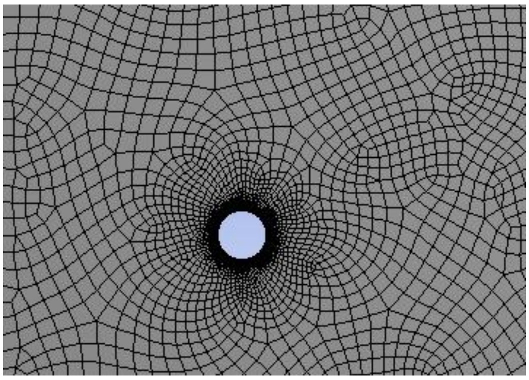

Figure 2. Meshing near the cylinder and the domain

4. Grid Independency

Figure 3 represents the drag coefficient of a cylinder for 200mm height (20mm dia) at different nodes, i.e., 50000, 100000, 150000, 200000, and 250000. It is clear from the figure 3, that the drag coefficient increases as the no. of nodes increases and then becomes constant at 4th and 5th node i.e., 200000 nodes and 250000 nodes. Therefore, further change in the meshing or refinement of meshing will show no effect on the drag coefficient values of the circular cylinder.

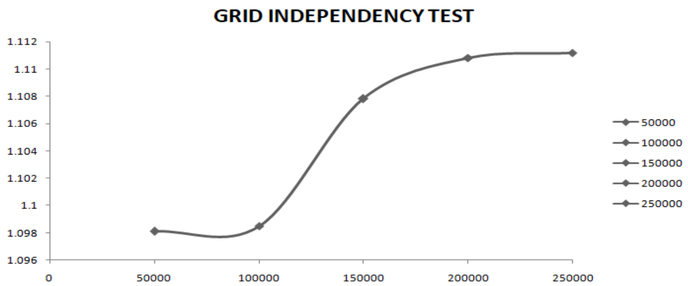

Figure 3. Grid Independency for different nodes

5. Results and Discussions

5.1. Drag Coefficient

Computational results mainly depend on the quality of mesh and selection of suitable solver control parameters. Figure 4 indicates that the increase in gap height reduces the drag coefficient at sub-critical range.

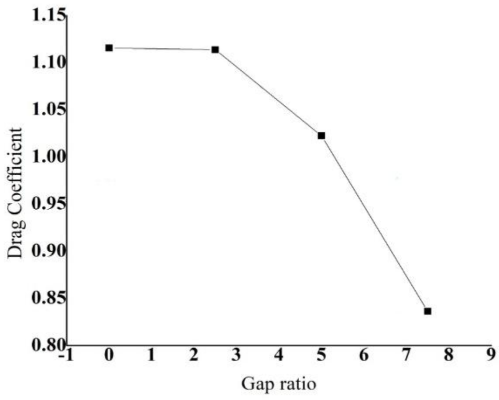

Figure 4. Drag coefficient at different gap ratios

5.2. Vortex Structures

The 3-D simulations were done at contrasting gap ratios, G/D=0, 2.5, 5, and 7.5 for Reynolds number (sub-critical), Re=37×10^4 to inspect the wall effects in the cylinder wake. For high Reynolds number range, Re=37×10^4, primary (counterclockwise direction) vortex structures and secondary (clockwise direction) vortex structure are observed at G/D=7.5(high gap ratios). Figure 6 represents the vorticity for particular gap ratios (G/D=0, 2.5, 5, and7.5) at z-mid-plane:

Fig.5 (a) represents the case in which the wake transition length (define the transition length or put the name as transition) is large and occurs early. The primary (counterclockwise direction) and secondary (clockwise direction) vortex structures starts coupling. This coupling effect is observed due to the shear effect produced by the plane wall. Fig.5 (b) represents the transition in wake takes place away from the cylinder wake. With the increase in the gap height, the transition length of the wake decreases. The wall effect has an impact on the stagnation point which tends to shift towards the wall. As the gap ratio increases, the transition length of the vortices decreases as seen in Fig.5 (c). Fig.5 (c) represents the case where the vortices are shed in an alternate fashion and the wall effect is diminished, whereas in Fig.5 (d), shear rate effect is absent in the cylinder wake. In such cases, the vortices are shed in alternate fashion. In this case large Von-Kármán-type vortices were generated in the cylinder wake and there is no synergy amidst the cylinder and boundary layer formed on the wall.

Fig.6 represents the vorticity in y-mid-plane. Fig.6 (a) indicates that the vortex shedding has been suppressed. Fig.6 (b) represents that impact of the wall shear rate leads to the shedding of vortices from the cylinder upstream, where the secondary vortices have large length compared to the primary vortices. Fig.6 (c) represents the shedding of vortices with minor shear rate effect whereas Fig.6 (d) represents the shedding of vortices in an alternate fashion with no shear wall effect. This is explained with frequency spectrum obtained for all four cases in next section.

