ANTISYMMETRICAL MODE OF VORTEX SHEDDING DUE TO STREAMWISE VORTEX INDUCED VIBRATIONS OF A BLUFF BODY

Bruna Oliveira Passos e Silva Siqueira, bruna.passos@gmail.com
Luiz Antonio Alcântara Pereira, luizantp@unifei.edu.br
Institute of Mechanical Engineering, Federal University of Itajubá, CP 50, Av. BPS, 1303, CEP. 37500-903, Itajuba, MG, Brazil

Miguel Hiroo Hirata, hirata@fat.uerj.br
State University of Rio de Janeiro, FAT-UERJ, Resende, Rio de Janeiro, Brazil

Abstract. *The antisymmetrical A-I mode of vortex formation synchronized with the circular cylinder forced oscillation with respect to the free stream has been studied. Capture of the wake frequency by structural motion analysis utilising a Poisson equation for the pressure and numerical simulations, using the Discrete Vortex Method were carried out. This typical VIV response was investigated in a high Reynolds number flow of* $Re=10^5$ *at reduced velocity of* $V_r=25$ *and ratio of amplitude and diameter* $A_x/d=0,13$*. The A-I mode ocurred as an alternate, out-of-phase shedding vortices from either side of the cylinder over an oscillation cycle, being so identified as the classical mode of formation of the Kármán street.*

Keywords*: bluff body, in-line oscillation, vortex shedding, lock-in phenomenon, vortex method.*

1. INTRODUCTION

Flow-Induced Vibrations of circular-cylindrical structures have received much attention of researchers as a result of its relevance in a variety of industrial settings: offshore platforms, heat-exchangers, nuclear power plants and so on. Special focus is given over the oscillations caused by VIV-Vortex Induced Vibrations, i.e., the unsteady flow will induce fluctuating drag and lift forces, which can cause the structure to vibrate when synchronized to one of the body's natural frequency, a phenomenon known as "lock-in". It is useful to define the flow speed non-dimensionalised by the cylinder diameter and the natural frequency of oscillation creating a parameter called reduced velocity, $V_r=U/df_0$, being U the free stream velocity, d the diameter of cylinder and f_0 the frequency of oscillation of the structure. The body oscillation in the direction normal to the flow tends to be an order of magnitude higher than those in the direction parallel to the flow. As consequence, the majority of research has focused on the situation of a cylinder free to vibrate only in the transverse direction (Williamson and Roshko, 1988). However, since the viscous wake induces a fluctuating drag curve with a frequency twice that of the fluctuating lift curve, the in-line vibrations occur at a lower free stream velocity, and despite their lower amplitudes, the higher frequency may cause them to have a comparable impact on the fatigue life of the cylindrical structures. The first manifestation of flow-induced streamwise (in-line) oscillation occurred during the construction of the Immingham Oil Terminal in 1968 (Wooton *et al.*, 1972). Since then, it is known that cylindrical structures may be easily induced to oscillate in the streamwise direction at a range of reduced velocities.

King *et al.* (1973), King (1975) and King and Johns (1976) revealed the first basic characteristics to determine the nature of flow-induced in-line oscillations of a marine structure using a water channel. Ongoren and Rockwell (1988) carried out an investigation addressed issues of synchronized and competing modes of vortex formation from an in-line oscillating circular cylinder by water tunnel tests. The cylindrical structure was subjected to forced oscillations at angle α with respect to the free stream, see "Fig. 1". Their results showed two basic vortex shedding patterns at ratio of amplitude and diameter $A_x/d=0.13$ and Reynolds number Re=855: symmetrical vortex formation and antisymmetrical vortex formation. The symmetrical mode, mode S, was identified when a pair of vortices shed in phase from both sides of the circular cylinder during one oscillation cycle. The antisymmetrical mode appeared in four forms: A-I, A-II, A-III and A-IV. The A-I mode was classified as alternate, out-of-phase shedding of vortices from either side of the circular cylinder over an oscillation cycle, i.e., a classical mode of vortex formation known in the literature as formation of the Kármán street. However, for modes A-II to A-IV, the period of the vortex pattern was doubled when compared to the classical A-I mode. This period doubling arises from the fact that shedding of two successively antisymmetrical vortices, or vortex combinations, from a circular cylinder oscillating in-line requires two cycles of body motion. The antisymmetrical mode A-II occurred only for $\alpha\neq0°$ corresponding to simultaneous excitation in symmetrical and antisymmetrical modes. The antisymmetrical modes A-III and A-IV occurred only when the circular cylinder was subjected to an in-line oscillation for $\alpha=0°$. When synchronization did not occur, there was competition between the symmetrical and antisymmetrical modes, where the near wake structure successively locked-on to each mode over a defined number of cycles and abruptly switched between modes. Finally, Ongoren and Rockwell (1988) emphasized that the generalizations for occurrence of these modes were restricted to the relatively small amplitude of the circular cylinder oscillation of $A_x/d=0.13$. Preliminary studies showed that this amplitude was sufficiently large to produce control of the near wake structure over a wide frequency range.

