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EFFECT OF GRADUAL AMPLITUDE INCREASE ON FLOW AROUND A CYLINDER OSCILLATED IN LINE

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Abstract
The present study deals with the numerical simulation of the flow around a circular cylinder oscillated in-line with the main stream. The primary aim of this paper is to investigate the effect of altering oscillation amplitudes during the course of computations on the time-mean values of force coefficients and to compare results with those of constant amplitudes. The two-dimensional computations are carried out at Re*=80 and at 80% of the natural vortex shedding frequency, while the oscillation amplitude is varied in the lock-in regime. The results show that for constant amplitudes there are several switches in the vortex structure, in contrast with altering amplitude solutions, where the solution can remain in one of the two state curves when the amplitudes are increased rapidly. Another finding is that the lock-in domain is substantially wider for the amplitude alteration model than for the constant amplitude case.*

Keywords: *amplitude alteration, circular cylinder, fluid flow, in-line oscillation, vortex switches*

1. INTRODUCTION

Fluid flow around an oscillating cylinder is a well-known fluid-solid interaction problem that is widely investigated due to its academic and practical importance, using numerical and experimental approaches. When a structure is exposed to wind or waves, vortices shed from the body induce a periodic load on the structure. When the vortex shedding frequency is near the natural shedding frequency of the structure and the damping is small, high amplitude oscillation can occur. Chimney stacks, transmission lines and offshore structures are good examples for this phenomenon.
Numerical studies often place a cylinder in forced motion in order to gain an approximation of this fluid-structure interaction. In this study we concentrate on forced oscillations, which can occur transverse or in-line to the main stream or in both directions. Until the early 1970s most researchers dealt with transverse oscillations. However, [1] showed that streamwise oscillation can occur in full scale piles, while [2] reported that the damage at the Monju nuclear power plant was caused by in-line oscillations.

The cylinder oscillation is characterized by the oscillation amplitude A and frequency f. The forcing frequency is often represented by the frequency ratio $FR=f/St_0$ where St_0 is the natural shedding frequency. The effect of the frequency ratio in the range of FR=0.44-3 was investigated in [3] using experimental techniques at medium Reynolds numbers. A similar frequency ratio range was investigated numerically in [4] at Reynolds number Re=200 and dimensionless oscillation amplitudes A=0.1 and 0.3, and found abrupt changes in the vortex structure. In [5] computations were carried out at low and medium amplitude values at FR=1. In [6] in-line cylinder oscillation was analyzed 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. An amplitude alteration model was introduced in [7] where the amplitude was varied with time for both streamwise and transverse cylinder oscillations. Results showed that for in-line oscillation with abrupt amplitude changes the vortex switches were avoided.

In this study an amplitude alteration model is presented which is tested for in-line cylinder oscillations. The Reynolds number and the frequency ratio are kept constant at Re=80 and FR=0.8, respectively. The oscillation amplitude is varied in the regime where the vortex shedding frequency synchronizes with the frequency of the cylinder motion, called locked-in regime. The results of the amplitude alteration and constant amplitude models are compared.

2. COMPUTATIONAL METHOD

The dimensionless governing equations for an incompressible, constant property, Newtonian fluid flow around a circular cylinder are the two components of the Navier-Stokes equations, the continuity equation and a Poisson equation for pressure. The equations of motion are written in a non-inertial system fixed to the moving cylinder. *Figure 1* shows the physical and computational domains where R_1 is the cylinder radius and R_2 is that of the far field. Undisturbed velocity field is assumed in the far field and no-slip boundary conditions are used on the cylinder surface for the velocity. Neumann type boundary conditions are used for pressure on both R_1 and R_2.

