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Numerical study of lock-in phenomena in 2D flow over a cylinder

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Abstract: The fluid flow over cylinders has been the object of study of many researchers and even today it is widely explored experimentally and computationally. In the present work it was studied the Lock-in Phenomena of the fluid flow over a cylinder of circular section. The study was based on a two-dimensional simulation of the fluid flow with low Reynolds numbers over a cylinder that can be stationary or moved periodically with given frequency and amplitude. This movement was imposed in the direction of the flow. This requires the use of irregular meshes in the simulation that increases the computational effort. For the simulations, the Immersed Boundary Method was used, allowing the use of Cartesian meshes. The time integration was carried out by a 4th order Runge-Kutta scheme. High orders compact difference schemes were used to calculate spatial derivatives. The Navier-Stokes equations were written in vorticity-velocity formulation. The results obtained showed a good agreement compared with experimental results.

Keywords: Immersed Boundary Method, flow over a cylinder, low Reynolds, Lock-in phenomena

NOMENCLATURE

f = frequency
u = velocity component in the streamwise direction x
v = velocity component in the wall normal direction y
p = pressure
f_r = relaxation term
F_x = Forcing term in the streamwise direction x
F_y = Forcing term in the wall normal direction y
Re = relative to the Reynolds number

Greek Symbols
ρ = the fluid density
ω = the vorticity

Subscripts
s = relative to Strouhal number
o = relative to cylinder oscillation

INTRODUCTION

The study of the dynamics of the flow over blunt bodies attracted the interest of many researchers in computational fluid dynamics, because of the great applicability in engineering. The understanding of the characteristics of these flows are of great importance in the design and optimization of structures such as power cables, bridge projects, heat exchangers tubes, riser tubes, the design of marines and lands vehicles, etc. Normally when these kind of flows becomes non stationary the body experiences a variation in drag and lift forces. These variations can cause structure failure of the body or a significant decrease in its lifetime. In the present work a forced oscillation of a circular cylinder was imposed in order to understand the interaction of the body oscillation with the oscillation imposed by the non stationary flow.

When a flow over a blunt body becomes unsteady a vortex shedding can be observed. If the body oscillates with a given frequency and amplitude, the flow can be influenced by this oscillation. When it happens it is called lock-in phenomena. These phenomena are of particular interest and were discovered over three hundred years ago when Christian Huygens observed that two pendula placed next to each other had a tendency to synchronize. As a consequence of vortex shedding induced resonance, the body oscillations can reach sufficient amplitudes such that body and wake oscillation frequency take on the same value. The vortex lock-in phenomena are also commonly referred to as vortex lock-on, phase locking, mode locking, and wake capture. The presence of certain sound fields was also found to cause vortex lock-in.

Various studies of lock-in phenomena can be found in the literature. Studies for high Reynolds numbers were performed by Barbi et al (1986). The Reynolds number adopted was $Re = 40.000$. The study was experimental using a circular cylinder in steady and oscillatory flows with non-zero mean velocity. The occurrence of lock-in phenomena was demonstrated and the experiments indicated that the shedding frequency might drift towards the driving frequency. Moreover, these results indicated that at the lowest frequency limit of lock-in, vortices are shed simultaneously on both sides of the model.

Choi et al (2002) investigated the effects of rotary oscillation on unsteady laminar flow past a circular cylinder. The numeric simulations were performed for the flow at Reynolds number $Re = 100$. It was shown that the forcing-frequency range of lock-in became wider as the rotational speed increased. In the non lock-in region, modulations in the velocity, lift and drag signals occurred and the modulation frequency was expressed as a linear combination of the forcing frequency and the vortex-shedding frequency. The work of Choi et al (2002) also show that the lowest values of the mean drag and the amplitude of the lift fluctuations occurred near the boundary between the lock-in and non lock-in regions irrespective of the Reynolds number investigated, but the amount of drag reductions was strongly Reynolds number dependent.

Also studying the vortex dynamics in a oscillatory flow, Kim et al (2003) investigated the variations of vortex dynamics using a time-resolved PIV system. Wake regions of recirculation and vortex formation, dynamic behavior of the shed vortices and the Reynolds stress fields were measured in the wake-transition regime at Reynolds number $Re = 360$. The occurrence of the vortex lock-in phenomena was verified when the oscillation frequency was set to be twice the natural shedding frequency. The measured mean recirculation and vortex formation regions exhibited that the lock-in phenomena substantially reduce the wake size and shift the flow energy closer to the cylinder base. The results showed that the shed vortices in lock-in state pass through the reattachment point and approach the wake centerline in the far wake.

