

## **EFFECT OF FREQUENCY RATIO ON FLOW AROUND A CYLINDER OSCILLATED IN-LINE AT $Re=80-200$**

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### **ABSTRACT**

This study deals with the numerical simulation of two-dimensional laminar incompressible Newtonian fluid flow past a circular cylinder forced to oscillate in-line with the main stream. The effect of frequency ratio  $FR=f/St$  on the flow is investigated for Reynolds numbers  $Re=80, 120, 160$  and  $200$  at a dimensionless oscillation amplitude  $0.5$ . Computations were carried out using a thoroughly tested finite-difference code developed by the authors. Lift, drag and torque coefficients are investigated. When the time-mean values of lift and torque coefficients are plotted against frequency ratio, abrupt changes can be found in the curves, suggesting the presence of switches in the vortex structure. No jumps were observed in the time-mean of drag and rms values of lift, drag and torque coefficients plotted against the frequency ratio. Both rms and time-mean values of force coefficients revealed a shift toward lower frequency ratio with higher  $Re$ . Where vortex switches occur, a pre-and post-jump analysis is carried out.

### **INTRODUCTION**

Fluid flow around an oscillating cylinder is a typical fluid-structure interaction problem which is widely investigated using experimental and numerical techniques. When a structure is exposed to wind or wave, the vortices shed from the structure induce a periodic load on the structure which can lead to high amplitude vibration, especially if the vortex shedding frequency is near the natural frequency of the structure and the damping is small. Underwater structures, chimneys and tall slender buildings are good examples of this phenomenon. This oscillation can happen transverse or in-line to the main stream or in both directions.

It is sometimes argued that in-line oscillation is of no practical interest. However, it is important to note that in-line oscillation can lead to structural damage, e.g. damage to a thermometer case at the Monju fast-breeder nuclear power plant – leading to the shutdown of the plant – was a result of symmetrical shedding [1]. Wootton et al. [2] carried out an experimental investigation on the vortex-induced motions of circular steel piles during tidal flow. This revealed large amplitude in-line oscillation in nature.

Various parameters have been studied for in-line motion, among them the frequency ratio. This is the ratio of frequency of cylinder oscillation and the Strouhal number. The cylinder in in-line oscillation has been investigated experimentally and numerically. An experimental study for in-line oscillation by Cetiner and Rockwell [3] was carried out at medium Reynolds numbers ( $Re=405-$

2482) over a frequency ratio range of 0.44 to 3. Al-Mdallal et al. [4] investigated a similar frequency ratio range numerically at  $Re=200$  at oscillation amplitude  $A=0.1$  and  $0.3$ , finding abrupt changes in the vortex structure, or vortex switches. Baranyi et al. [5] analyzed in-line cylinder oscillations at frequency ratios  $0.8$  and  $0.9$ , where the oscillation amplitude was varied between  $0.1$  and  $0.7$ . A large number of jumps were identified in the time-mean values of lift and torque coefficients, indicating vortex switches. From these studies only scattered data are available; there is a need for a systematic investigation of the effect of frequency ratio on flow past a cylinder oscillating in-line.

This two-dimensional numerical study aims to investigate the effect of frequency ratio on the flow past a circular cylinder oscillating in-line at a fixed oscillation amplitude value and at four Reynolds numbers ( $Re=80, 120, 160$  and  $200$ ). The frequency ratio range investigated is from the lower threshold value for lock-in to  $1$ .

### COMPUTATIONAL METHOD

The non-dimensional governing equations for the incompressible, constant property, laminar two-dimensional Newtonian fluid flow around a circular cylinder oscillating in-line with the main stream are the two components of the Navier-Stokes equations written in a non-inertial system fixed to the moving cylinder, the continuity equation and a Poisson equation for pressure. Figure 1 shows the physical and computational domains, where  $R_1$  represents the cylinder surface and  $R_2$  is the far field, where undisturbed uniform flow is assumed. Undisturbed velocity is assumed at  $R_2$  and no-slip boundary conditions are used for velocity on  $R_1$ ; a Neumann-type boundary condition is applied for pressure both on the cylinder surface and on the outer surface.