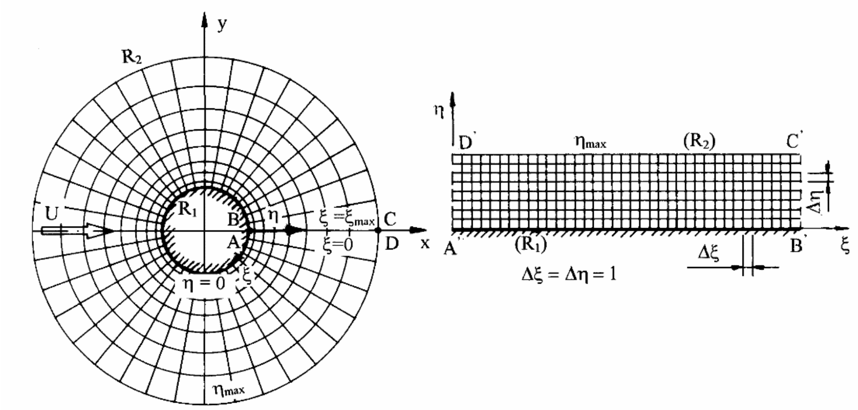


Figure 1 The physical and computational domains

In order to be able to impose boundary conditions accurately and to avoid numerical inaccuracies, boundary-fitted coordinates are used. The physical domain is transformed into a rectangular computational domain applying linear mapping functions [8]. The properties of the mapping functions ensure that the grid on the physical plane is very fine in the vicinity of the cylinder surface and coarse in the far field, while the grid is equidistant on the computational domain. The transformed governing equations with the boundary conditions are solved applying finite difference method [8]. 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.

The computational code was tested thoroughly against results in the literature for stationary and moving cylinders and very good agreement was found [8]. During the computations the radius ratio R_2/R_1=160 and the computational grid is characterized by grid points 360×292 (peripheral × radial) and the dimensionless time step Δt is 0.0005. Applying these parameters the code results in a solution independent from the domain, grid and time step. Following [6-7] the vortex switches are analyzed using lift and torque. From their time histories the time-mean (mean) values are computed.

3. RESULTS

The non-dimensional displacement of the center of the cylinder

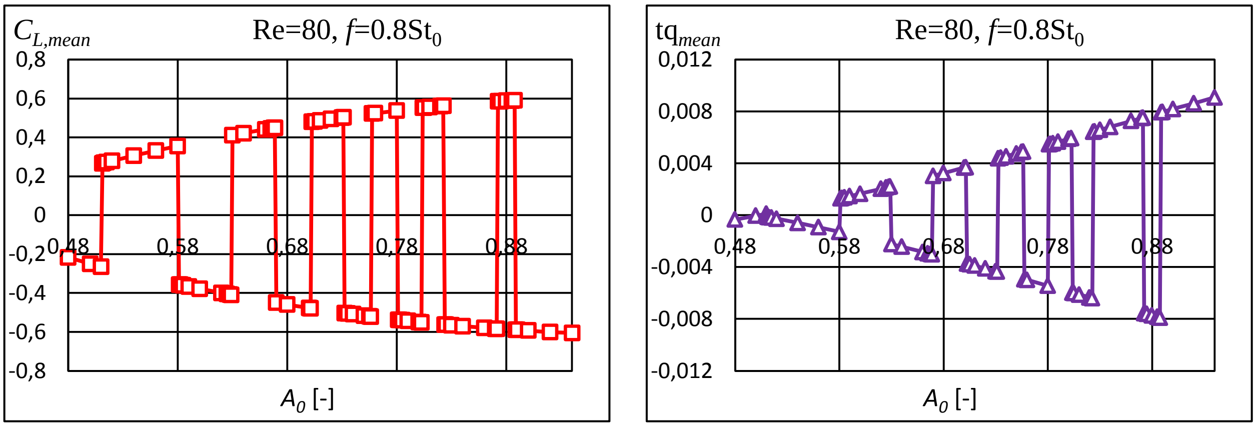
$$x(t) = A\cos(2\pi f t), \tag{1}$$

where *t*, *A* and *f* are the dimensionless time, amplitude and frequency of the cylinder.

Flow around a circular cylinder is a typical non-linear problem with two solutions. There are two attractors in this system (see [9]), each with a basin of attraction. If the set of parameters is near the boundary which separates the two basins of attraction, then even a tiny change in a single parameter is sufficient to change the attractor, yielding a switch in the solution. For example, [6,7] found large jumps in the time-mean values of lift and torque, indicating switches in vortex structure.