Recently, Morse and Williamson (2009) published results of an extensive experimental study of the controlled forced vibration of a circular cylinder by water flume tests, varying body amplitude and frequency, at two constant Reynolds numbers of Re=4,000 and Re=12,000. Their results provide new insights into VIV: "With free vibration, a small increase in flow speed can result in large changes in body oscillation amplitude, possibly accompanied by a change in the mode of vortex shedding. Such jumps, or transitions, are difficult to study under condition of free vibration" (Bearman, 2009). In general, forced vibration needs a large number of runs in order to map precisely the conditions under which energy transfers from the fluid to the body.

In this paper is presented the first phase of a fundamental study of streamwise VIV of a circular cylinder, in which the only the antisymmetrical mode A-I is discussed. A Lagrangian mesh-free Vortex Method (Hirata *et al.*, 2008) is used to simulate the two-dimensional, time dependent viscous incompressible flow around a circular cylinder subjected to forced in-line oscillation (α=0°). The present result for case Re=100,000 shows that the drag curve has the same frequency as the body vibration frequency. The three-dimensional effects in experiments ever for small Reynolds number are identified. The two-dimensional flow assumption is adopted in this work, which is expected to show the main characteristics of the Vortex Induced Vibrations mechanisms of a circular cylinder and predict qualitatively the features of this fluid-structure interaction problem using a high Reynolds number. Numerical studies on the flow around an oscillating circular cylinder had mainly been restricted to Reynolds number of O (100), e.g. Song and Song (2003).

2. NUMERICAL METHOD FOR THE VORTEX INDUCED VIBRATION SIMULATIONS

To understand how the approaching wake interacts with an in-line forced body oscillation, consider a point P located at the circular cylinder surface and viewed from the (x,o,y), which is defined as the inertial frame of reference, as sketched in Fig. 1. A second frame of reference (ξ,o,η) is defined as the coordinate system fixed to the body and, therefore, free to oscillates in a harmonic motion. The boundary S of the fluid domain can be defined as $S = S_b \cup S_\infty$, being S_b the circular cylinder surface (which contains the P point) and S_∞ the far away boundary (which can be viewed as $r = \sqrt{x^2 + y^2} \to \infty$).