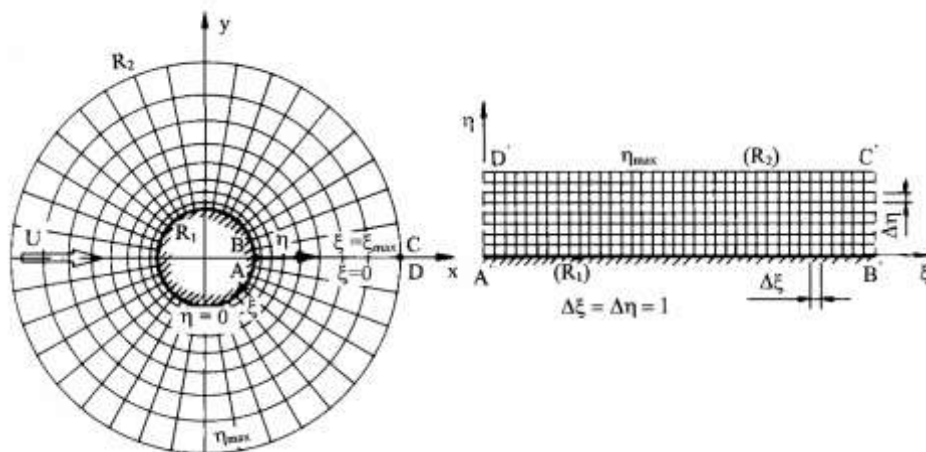


Figure 1  
The physical and computational domains

In order to impose boundary conditions accurately and to avoid numerical inaccuracies, boundary-fitted coordinates are used. The physical domain is transformed into the rectangular computational domain applying linear mapping functions [6]. Due to the properties of the mapping functions, the grid on the

physical plane is very fine in the vicinity of the cylinder surface and coarse in the far field, but the grid is equidistant on the computational domain. The transformed governing equations with the boundary conditions are solved applying finite difference method [6]. The space derivatives are discretized using fourth order schemes except for the convective terms which are approximated by a third order upwind difference scheme. The Poisson equation is solved using successive over-relaxation, the equation of motion is integrated explicitly and continuity equation is satisfied at every time step.

During the computations the radius ratio  $R_2/R_1=160$  and the computational grid is characterized by grid points  $360 \times 292$  (peripheral  $\times$  radial) and the dimensionless time step ( $\Delta t$ ) is 0.0005.

The lift and drag coefficients are defined as

$$C_L = \frac{2F_L}{\rho U_\infty^2 D} \quad C_D = \frac{2F_D}{\rho U_\infty^2 D}. \quad (1)$$

In equation (1)  $D$  is the diameter of the cylinder,  $\rho$  is the fluid density,  $U_\infty$  is the free-stream velocity, and  $F_L$  and  $F_D$  are the lift and drag per unit length of the cylinder, respectively. The torque coefficient is computed as [5]

$$tq = -\frac{1}{4} \int_0^{2\pi} \tau_0(\psi) d\psi, \quad (2)$$

where  $\psi$  is the polar angle and  $\tau_0$  is the dimensionless wall shear stress. The torque coefficient is positive if the torque acts in counterclockwise direction. From the time-histories of the signals defined in equations (1) and (2) the time-mean (mean) and root-mean-square (rms) values are computed as

$$h_{mean} = \frac{1}{mT} \int_{t_1}^{t_1+mT} h(t) dt; \quad h_{rms} = \sqrt{\frac{1}{mT} \int_{t_1}^{t_1+mT} [h(t) - \bar{h}]^2 dt}. \quad (3)$$

