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Flow past a rotating cylinder translating at different gap heights along a wall

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ABSTRACT

The flow past a rotating circular cylinder translating parallel to a wall at different heights is investigated for Reynolds numbers up to 400 for three discrete rotation rates. In particular, the various wake transitions that occur as a function of gap height are quantified for the three cases examined: non-rotation, and forward and reverse rotations. At low gap heights, only a single steady three-dimensional mode is found to become unstable on the steady base flow. As the gap height is increased, several new three-dimensional modes are observed, of which one attains large amplitudes in the near wake and another preferentially in the far wake. At still larger gap heights, the transition sequence resembles that observed in a rotating cylinder wake, for which the wake first undergoes transition to a periodic state, prior to the onset of three-dimensional flow. Parameter space maps showing the neutral stability curves and regions of instability for each mode are presented for each rotation rate, together with a discussion of the spatio-temporal characteristics and spatial distributions of the new modes. Finally, the force coefficients for the steady and periodic two-dimensional base flows are presented.

1. Introduction

The wake of bluff bodies can be altered through external forcing, e.g., by induced rotation or oscillation, by introducing another bluff body in its vicinity or by changing physical boundaries. Here, a combination of two effects is studied: rotation and proximity to a surface. These effects have relevance to flows where wall-particle interactions are important. Examples include sedimentation tanks used in the chemical and mining industries, cells in blood vessels and micro-carrier beads in bioreactors (Gupta et al., 2014; Ismadi et al., 2014). Numerical modelling of bluff bodies would enable the prediction of the movement of these particles and their settling behaviour in the above stated applications.

Flow past isolated bluff bodies have been the subject of many investigations, and the nature of the wake has been explored in great detail. The experimental studies of Williamson (1988, 1996a,b) investigated the three-dimensional wake structures that evolve from a two-dimensional wake as the Reynolds number is increased. At approximately $Re=190$ (with Re being the Reynolds number based on diameter), the previous two-dimensional wake vortices developed a strong waviness with a wavelength of approximately four cylinder diameters. This was termed *mode A* shedding. At higher Reynolds numbers ($Re \gtrsim 230$), a shorter wavelength mode (*mode B*) progressively dominated the wake. This had a spanwise wavelength of approximately one

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cylinder diameter. The instabilities responsible for these wake states were predicted by linear stability analysis (Barkley and Henderson, 1996), and also found in DNS (Direct Numerical Simulations) (Thompson et al., 1996, 2001; Henderson, 1997). The analogues of these modes were observed in the wakes of other bluff bodies, such as square cylinders (Robichaux et al., 1999) and elongated cylinders (Ryan et al., 2005). The periods of modes A and B correspond with those of the base flow. Modes that are incommensurate with the base flow have also been observed in bluff bodies wakes; such modes are known as quasi-periodic modes (Blackburn and Lopez, 2003; Blackburn et al., 2005). Subharmonic modes have also been observed when the wake symmetry is altered, as in the flow past rings (Sheard et al., 2005b, 2004a), and inclined square cylinders (Sheard et al., 2009; Sheard, 2011). In addition, such modes have also been observed in a non-rotating cylinder wake when a wire was placed downstream of the cylinder (Zhang et al., 2005; Yildirim et al., 2013) or upstream (Rao et al., 2015b).

The wake of a circular cylinder is substantially altered by applied rotation. An extra governing parameter that this introduces is the non-dimensional rotation rate, α, defined as the ratio of the cylinder surface speed to the relative freestream speed. As the rotation rate is increased from zero, the onset of unsteady flow is delayed to higher Reynolds numbers; for $\alpha \gtrsim 2$, vortex shedding was found to be suppressed for $\mathrm{Re} \leq 400$ (Mittal and Kumar, 2003; Kang et al., 1999; Akoury et al., 2008; Pralits et al., 2010; Rao et al., 2013a) until higher rotation rates, where it again reappears but only over a very small range of rotation rates Stojković et al., 2003, 2002; Mittal and Kumar, 2003). Recent linear stability analysis by Rao et al. (2013a,b) showed that the critical Reynolds numbers for the onset of modes A and B are increased as the rotation rate is increased from $\alpha = 0$. In fact, for rotation rates $1.5 \lesssim \alpha \lesssim 1.85$, a subharmonic mode, *mode C*, is the first three-dimensional mode to become unstable, prior to the onset of mode A. Two other modes having spatio-temporal characteristics similar to mode A were observed at higher rotation rates close to the boundary of transition to steady flow.