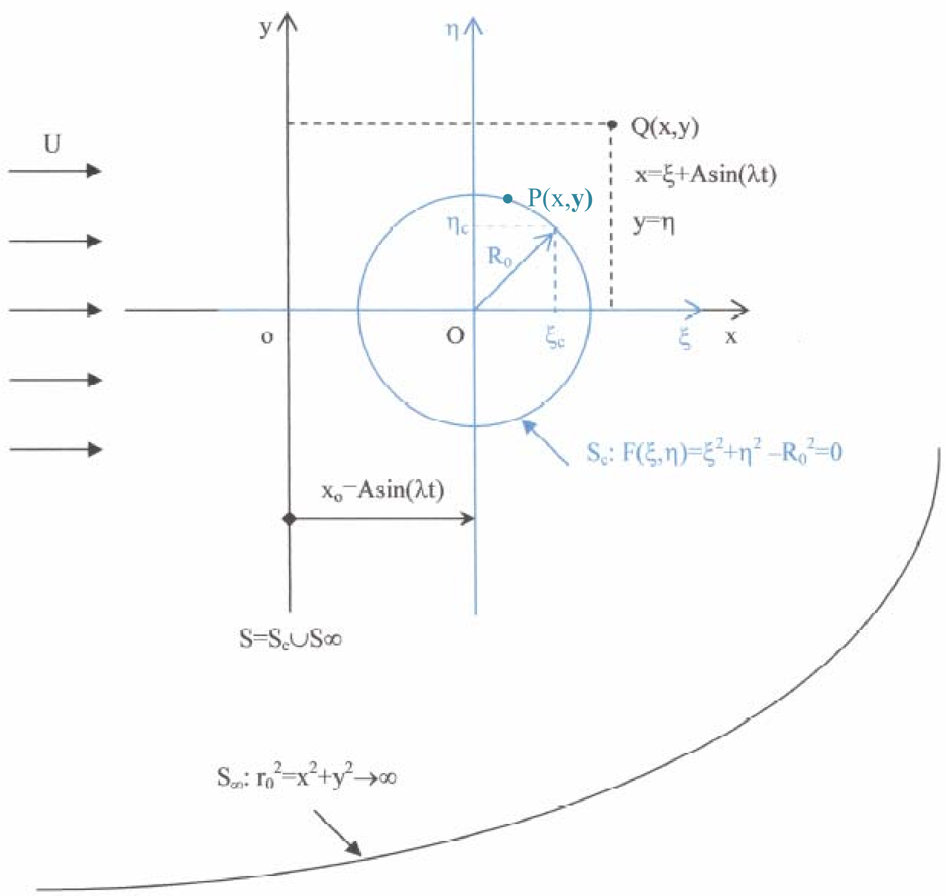


Figure 1. Streamwise Vortex Induced Vibrations of a circular cylinder (adapted from Ongoren & Rockwell, 1988).

The dynamics of the fluid motion is studied in a more convenient way taking the curl of the Navier-Stokes equations to obtain the vorticity equation

$$\frac{\partial \omega}{\partial t} + \mathbf{u} \cdot \nabla \omega = \frac{1}{Re} \nabla^2 \omega \tag{1}$$

where $\omega(\mathbf{x}, t) = \nabla \times \mathbf{u}(\mathbf{x}, t)$ represents the only non-zero component of the vorticity field for 2-D flow. Note that the pressure is absent from the formulation. An algorithm that splits the convective-diffusive operator of Eq. (1) is employed in accordance with Chorin (1973). The Reynolds number is defined as Re=Ud/ν, where ν the kinematic viscosity of fluid and d is the diameter cylinder; the dimensionless time is d/U. The Vortex Method proceeds by discretizing spatially the vorticity field using a cloud of elemental vortices, which are characterized by a distribution of vorticity, ς_{σ_i} (commonly called the cutoff function), the circulation strength Γ_i and the core size σ_i. Thus, the discretized vorticity is expressed by

$$\omega(\mathbf{x}, t) \approx \omega^h(\mathbf{x}, t) = \sum_{i=1}^{Z} \Gamma_i(t) \varsigma_{\sigma_i}(\mathbf{x} - \mathbf{x}_i(t)), \tag{2}$$

where Z is the number of point vortices of the cloud used to simulate the vorticity field. The numerical analysis is conducted over a series of small discrete time steps Δt for each of which a discrete vortex element Γ_i is shed from body surface. The intensity Γ_i of these newly generated vortices is determined using the no-slip condition on S_b. NP flat source panels represent cylinder surface and ensure the impermeability condition on S_b (Katz and Plotkin, 1991); it is assumed that the source strength per length is constant.

The position and velocity of the frame of reference (ξ,o,η) are defined, respectively, as

$$\xi_x = A_x \sin(\lambda_x t) \text{ and } \dot{\xi}_x = u_{oscx} = A_x \lambda_x \cos(\lambda_x t), \tag{3}$$

where A_x is the body oscillation amplitude, $\lambda_x = 2\pi f_{bx}$ is the angular velocities, $f_{bx} = f_0$ is the body oscillation frequency and t is the time in the physical domain.