Griffin and Ramberg (1976) studied experimentally the wake of a cylinder vibrating in line with an incident steady flow. All the experiments reported were performed at a Reynolds number $Re = 190$. In the study some bounds for the lock-in regime within a wind-tunnel measurements were obtained. For this, the shedding frequency f_s of the stationary cylinder was measured and the cylinder was then oscillated at various frequencies and amplitudes near twice the Strouhal frequency. At each frequency the amplitude of oscillation was increased until the vortex-shedding frequency became synchronized with the cylinder motion. The lock-in range for the in-line vibrations extended from about 120% to nearly 250% of the Strouhal frequency f_s.

In the present work, the simulations of the flow around a circular cylinder will be made through the use of immersed boundary technique. This method was proposed by Charles S. Peskin (1972) with the objective to simulate the flow of blood through the human heart. A good review of the method proposed by Peskin can be seen in Peskin (2002). This method possesses different characteristics of the ones commonly found in computational fluid dynamics: instead of using numerical meshes that adjust to the format of the solid that serves as obstacle to the flow, it uses the governing equations in a Cartesian mesh, adding a forcing term in the governing equations, given the presence of some immersed boundary in the flow. This force is calculated from the body configuration. The simulations were performed at low Reynolds numbers ($Re = 190$) to allow comparisons with experimental results of Griffin and Ramberg (1976).

The current work is divided as follows: in the next section are described the governing equations, the immersed boundary method and details of the numerical scheme; the Numerical Results section are shown the results obtained with the numerical simulations and the analysis of the vortex streets formation; in the last section are given the conclusions and final comments.

NUMERICAL METHODS

In this study, the governing equations are the incompressible, unsteady Navier-Stokes equations with constant density and viscosity. They consist in the momentum equations for the velocity components (u, v), given by:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \nabla^2 u + F_x, \tag{1}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \nabla^2 v + F_y, \tag{2}$$

and the continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{3}$$

where u is the velocity component in the streamwise direction x, v is the component velocity in the wall normal direction y, ρ is the density, p is the pressure, ∇ is given by:

$$\nabla = \frac{1}{Re}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right), \tag{4}$$

and F_x and F_y are the forcing terms used by the immersed boundary technique.

The vorticity is here defined as the negative curl of velocity vector. Taking the curl of the momentum equations, the vorticity transport equation can be obtained:

$$\frac{\partial \omega_z}{\partial t} = -u\frac{\partial \omega_z}{\partial x} - v\frac{\partial \omega_z}{\partial y} + \nabla^2 \omega_z + \frac{\partial F_x}{\partial y} - \frac{\partial F_y}{\partial x}. \tag{5}$$

Taking the definition of vorticity and the continuity equation, one can obtain the Poisson equation for v velocity component:

$$\frac{\partial v^2}{\partial x^2} + \frac{\partial v^2}{\partial y^2} = -\frac{\partial \omega_z}{\partial x}. \tag{6}$$

The boundary conditions adopted here are: at the inflow boundary in the integration domain ($x = x_0$), the velocity and vorticity components are specified. At the outflow boundary ($x = x_{max}$), the second derivative of the velocity and vorticity components in the streamwise direction is set to zero. At the upper ($y = y_{max}$) and lower ($y = 0$) boundaries, the derivatives of v in the y direction are set to zero.

Three damping zones were used in the simulations to force the disturbances to gradually decay to zero. The basic idea is to multiply the vorticity components by a ramp function $f_2(x)$ after each step of the integration scheme. This technique has been proved by Kloker (1998) and Souza (2003) to be very efficient in avoiding reflections that could come from the boundaries when simulating flows with disturbances. Using this technique, the vorticity components are taken as:

$$\omega_z(x,y) = f_2(x)\omega(x,y,t) \tag{7}$$

where $\omega(x,y,t)$ is the disturbance vorticity component that comes out from the time integration scheme and $f_2(x)$ is a ramp function that goes smoothly from 1 to 0. The implemented function, in the x direction, was:

$$f_2(x) = f(\in) = 1 - 6\in^5 + 15\in^4 - 10\in^3 \tag{8}$$

where $\in = \frac{(i-i_3)}{i_4-i_3}$ for $i \leq i \leq i_4$ correspond to the positions x_3 and x_4 in the streamwise direction respectively. To ensure a good numerical results, a minimum distance between x_4 and the end of domain x_{max} should be specified.