In this study low-Reynolds-number-flow ( $Re=U_\infty D/\nu=80, 120, 160, 200$ ) around a cylinder oscillated mechanically in streamwise direction is analyzed. The cylinder displacement is defined as

$$x(t) = A \cos(2\pi ft), \quad (4)$$

where  $A$  and  $f$  are the dimensionless oscillation amplitude and frequency, respectively. Instead of the frequency of cylinder oscillation  $f$  the frequency ratio  $FR = f/St$  will be used as an independent variable, where  $St$  (called Strouhal number) is the dimensionless vortex shedding frequency from a stationary cylinder at the same Reynolds number.  $St$  values are taken from [7]. For the present investigation the amplitude of cylinder oscillation is fixed at  $A=0.5$ . This value ensures a relatively wide frequency ratio  $FR$  within which the vortex shedding frequency synchronizes with the cylinder motion (a phenomenon called lock-in). Since only locked-in cases are investigated in this study, it is important to determine the threshold values of  $FR$  for lock-in at the Reynolds numbers investigated.

## COMPUTATIONAL RESULTS

Computations were carried out for four Reynolds numbers of  $Re=80, 120, 160$  and  $200$  at a dimensionless oscillation amplitude of  $A=0.5$  while FR was varied. Figure 2 shows the time-mean values of the lift and torque coefficients against FR for the four  $Re$  values investigated. It can be seen that there are a large number of jumps in the curves. In all cases, the solution switches between two so-called state curves [6]; the number and location of jumps varies. The two state curves in each set of curves, for lift coefficient and torque, are mirror images of each other. This, coupled with the existence of a critical frequency ratio values beyond which the pair of curves appears, strongly suggests pitchfork bifurcation [8]. There are two attractors in this non-linear system, each with a basin of attraction. If the sets of parameters are near to the boundary separating the two basins of attractions, then even a tiny change in a single parameter might be sufficient to change the attractor [8].

