INFLUENCE OF A MOVING WALL CONTOUR IN THE VORTEX STREET OF A CIRCULAR CYLINDER

Ivan Zampiron
Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul.
Av. Bento Gonçalves, 9500, CEP 90650-001, Porto Alegre - RS - Brasil
izampiron@yahoo.com.br

Marcelo de Araujo Vitola
Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul.
Av. Bento Gonçalves, 9500, CEP 90650-001, Porto Alegre - RS - Brasil
mvitola@yahoo.com.br

Edith Beatriz Camaño Schettini
Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul.
Av. Bento Gonçalves, 9500, CEP 90650-001, Porto Alegre - RS - Brasil
bcamano@iph.ufrgs.br

Jorge Hugo Silvestrini
Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio Grande do Sul
Av. Ipiranga, 6681, CEP 90619-900, Porto Alegre - RS - Brasil
jorgehs@pucrs.br

Abstract. *The uniform flow around an isolated circular cylinder was widely studied in many practical applications in the last decades. However, in the case where the axis of the cylinder is parallel to a wall, the results still present some misunderstood. This type of flow is considerably complex and depends principally of three parameters: a) the relation between the boundary layer thickness (δ) and the cylinder diameter (D); b) the velocity gradient in the boundary layer, and c) the gap ratio. In the present work, the influence of the boundary layer was suppressed using a moving wall. This case has practical applications in the simulation of flows around automobiles in wind tunnels and cylinders on moving sediment layers. The study use numerical simulation of the Navier-Stokes equations of two-dimensional incompressible flow, with a compact finite differences scheme, for the spatial discretization, and a third-order low-storage Runge-Kutta method, for the time integration. A virtual boundary method is used to include the cylinder and the wall in the simulations. The presented results correspond to Re = 300 and, the gap ratio in the range 5.0 – 0.1. The particular case of 5.0 corresponds to the flow around an isolated circular cylinder, or either, the effect of the wall is partially worthless. The effect of the wall on the flow is evaluated through the analysis of the streamlines and the velocity fields, the variation of the Strouhal number and the drag and lift coefficients. The results indicate that with the reduction of the gap, an increase of the aerodynamic coefficients and the Strouhal number is verified. However, this behavior inverts when the gap ratio approaches to zero. In none of the studied cases, the suppression of the vortex shedding was observed.*

Keywords*: Circular cylinder, Moving wall, Vortex shedding, Virtual boundary methods.*

1. Introduction

There are many examples of practical applications in which cylindrical structures are found near to a solid surface or another structure. The flow around a pipeline near to the sea bottom, heat exchangers, and sets of risers, and sets of cables of transmission lines are some examples. However, this type of flow has received less attention when compared with flow around of an isolated cylinder.

The presence of the solid surface modifies the vortex shedding, the formation of the vortex street and the forces that acts upon the cylinder. In the case of plain surfaces, these modifications are due the boundary layer that develops over the plate upstream of the cylinder. Three non-dimensional parameters control this kind of flow: i) the relation between the boundary layer thickness (δ) and the gap (G), ii) the vertical gradient of streamwise velocity existing in the boundary layer (β), and iii) the relation between the gap (G) and the cylinder diameter (D).

In last the two decades, some works have been developed with the objective of understand the physical mechanism which govern the flow around a circular cylinder near to a plane wall, mainly for moderate Reynolds numbers (Angrilli, 1982; Bearman, 1978; Grass, 1984; Lei, 2000; Lei , 1999; Price, 2000; Taniguchi, 1990; Zdravkovich, 1985).

The main characteristic observed in these works is the vortex shedding suppressing as the cylinder approaches to the wall. This occurs at value of the gap defined as critical gap. The existence of this suppression is still questioned by some authors (Price et al., 2000), moreover, the gap ratio where it occurs and the mechanism that leads to this suppression isn't well defined. Another characteristic observed in the majority of the works is the existence of a vertical force that tends to move the cylinder away from the wall, however Zdravkovich (1985) showed that this behavior depends on the boundary layer characteristics while Lei et al. (2000) had not observed the existence of this force.