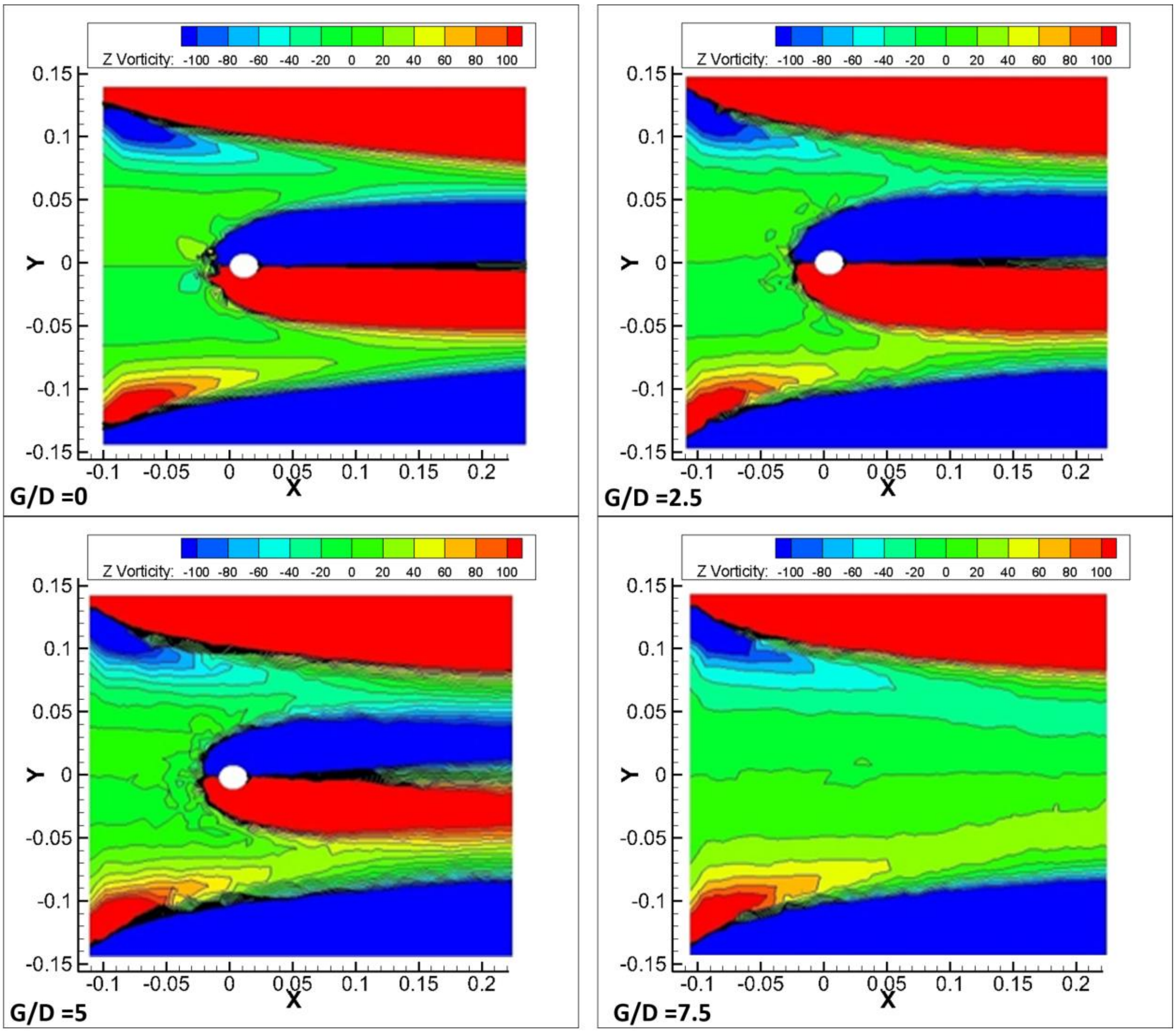

Figure 5. z-vorticity at z=0(mid-plane): a) G/D=0, b) G/D= 2.5, c) G/D= 5 and d) G/D=7.5

