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Simulations of flow around a confined oscillating circular cylinder using a virtual boundary method

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Abstract

In this paper streamwise and transverse oscillations of a rigid circular cylinder in a rectangular channel are investigated using the Virtual Boundary method. Numerical study of the three-dimensional flow around the cylinder is done for the uniform Cartesian grid. All computations are performed at Reynolds numbers of Re=500 and 1000 based on the mean flow velocity. The Keulegan-Carpenter number (Kc) of cylinder forced oscillation is equal to 6 and the excitation frequencies considered are higher, lower and equal to the vortex shedding frequency. The locked-on state of the wake for the transverse and streamwise oscillations of a cylinder in uniform flow are obtained. The force coefficients spectra show the presence of a dominating component that is equal to the excitation frequency.

1 Introduction

The flow around bluff bodies of different configurations and accompanied periodic flow and vortex wake properties have been studied for many years. The ideal case when the body is regarded as solid and stationary appears in many industrial applications, e.g. gas turbines, offshore risers, chimney tubes etc. Any body immersed into the flow produces a wake behind it, but in the case when one of the natural mechanical frequencies of the structure is close to the vortex shedding frequency and system damping is sufficiently low, self-excited vibrations may be observed. Besides a range of frequencies near the frequency of vortex shedding exists where enforced oscillations of a body cause the body and vortex shedding frequencies to lock each other, or synchronize. In that case the frequency of the vortex shedding from a stationary body is suppressed and a body and its wake have the same characteristic frequency. The enforced body oscillation brings changes into the wake structure and vortex formation, but at the same this new structural characteristics can cause vortex-excited vibrations of the body which can lead to failures. This situation arises, for instance, in offshore structures and this fluid-structural interaction phenomena is evidently of practical importance. As a particular case of such an interaction a flow around solid circular cylinder placed normally in the rectangular channel and oscillating streamwisely and crosswisely relative to the meanflow direction is studied. The numerical study of this kind of interactions is a complicated problem, especially if the object has a complex geometry. For stationary geometries the most common method is to use body-fitted grids to get an accurate description of geometry. However, using this method for moving solid structures one has to regenerate the grid at each time step. Other possibilities include the use of moving, deforming or overlapping grid. As an alternative to these approaches the Virtual Boundary (VB) method [1],[2] can be applied. In this paper we use a fixed uniform unstructured Cartesian grid and the VB method to represent an object. The main reason for using Cartesian grid is that it simplifies both grid generation and implementation of higher order finite differences. The Virtual Boundary method [3],[4],[5] represents a solid body in the flow by replacing the solid boundary with the surface force distribution on the surface of the body.

The general situation on bluff body flows and especially on the circular cylinder flow can be found in Williamson [6]. The global development of the vortex shedding behind the cylinder has been studied numerically and experimentally for many years. For Re=47, due to the flow instability, a Hopf bifurcation exists which leads to the formation of the so called Karman vortex street, leading to an naturally occurring large-scale vortex formation. For low Reynolds numbers, the flow is quasi-steady, periodical and two-dimensional. With increasing Re three-dimensional structures of wake will develop. There are two types of instability - mode A and mode B. Mode A takes its origin at Re=180-194 and mode B - at Re=230-250. Mode A can be described as streamwise vortex pair formation while mode B has less large-scale of vorticity. For the certain Reynolds numbers both regimes can coexist. In Zdravkovich [7] one can get an overview of vortex shedding modes concentrated on the fact that mechanism of vortex shedding is not unique and can be changed depending on the situation.

When a circular cylinder is forced to oscillate in streamwise or in the cross-plane to the main flow, the flow structure is changed. The investigation on flow structure from an oscillating cylinder was performed experimentally by Ongoren and Rockwell [8]. They investigated the transverse oscillations of the cylinders of different cross-section and in the Reynolds number range between 594 and 1300 and found that wake is synchronized (locked-in) for the frequencies ratio $f_e/f_o = 0.5, 1, 2, 3...$ although the synchronization mechanism is distinctly different for different frequencies. Near or at $f_e/f_o = 1$ the phase of the shed vortex with respect to the cylinder displacement switches by approximately 180°. Carberry et al [9] experimentally investigated a wake past a transversely oscillating cylinder and described two different states which is characterized in terms of the lift force and a change in the mode of vortex shedding. The emphasis of their work was on the transition between these two states: as the frequency of cylinder excitation

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increases, there was simultaneously an abrupt jump in the lift force and a change in the mode of vortex shedding from 2P to 2S mode, which also was described by Williamson and Roshko [10].

