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NUMERICAL INVESTIGATION OF LOW REYNOLDS NUMBER FLOW AROUND TWO CIRCULAR CYLINDERS IN TANDEM

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1 INTRODUCTION

Flow interference among pairs of circular cylinders with same diameter *D* in a tandem arrangement has been the subject of many investigations since this basic example of an array of multiple cylinders contributes to understand the interaction of multiple structures in a flow. The interference occurring in this type of arrangement causes significant changes in the parameters characterizing the aerodynamics of a single cylinder, such as: average and fluctuating lift and drag forces, time average and fluctuating pressure distributions, Strouhal number and vortex shedding patterns. Obviously these changes are strongly influenced by centre-to-centre spacing, *L*, between the cylinders.

Many of the previous works regarding the flow around two circular cylinders were based primarily on flow visualization. These experimental investigations allowed to identify various interference regimes and authors, such as Igarashi [1], Zdravkovich [2] [3] and Sumner *et al.* [4], proposed classifications of these regimes. These studies showed the existence of a critical spacing between the cylinder, at L/D=4.0, that corresponds to a large jump in the fluctuating forces and Strouhal number. More recently, Alam *et al.* [5] show, for a subcritical Reynolds number, that the phase lag between vortex shedding from two cylinders in tandem influences the forces acting on them.

With the development of computational methods in fluids dynamics a better understanding of complex flows through numerical simulation became possible and detailed information has been obtained reproducing experimental studies. Following this trends, numerical investigations have been conducted by Li *et al.* [6], Slaouti and Stanby [7], Mittal *et al.* [8], Meneghini *et al.* [9], Sharman *et al.* [10], Carmo [11], and Carmo and Meneghini [12]. Different computational methods have been used in these investigations, essentially for two-dimensional simulations at various Reynolds numbers, such as: vortex discrete method, finite volume method or spectral element method. Only Carmo and Meneghini [12] present a two-

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and three-dimensional study of flow around two cylinders in tandem, at Reynolds numbers, *Re*, between 160 and 320 using a spectral method. These authors found that, for *Re*>190-200, when three-dimensional structures are present in the flow field, a two-dimensional simulation is not sufficient to predict the parameters of aerodynamics characteristics. However, even if two-dimensional computations are adapted for flow at *Re*<190-200, the various authors only studied some gaps and so doing estimated only roughly the critical distance. To the best of our knowledge, only Sharman *et al.* [10] published a more detailed numerical investigation for flow at *Re*=100, although not very detailed beyond the critical gap.

Recently the present authors, Didier and Borges [13], published a detailed numerical investigation of flow interference between two circular cylinders in tandem at *Re*=100. They demonstrated that: i) forces acting on each cylinders are influenced by the phase lag of fluctuating lift between the cylinders; ii) fluctuating lift force acting on the downstream cylinder reaches its maximum for *L/D*=5.25 and not at the critical spacing, *L/D*=4.0, as observed at subcritical Reynolds numbers [1-5].

The present study focuses on the flow interference considering cylinder gaps varying from 1.5*D* to 10.0*D*, with a small spacing step in order to follow in detail the interaction between the cylinders and the flow. Flow simulations at Reynolds numbers 200 are carried out using a fully coupled resolution method for solving the Navier-Stokes equations. Comparing and analyzing Strouhal number, mean and fluctuating lift and drag, cross-correlation of fluctuating lift of each cylinder and the flow field patterns. Details of the two-dimensional mechanism involved in the flow interference are presented and compared to that obtained previously for *Re*=100 [13].

2 NUMERICAL METHOD AND CONVERGENCE

A fully coupled second order resolution method for unstructured cell-centered collocated grid is used for solving the Navier-Stokes equations, Didier and Borges [14]. No-slip condition is applied to the surface cylinder. Free-stream velocity condition is applied on the external boundary far from the cylinders. With this numerical method only one linear system gathering all discrete equations is constructed and solved using the iterative resolution algorithm BiCGSTAB-ω preconditioned *LU*. Study convergence at *Re*=100 demonstrates that independent results are obtained for a 51100 elements mesh (for a centre-to-centre spacing *L/D*=4.5) with an external boundary at 100*D* from the cylinders and a non dimensional time step 10^{-2} [13]. The same computational parameters are adopted to carry out flow simulations at *Re*=200.

3 RESULTS AND DISCUSSION

Numerical results of Strouhal number, *St*, and lift fluctuating force, $C_{L,rms}$, obtained for *Re*=100 [13] are presented in Fig.(1) and Fig.(2) respectively and compared with experimental data [15] and numerical results [6] [10]. Fig.(3) and Fig.(4) present the Strouhal number and lift fluctuating force vs. the centre-to-centre cylinder spacings at *Re*=200, compared with numerical results of Carmo [11]. One can see that the present numerical results for *Re*=100 and 200 are in very good accordance with the numerical ones of Sharman *et al.* [10] and Carmo [11] respectively.

For the two Reynolds numbers considered, a similar behaviour is observed. The large jump in fluctuating forces and Strouhal number at *L/D*=4.0 corresponds to the critical spacing, where a bistable regime takes place.