The velocity field **u** is calculated at the location of elemental vortices in a typical Lagrangian description. The velocity induced by body is calculated in the frame of reference (ξ,o,η), see Alcântara Pereira & Hirata (2010). The vortex-vortex interaction is obtained from the vorticity field by means of the Biot-Savart law. The convective motion of each vortex generated on the body surface is determined by integration of each vortex path equation using a first order Euler scheme. The diffusion of vorticity is taken care of using the random walk method (Lewis, 1999).

Starting from the Navier-Stokes equations is obtained a Poisson equation for the pressure. This equation is solved through the following integral formulation (Shintani and Akamatsu, 1994)

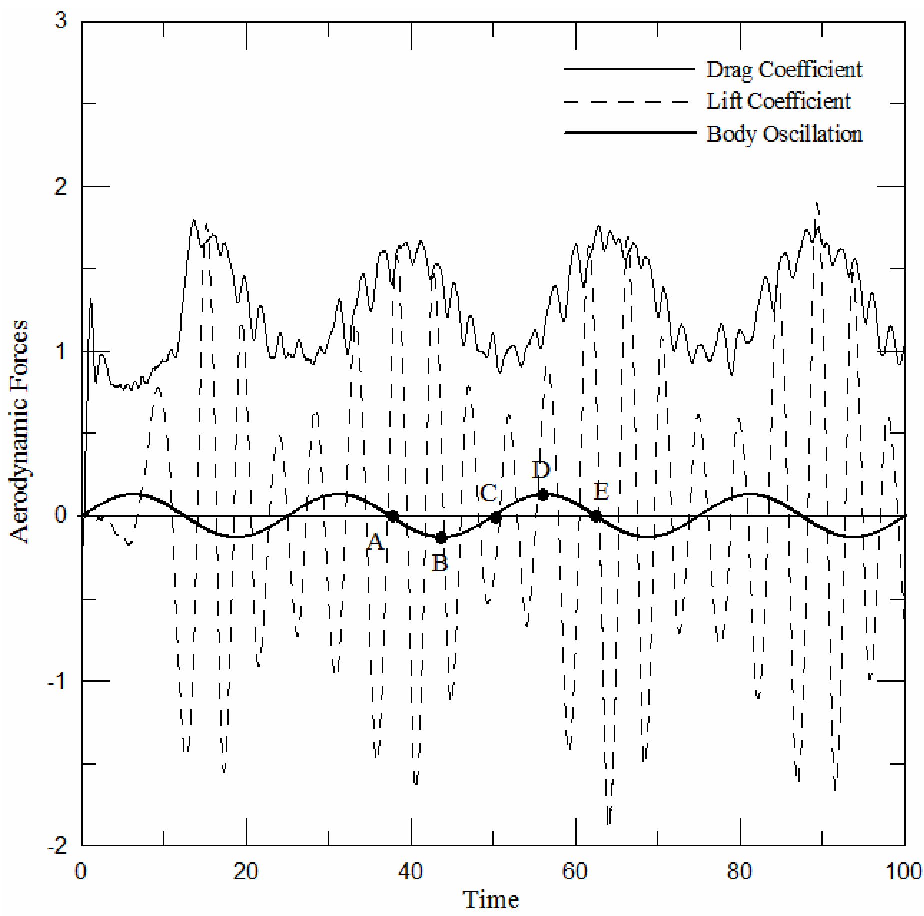
$$H\overline{Y}_i - \int_S \overline{Y} \nabla \Xi_i \cdot \mathbf{e}_n dS = \iint_\Omega \nabla \Xi_i \cdot (\mathbf{u} \times \boldsymbol{\omega}) d\Omega - \frac{1}{Re} \int_S (\nabla \Xi_i \times \boldsymbol{\omega}) \cdot \mathbf{e}_n dS, \ \overline{Y} = p + \frac{u^2}{2}, \ u = |\mathbf{u}|, \tag{4}$$

where $H = 1$ in the fluid domain, $H = 0.5$ on the boundaries, Ξ is a fundamental solution of the Laplace equation and $\mathbf{e}_n$ is the unit vector normal to the body surface, S_b. The drag and lift coefficients are obtained from pressure integration.