Ongoren and Rockwell [11] studied the mode competition in the near wake of a circular cylinder subjected to forced oscillations at angle (which is equal to zero for the case of streamwise cylinder oscillation). They described two basic groups : symmetrical and antisymmetrical vortex formation modes. When synchronization does not occur, there is a competition between the symmetrical and antisymmetrical modes. The near wake structure successfully locks on to each mode over a defined number of cycles, abruptly switching between modes. Particularly, for the streamwise oscillation case they observed two synchronized modes: antisymmetrical and symmetrical. The case of streamwise cylinder oscillations in a steady current was investigated experimentally by Cetiner and Rockwell [12]. They showed that it is possible to attain either locked-on or quasi-locked-on states due to the streamwise oscillations in the analogy with the classical locked-on state which takes place in the case of the transverse oscillations of a cylinder in uniform flow. The observations of the spectra indicate a remarkable downward shift to lower frequencies of the predominant spectral peaks as the cylinder excitation frequency is increased.

2 Numerical method

The incompressible Navier-Stokes equations are discretized on a system of uniform or locally refined Cartesian grids as described by Revstedt and Fuchs [13]. The dependent variables are defined on a staggered grid. The different terms of the momentum and continuity equations are appoximated by finite differences. For the presented computations up-wind finite differences of first and third order of accuracy were used. To combine numerical efficiency with higher order accuracy, we introduce the higher order terms as a "single step" defect correction [14]. In each time step the system of equations is solved iteratively using a Multi-grid solver. The relaxation scheme within the Multi-grid solver comprises of pointwise relaxation of the momentum equations coupled with a pointwise smoothing of the continuity equation. At the last step both the velocity vector and the pressure are corrected so that the residuals of the momentum equations will not be changed as the continuity equation is satisfied. To solve the problem of incompressible fluid-solid structure interactions using a uniform Cartesian grid the Virtual Boundary (VB) method has been used. The VB method is based on the idea to use momentum sources to represent solid boundary in the flow. The incompressible momentum equations can then be written as

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \frac{\partial p}{\partial x_i} + \frac{1}{Re} \frac{\partial}{\partial x_j} \frac{\partial u_i}{\partial x_j} + \Phi_i \tag{1}$$

The body, Φ_i, are computed on the boundaries so as to satisfy the local boundary conditions. The magnitude of these source terms is calculated based on the local velocity defect and they are update through the iterative procedure of the flow solver. Hence the boundary of the object is a part of a numerical solution. In short the method can be described by the following steps :

- Discretization of the surface : a two-dimensional grid is generated on the surface of the body, in such a way that the node distance is of th same order as the mesh spacing of the flow solver.
- Determining the velocity defect : the velocity of the boundary is calculated using a Gaussian weighted average of the flow velocities around the surface nodes.
- Calculating the force contribution : the force contributions in the surface nodes are calculated, based on the difference between the calculated velocity on the boundary and the boundary condition

$$\tilde{F}_i^n = \tilde{F}_i^{n-1} + \Delta F_i^n, \Delta F_i^n = \alpha \frac{u_i^f - u_i^b}{h^2} \tag{2}$$

  With desirable boundary velocity error accuracy one can calculate new force distribution in the flow. Here u_i^b is the prescribed velocity of the boundary, n is an iteration number within one time step, α is a constant chosen to ensure both numerical stability as well as optimal convergence.
- Distribution of the surface forces : the surface forces are distributed using the same Gaussian function as it is used for determining the boundary velocity

$$G_F = \frac{1}{\left(\sigma\sqrt{2\pi}\right)^3} e^{\frac{-\left(\xi^2+\eta^2+\varsigma^2\right)}{2\sigma^2}} \tag{3}$$

  where σ is of the order of the computational grid size.

3 Computational set-up

All the computations in the frame of this investigation has been performed in the rectangular domain representing a rectangular channel. A rigid circular cylinder is placed normal to the width of the channel, its height is equal to 2D, where D is a cylinder diameter. The height, width and length of channel are 2D, 6D, 10D respectively. The cylinder center position is at 4D distance from the inlet in the middle of the channel. On the walls of channel and cylinder surface no-slip boundary conditions are imposed. In the inlet we put flat velocity profile, in the outlet - zero-gradient boundary condition. As a computational mesh a uniform cartesian grid has been taken. The grid resolution used for the main computations was chosen to D/8 - 73800 cells totally. In the present paper we study two sorts of cylinder oscillation: transversely and parallel to inlet flow direction. In the Table 1 one can see the all parameters value which we used for the computation.

