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Secondary instabilities of the in-phase synchronized wakes past two circular cylinders in side-by-side arrangement

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ABSTRACT

In the present study we investigate the secondary instability of the in-phase synchronized vortex shedding from two side-by-side circular cylinders at low Reynolds numbers. Two distinct Floquet modes become unstable for different values of the Reynolds number and of the non-dimensional gap spacing, leading to the onset of the well-known *flip-flop* instability of the two cylinder wakes. In both cases the two-dimensional Floquet analysis reveals that at very low Reynolds numbers, a pair of complex-conjugate multipliers crosses the unit circle, showing the same frequency as the biased gap-flow flip-over. In the past literature this behaviour has been often ascribed to a bistability of the flow. On the contrary, the present DNS and stability results provide evidence that at low Reynolds numbers, the flip-flopping behaviour originates from a Neimark–Sacker bifurcation of the in-phase shedding cycle.

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1. Introduction

Bluff-body wake interaction plays an important role in several industrial applications, such as, for instance, in the flow past tube bundles in heat exchangers or in the design of high-rise buildings. A simple, yet interesting prototype of this kind of flows is represented by the incompressible flow past two side-by-side circular cylinders (Zdravkovich, 1977). In this configuration, the two cylinders are aligned along the direction perpendicular to the free stream (see Fig. 1) and the flow is governed by two independent non-dimensional parameters: the Reynolds number $Re = U_\infty^* D^* / \nu^*$ and the non-dimensional distance between the cylinder surfaces $g = g^* / D^*$, U_∞^* being the free-stream velocity, D^* the cylinder diameter and ν^* the kinematic viscosity. As the gap size is varied, basically three distinct vortex shedding regimes are observed: the single bluff-body regime ($g \leq 0.2$), the asymmetric regime ($0.2 \leq g \leq 1.2$) and the symmetric regime ($1.2 \leq g \leq 5$) with a synchronization of the vortex shedding from the two cylinders (Sumner, 2010). The synchronization may occur either in phase, leading to an anti-symmetric wake pattern, or in phase, resulting in a wake pattern symmetric with respect to the flow centerline. At low Reynolds numbers both these synchronized patterns have been described in the experimental work of Williamson (1985). In particular, while the symmetric double vortex street configuration is intrinsically more persistent and survives at larger distance from the two cylinders, the idealized anti-symmetric pattern rapidly evolves into a single large-scale street called *binary vortex street* (Williamson, 1985).

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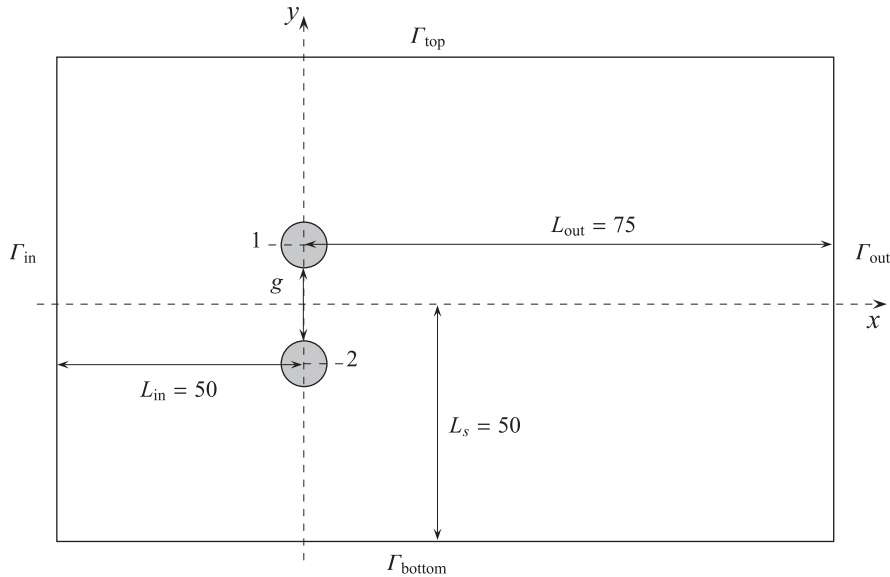


Fig. 1. Sketch of the flow configuration and of the computational domain Ω_c .