The misunderstood shown before could be explained by the complexity of the flow around a cylinder near a plane wall. A common approach to study complex flows is to understand physics for simpler case, with this aim in this work we present the result of flow around a circular cylinder near a moving plane wall. In this case, the effect of the boundary layer thickness and the velocity gradient are eliminated, and the influence of the wall over the vortex street could be studied. This work is a continuation of that published in XIX Congresso Regional de Iniciação Científica e Tecnologia em Engenharia, however with more values of gap.

2. Numeric metod

The incompressible Navier-Stokes equations

$$\vec{\nabla}\cdot\vec{u} \;=\; 0 \qquad (1)$$

$$\frac{\partial\vec{u}}{\partial t}+\vec{u}\cdot\vec{\omega} \;=\; -\vec{\nabla}p+\nu\nabla^{2}\vec{u}+\vec{f} \qquad (2)$$

where $p(\vec{x},t)$ is the modified pressure field, $\vec{u}(\vec{x},t)$ the velocity and $\vec{\omega}(\vec{x},t)$ the vorticity, are solved on a uniform rectangular non-staggered grid. The external force $\vec{f}(\vec{x},t)$ is used to include the virtual cylinder and the moving wall. The spatial derivatives are evaluate using a sixth-order compact difference schemes (Lele, 1992) in all the mesh points except near the in and outflow boundaries were single sided schemes of third order are employed for the x-derivates for i = 1 and i = nx, while centered fourth order scheme is used for i = 2 and i = nx-1. The time integration is performed with a third-order low-storage Runge-Kutta method (Williamson, 1980).

The virtual boundary method is used to include the cylinder and the moving wall in the simulation. It added to the momentum equation a feedback unsteady forcing term $\vec{f}(\vec{x},t)$ for the imposition of the boundary condition within the flow field (Goldstein et al. 1993),

$$\vec{f}(\vec{x},t)=\varepsilon(x)\left[\alpha\cdot\int_{\infty}^{t}(\vec{u}(x_s,t)-\vec{u}_s)dt+\beta\cdot(\vec{u}(x_s,t)-\vec{u}_s)\right] \qquad (3)$$

where t is the time, $\varepsilon(x)$ is a scalar field which defines the localization of the immersed boundary , α and β are negative constants and u_s is the immersed boundary velocity, which was set as null for the circular cylinder and equal to the freestream velocity for the moving wall.

More details about the numeric code can be obtained in Lardeau *et al.* (2002) and Silvestrini and Lamballais (2002) and more details about the virtual boundary in Lamballais and Silvestrini (2002).

The layout of the computational domain used is shown in Fig. 1. The cylinder axis is normal to the plan xy and it is located X_c from the inflow and G from the moving wall.