Table 1. The list of all cases and oscillation parameters

Reynolds number, Re	Channel size, D	Grid resolution	Keulegan-Carpenter number, Kc	Dimensionless frequency of vortex shedding, f_0	Dimensionless cylinder excitation frequency, f_e	Excitation - vortex shedding frequency ratio, f_e/f_o
					0,1	0,545
500	2x6x10	D/8	6,0	0,1835	0,2	0,109
					0,3	1,635
					0,1	0,549
1000	2x6x10	D/8	6,0	0,1821	0,2	1,098
					0,3	1,647

In all cases the cylinder was excited sinusoidally, its motion started from the center position, the corresponding equation of motion is

$$x = x_0 + A\sin(2\pi f_e t) \tag{4}$$

where x_0 is initial central position for corresponding coordinate, A is an oscillation amplitude, f_e is the cylinder oscillation frequency, t is a time. The starting solution for the flowfield was a state of initial rest. In the case of cylinder oscillation, one more parameter is frequently used - Keulegan-Carpenter number Kc, which is defined as

$$Kc = 2\pi\frac{A}{D} \tag{5}$$

4 Results

In the table 2 below the computed dimensionless frequency of the vortex shedding are presented, depending on the Reynolds number of the flow.

Table 2: Reynolds number dependence of the shedding frequency for the flow around a stationary cylinder :Roshko's 3-D approximation [15], free cylinder, and VB method computation, stationary cylinder in a channel

Reynolds number, Re	300	400	500	600	700	800	900	1000
Roshko's approximation	0,2030	0,2053	0,2066	0,2075	0,2081	0,2086	0,2090	0,2093
VB method computation	0,1790	0,1820	0,1835	0,1850	0,1830	0,1825	0,1817	0,1821

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4.1 Transverse cylinder oscillations

In Fig.1 (a-d) the lift coefficient C_L spectra and its time history are presented for the Re=500 and selected cylinder oscillation frequencies.The general trend is that for higher cylinder excitation frequency the loading is much less sensitive to the Reynolds number of the main flow - although even for lower excitation frequency the difference is not dramatic. In the case Re=500,$f_e = 0.1$ the lift spectrum reveals the existence of a component at the vortex shedding frequency.

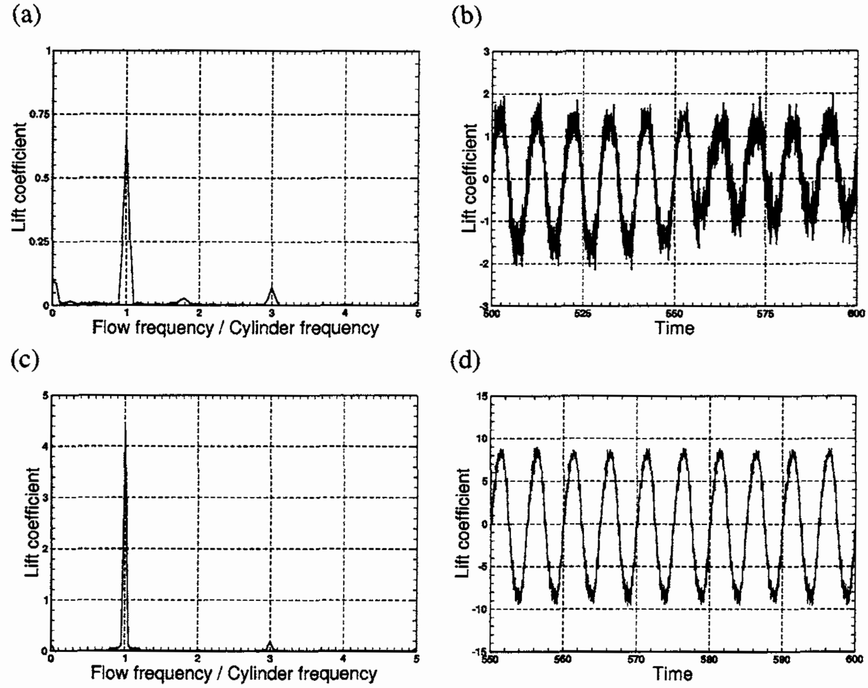

Figure 1: Spectra and time history of lift coefficient for Re=500, (a-b) $f_e = 0.1$, (c-d) $f_e = 0.2$.

