Numerical simulation of the flow-induced vibration in the flow around two circular cylinders in tandem arrangements

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Abstract. Two-dimensional numerical simulations of the flow around two circular cylinders in tandem arrangements are performed. The upstream cylinder is fixed and the downstream cylinder is free to oscillate in the transversal direction, in response to the fluid loads. The centre-to-centre distance is varied from 1.5 to 15.0 diameters, and the results are compared to that of a single isolated flexible cylinder with the same structural characteristics. Significant changes occur in the structural behaviour of the cylinders, and these are related to the flow regime in each of the configurations.

Key words: Flow-induced vibration, bluff bodies, flow interference.

1. Introduction

The flow-induced vibration of cylindrical structures is a key issue in engineering, due to the innumerable situations where components with this geometry are used in structures immersed in fluid streams. Also common is the utilisation of such components grouped together; transmission lines and riser pipes are typical examples. When two or more bodies are placed in close proximity, the flow field, fluid forces and, consequently, structural response change completely, and this phenomenon is called flow interference. Structures are usually designed to operate under specific limits of vibration amplitudes, thus knowledge about the flow-induced vibration under flow interference conditions is crucial.

Among all the possibilities of relative placement of two identical bluff bodies, it is expected that the highest lift forces will appear when one body is located in the wake of the other. This happens when the arrangement is aligned with the flow, i.e., when the bodies are in tandem arrangement. To understand how the the wake interacts with the moving body, it is reasonable to choose a configuration where this interaction is kept as isolated as possible. A good choice is the flow around a circular cylinder mounted in an elastic basis, allowed to move only in the transversal direction, immersed in the wake of an upstream fixed circular cylinder of same diameter.

Not many papers have been published on the flow-induced vibration in this configuration. Brika and Laneville [4] performed wind tunnel experiments upstream cylinder fixed. When comparing to the single cylinder case, their main findings were that the dynamic response of the downstream cylinder is not hysteretic, the synchronisation onset is at higher reduced velocities and the synchronisation region is wider. Hover and Triantafyllou [6] did experiments in a water channel, for a tandem configuration with centre-to-centre distance, L_x, of 4.75. They reported that frequency lock-in occurred at a low reduced velocity and remains through $V_r = 17$, but the phase change, which typically accompanies frequency lock-in, occurred at higher speeds. Examples of computational work on fluid-structure interaction in tandem arrangements are [7] and [11], however, they dealt with configurations other than the upstream cylinder fixed and the downstream flexible.

Computational simulations allow for detailed investigation of the flow field, being extremely useful to understand the physics of fluid mechanics phenomena. Nevertheless, to our knowledge, no paper using this tool to analyse the flow interaction between a stationary cylinder and a downstream flexible cylinder has been published so far. In the present work, numerical simulations are carried out to investigate this particular case of fluid-structure interaction. We focus on the results of oscillation amplitude and propose physical mechanisms to explain the phenomena.

2. Methodology

The incompressible fluid flow is modelled with the two-dimensional incompressible Navier-Stokes equations, which are discretized using the highly accurate Spectral/hp element method [9]. A stiffly stable time splitting scheme [8] is used to advance the solution in time. Because the two cylinders have non-zero relative displacement in time, the method must comply with domain deformation. For that reason, an ALE scheme is incorporated to the code. Following [2], the mesh is adapted to the boundary displacement in every time step by modelling each edge by a spring with stiffness inversely proportional to its length. The mesh movement is coupled to the time splitting scheme in a similar fashion as in [3].

The downstream cylinder is modelled as a uni-dimensional linear mass-spring-damper system that is able to move in the transversal direction only. The structural equation is integrated using Newmark's scheme [12] and loosely coupled to the time stepping scheme of the flow solver [7].

3. Numerical simulations

Numerical simulations were performed for a single flexible circular cylinder and for two circular cylinders with diameter D in tandem configurations with $1.5 \leq L_x/D \leq 15$, where L_x is the centre-to-centre distance between the cylinders. For the tandem arrangements, the upstream cylinder was stationary and the downstream one was flexible. The structural parameters of the flexible cylinders were kept constant and were chosen to match those in the experiments reported in [1], and they were allowed to move only in the cross stream direction y. The Reynolds numbers (Re) tested varied from 60 to 150, corresponding to reduced velocities (V_r) from 3.0 to 10.0, approximately ($V_r \equiv U_\infty/(Df_n)$, where U_∞ is the free stream speed and f_n is the natural frequency of the structure).