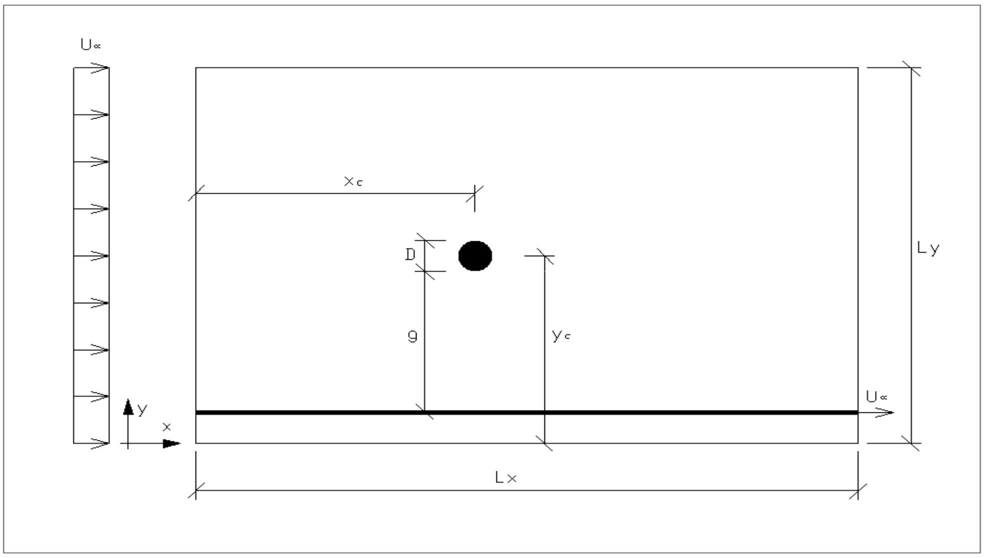


Figure 1. Scheme of the calculation domain

At the inflow section uniform velocity for the streamwise velocity was set with null vertical velocity. At the outflow boundary are deduced when solving a simplified convection equation. And free-slip boundary condition was applied to the upper/lower boundary. No perturbation was superimposed to the inflow mean velocity.

The numerical code, described briefly in this section, was submitted to some tests for the case of uniform flow with Reynolds number 300 to define the necessary computational domain with the aim of minimize the computational cost and to get real values of the Strouhal number and the aerodynamic coefficients (Vitola *et al.*, 2004). In Table 1 the aerodynamic coefficients and the Strouhal number obtained for two different resolutions are presented, as well the references values. The difference between the present results and the reference value (Mittal and Balachandar, 1997) is less then 7% this difference is related with dubiousness of the virtual boundary method and the blockage effect.

The results are presented here for the flow past a circular cylinder near a moving wall at Re=300 and gap ratio in the range of 0.1-2.5. The main characteristics of the computational domain used in all this simulation are shown in Tab. 2.

Table 1: The mean drag, rms litf coefficients and Strouhal number for different resolutions of the computational grid, for Re = 300.

Resolução	CD	CL’	St
D = 18Δ	1.690	0.788	0.192
D = 36Δ	1.476	0.694	0.210
Mittal and Balachandar (1997)	1.38	0.65	0.213

Table 2: Numerical parameters of the computational domain.

Lx	19D	Domain size in direction x
Ly	12D	Domain size in direction y
Xc	8D	Localization of the cylinder center in direction x
D	36Δ	Grid resolution in directions x and y
α, β	-10000, -100	Parameters of the virtual boundary method
Nx, Ny	685, 433	Number of grid points in direction x and y.
T	≈350	Total time of simulation

3. Results

3.1. Vorticity Fields

Figures 2 shows the instantaneous vorticity field for gap ratio in the range of G/D = 2.5 - 0.1. The vorticity structure observed for G/D = 2.5 is very similar to the von Kármán vortex street. A very week interaction between vortex shed from the cylinder with the moving could be observed. Reducing the gap to 1.0, the vortex street is still evident but the interaction between the vortices shed from cylinder with the moving wall is stronger. The induced boundary layer separated from the wall in a periodic fashion at the same frequency of the vortex shedding. It has the same vorticity sign as the upper shed vortices from the cylinder.

Reducing the gap ratio to G/D =0.5, the vortex shedding is still evident, but the vortex street loose his symmetry and displace away from the wall. Upstream of the cylinder a very small separation occurs. Under the cylinder and downstream of it a more evident boundary layer occurs, which separate from the moving wall at the same frequency of the vortex shedding in the same way as for the previous case. The main difference is that after this boundary layer separates it interacts with the vortex shed from the cylinder and create region of up and down flow.

At gap ratio of G/D = 0.1, the vortex shedding still evident, but the vorticity structure is completely asymmetric and the formation of vortex street is completely different from the traditional von Kármám vortex street. The outer shear-layer rollup and form clearly a vortex that grow and induce the formation of a boundary layer over the moving wall. This boundary layer seems to be the source of vorticity to form the inner vortex, not the inner shear layer of the lower side of the cylinder. As this inner vortex grows it cut the vorticity from the outer vortex that is shed from the cylinder. This mechanism of vortex shedding is completely different from the usual case of isolated cylinder.