For both Reynolds number and all cylinder excitation frequency the similar structure of spectra for force coefficients were obtained. This indicates that the synchronization range is much wider in the case of confined flow than for the case of a free cylinder. The change in C_L that one can see in Fig.1-b at $t \approx 550$ is due to the transition from one mode to another in the wake formation. For the cylinder frequency higher than fundamental, there is almost no difference between spectra and timing of force coefficients independently of mean flow Reynolds number. In Fig.2 the mean drag coefficient values and amplitude of lift coefficient oscillation are drawn for the different values of Re and cylinder excitation frequency. In spite of great increase of drag oscillations amplitude, the mean value of that is almost the same for the case of fundamental excitation frequency and higher,

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while for the case of subharmonic excitation the mean drag coefficient value is much lower. The amplitude of the lift coefficient oscillation highly increases with excitation frequency.One can see in Fig.2 that lift oscillation amplitude and mean drag coefficient are also Reynolds number independent - for used Reynolds number, of course. The drag coefficient spectra and timing are not presented here, as they show the same trend as for the C_L. The comparison of lift coefficient timing and cylinder displacement is also omitted here. For all Reynolds number and excitation frequency the phase shift obtained was small, which is usual for synchronization range.

(a) (b)

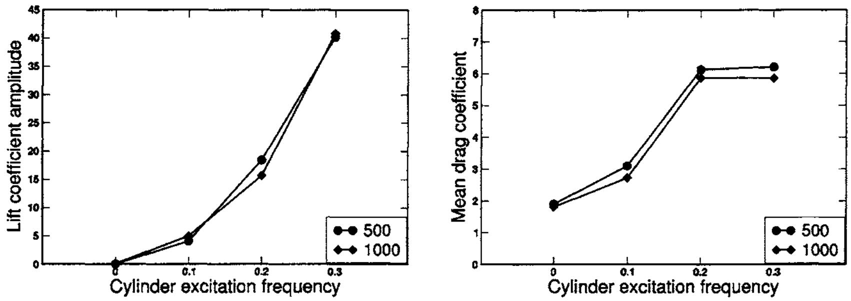

Figure 2: (a) Amplitude of the lift coefficient oscillations, (b) Mean value of the drag coefficient.

4.2 Streamwise cylinder oscillations

The VB method predicted the locked-on state appearance for the cylinder oscillation frequency close to fundamental ($f_e = 0.2$), the difference from the data obtained by Cetiner and Rockwell [12] is that the predominant peak in the spectrum of the lift coefficient C_L is situated at 0.5 in their measurements when in our computations two distinct peaks of approximately the same height appear at 0.5 and 1.5 positions. For the higher cylinder excitation frequency, the spectrum contains more frequencies than for the lower one; in Fig.3-c for Re=500 and $f_e = 0.3$ one can see the set of the frequencies in the wake (which is even stronger developed for Re=1000 - omitted here) which are presented by the peak series in the spectra. Exactly, besides the harmonical and superharmonical frequency peaks at 1.0, 2.0, 3.0 etc, there are constantly repeating peaks at + 0.29-0.32 and - 0.27-0.30 (Re=1000) and + 0.24-0.25 and - 0.23-0.24 (Re=500). The similar set of "accompanying" frequency was observed during the computations of flow past a stationary cylinder in the channel.

For subfundamental (not presented here) and fundamental frequencies the lift time history does not differ much, however for superfundamental frequency the

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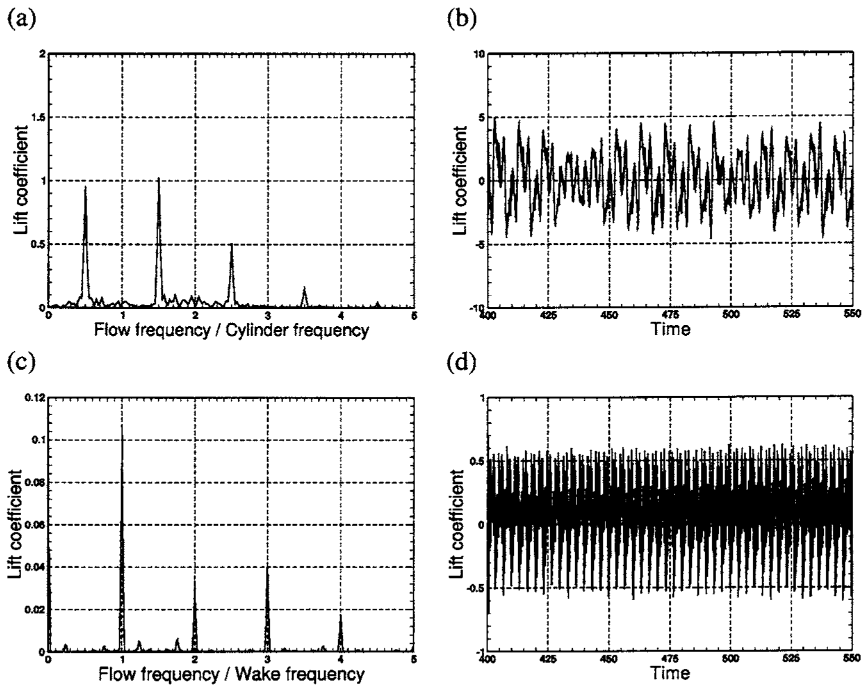