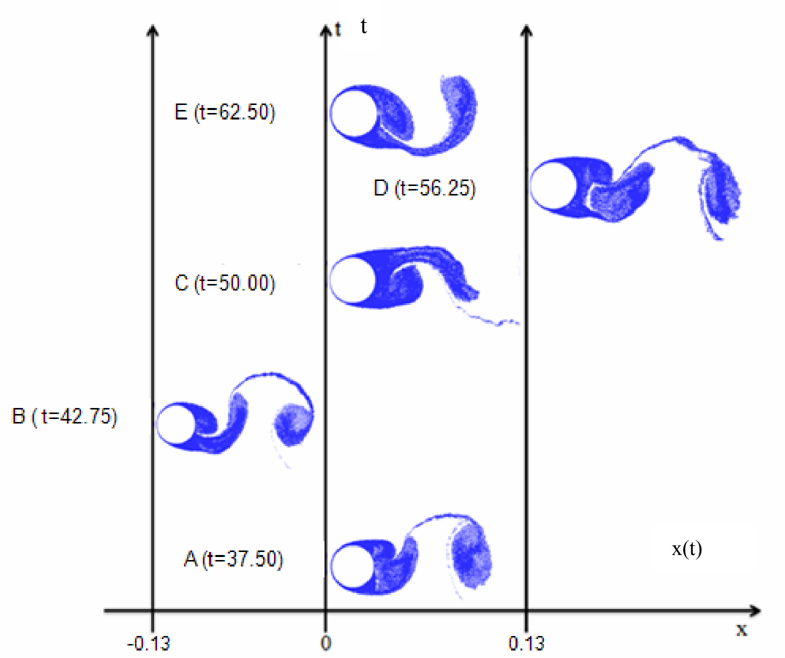
3. RESULTS AND DISCUSSIONS

The first providence to validate the vortex code simulated the flow around an immovable circular cylinder. This was done in order to determine the parameters associated with the numerical method, like: number of flat panels used to represent the circular cylinder (NP=300); position of detachment of the discrete vortices ($eps = 0.0010$); Lamb core size ($\sigma_0 = 0.0010$); for more details see Silva Siqueira (2011). The simulation was performed up to 2,000 time steps with a value of $\Delta t = 0.05$ for dimensionless time step.

Figure 2(b) shows instants of near wake when cylinder is in maximum upstream position (Point A), in minimum upstream position (Point C) during oscillation cycle, and so on. All points (A to E) are related to instants as identified in Fig. 2(a). The numerical results for mean drag (Cd=1.31) and Strouhal number ($St=f_{cl}=0.21$ from lift curve) reflect a good simulation of the flow, because are the consequence of the Kármán vortex shedding related to antisymmetrical mode A-I. The drag frequency $f_{cd}=0.04$ is locked on to body oscillation frequency $f_0=0.04$. As can been noted in Fig. 2(b) the vortex shedding is identified as formation of the classical mode of the Kármán street.



(a) temporal series of drag and lift coefficients



(b) instants of the cylinder position during one cycle of oscillation

Figure 2. Details of antisymmetrical A-I mode of vortex formation (V_r=25, A_x/d=0,13, f_0/f_{cd}=1, Re=10^5).

Figure 3 presents the pressure distributions on the cylinder surface during the shedding of two alternating vortex structures. The C_{Lmax} point corresponds to the vortex shedding on the upper cylinder surface where there is a negative peak pressure around the 80º. The C_{Lmin} point represents the vortex shedding in the lower cylinder surface and the negative pressure peak occurs nearby 170º. The $C_{Lshedding}$ points indicate instants where vortex structures are detached from the cylinder surface and are incorporated into the viscous wake. Comparing Fig. 2 and Fig. 3 it is observed that the instants of the vortex shedding type are not coincident with the instants of maximum and minimum amplitudes of the motion cylinder.

