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Effect of in-line or transverse cylinder oscillations on laminar flow – a numerical study

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Abstract
The different effect of forced in-line and transverse cylinder oscillation on the low Reynolds number flow is investigated using a thoroughly tested FD in-house code. Both the pure in-line and pure transverse oscillations are perturbed by adding small amplitude oscillation in the other direction. Results show that the flow features can be drastically different in terms of occurrence of vortex switches.

1. Introduction
Oscillating cylinders are of interest in situations such as slender structures exposed to wind and off-shelf structures and are also an area of fundamental research in the effort to clarify wake phenomena, in all its complexity. Transverse oscillation is most often studied (e.g. Williamson and Roshko (1988), Meneghini and Bearman (1995), Lu and Dalton (1996), Blackburn and Henderson (1999), Leontini et al. (2006), Kaiktsis et al. (2007) due to its relevance to real-life situations, but there are quite a few researchers dealing with in-line cylinder oscillation as well, e.g. Rodriguez and Mureithi (2006), Al-Mdallal et al. (2007), Baranyi (2009). There are fewer papers for the cylinder orbiting in uniform flow, e.g. Teschauer et al. (2002), Didier and Borges (2007), Baranyi (2008).

An interesting phenomenon was found by the present author when looking at the time-mean (TM) and rms values of lift ($C_L$), drag ($C_D$), torque ($t_q$) and base pressure ($C_{pb}$) coefficients of an orbiting cylinder (the path being obtained by a superposition of two oscillations) in uniform flow. Abrupt jumps were found when each of these values was plotted against transverse amplitude value $A_y$ while other parameters of the flow were kept constant, Baranyi (2004, 2008). It has become clear that two so-called state curves exist and the solution jumps between them at some parameter values. It seems that there are two attractors in this non-linear system; whether the solution is attracted to one attractor or the other depends on the parameters of the system. It is likely that this is a symmetry-breaking bifurcation, Crawford and Knobloch (1991).

Later the present author investigated the effect of amplitude, either pure transverse or pure in-line cylinder motion on the TM and rms values of force coefficients. For in-line motion jumps were found in the TM of lift and torque coefficients only, while no jumps at all were found for transverse motion, Baranyi (2009). These jumps represent switches in the vortex structure.

The main purpose of this study is to investigate the effect of adding a small-amplitude transverse oscillation to in-line cylinder motion, resulting in a thin elliptical path. By comparing this with data for the superposition of small-amplitude in-line motion to transverse cylinder motion, the completely different behaviour of flow around a cylinder forced to oscillate in in-line or transverse directions can be demonstrated.

2. Governing equations and computational setup
The dimensionless governing equations for an incompressible constant property Newtonian fluid flow around a moving circular cylinder are the two components of the Navier-Stokes equations, the continuity equation and pressure Poisson equation written in a non-inertial system fixed to the cylinder (not shown here due to lack of space; for further details see Baranyi (2008)).

Using boundary-fitted coordinates the governing equations and the boundary conditions are transformed into the computational plane and the equations are solved by using the finite difference method. The in-house code developed by the author was tested thoroughly against available experimental and computational results for stationary and moving cylinders. For further details see Baranyi (2008).

During one computation all parameters are fixed, such as Reynolds number $Re=Ud/v$ (with free stream velocity $U$, cylinder diameter $d$ and kinematic viscosity $v$), dimensionless oscillation amplitudes $A_x$ and $A_y$, and frequencies $f_x$ and $f_y$ ($f_y=f_x$ in this study) of cylinder motion, domain size, computational mesh, time step and the initial position of the cylinder characterised by a polar
angle. The dimensionless frequencies of oscillation \( f_x = f_y \) are chosen to be 90\% of the natural vortex shedding frequency \( S_{0} \) to avoid the need for large amplitude oscillation to reach lock-in.

From a single computation velocity, pressure and vorticity fields and also time histories of \( C_L \), \( C_D \), \( C_{p} \) and \( C_{q} \) are obtained. From the time-history curves their TM and rms values can be determined. Then computations are repeated 40-60 times, depending on range of lock-in, at different values of independent variable \( A_x \). Only locked-in (subharmonic for in-line oscillation) cases were considered. As a result of these computations we obtain a set of TM and rms values which can be plotted against \( A_x \) to form a curve. This whole procedure can be repeated at a different \( A_y \) value. In this investigation, computational sets were carried out for \( A_y = 0, 0.01 \) and \( 0.05 \) (\( A_y \) as parameter) at \( Re=140, S_{0}=0.1821 \).

Later, computational sets were carried out for fixed parameters (here, \( Re=160, S_{0}=0.1882 \)) with \( A_x \) as the independent variable. Five values of \( A_y \) (as parameter) are investigated: \( A_y = 0, 0.01, 0.05, 0.1 \) and \( 0.15 \).