4. Results and discussion

Figure 1 shows the displacement amplitude results. The higher amplitudes for the single cylinder case appear for $4.4 \leq V_r \leq 6.0$, which is the lock-in range. If we compare the single cylinder results to the experimental results in [1], we notice a similar

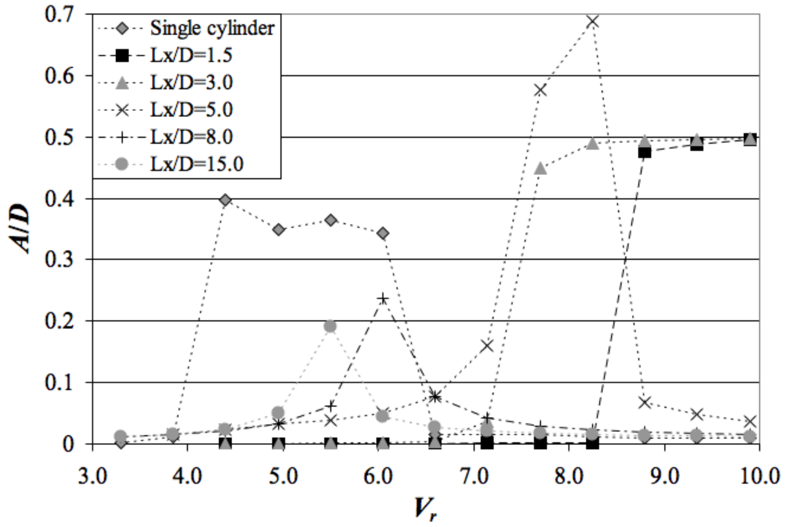
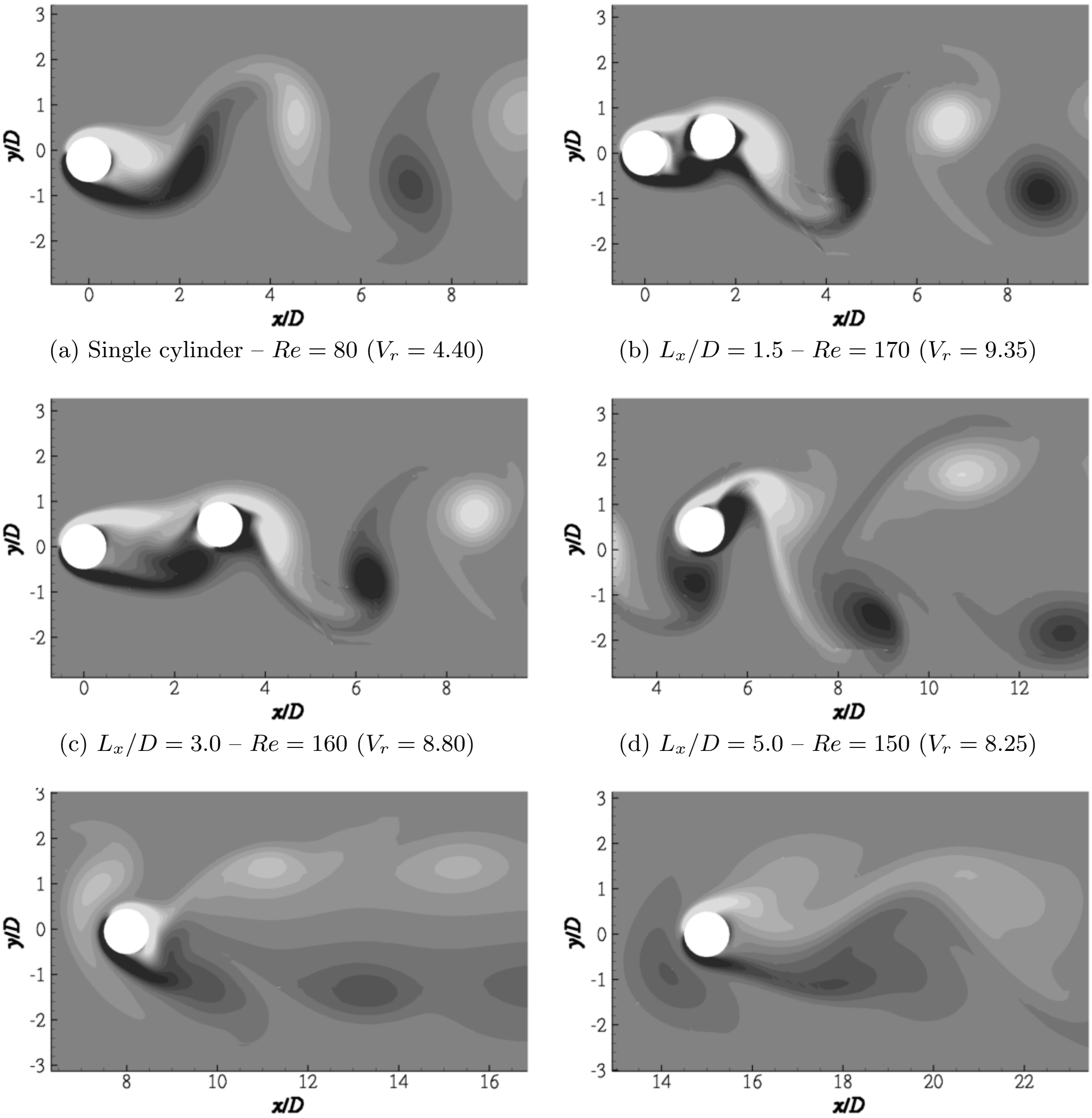