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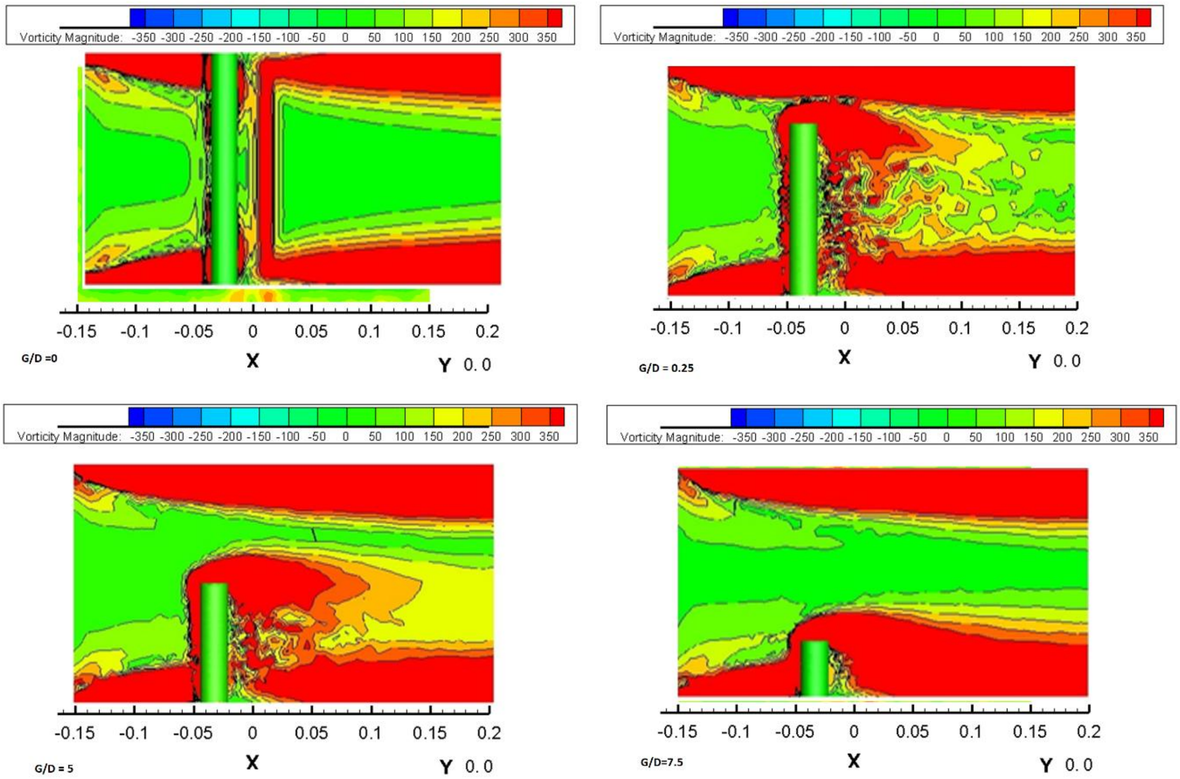

Figure 6. Vorticity magnitude contours: a) G/D=0, b) G/D= 2.5, c) G/D= 5 and d) G/D= 7.5

5.3. Frequency Spectrum

Figure 7 depicts that with increase in the G/D, the frequency of lift coefficient decreases. In Fig.7 (a), the frequency is observed as 439 Hz which is higher as compared to the case G/D=2.5; in Fig.7 (b) where frequency reduced to 316 Hz. Whereas in Fig.7 (c), the frequency is further reduced to 229 Hz and it decreases to 160 Hz in the case when G/D= 7.5 in Fig.7 (d). It is clear from the Fig. 7 that the frequency of the lift coefficient decreases with increase in the gap ratio.