Synchronization of Strouhal number between the two cylinders occurred for both Reynolds numbers. Before the critical gap, the dynamics in the near wake of the downstream cylinder and the shedding frequency are determined by the incident oscillatory flow. Fig.(1) and Fig.(3) show that distribution of *St* is undulating and presents maximum and minimum values. Cross-correlation between the fluctuating lift force of the two cylinders demonstrates the existence of in-phase and out-of-phase situations. Therefore, the interference between the bodies influences the resulting forces acting on the cylinders and fluctuating lift force presents undulation associated to in- and out-of- phase configurations. These results indicate that a proximity interference occurs between the cylinders. The downstream cylinder influences the resulting forces in the upstream one. This suggests that vortex shedding from the upstream cylinder can be inhibited, in out-of-phase situation, or reinforced when in-phase configuration occurs, altering the forces acting on the two cylinders. Due to these interferences, the Strouhal number decreases with the diminution of the spacing between the cylinders.

In Fig.(2) and Fig.(4) it can be seen that the fluctuating lift force does not necessary reach its maximum at the same gap: at *Re*=100, the maximum occurs at *L/D*=5.25 whereas it is reached at *L/D*=4.0, the critical gap, at *Re*=200. The Strouhal number can be expressed as $St=D/\lambda$, with λ the characteristic length between a vortices pair [13]. For a single cylinder in an uniform flow, the Strouhal number at *Re*=100 and *Re*=200 is $St_{Re=100}$=0.164 and $St_{Re=200}$=0.2 respectively. Therefore, considering a cylinder diameter *D*=1.0, the characteristic length for each of these Reynolds number flows are $\lambda_{Re=100}$=6.25 and $\lambda_{Re=200}$=5.00. These length correspond to the distance between the downstream and upstream stagnation points of the cylinders, when the gap is $L/D_{Re=100}$=5.25 and $L/D_{Re=200}$=4.0, when the fluctuating lift force reaches its maximum. Therefore a spatial synchronization is identified in addition to the in- and out-of- phase phenomenon. For a Strouhal number, a particular gap exists where vortices shed from the upstream cylinder add to the vortices shed from the downstream cylinder, in a way that fluctuating lift forces reaches its maximum.

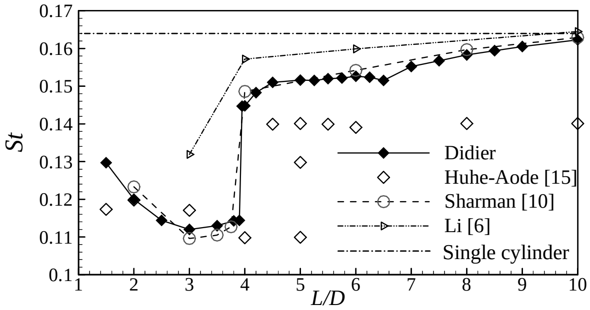

Figure 1: Strouhal number, *Re*=100, from [13].

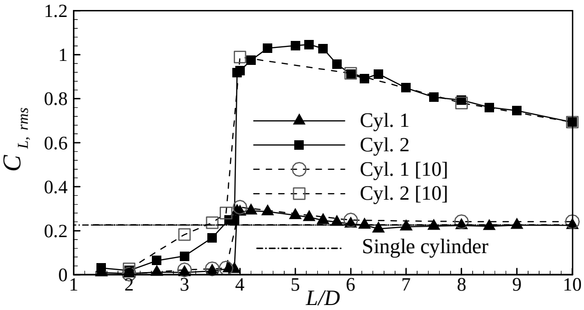

Figure 2: Lift fluctuating force, *Re*=100, from [13].

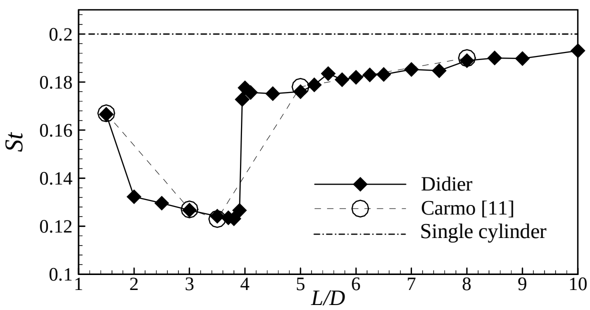

Figure 3: Strouhal number, *Re*=200.

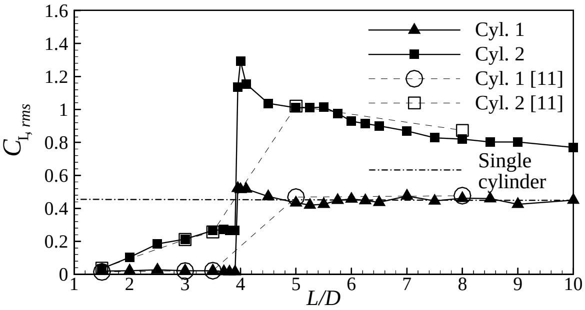

Figure 4: Lift fluctuating force, *Re*=200.

Summarizing: the goal of this work is to achieve a deeper understanding of the physical mechanisms that are involved in the interference phenomenon. With the aid of numerical simulations, mean and fluctuating drag forces, phase lag between vortex shedding from the two cylinders, mean and fluctuating pressure coefficient distribution on the two cylinders, separation and reattachment points on the cylinders, mean velocity and pressure along the symmetric central line and flow topology are calculated and analyzed in function of the cylinders gap. These results will be presented in the final paper.

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