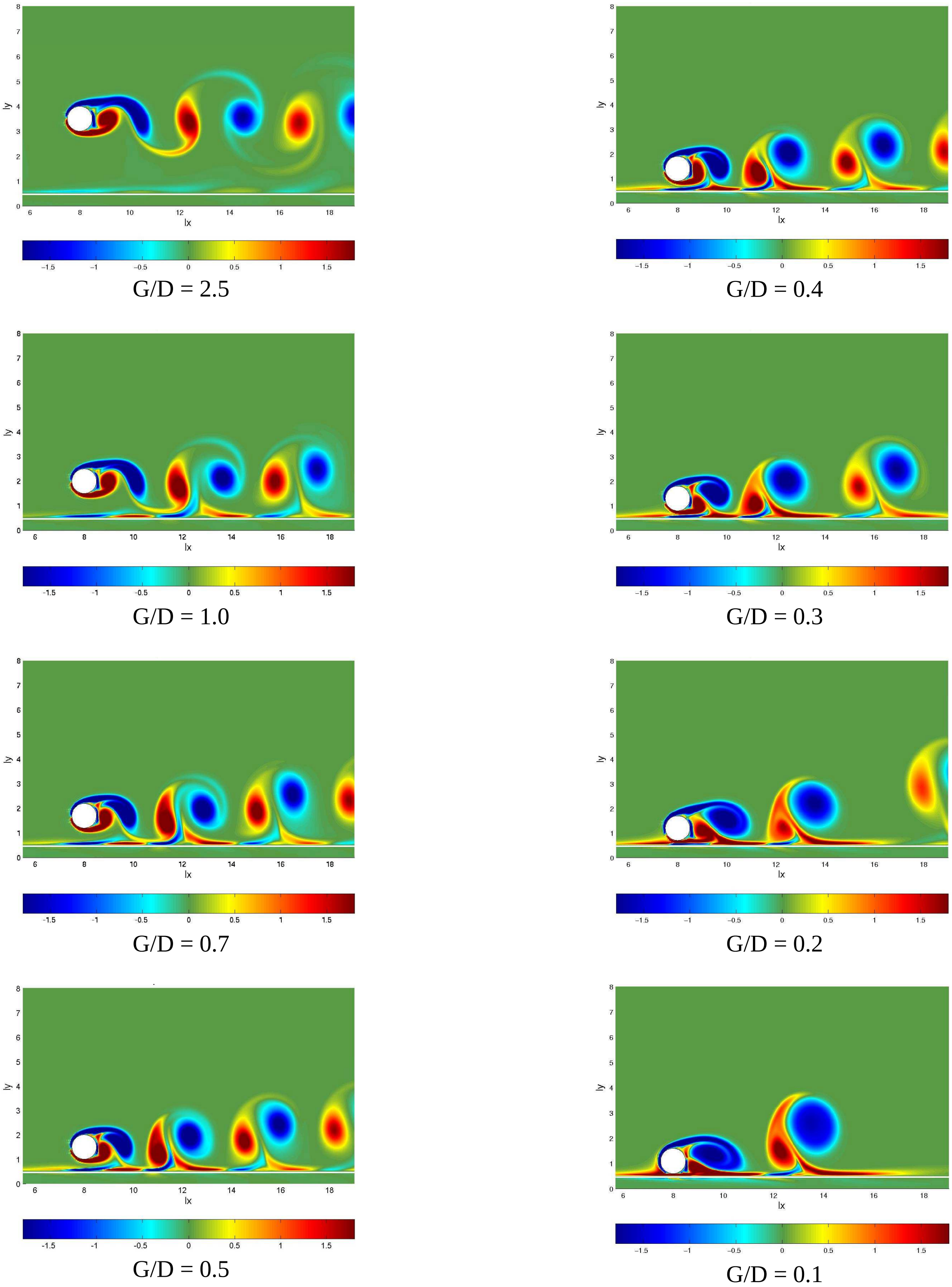


Figure 2. Instantaneous vorticity field for gap ratio in the range of G/D = 2.5 - 0.1.

3.2. Mean fields

The mean streamline fields for different gap ratios are presented in Fig. 3. For gap ratio 1.5, the field is very similar to that observe in the case of an isolate cylinder. As the gap ratio is reduced the asymmetry of the field is evident. For gap ratio below 0.4, we could be observed that the stagnation point is dislocated in the direction of the moving wall. This behavior is more evident for smaller gaps. For gap ratio lower than 0.2 the formation of two asymmetric bubbles downstream of the cylinder is observed. And at gap ratio 0.1 the flow seems to be very weak or absent between the cylinder and the moving wall and begins to create a bubble of recirculation upstream of the cylinder.