The spatial derivatives were calculated using a 6^{th} order compact finite difference scheme (Souza et al (2005)). The v-Poisson was solved using a Full Approximation Scheme (FAS) multigrid a v-cycle working with 4 grids.

The boundary forces values were calculated using the following equations:

$$F_x(i,j) = \delta fr(vel_u - vel_{cil}), \tag{9}$$

$$F_y(i,j) = \delta fr(vel_v - vel_{cil}), \tag{10}$$

where fr is the relaxation term, here $fr = -300$, u an v are the velocity components in the streamwise and normal directions respectively and δ is a value that varies from $\delta(i,j) = 0$ outside the immersed boundary to $\delta(i,j) = 1$ at the boundary and inside the immersed boundary.

The time integration is calculated using a fourth-order Runge-Kutta scheme, and the numerical procedure works as described below; at each step of the Runge-Kutta scheme the following instructions are necessary:

1. Compute the spatial derivatives of the vorticity transport equation;
2. Calculate the immersed boundary forces F_x and F_y;
3. Calculate the rotational of the immersed boundary force;
4. Integrate the vorticity transport equation over one step (or sub-step) of the scheme using the values obtained in steps 1 and 3;
5. Calculate v from the Poisson equation;
6. Calculate u from the continuity equation;
7. Verify the values of the velocity components at the immersed boundary, if they are below a predefined value continue, otherwise go to step 2

This scheme is repeated until a stable or periodic solution is reached. The next section shows the results obtained for steady or oscillating cylinder using the numerical code described here.

NUMERICAL RESULTS

In the present section are shown the results of numerical simulations of a flow around an oscillating circular cylinder for low Reynolds number ($Re = 190$). The simulations were performed with a steady cylinder and with the cylinder oscillating in the same direction of the flow. The simulations with the cylinder vibrating were performed for frequencies $F = f_s/f_o = 0.5, 1.5, 2.0$ and 3.0, where f_s is the Strouhal frequency, obtained with steady cylinder, and f_o is the cylinder oscillation frequency. These frequencies were chosen with the objective to capture the lock-in phenomena. The amplitude of the oscillation was $A = 0.2$ in all cases.

Experimental results given in Griffin and Ramberg (1976) were used for validation of the numerical code. The numeric results were in good agreement with the experimental results. Figure 1 shows vorticity contours obtained with the simulation of a flow over a stationary cylinder. The street is composed of vortices of opposite sign that shed from alternate sides of the cylinder.

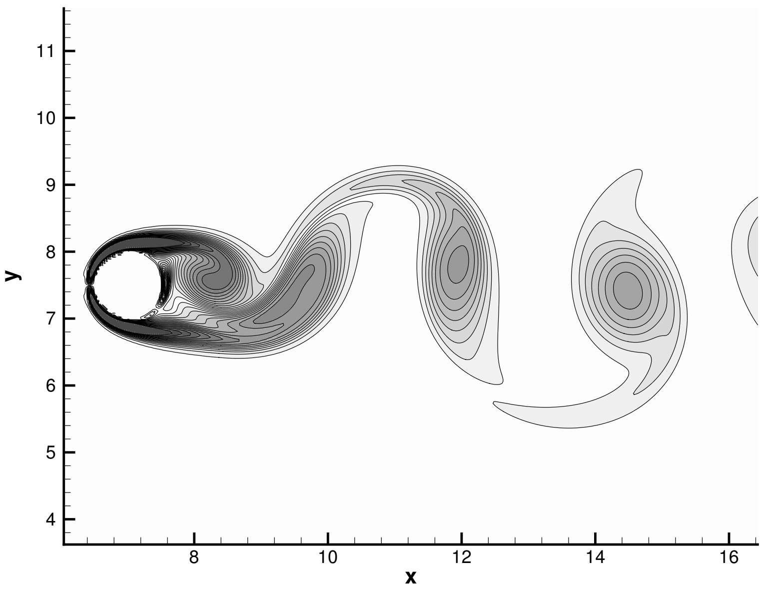

Figure 1 – Vorticity contours of a flow over a stationary cylinder – $Re = 190$**.**

Performing simulations with an oscillating cylinder, employing frequencies $F = 0.5, 1.5, 2.0$ and 3.0, it was observed four distinct behaviors of the street. The results of these simulations are shown in Figs. 2, 3, 4 and 5 respectively. In these figures, the position of the cylinder was the same.