3. Computational results and discussion

First, results of computations are shown for the case when small amplitude transverse cylinder oscillation is superimposed on a larger amplitude in-line oscillation. Figure 1 shows the TM and rms values of lift against \( A_x \) for the three \( A_y \) values. The filled square signs denote the pure in-line oscillation (\( A_y = 0 \)), the empty triangles are for \( A_y = 0.01 \) and the empty diamonds are for \( A_y = 0.05 \). As can be seen in Fig. 1a, for pure in-line oscillation (\( A_y = 0 \)) the TM of lift has two state curves which are symmetric to reflection around axis \( A_x \), and the solution jumps between them. With the increase in the amplitude \( A_y \), the state curve move away from the \( A_y = 0 \) state curves and cease to be symmetric. The location of jumps also shifts. Fig. 1b shows a single curve without jumps for \( A_y = 0 \), but jumps appear for \( A_y > 0 \) cases. The location and number of jumps are identical on Figs. 1a and 1b. The TM of torque (not shown) also has two symmetric state curves.

![Figure 1: Time-mean (a) and rms (b) values of lift coefficient vs. \( A_x \) for three \( A_y \) values](image)

Figure 2 shows the TM and rms values of drag for the three \( A_y \) values against \( A_x \). For pure in-line oscillation (\( A_y = 0 \)) there are no jumps on TM and rms curves. Jumps appear as \( A_y > 0 \). Again, for cases \( A_y > 0 \), the location and number of jumps are identical to those of in Fig. 1. Figure 2b shows that the added transverse oscillation does not have much effect on the rms of drag. The TM and rms curves for the base pressure coefficient are quite similar to the curves shown in Fig. 2 and hence they are omitted.

All these results are in accordance with earlier findings, Baranyi (2008, 2009). Figure 3 shows the TM and rms values of lift against \( A_y \) for an orbiting cylinder for \( Re=160 \) and \( f=0.85S_{0} \). Here the value of \( A_y = 0.4 \) ensures lock-in even at zero \( A_y \) value. In the case of orbiting cylinder these two types of states curves were found: the almost parallel state curves are characteristic of the TM of \( C_L \) and \( C_q \) (Fig. 3a) and the diverging state curves which intersect each other at zero \( A_y \) value represent all rms curves and the TM of drag and base pressure. In the limiting case, as \( A_y \) tends to zero pure in-line oscillation is obtained. Looking at Fig. 3 it can be seen that in this
limiting case there are two possible solutions for the "parallel" (and that they are mirror images) and only one for the "diverging" type. This accounts for the double state curves seen in Fig. 1a, and for the single curves in Fig. 1b and Fig. 2 for the filled squares ($A_y=0$). On the other hand, as shown in Fig. 3b, as $A_y>0$ two curves appear, meaning that jumps will occur in all TM and rms curves (see also Figs. 1 and 2).

![Figure 2: Time-mean (a) and rms (b) values of drag coefficient vs. $A_x$ for three $A_y$ values](image)

![Figure 3: Time-mean (a) and rms (b) values of lift coefficient vs. $A_y$ for a fixed $A_x$ value](image)

![Figure 4: Time-mean of lift vs. $A_y$](image)

![Figure 5: Time-mean of lift & rms of drag vs. $A_x$](image)

Next, let us consider the case when the cylinder is oscillating in transverse direction and a small amplitude oscillation is superimposed on this motion. Figure 4 shows the TM of lift against
for five different \( A_x \) values, where \( A_x=0 \) represents pure transverse cylinder oscillation. No jumps can be seen in this figure even at larger \( A_x \) and \( A_y \) values. This result is in accordance with the earlier results of Baranyi (2009), shown in Fig. 5, where the TM of lift and rms of drag can be seen. In this case the \( A_y=0.3 \) amplitude value ensures lock-in even for \( A_x=0 \). The limiting case of \( A_x=0 \) means pure transverse oscillation. It can be seen in Fig. 5 that there is only one solution for a transversely oscillating cylinder for both TM of lift and rms of drag (and for the rest of the TM and rms curves, not shown), so no jumps can be expected in the solution for a transversely oscillated cylinder. It can be seen that the TM of lift is zero for a transversely oscillating cylinder, as in the case of a stationary cylinder. This was found to be true for the TM of torque as well. The \( A_y=0 \) case in Fig. 5 corresponds to the empty rectangles in Figure 4. As can be seen in Fig 5, a relatively large \( A_x \) amplitude is needed to cause jumps in the TM and rms values. The comparison of Figs. 1 to 3 and Figs. 4 and 5 shows the profoundly different effects of in-line and transverse cylinder oscillation on the force coefficients and on the fluid-structure interaction.

4. Conclusions
The main findings of this study were that by superimposing small-amplitude transverse cylinder oscillation on pure in-line cylinder motion, vortex switches occur, resulting in jumps in all TM and rms values of force coefficients. When small-amplitude in-line oscillation is superimposed on pure transverse cylinder motion, however, no vortex switches occur. This is in full accordance with earlier findings of the author for an orbiting cylinder.

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References