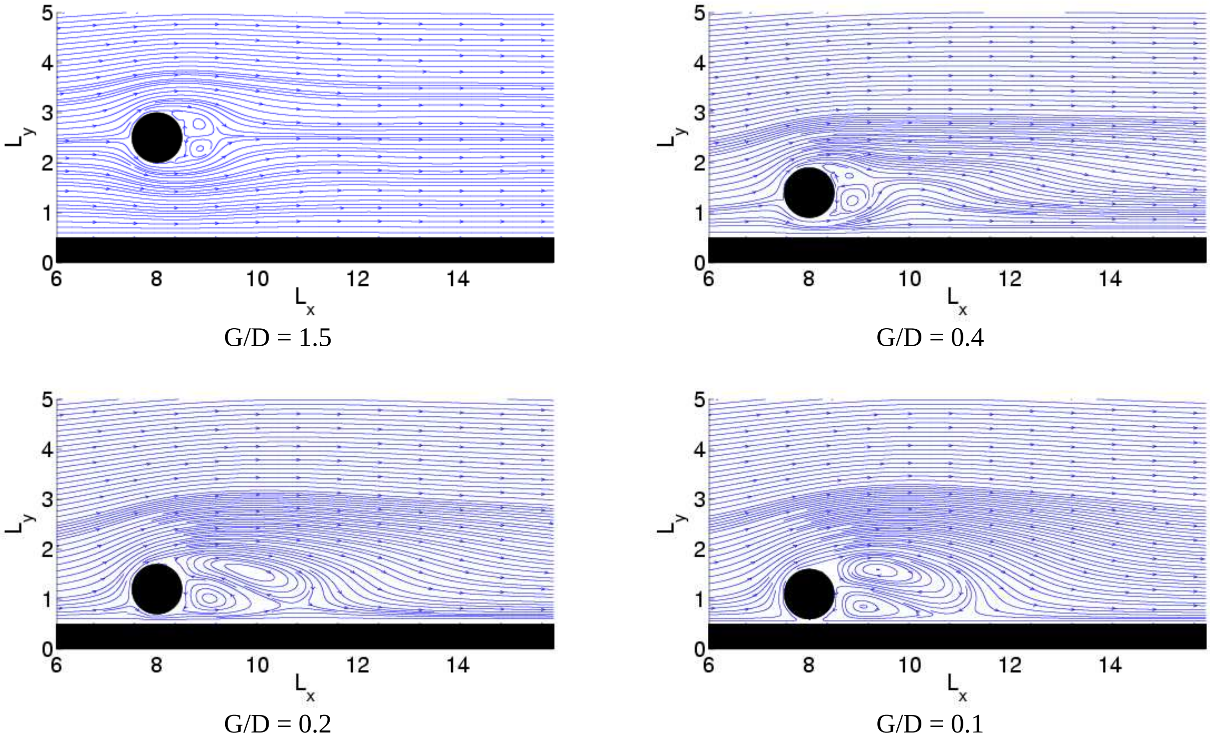


Figure 3. Mean streamlines velocity fields.

The asymmetry of the flow and the dislocation of the stagnation point are confirmed by the mean vertical velocity field, shown in Fig. 4.