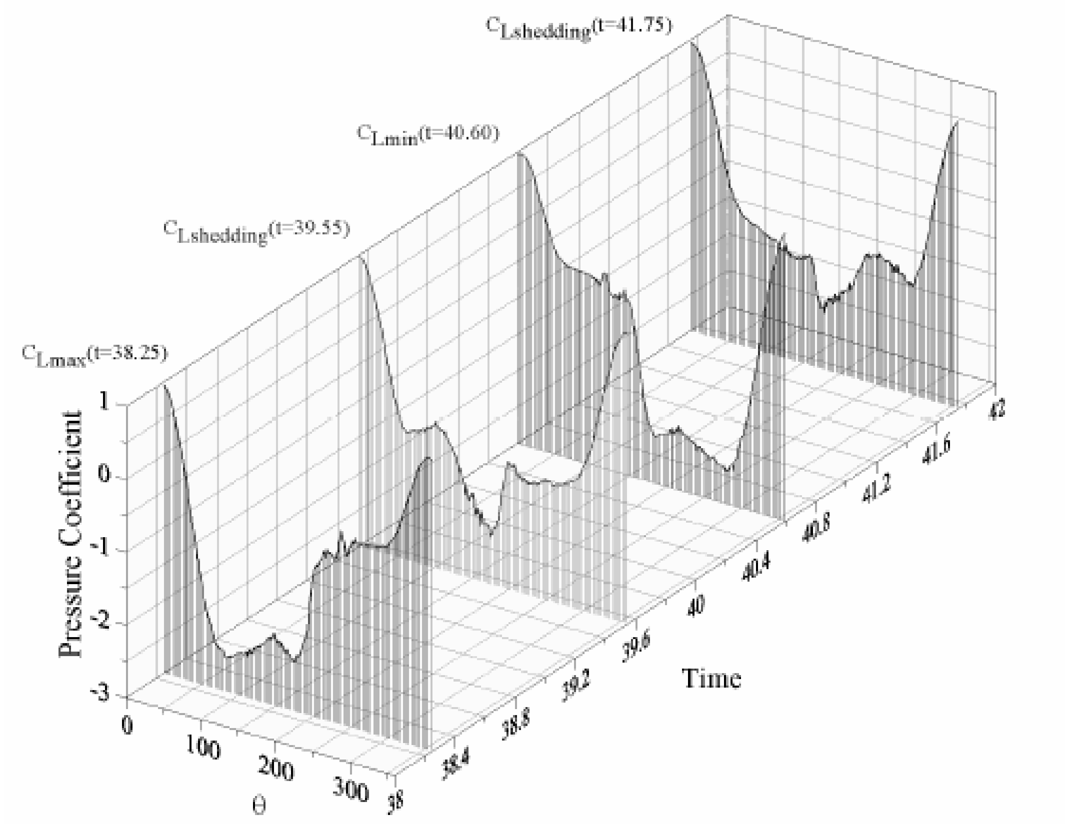


Figure 3. Pressure distribution on the surface of the cylinder (V_r=25, A_x/d=0,13, f_0/f_{cd}=1, Re=10^5).

Another frequency of f_{cd}=0.08 was investigated and the antisymmetrical mode A-I have been identified with success. The drag frequency f_{cd}=0.08 is locked on to the body oscillation frequency f_0=0.08. An interesting observation when the antisymetrical mode AI occurred is related to the lift frequency; it has the same value (f_{cl}=0.21) in both f_0=0.04 and f_0=0.08 frequencies. Through this study can be concluded that the antisymetrical mode A-I occurs when the drag frequency is locked on to the body oscillation frequency and the lift frequency must be equal to f_{cl}=0.21. The result for the mean drag is C_d=1.28. This result combined with the Strouhal number (f_{cl}=0.21) characterize again the Kármán vortex shedding.

Figure 4 shows the temporal series of drag and lift coefficients for body oscillation frequency of f_0=0.08. It is noted that the drag and the lift curves have a behavior similar to the drag and lift curves to f_0=0.04. In both cases it is observed the shedding of several pairs of alternating vortices. The drag curve has a different behavior in the second case (f_0=0.08), this is associated with increased body oscillation frequency. As the body oscillation frequency increases the drag and lift curves assume other disposition and their coefficients change values.

Experiments from Ongoren & Rockwell (1988) for Re=855 showed values in the range $0.5 \leq f_0/f_{cl}* \leq 4.0$ as suitable to examinate the modal structure of the near wake for sub harmonic and super harmonic excitation, being $f_{cl}*$ the natural vortex-shedding frequency from the corresponding stationary cylinder. In the present results the antisymmetrical mode A-I was identified for $f_0/f_{cl}*$=0,19. Previous works showed that regimes of vortex shedding seem to be a stronger function of the oscillation amplitude and frequency than the Reynolds number (Song and Song, 2003).