3.1. Constant amplitude solutions

In Figs. 2(a) and (b) the time-mean values of lift C_L and torque tq coefficients (see [6]) are plotted against oscillation amplitude A_0, while A_0 does not change with time. During these computations the Reynolds number and frequency are kept at constant values of Re=80, f=0.8St$_0$ (where St$_0$=0.15229 taken from [10]). It can be seen that (1) lock-in takes place between A_0=0.48–0.94 which agrees well with results in [6]; (2) the number of the jumps increases with A_0; (3) the locations of jumps are identical for the time-mean of lift and torque but their signs are opposite.



(a) (b)

Figure 2 Time-mean values of lift (a) and torque (b) for A=A_0=const. oscillation amplitude

Both state curves, which form the envelope, are clearly visible in the figure. As also found in [6,7], the state curves are mirror images. While the curves can be determined using different initial conditions, repeating the set of computations for several initial values is computationally expensive.

3.2. Altered amplitude solutions

In order to reduce the computational cost, [7] suggests that by applying amplitude alteration the solutions can be kept in one state curve. In the model applied in [7] the cylinder started to oscillate at an amplitude of A_{x1}, which was altered with time to a higher A_{x2} value either abruptly or gradually. The rate of change between A_{x1} and A_{x2} was linear. Here, a more gradual rate of increase is used, as shown in *Figure 3*.

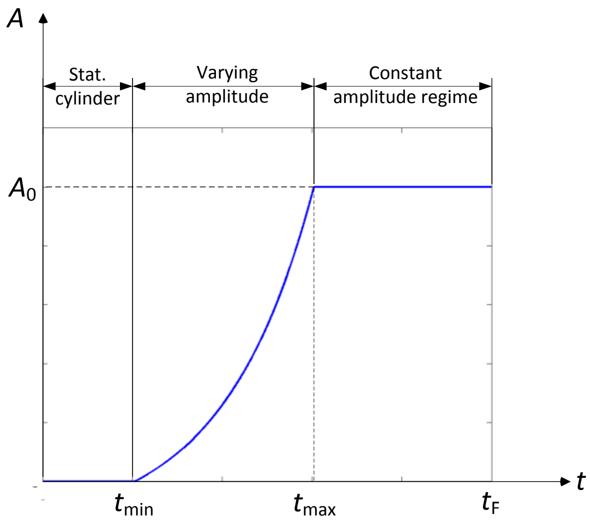


Figure 3 The amplitude alteration model based on equation (2)

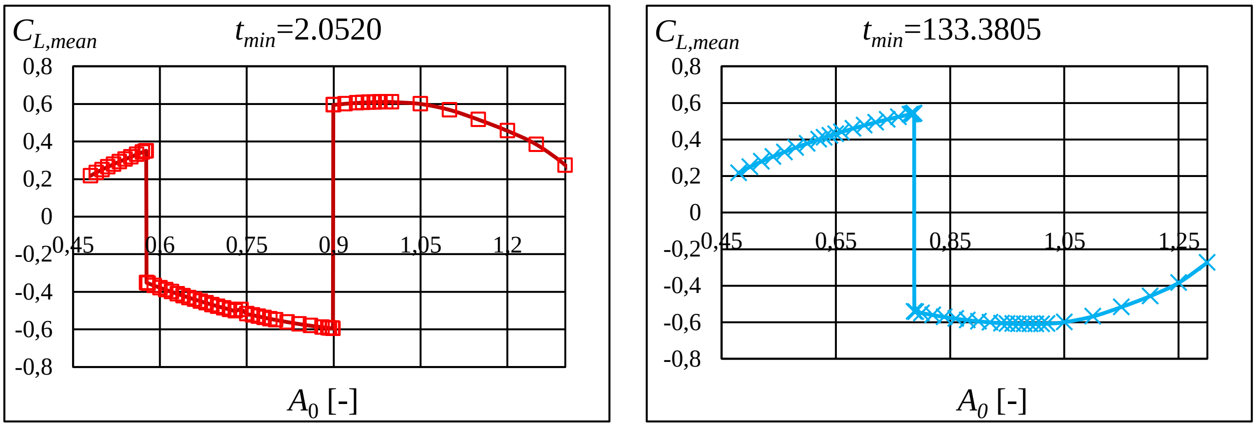
It can be seen that the full investigation time t_F is divided into three parts: (a) $0<t<t_{min}$ the cylinder is stationary; (b) $t_{min}<t<t_{max}$ the amplitude is altered from A=0 to A_0 using an exponential function; (c) $t_{max}<t<t_F$ constant amplitude regime of $A=A_0$. This can be written mathematically as