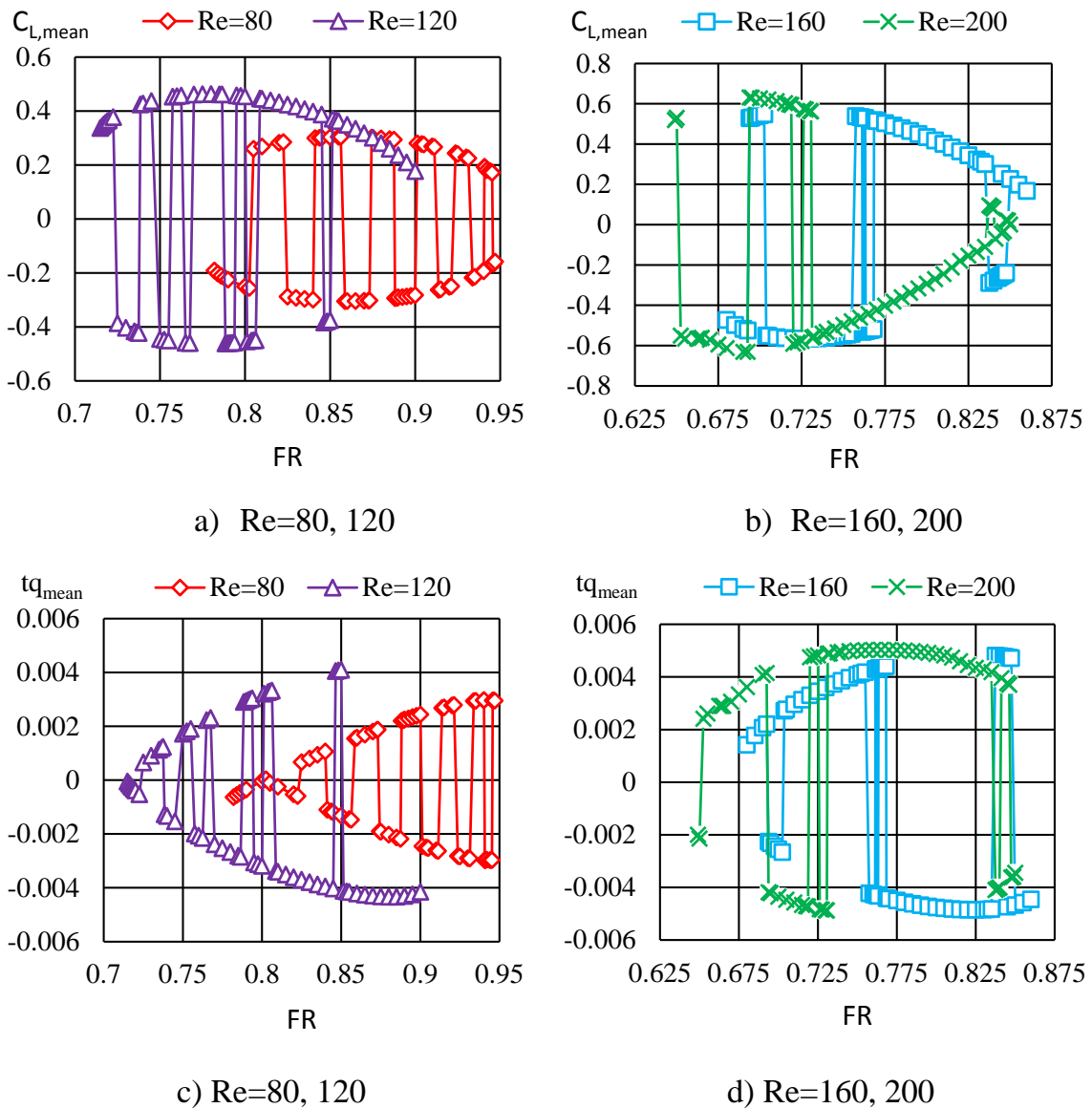


Figure 2  
Time-mean value of lift and torque coefficients against frequency ratio

It can be seen in Fig. 2 that with increasing  $Re$  the locked-in domain shifts towards smaller FR values. The location of jumps in  $C_{L,mean}$  and  $tq_{mean}$  are the same at identical Reynolds numbers. It can also be observed that the signs of  $C_{L,mean}$  and  $tq_{mean}$  are always opposite to each other.

In Fig. 3 the vorticity contours at  $Re=80$  and  $200$  are shown at a particular switching point when  $C_{L,mean}$  changes from the positive to negative sign. These vorticity contour snapshots are taken at the upstream-most position of the cylinder for both  $Re$ . Blue means negative vorticity (rotating in clockwise direction) and red positive vorticity (counterclockwise). It can be seen that

- (1) the flow patterns before (Figs. 3a and 3c) and after (Figs. 3b and 3d) the vortex switching point are practically mirror images of each other;
- (2) with increasing Reynolds number the angle of inclination of the vortex row increases.

