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Flows past rotating cylinders next to a wall

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A B S T R A C T

Two-dimensional simulations are used to investigate the flow past rotating circular cylinders near a wall in the low Reynolds number regime ($20 \le Re \le 750$). For the single cylinder case, rotation rates higher than previously studied are considered. For cylinders rolling forward, the wake flow structures observed are similar to those seen in previous studies; however, it is found that reverse rotation of the cylinder can completely suppress vortex shedding. The drag force on the cylinder is quantified. Linear stability analysis is used to determine the onset of three-dimensionality in the wake. Increased forward rotation triggers three-dimensionality at increasingly lower Reynolds numbers, while reverse rotation delays this transition to much higher values. For the highest reverse rotation rate, three-dimensionality was suppressed at the higher end of the Reynolds number range investigated. A study of two sliding cylinders is also performed, especially focusing on the interaction of the first wake with the second, the effect on the overall wake dynamics and quantification of the drag on each cylinder.

1. Introduction

The separated flow over a circular cylinder is one of the classical fluid dynamics problems, studied in detail for over a century since the pioneering investigations of Bénard (1908) and von Kármán (1911). Since then, there have been many comprehensive review articles, including Williamson (1996a,b), Norberg (2003), and reviews of wake transition for other cylindrical or axisymmetric bluff bodies (e.g., Thompson et al., 2006b). The flow dynamics are dramatically altered when such bodies are placed close to a plane wall. A significant change in shedding frequency and forces experienced by these bodies is observed, compared with similar bodies in an unbounded flow. An added parameter to such investigations is the effect of body rotation. By use of a numerical solver, we examine the flow structures and wake dynamics, and compute the forces on a circular cylinder as a function of rotation rate and Reynolds number, and then extend this study to examine two sliding cylinders.

One motivation for this study is to improve our understanding of the flow dynamics of, and forces on, cells near blood vessel walls of which the current problem is a simplified two-dimensional analogue. Certain cell types such as platelets and leukocytes depend on rolling and sliding along a vessel wall as part of the activation process to initiate the clotting or

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immune response (Lawrence and Springer, 1991; Wagner and Frenette, 2008). This study is a prelude to studies investigating flow behaviour at much lower Reynolds numbers, which may be directly applicable to the above mentioned examples. The current study is also applicable to many particle–particle and particle–wall interactions, (e.g., particles in a sedimentation tank), as it considers a wider parameter range.

2. Flows around a single cylinder close to a plane wall

The effect of placing a body in close proximity to a wall brings about a substantial change to the wake flow structure and consequently the forces experienced by the body, compared with an unbounded flow. Investigations in a wind tunnel by Bearman and Zdravkovich (1978) showed a strong suppression of vortex shedding for a gap to diameter ratio $G/D = 0.3$, for a cylinder adjacent to a stationary wall. The lift force experienced by the cylinder was directed away from the wall for the cases investigated but the Strouhal number (St) remained approximately constant as the cylinder moved closer towards $G/D = 0.3$.

A single row of vortices was observed by Taneda (1965) for a cylinder moving close to a wall at $\mathrm{Re} = 170$. The experiments were conducted using condensed milk and aluminium dust to visualise the vortex structures. It was noted that the time period for the vortex formation was longer than that in free stream.

Lei et al. (2000) investigated the effect of gap ratio (G/D) between 0.1 and 3 for a Reynolds number range of 80–1000. Using a finite-difference method, they describe the flow structure formation behind the cylinder for $G/D < 3$. The lower wall is stationary, leading to the formation of a boundary layer, which interacts with the shear layer shed from the lower side of the cylinder. At different gap ratios and Reynolds numbers, the opposite signed vorticity in the wall shear layer and the shear layer shed from the cylinder cancel each other out, leading to the suppression of vortex shedding. It was also found that the critical gap ratio at which the shedding ceases decreases with an increase in Reynolds number, asymptoting to 0.2 at higher values.

Nishino et al. (2007) conducted experiments in a wind tunnel for intermediate Reynolds numbers $O(10^5)$ with a moving wall to prevent the development of a boundary layer. Three regions of vortex shedding based on the gap height were identified. For $G/D > 0.5$, regular vortex shedding was observed; and as the cylinder was moved closer to the wall, the shedding became intermittent and ceased to exist for gap ratios ≤ 0.35. The experiments showed a decrease in drag coefficient as the cylinder was moved progressively closer to a wall, becoming constant for $G/D \leq 0.35$.

Numerical simulations for a stationary cylinder close to a moving wall have been performed by Huang and Sung (2007). They obtained a critical vortex suppression value of $G/D = 0.28$, which is close to that observed for simulations conducted with a stationary wall. Furthermore, they attributed the formation of the vortex from the lower side of the cylinder to the higher flow rate between the cylinder and the moving wall. For a constant gap ratio, the lift and drag values increased as the Reynolds number was increased from 200 to 500. Numerical simulations have also been carried out for rotating bodies close to a stationary wall. Using the lattice Boltzmann method, Cheng and Luo (2007) obtained flow structures and quantified the forces on a rotating cylinder near a stationary wall. The magnitude and sense of rotation affect the critical height at which vortex shedding is suppressed. For a given gap ratio, the lift coefficient increased as the rotation rate was changed from retrograde to prograde, while the drag coefficient showed the reverse trend.

Two- and three-dimensional studies for a square cylinder near a stationary wall have been conducted by Mahir (2009). The mean drag force decreased as the cylinder was brought close to a wall. It was also noted that the two-dimensional simulations overpredicted the mean lift and drag values. Their simulations considered a body adjacent to a stationary wall, while the present work focuses on a body in motion along a plane surface.

Stewart et al. (2010) conducted two- and three-dimensional numerical simulations for a single cylinder rolling along a wall. The gap ratio was maintained at 0.005 to prevent the grid singularity that occurs if the cylinder is touching the wall. Forward rolling of the cylinder destabilised the flow, reducing the Reynolds number at which shedding first occurred, while reverse rolling stabilised it. The lift and drag values were found to be highly dependent on the rotation rates. The steady and unsteady regimes of the flow for different rotation rates were mapped. In the unsteady regime, the shear layer shed from the top of the cylinder combined with the wall shear layer downstream, forming a vortex pair with a net rotation. Their stability analysis reported that the wake undergoes a transition to three-dimensionality and then becomes unsteady, as the Reynolds number is increased. The transition mechanism to three-dimensionality was not clearly understood. Experimental work carried out in a water channel confirmed the flow features visualised in the numerical simulations. The current work is an extension of that study: first to higher forward and reverse rotation rates and then to multiple circular cylinders.

3. Problem definition and methodology

This study is an extension to the generic flow problem of a single cylinder rolling, without slipping, along a wall in a quiescent fluid. That problem is governed by a single parameter, the Reynolds number $\mathrm{Re} = UD/\nu$, where D is the cylinder diameter, U the velocity of its centre, and ν the kinematic viscosity of the fluid. In the general case, in which slip between the cylinder and the wall is allowed, another parameter is needed to fully describe the flow. A convenient choice is the rotation speed at the cylinder surface relative to the linear speed at its centre $\alpha = (\omega D/2)/U$, where ω is the angular velocity. Forward rolling (i.e., rotation against the flow at the top of the cylinder—anti-clockwise in this case) corresponds