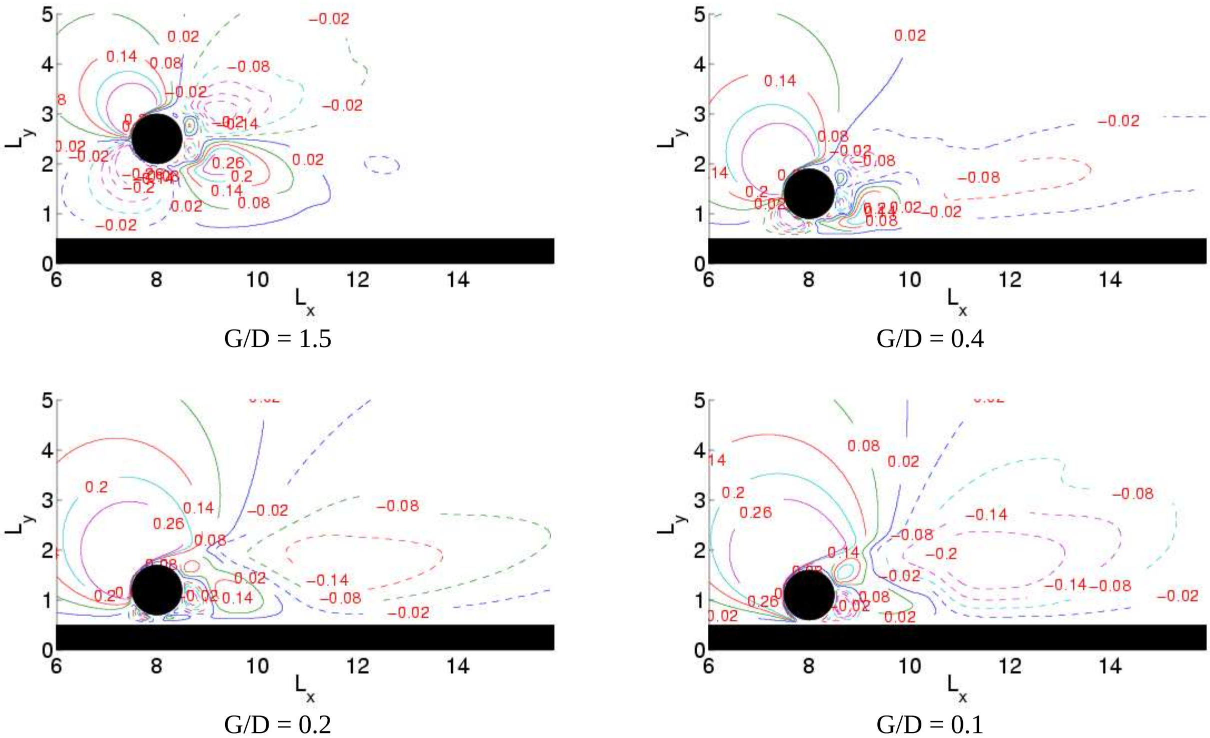


Figure 4. Isolines of mean vertical velocity.

3.3. Strouhal number

The behavior of the Strouhal number is presented in Fig. 5. Theses values were obtained from the analysis of temporal series of the lift coefficient, as recommended by Lei *et al.* (1999). This is due the fact that when exist an asymmetry in the flow field the position for which the measurements are made could influence the analysis, as was observed by Bearman and Zdravkovich (1978).

The Strouhal number increase as the gap ratio is reduced, until the gap ratio is 0.7. After that a rapidly decrease with the gap ratio is observed. The increase tendency could be explained by the acceleration of the flow that occurs between the cylinder and the moving wall, which cause a faster interaction between the outer and the inner vortex. The reduce tendency, for gap ratio less than 0.7, could be explained by the change of formation mechanism for small gap ratio and the flow reduce between the cylinder and the moving, which seems to ceases for gap ratio 0.1.

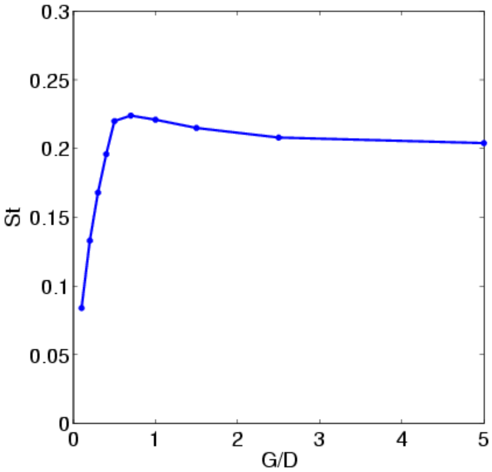


Figure 5. Variation of the Strouhal number with the gap ratio

3.4. Drag coefficient

The variation of the mean drag coefficient with the gap ratio is shown in the Fig. 6. It is clearly that there is an increase in the drag with the reduction of the gap ratio. This behavior is change for gap ratio 0.4, after this point the drag has a decrease with the gap ratio. This behavior is similar to that observed for the Strouhal number, only the point where occurs the decrease is different. The first trend observed in Fig. 6 for the behavior of the drag coefficient is not understood yet, but the we believe that it is relate with the change that occurs in the processes of vortex formation and shedding. The second trend confirms that when the cylinder is seated on the plane wall (G/D ≈ 0.0) it is subject to the minimum drag.