Figure 1: Oscillation amplitude as a function of the reduced velocity for different L_x/D.

behaviour. However, in the experimental results the lock-in range starts at a higher value of $V_r = 5.8$, and the maximum amplitude observed in the experiments was $A/D = 0.53$, while in the present computations this value was $A/D = 0.40$. Similar discrepancies between this experimental data and computations were reported in previous studies [10].

The differences seen in the lock-in region V_r range for each of the tandem cases can be justified by the deceleration of the flow due to the presence of the upstream cylinder. The smaller L_x, the slower is the flow when it reaches the downstream cylinder. Consequently, we see that the lock-in starting V_r approaches the single cylinder case for progressively increasing L_x.

The spectra of lift force and displacement showed that the upstream cylinder vortex shedding is synchronised with the displacement and vortex shedding of the downstream cylinder in all lock-in cases. Bearing this in mind, some links between the amplitude of motion and shedding regimes, illustrated in figure 2, can be proposed. For cases $L_x/D = 1.5$ and $L_x/D = 3.0$ the downstream cylinder is immersed in the formation region of the upstream cylinder, as can be seen in figures 2b and 2c. This is a region of very slow flow. The mean pressure in the near wake of the upstream cylinder is also very low, and it is possible that the principal mechanism of flow-induced vibration that occurs for these cases is a type of wake-induced galloping, instead of vortex-induced vibration. This could explain why the lock-in region for these cases is much longer and flatter than the other cases of tandem arrangements. For $L_x/D \geq 5.0$ the downstream cylinder is located out of the formation region of the upstream cylinder, as can be seen in figures 2d, 2e and 2f, and in this region the mean pressure is not so low. Therefore, for this configuration it seems that galloping is not very important, and vortex-induced vibration plays the leading role in the movement of the cylinder. This is consistent with the shorter lock-in region. Previous studies [5] show that for stationary cylinders in tandem arrangements, there is a peak in the fluctuating lift coefficient (${C_L}'$) acting on the downstream cylinder when it is located at the lowest L_x where a complete wake can be observed between the cylinders, and that ${C_L}'$ decreases if L_x is increased from this point on.



(a) Single cylinder – $Re = 80$ ($V_r = 4.40$)

(b) $L_x/D = 1.5$ – $Re = 170$ ($V_r = 9.35$)

(c) $L_x/D = 3.0$ – $Re = 160$ ($V_r = 8.80$)

(d) $L_x/D = 5.0$ – $Re = 150$ ($V_r = 8.25$)

(e) $L_x/D = 8.0$ – $Re = 110$ ($V_r = 6.05$)

(f) $L_x/D = 15.0$ – $Re = 100$ ($V_r = 5.50$)

Figure 2: Instantaneous vorticity contours for lock-in cases. Dark contours represent positive vorticity and light contours represent negative vorticity.

This behaviour was attributed to the strength of the vortices impinging upon the downstream cylinder: the closer the body is to the upstream cylinder, the stronger the vortices are. This may justify why the peak of amplitude is higher for smaller $L_x/D = 5.0$.

5. Conclusion and future work

The results presented show that the different structural responses that are obtained according to L_x in this V_r range might be related to the vortex shedding regime. Of note is the fact that depending on the distance between the cylinders, the vibrations observed can be remarkably higher and the peak of vibration can occur for a completely distinct V_r value.

The next steps of the research are to run simulations for configurations $L_x/D = 1.5$ and $L_x/D = 3.0$ at higher V_r, in order to better characterise the flow-induced vibration mechanism that takes part for such cases. Also, simulations for the same V_r range keeping Re constant and varying the natural frequency of the system will be performed, in order to isolate the Re effects.

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