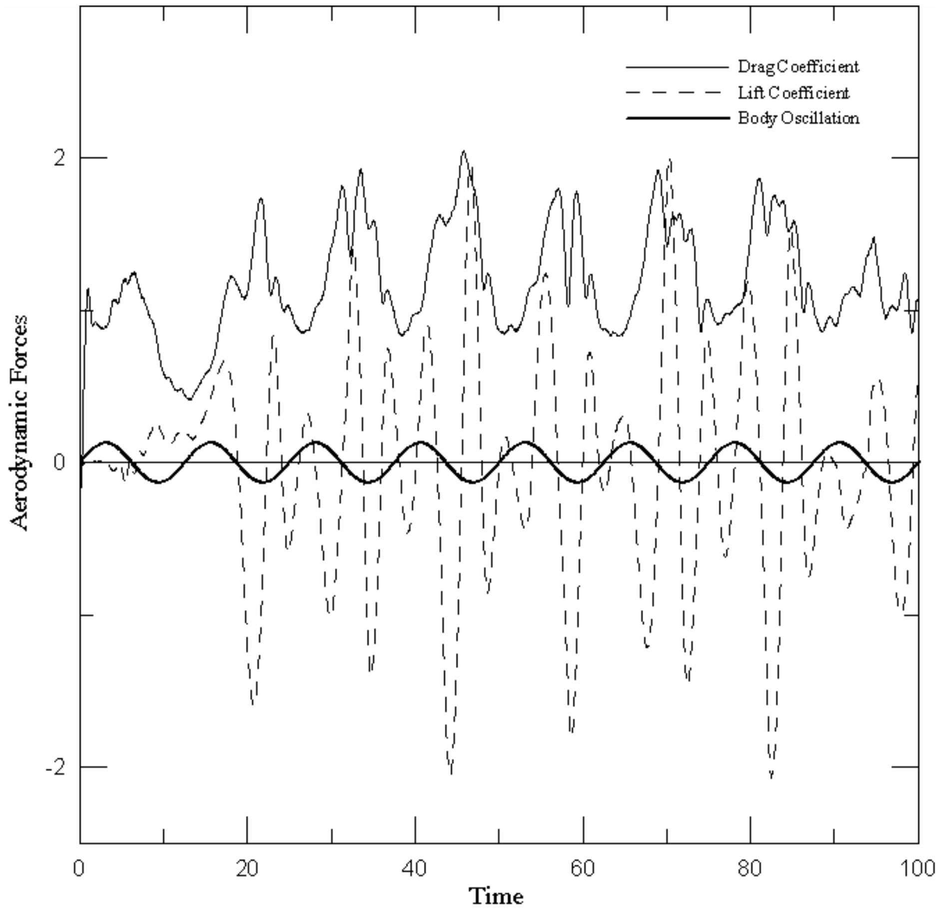


Figure 4 - Series of drag and lift coefficients (V_r=12,5, A_x/d=0,13, f_0/f_{cd}=1, Re=10^5).

4. CONCLUSIONS

In the present study the vortex method has been utilized for the analysis of the high Reynolds number flow past a cylinder oscillating forcedly in the in-line direction. The main purpose was to identify the antisymmetrical mode A-I, which occur when the frequency of drag curve locks with the body oscillation frequency. The lift frequency was identified as f_{cl}=0.21; this is a crucial consideration for the characterization of the antisymmetrical mode A-I.

Ongoren & Rockwell (1988) found the antisymetrical mode A-I to the body frequency less than f_0=0.10 and the results of the present simulation were found in the same frequency range (f_0=0.04 and f_0=0.08). Therefore it is concluded that the present numerical results are in a good accordance with experimental visualizations given by Ongoren & Rockwell (1988). The antisymmetrical mode A-I has been identified here for a high Reynolds number of Re=10^5. Results involving other regimes of vortex formation will be presented elsewhere.

5. ACKNOWLEDGEMENTS

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