Placing a bluff body near a plane surface can alter the classical Bénard–von Kármán (BvK) shedding seen for isolated bluff bodies. The controlling parameter here is the gap ratio or more commonly the gap height (G/D), where the gap between the body (G) and wall is normalised by the cylinder diameter (D). For a circular cylinder at a gap height of $G/D = 0.1$, Taneda (1965) observed that the vortices were separated by large streamwise distances and diffused rapidly compared with those formed when the gap height was $G/D = 0.6$.

Huang and Sung (2007) investigated the flow past a non-rotating cylinder for $\mathrm{Re} < 600$ and for $G/D \geq 0.1$. They observed that the critical gap height, below which alternate vortex shedding was suppressed, decreased from $G/D = 0.28$ to $G/D = 0.25$ as the Reynolds number was increased. They further quantified the forces on the cylinder and the non-dimensional shedding frequency or Strouhal number ($\mathrm{St} = fD/U$, with f being the shedding frequency). For a given gap height, the shedding frequency was found to increase with Reynolds number. However, for a given Reynolds number, St increased over $0.15 < G/D < 0.5$ before decreasing at greater gap heights. Their numerical simulations were performed with the lower wall stationary. Similar investigations undertaken by Yoon et al. (2010, 2007), using an immersed-boundary method, quantified the forces on the cylinder for $\mathrm{Re} < 200$. As the gap height was increased from low values, the drag and lift coefficients showed an exponential decrease. They further observed that the onset of unsteady flow was delayed to higher Reynolds numbers as the gap height was reduced. For $G/D = 0.1$, vortex shedding was first observed at $\mathrm{Re} = 120$, as compared to $\mathrm{Re} \simeq 47$ for a cylinder in freestream.

Recent investigations by Rao et al. (2013d) determined the variation of unsteady flow for a circular cylinder translating parallel to a wall for $\mathrm{Re} \leq 200$. They further quantified the forces and the shedding frequency with Reynolds number, as well as the onset of three-dimensional flow as the cylinder is moved from the freestream ($G/D = \infty$) towards the wall ($G/D = 0$). For gap heights $G/D \leq 0.25$, transition to three-dimensional flow occurred in the steady flow regime at low Reynolds numbers. They also tracked the onset of the mode A instability for $G/D \gtrsim 0.3$. While the spanwise wavelength at onset remained approximately $4D$, the critical Reynolds number decreased for $G/D \lesssim 0.45$ before increasing towards the freestream value of $\mathrm{Re}_c \simeq 190$. Additionally, they demonstrated the occurrence of multiple instability modes in the wake at $\mathrm{Re} = 200$, with interactions between these modes leading to a chaotic saturated wake state.

Very few studies have investigated the combination of rotation and wall proximity for bluff bodies. Russel et al. (1977) showed that long slender rods tend to rotate as they approached a wall, which was not the case in a symmetrical unbounded flow. More recently, Cheng and Luo (2007) investigated the flow for a rotating cylinder for $-1 \leq \alpha \leq +1$ at $\mathrm{Re} = 200$ for a fixed lower wall. For low gap heights, the flow was observed to be steady, and on increasing the gap height, the flow became aperiodic, before the characteristic BvK street was observed at greater gap heights. The wake was displaced towards the wall for $\alpha < 0$ and away from it for $\alpha > 0$. They further quantified the lift and the drag forces experienced by the cylinder.

Stewart et al. (2006, 2010) investigated the flow past a rotating cylinder next to a wall. For rotation rates $-1 \leq \alpha \leq +1$, the experimental and numerical investigations showed significant differences in wake structures compared with those for bodies in freestream. In addition, the onset of unsteady flow occurred at higher Reynolds numbers compared with bodies in freestream. As the rotation rate was decreased, the onset of unsteady flow increased to higher Reynolds numbers. Furthermore, linear stability analysis showed that the onset of three-dimensional flow occurred prior to the wake becoming (two-dimensionally) unsteady. Their numerical and experimental investigations were in good agreement. That study was extended by Rao et al. (2011) with the rotation rate range expanded to $-2 \leq \alpha \leq +2$. For $\alpha \leq -1.5$, vortex shedding was suppressed and for $\alpha \leq -2$, the flow remained two-dimensional for $\mathrm{Re} \leq 750$. For forward rolling cylinders, the onset of both three-dimensional and unsteady flow occurred at very low Reynolds numbers ($\mathrm{Re} \lesssim 50$).

In this study, we characterise the wake transitions of a translating, rotating circular cylinder, positioned at different heights from a stationary wall in a quiescent fluid. The parameter space considered covers gap heights from almost touching the wall ($G/D \simeq 0$) to freestream ($G/D \to \infty$), for $\mathrm{Re} \leq 400$ and three rotation rates $\alpha \in (+1, 0, -1)$. Characteristics of the