Figure 3: Spectra and time history of lift coefficient for Re=500, (a-b) $f_e = 0.2$, (c-d) $f_e = 0.3$.

Reynolds number dependence is clearly seen. When $f_e = 0.3$, the modulation of lift oscillation is higher. Drag coefficient spectra and timing are omitted, but like Cetiner and Rockwell we obtained generally repetetive behaviour of drag with a very slight modulation. The influence of the Reynolds number on the drag is very small. The mean drag coefficient (Fig.4-b) shows a tendency to decrease as the cylinder oscillation frequency f_e is increased which is in agreement with experimental data. The mean value of the drag coefficient computed for confined flow is less then for free cylinder - for example, Cetiner and Rockwell obtained mean drag value 5.77 for $f_e/f_0 = 0.44$.

The samples of lift and drag cycles correspond very well to the ones presented in Cetiner and Rockwell for the locked-on situation when cylinder oscillates with fundamental frequency. The lift time trace shows the same behavior as their first mode of synchronization (Fig.4-a). Ongoren and Rockwell [11] described two main groups of vortex formation modes : antisymmetrical and symmetrical. In our computation for $f_e = 0.2$ the wake is locked-on with antisymmetrical mode, for $f_e = 0.3$ the symmetrical mode prevails.

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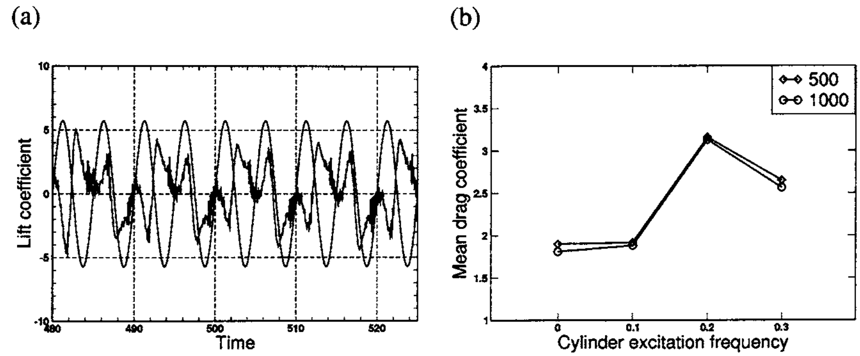

Figure 4: (a) Timing of the lift coefficient oscillations and cylinder displacement, (b) Mean value of the drag coefficient.

5 Concluding remarks

The Virtual Boundary (VB) method was applied to investigate the flow around a circular rigid cylinder oscillating in rectangular channel transversely and in-line respectively to the steady stream. The VB method uses an additional source terms in the governing equations to describe moving solid body of complex geometry in the flow using uniform Cartesian grid. When the cylinder is forced to oscillate in the cross plane, for all considered Re numbers and cylinder excitation frequency the locked-on state was obtained.The time histories of the lift and drag coefficients, velocity components were calculated for the different cases of cylinder oscillations. The phase angle for all excitation frequency values remained quite small. The mean drag and the lift oscillations amplitude increase with increasing of cylinder excitation frequency. When the cylinder is forced to oscillate in-line, in analogy with the classical case of a cylinder oscillation in the transverse direction the locked-on patterns of vortex formation can be obtained, although time traces and spectra for lift coefficient have more complicated shape and criteria for defining lock-on are not so evident. The time histories of the lift and drag coefficients, velocity components were calculated for the different cases of cylinder oscillations. The symmetrical and antisymmetrical wake modes have been obtained. The mean drag trends to decrease with increasing of cylinder excitation frequency. For the fundamental frequency of cylinder excitation good agreement with experimental data was found. The Virtual Boundary method was shown to be effective for the computation of the flow past a moving rigid bluff body of complex geometry (a circular cylinder in our case) using simple uniform cartesian grid. It predicts main features of a such kind of flow like the synchronization phenomena, different wake mode appearance etc, and gives the direct access to the forces loading on the object surface, which allows to treat the free vibration problems in a convenient way.

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