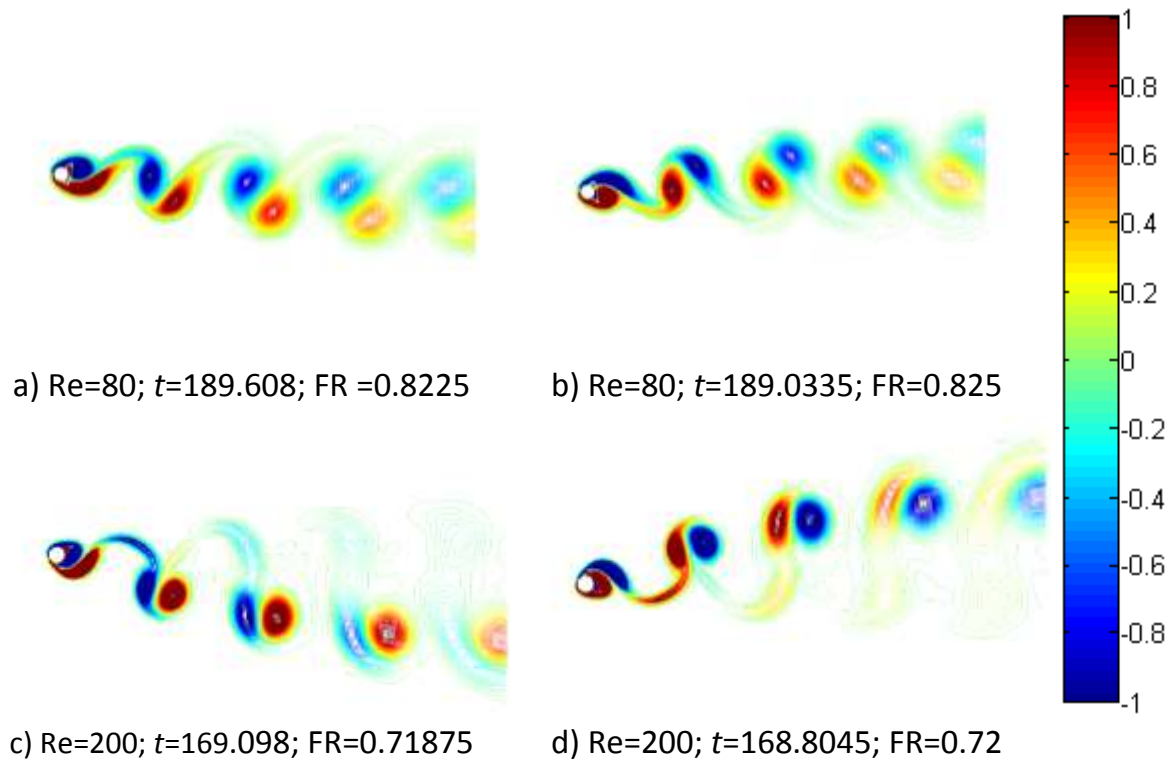


Figure 3

Vorticity contours before and after vortex switch at  $Re=80$  and  $200$

When the flow becomes periodic a limit cycle curve of two periodic signals can be plotted. In Fig. 4a limit cycle curves  $(x, C_L)$  are shown for  $Re=200$  for FR values before (red, lower curve) and after (blue, upper curve) a vortex switch. The two curves appear to be mirror images of each other. This is confirmed by Fig. 4b, where the pre-switch limit cycle curve is  $(x, C_L)$  and the post-switch curve is  $(x, -C_L)$ . As can be seen in Fig. 4b, the two curves are practically identical. This is an indication of pitchfork bifurcation [8].

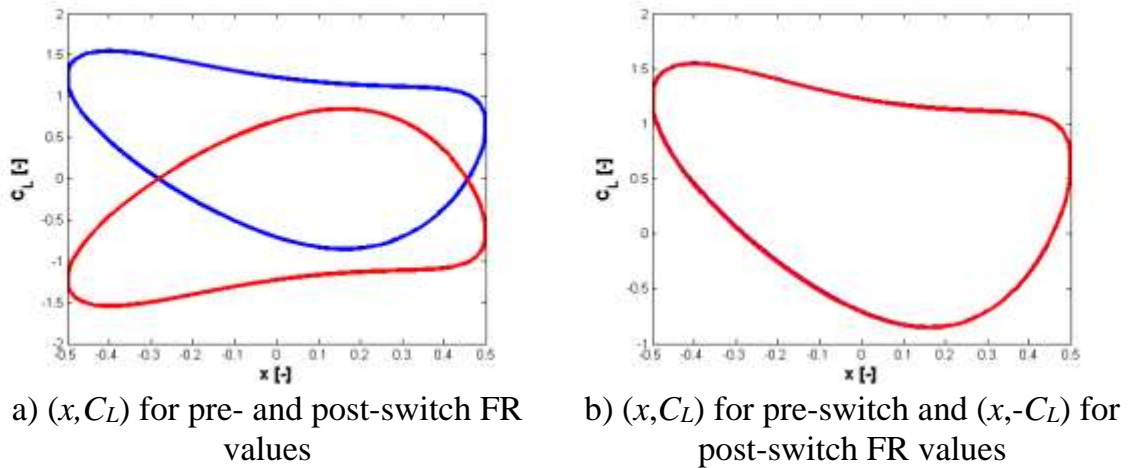


Figure 4  
 Limit cycles at  $Re=200$   
 red –  $FR=0.71875$ ; blue –  $FR=0.72$

Let us see now the time-mean and rms values of drag against FR shown in Fig. 5, where no abrupt jumps can be observed. It can be seen in Fig. 5a that the lower FR threshold for the lock-in phenomenon shifts to smaller FR values with increasing Reynolds numbers and that the peak time-mean drag value increases with  $Re$ , as expected. Figure 5b shows that the rms of drag increases with FR and basically with  $Re$  as well (except for below FR around 0.74, where the rms value is larger for  $Re=160$  than for  $Re=200$ ).