The shedding vortex in the case that $F = 0.5$, shown in Fig. 2, presents similarities with the results obtained with the flow over a stationary cylinder, with a phase shift of 180 degrees in the vortex street. However, with the cylinder oscillation, it was observed an increase in the longitudinal spacing of the shedding vortices, in comparison with the vortex street of the flow over a stationary cylinder. The result of the vortex shedding for the frequency $F = 1.5$, plotted in the Fig. 3, was analogous to the result obtained with frequency $F = 0.5$, that is, both of them presented an increase in the longitudinal spacing of the vortices.

For the frequency $F = 2.0$, it was observed an interesting vortex street. It occurred a shedding of two vortices coupled, as can be observed in Fig. 4.

For the oscillation frequency $F = 3.0$, it was found a complex vortex street formation, as can be observed in Fig. 5. Near the cylinder occurs the formation of two vortices with opposite signs. These vortices in each side of the cylinder merge with the next vortex, developing new large-scale vortices.

The numerical simulation of a flow over a cylinder has the advantage of supplying a better visualization of the vortex street formation in the region near of the cylinder. These details are hard to capture via experimental studies.

The lock-in phenomena, according to the work of Griffin and Ramberg (1976) occur for a frequency range of 120% to 250%, approximately. In this work, the lock-in was captured in for the frequencies $F = 1.5$ and $F = 2.0$, with shedding of seven and nine vortices, respectively, in the determined interval. For the frequencies $F = 0.5$ and $F = 3.0$ the lock-in phenomena did not occur and the street formed five vortices in the same region. In Fig. 5, five vortices were considered, instead of eight, because the vortices with the same signal are coalescent. Hence, the numerical results found in the present work are in agreement with the experimental results obtained by Griffin and Ramberg (1976).

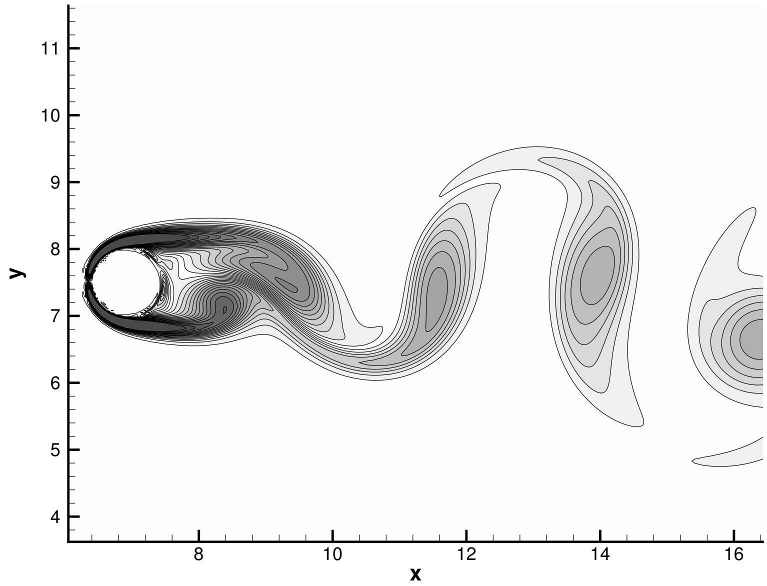

Figure 2 – Vorticity contours – oscillation frequency $F = 0.5$.

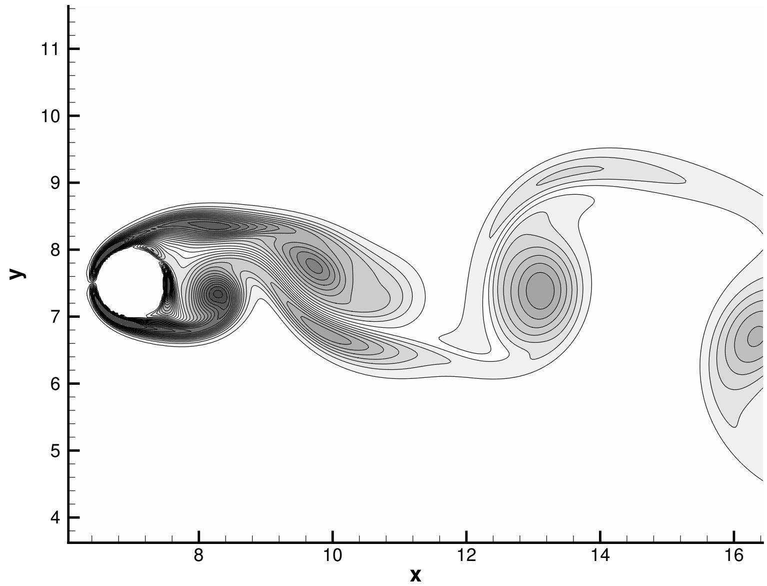

Figure 3 – Vorticity contours – oscillation frequency $F = 1.5$.