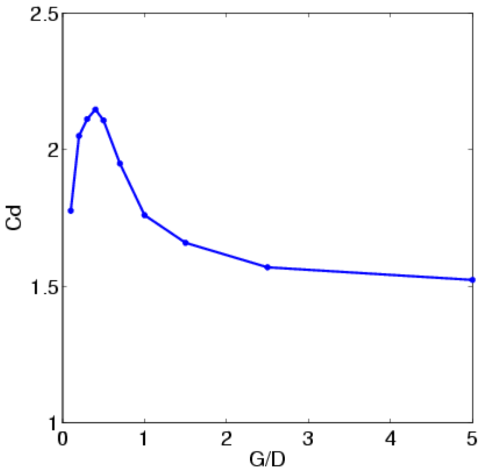
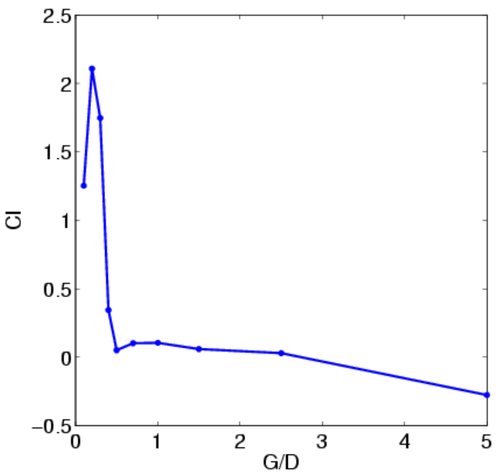


Figure 6. Variation of the Strouhal number with the gap ratio

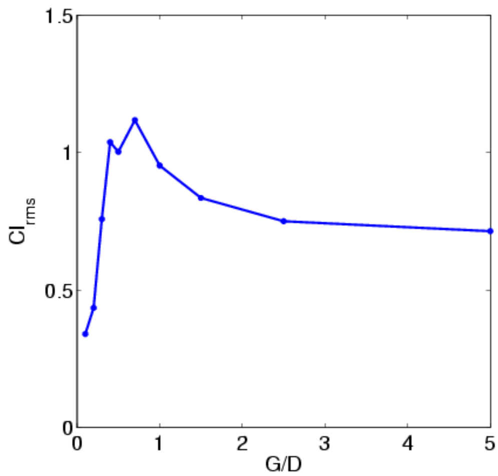
3.5. Lift coefficient

The variations of the mean and *rms* lift coefficient with the gap ratio are presented in Fig. 7. For values of the gap ratio greater than 0.6 the mean lift coefficient is approximately zero and does not change much with the gap ratio (Fig. 7a). This reveal that the effect of the moving boundary in the lift coefficient is very limited or null for gap ratio greater than 0.6. In the range of 0.4-0.6 the mean lift has a significant increase. The positive value observed in this range indicate the existence of a mean force that tend to move the cylinder away from the wall, similar which was observed for a steady wall (Lei et al, 1999). This force is due to the displacement of the front stagnation point in the direction of the wall, which create asymmetry in the pressure fields. The strong reduce of the mean lift for gap ratio 0.1 is due the ceases of flow between the cylinder and the moving wall.

The increase of the fluctuations of the lift coefficient (Fig. 7. (b)), for G/D < 0.7, is due to intensification of the turbulence caused for the approach of the wall. The decrease is due to reduction of the flow between the cylinder and the wall.



(a)



(b)

Figure 7. Variation of the mean value (a) and *rms* value (b) of the lift coefficient, with the gap ratio.