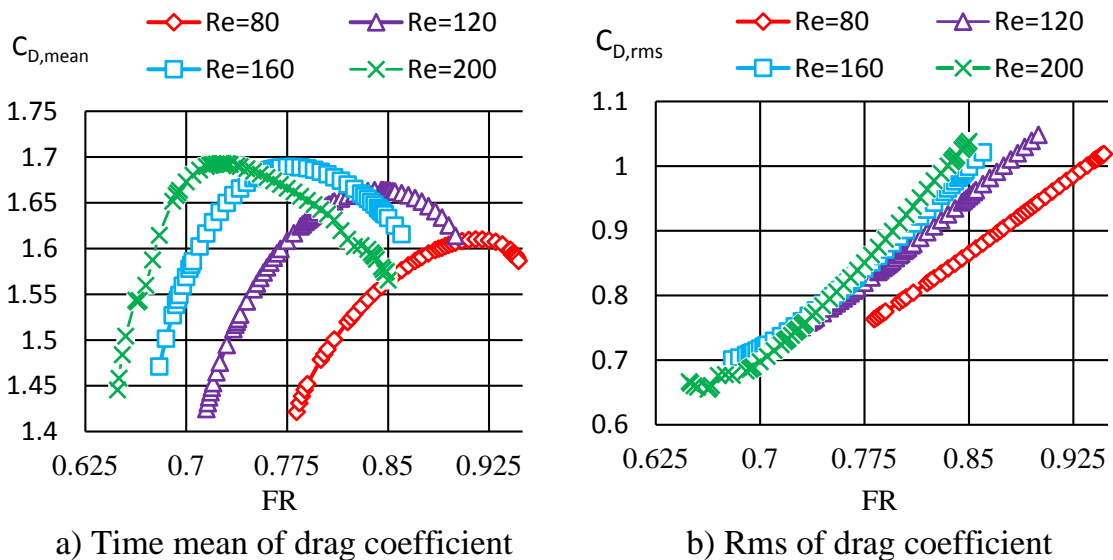


Figure 5  
 Time-mean and rms values of drag coefficient against frequency ratio

Figures 6a and 6b show the rms values of lift and torque coefficients against FR. No jumps are found and rms values shift up with increasing  $Re$ , except for the rms of torque coefficient for  $Re=200$ . As can be seen, none of the rms value curves have

jumps, meaning that vortex switches affect the time mean of lift and torque but have no effect on any rms curves or on the time mean of drag.