CONCLUSIONS

In the present study, numerical simulations of two-dimensional laminar flow over a steady and oscillating circular cylinder were performed. The Reynolds number adopted was $Re = 190$, and the cylinder was imposed to the flow by an immersed boundary technique.

Five distinct cases were studied, including the flow over a stationary cylinder. With the increase of the frequency oscillation, it was observed that the vortex street becomes more complex.

The lock-in phenomena were captured for frequencies $F = 1.5$ and $F = 2.0$, and are in agreement with the experimental results used for validation of the present code. Therefore, with the numerical simulations it becomes easy to visualize the vortex street formations in the region near the cylinder.

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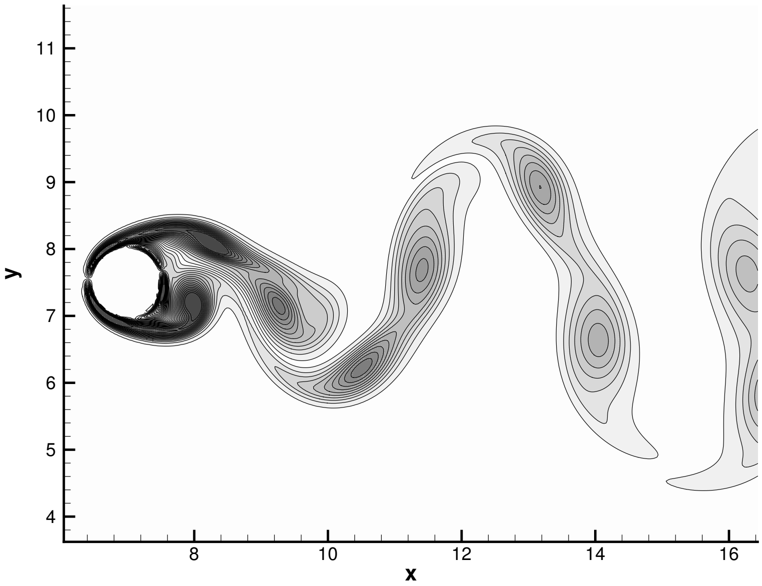

Figure 4 – Vorticity contours – oscillation frequency $F = 2.0$.

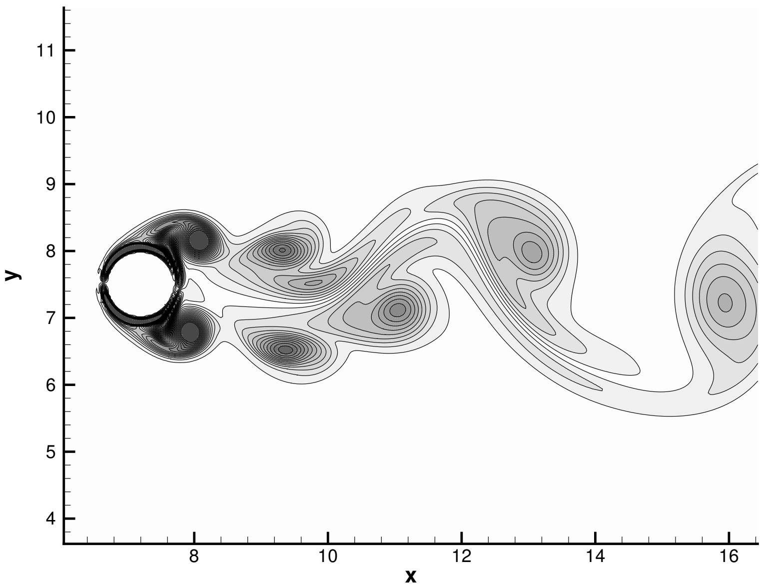

Figure 5 – Vorticity contours – oscillation frequency $F = 3.0$.

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