4. Conclusions

The results show as the presence of a moving wall affects the behavior of the Strouhal number and the aerodynamic coefficients. A change in the behavior of these parameters with the reduction of the gap was observed, however, the point where this change occurs is different for each analyzed parameters.

The preliminary analysis of the presented results gives an idea of the mechanisms that control each of the parameters, and also evidences the necessity of an analysis more detailed to describe the physical mechanism that governs this phenomenon.

The suppression of the vortex shedding was not observed. It is belived that this is a behavior influenced for the absence of the boundary layer.

5. Acknowledgements

The authors thanks the FAPERGS and CNPq for the scholarship received.

6. References

Angrilli, F., Bergamaschi S., and Cossalter V., 1982. “Investigation of wall induced modification to vortex shedding from a circular cylinder”. Journal Fluids Mechanics, vol. 104, pp. 518–522.

Bearman, P. W. and Zdravkovich, M. M., 1978. “Flow around a circular cylinder near a plane boundary”. Journal Fluid Mechanic, vol. 89, n. 1, pp. 33–47.

Goldstein, D., Handler, R., and Sirovich, L., 1993. “Modeling a no-slip boundary condition with an external force field”. J. Comp. Phys., vol. 105, pp. 354–366.

Grass, A. J., Raven P.W.J., Stuart R.J. and Bray J.A., 1984. “The influence of boundary layer velocity gradients and bed proximity on vortex shedding from a free spanning pipeline”. Journal of Energy Resources Technology, vol. 106, pp. 70–78.

Lamballais, E. and Silvestrini, J. H., 2002. “Direct numerical simulation of interactions between a mixing layer and a wake around a cylinder”r. J. Turbulence, vol. , pp. 3–28.
Lardeau, S., Lamballais, E. and Bonnet, J., 2002. “Direct numerical simulation of a jet controlled by fluid injection”. Journal of Turbulence, vol. 3, pp. 002.
Lei, C., Cheng, L. and Kavanagh K., 1999. “Re-examination of the effect of a plane boundary on force and vortex shedding of a circular cylinder”. Journal of Wind Engineering and Industrial Aerodynamics, vol. 80, pp. 263–286.
Lei, C., Cheng, L., Armfield, S.W. and Kavanagh K.,2000. “Vortex shedding suppression for flow over a circular cylinder near a plane boundary”. Ocean Engineering, vol. 27, pp. 1109–1127.
Lele, S. K., 1992. “Compact finite difference schemes with spectral-like resolution. Journal of Computational Physics”, vol. 103, pp. 16–42.
Mital, R. and Balachandar, S., 1997. “On the inclusion of three-dimensional effects in simulation of two-dimensional bluff-body wake flows”. In Proceedings of the 1997 ASME Fluid Engineering Division Summer Meeting, pp. 1–10.
Price, S., Sumner D., Smith J. G., Leong K., and Paidoussis M. P., 2000. “Flow visualization around a circular cylinder near to a plane wall”. Journal of Fluid and Structures, vol. 16, n. 2, pp. 175–191.
Silvestrini, J. H. and Lamballais, E., 2002. “Direct numerical simulation of wakes with virtual cylinders”. Int. J. Comp. Fluid Dynamics, vol. 16, n. 4, pp. 305–314.
Taniguchi, S. and Miyakoshi, K., 1990. “Fluctuating fluid forces acting on a circular cylinder and interference with a plane wall”. Experiments in Fluids, vol. 9, pp. 197–204.
Vitola, Marcelo de Araujo ; Schettini, E. B. C. ; Silvestrini, Jorge Hugo . Vortex shedding from a cylinder in a constant-shear flow . In: 10th Brazilian Congress of Thermal Engineering and Sciences, 2004, Rio de Janeiro. Proceedings10th Brazilian Congress of Thermal Engineering and Sciences, 2004. v. 1. p. 11-21.
Williamson, J. H., 1980. “Low-storage runge-kutta schemes”. Journal of Computational Physics, vol. 35, pp. 48–56.
Zdravkovich, M. M., 1985. Forces on a circular cylinder near a plane wall. Applied Ocean Research, vol. 7, n. 4, pp. 197–201.

5. Responsibility notice

The authors are the only responsible for the printed material included in this paper.