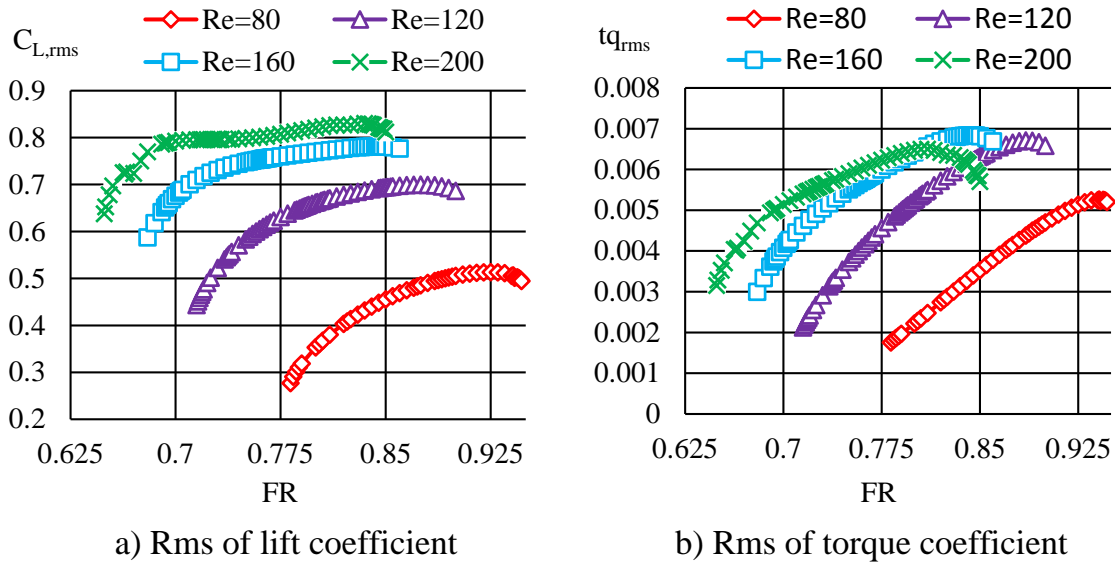


Figure 6  
Rms values of lift and torque coefficients against frequency ratio

## CONCLUSIONS

This study deals with the numerical simulation of a two-dimensional incompressible, laminar Newtonian fluid flow around a circular cylinder mechanically oscillated in-line with the main flow. The objective is to clarify the effect of frequency ratio on the flow at Reynolds numbers  $Re=80, 120, 160$  and  $200$  and at a fixed dimensionless oscillation amplitude of  $0.5$ . Time-mean and rms values of force coefficients were plotted against frequency ratio  $f/St$ . It was found that:

- with increasing Reynolds number, the general trend was for both time-mean and rms curves to shift to smaller frequency ratio values, thus the lower threshold values for lock-in shift to smaller frequency ratio values with  $Re$ ;
- jumps between two solutions were found for all  $Re$  numbers for the time mean of lift and torque, indicating switches in the vortex structure;
- post-switch solutions are mirror images of pre-switch solutions, as shown by both vorticity contours and limit cycle curves.

In this study only one oscillation amplitude was investigated, due to the huge amount of computational work needed. Further investigation on the effect of frequency ratio at other oscillation amplitude values would be useful.

## ACKNOWLEDGEMENT

The work was carried out as part of the TÁMOP-4.2.1.B-10/2/ KONV-2010-0001 project in the framework of the New Hungarian Development Plan. The realization of this project is supported by the European Union, co-financed by the European Social Fund.

## REFERENCES

- [1] NISHIHARA, T., KANEKO, S., WATANABE, T.: **Characteristics of fluid dynamic forces acting on a circular cylinder oscillated in the streamwise direction and its wake patterns.** Journal of Fluids and Structures **20** (2005), 505–518.
- [2] WOOTTON, L.R.: **Resume on full-scale tests on oscillation of piles in marine structures.** Construction Industry Research & Information Association (CIRIA), 1972, London
- [3] CETINER O., ROCKWELL, D.: **Streamwise oscillation of a cylinder in a steady current. Part 1. Locked-on states of vortex formation and loading.** Journal of Fluid Mechanics **427** (2001), 1-28.
- [4] AL-MDALLAL, Q.M., LAWRENCE, K.P., KOCABIYIK, S.: **Forced streamwise oscillation of a circular cylinder: Locked on modes and resulting fluid forces.** Journal of Fluids and Structures **23** (2007), 681-701.
- [5] BARANYI, L., HUYNH, K., MUREITHI, N.W.: **Dynamics of flow around a cylinder oscillating in-line for low Reynolds numbers.** Proc. FEDSM2010-ICNMM2010 ASME Conference 2010, Montreal, Québec, Canada, (2010), on CD ROM, pp. 1-10, Paper No. FEDSM-ICNMM2010-31183
- [6] BARANYI, L.: **Numerical simulation of flow around an orbiting cylinder at different ellipticity values.** Journal of Fluids and Structures **24** (2008), 883-906.
- [7] POSDZIECH, O., GRUNDMANN, R.: **A systematic approach to the numerical calculation of fundamental quantities of the two-dimensional flow over a circular cylinder.** Journal of Fluids and Structures **23** (2007), 479-499.
- [8] STROGATZ, S.H.: **Nonlinear Dynamics and Chaos.** Westview Press, 1994.