$$A = \begin{cases} 0, & if\ 0 < t < t_{min} \\ A_0 \dfrac{e^{n(t-t_{min})}-1}{e^{n(t_{max}-t_{min})}-1}, & if\ t_{min} < t < t_{max}, \\ A_0, & if\ t_{max} < t < t_F \end{cases} \tag{2}$$

where A_0 is the maximum amplitude, n influences the slope of the curve, t_{min} and t_{max} are the start and the end of the alteration, respectively. Compared to [7], small n values correspond to gradual amplitude alteration. However, when the alteration is abrupt the value of n is relatively high. The course of amplitude alteration can be controlled using t_{min} and t_{max}. In order to avoid discontinuity in the velocity and the acceleration of the cylinder, at the start of the alteration (t_{min}) the cylinder has to be in the origin, i.e, condition $cos(2\pi f t) = 0$ is satisfied, and at the end of the amplitude alteration the cylinder has to be in the position of x= A_0. At this instant the condition of $cos(2\pi f t) = 1$ is satisfied. In the further part of this study the effect of t_{min} is investigated. The end point of the alteration was fixed at t_{max}=205.2005 and parameter n is chosen to be n=0.024375. The starting point of the alteration t_{min} was varied between 0 and t_{max}.

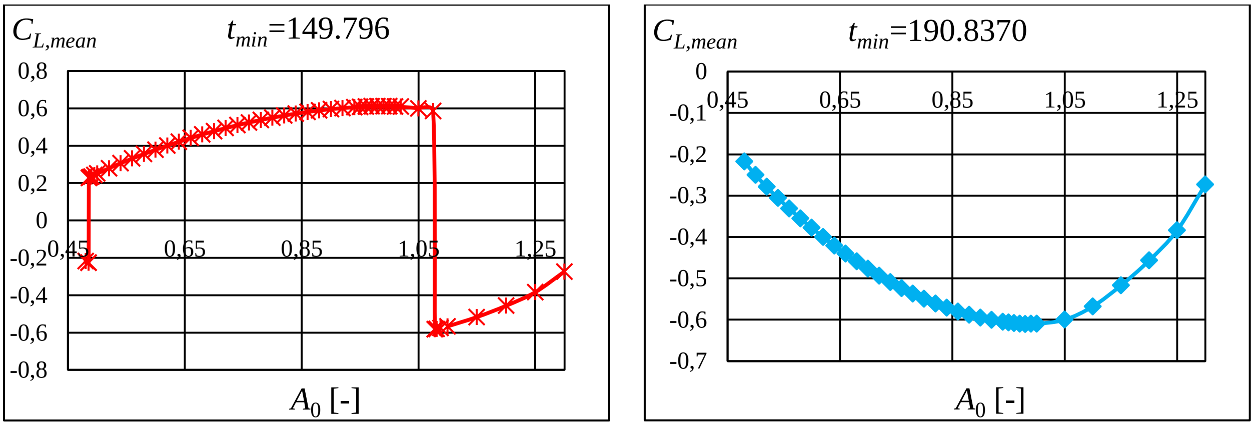
In *Figures 4 and 5* the time-mean values of lift are shown for different t_{min} values. It can be observed that compared with *Figure 3(a)* the number of jumps is significantly smaller. In *Figure 4(a)* only two jumps occur. Increasing t_{min} the location of jumps from the upper state curve to the lower shift to higher amplitude values. *Figure 4(b)* shows that for t_{min}=133.3805, there is only one jump. For t_{min}=149.796 shown in *Figure 5(a)* two jumps occur again. However, in *Figure 5(b)*, there are no jumps at all, and the solutions lay on the lower state curve. This is probably due to the short alteration time, which in this case is only t_{max}-t_{min}=14.3635.