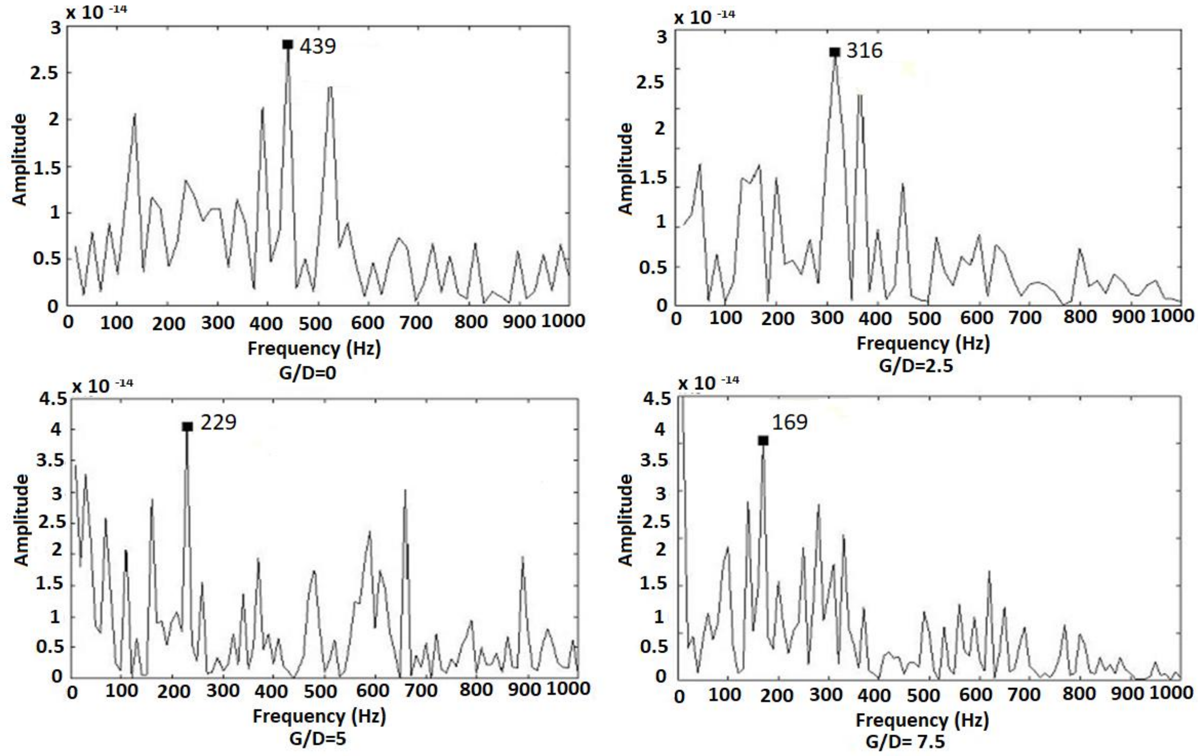

Figure 7. frequency spectrum for circular cylinder: a) G/D=0, b) G/D= 2.5, c) G/D= 5 and d) G/D= 7.5

6. Conclusion

We have numerically performed the fluid flow analysis of a circular cylinder at contrasting gap heights at sub-critical Reynolds number range of 3.7x104. Three-dimensional simulations were carried out with proper grid independent to show the impact of wall on the vortex structures formed in the cylinder wake. The bluff body characteristics were computed and it was inspected that the amplitude of lift coefficients and the drag coefficient decreases, the frequency of shedding increases and with the increase in G/D, there is a decrease in the transition length of the vortices.

7. References

[1] Achenbach E 1968 Distribution of local pressure and skin friction around a circular cylinder in cross-flow up to Re=5×10^6, Journal of Fluid Mechanics . **34**, 625-639.

[2] Achenbach, E 1971 Influence of surface roughness on the cross-flow around a circular cylinder, Journal of Fluid Mechanics .**46**, 321-335.

[3] Roshko, A 1961 Experiment on the flow past a circular cylinder at very high Reynolds number, Journal of Fluid Mechanics. **10,** 345-356 .

[4] Schewe, G 1983 On the force fluctuations acting on a circular cylinder in cross-flow from subcritical up to transcritical Reynolds number, Journal of Fluid Mechanics **133,** 265-285

[5] Bearmann, P.W., Zdravkovich, M.M 1978 Flow around circular cylinder near a plane boundary, Journal of Fluid Mechanics . **89,** 33-47.

[6] Ayukawa, K., Ochi, J., Kawahawa, G., Hirao, T 1993 Effects of shear rate on the flow around a square cylinder in a uniform shear flow, Journal of Wind Engineering and Industrial Aerodynamics. **50,** 97-106 .

[7] Price, S.J., Sumner, D., Smith, J.G., Leong, K., Paidoussis, M.P 2002 Flow visualization around a circular cylinder near to a plane wall, Journal of Fluids and Structures. **16,** 175-191.

[8] Bhattacharyya, S., Maiti, D.K. 2004 Shear flow past a square cylinder near a wall, International Journal of Engineering Science. **42,** 2119-2134.

[9] Bhattacharyya, S., Maiti, D.K. 2005 Vortex shedding from a square cylinder in presence of a moving wall, International Journal of Numerical Methods in Fluids. **48**, 985-1000.

[10] Wang, X.K., Tan, S.K. 2008 Comparison of flow patterns in the near wake of a circular cylinder and a square cylinder placed near a plane wall ,Ocean Engineering. **35,** 458-472.

[11] Mahir, N 2009 Three-dimensional flow around a square cylinder near a wall ,Ocean Engineering. **36,** 357-367.

[12] Harichandan, A.B.,Roy,A 2012 Numerical investigation of flow past single and tandem cylindrical bodies in the vicinity of a plane wall, Journal of Fluids and Structures.**33,** 19-43.

[13] Rao, A., Thompson, M.C., Leweke, T., Hourigan, K. 2013 The flow past a circular cylinder at different heights above a wall, Journal of Fluids and Structures. **41,** 9-21.

[14] D'Souza, J.E., Jaiman, R.K., Mak, C.K. 2016 Dynamics of tandem cylinders in the vicinity of a plane moving wall, Computers and Fluids. **124,** 117-135 .