Among the various wake patterns that characterize the considered flow, we are particularly interested in the so-called *flip-flopping* pattern that mainly arises in the asymmetric regime. Within this regime, a biased vortex shedding takes place from the two cylinders, the gap flow between them being deflected toward one of the two cylinder surfaces. In some cases the gap flow direction alternatively switches from one side to the other, which is commonly referred to as the flip-flopping behaviour. This phenomenon has been observed in several experiments (Bearman and Wadcock, 1973; Kim and Durbin, 1988; Sumner et al., 1999; Zhou et al., 2002; Wang et al., 2002) and in numerical simulations (Kang, 2003; Chen et al., 2003; Afgan et al., 2011). For relatively high Reynolds numbers, the gap flow changes direction in an apparently random way as described by Kim and Durbin (1988) for $g=0.75$ and $Re=2-7 \times 10^3$ or by Zhou et al. (2002) for $g=0.5$ and $Re=5800$. At low Reynolds numbers the occurrence of the flip-flopping has been described by Kang (2003) using two-dimensional numerical simulations. Kang (2003) found that during the flip-flopping regime the drag coefficient of each cylinder slowly changes over a time scale one order of magnitude greater than that of vortex shedding, which is much smaller compared to the high Reynolds number case. Two parameter ranges have been described by the author for the occurrence of the flip-flopping: one main region at intermediate gap spacing $0.4 \leq g \leq 1.4$ for $Re > 50$ and one smaller region at larger gap spacing $1.4 \leq g \leq 2.2$ for $50 \leq Re \leq 70$ where the flip-flopping is found to coexists with the in-phase synchronized pattern. For $g=0.7$ and $Re=150$ and 230 the flip-flop of the gap flow has been experimentally described by Wang et al. (2002), who provided a detailed analysis of the vortex dynamics associated with the switch-over phase by means of flow visualizations.

In the past literature, a bistability conjecture has been often invoked to explain the onset of the flip-flopping (Le Gal et al., 1994; Peschard and Le Gal, 1996). In these works the authors proposed a system of two coupled Landau equations to model the interactions between the two side-by-side cylinder wakes. Besides in-phase and anti-phase synchronized states, the model shows the existence of dual asymmetric locked solutions with a non-trivial phase difference and amplitude ratio between the two oscillators. Based on these results, the authors suggested that the flip-flop can be interpreted as the alternate switching between these dual asymmetric solutions, driven by external perturbations. This hypothesis has been further supported by Mizushima and Ino (2008), who showed that in a narrow range of gap spacing ($0.594 \leq g \leq 0.607$) the steady base flow past the two cylinders bifurcates to an asymmetric steady state, thus providing a rationale for such interpretation. Recently, the global stability analysis of the steady symmetric base flow has been considered by Carini et al. (2014b), showing that this pitchfork bifurcation occurs for a remarkably wider interval of the gap width ($0.566 \leq g \leq 0.725$). Notwithstanding, for low Reynolds numbers, the bistability conjecture is not convincing. In fact, the second small parameter region where the emerging of the flip-flopping has been documented by Kang (2003) falls outside the gap spacing range of bifurcated asymmetric states (Carini et al., 2014b). Furthermore, within the second parameter region reported by the former author, the co-existence of both the in-phase and the flip-flopping states suggests us that the latter could arise from a secondary, two-dimensional instability of the in-phase shedding cycle through a subcritical bifurcation.

Based on two-dimensional DNS and stability analyses, we show that at low Reynolds numbers and for $0.6 \leq g \leq 2.4$ the flip-flopping behaviour originates from a Neimark–Sacker bifurcation of the in-phase vortex shedding cycle, leading to a torus in the phase space. For both the in-phase synchronized and the flip-flopping wake patterns, a different vortex dynamics is observed between $g=0.7$ and $g=1.8$, thus indicating that different physical mechanisms are involved at intermediate and large gap spacing. Correspondingly two distinct unstable Floquet modes breaking the spatio-temporal symmetry of the periodic base flow are found, both characterized by the low-frequency of the respective gap flow flip-over. Their corresponding instability domain is described in the parameter plane (g, Re). In addition a weakly nonlinear analysis in

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