In *Figure 6* a comparison of the constant and altered amplitude solutions using the time-mean of lift and torque coefficients is shown. It can be seen that (1) the number of jumps is much smaller for the altered amplitude than for the constant amplitude case shown earlier, and (2) using the altered amplitude model the locked-in regime can be made substantially wider. In case of constant amplitudes, synchronization takes place between A_0=0.48–0.94, but with altering amplitudes this regime is almost twice as wide, A_0=0.48–1.31.



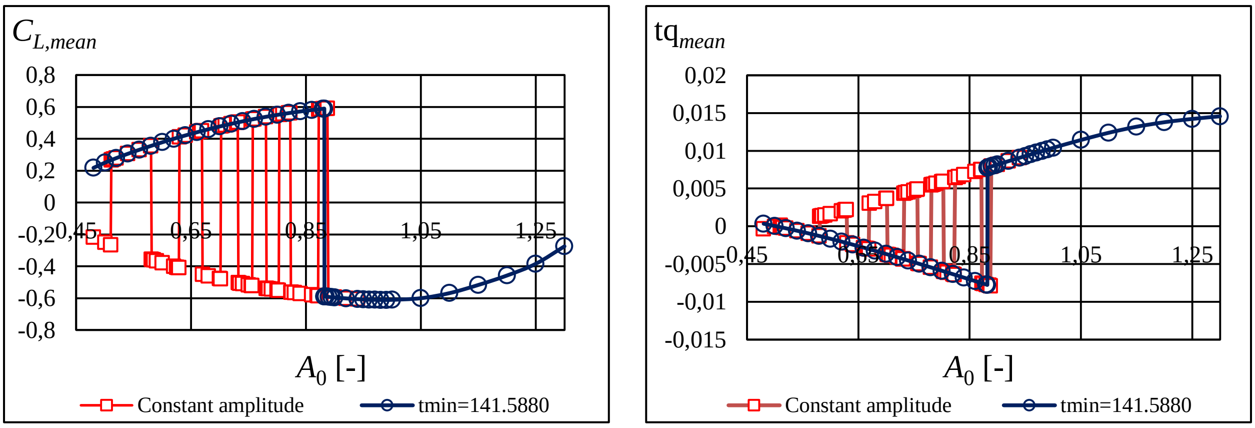
(a) (b)

Figure 4 Time-mean of lift vs. amplitude for (a) $t_{\min}$=2.0520 (b) $t_{\min}$=133.3805



(a) (b)

Figure 5 Time-mean of lift vs. amplitude for (a) $t_{\min}$=149.796 (b) $t_{\min}$=190.8370



(a) (b)

Figure 6 Comparison of constant and altered amplitude solutions (a) lift and (b) torque

CONCLUSION

In this study the flow around a circular cylinder oscillated in-line with the main stream was investigated using a numerical approach. The time-mean values of the force coefficient were plotted against the oscillation amplitude. The comparison of the constant and altering amplitude solutions show that

1) using the constant amplitude model several jumps between the upper and lower state curves in the time-mean of lift and torque coefficients were identified, indicating switches in the vortex structure;
2) applying the altering amplitude model a maximum of two jumps was detected. For t_{min}=190.8370 no jump was observed, with all of the solutions staying on a single state curve;
3) the locked-in regime at constant amplitudes was A_0=0.48-0.94 and at altering amplitudes the synchronization regime extended considerably to A_0=0.48-1.31.

In the near future an investigation into the effect of initial conditions is planned.

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