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Three-Dimensional Numerical Simulations of Flow Past a Rotating Circular Cylinder at a Reynolds Number of 500

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Flow around a rotating circular cylinder at a Reynolds number of 500 is investigated numerically. The aim of this study is to investigate the effect of high rotation rate on the wake flow past a circular cylinder. Simulations are performed at a constant Reynolds number of 500 and a wide range of rotation rates from 1.6 to 6. Rotation rate is the ratio of the rotational speed of the cylinder surface to the incoming fluid velocity. It is found that increasing the rotation rate beyond a critical value results in transition to a secondary instability regime where the oscillation of the lift force on the cylinder increases drastically. There is significant increase in the three-dimensionality of the flow inside the secondary instability regime. The flow pattern in the secondary instability regime is characterized by ring-type vortices wrapping around the cylinder. The oscillation of the force coefficient in the secondary instability regime is very irregular.

INTRODUCTION

Vortex shedding flow in the wake of circular cylinders has been investigated extensively, mainly because of its increasing applications in (but not limited to) offshore oil and gas engineering. Many experimental and numerical studies have been conducted on the transition of the wake flow to turbulence (Roshko, 1954; Williamson, 1988; Hammache and Gharib, 1991; Karniadakis and Triantafyllou, 1992; Barkley and Henderson, 1996; Thompson et al., 1996). It was concluded that the transition of wake flow from two-dimensional to three-dimensional flow occurs when the Reynolds number is approximately $Re = 140$–190. The Reynolds number is defined as $Re = UD/\nu$ where U is the incoming velocity, D is the diameter of the cylinder, and ν is the kinematic viscosity of the fluid. In the numerical study by Zhao et al. (2013), the critical Reynolds number was found to be 200. The critical Reynolds number varies in different experimental studies, mainly because of the end effects in the experimental condition.

When a circular cylinder rotates in a fluid flow, the speed of the rotation breaks the symmetry of the wake flow and thus influences the corresponding forces on the cylinder. In addition to the Reynolds number, the rotation rate α has significant influence on flow past a rotating cylinder (Chang and Chern, 1991). The rotation rate α is defined as $\alpha = \omega D/(2U)$ where ω is the angular rotation speed of the cylinder. Early studies on flow past rotating cylinders were focused on the small Reynolds numbers in the range of $Re \leq 100$ (Tang and Ingham, 1991). The vortex shedding flow was found to be fully suppressed at $\alpha = 2$ (Diaz et al., 1983; Badr et al., 1990; Chew et al., 1995; Chou, 2000). Kang et al. (1999) numerically investigated laminar flow past a rotating circular cylinder and concluded that the critical α above which there was no vortex shedding increased logarithmically with increasing Reynolds numbers. As a result, Kang et al. (1999) observed the critical rotation rates of approximately 1.4, 1.8, and 1.9 for $Re = 60$, 100, and 160, respectively. It was found that, for rotation rates lower than the critical rotation rate, the flow pattern changed, but the Strouhal number did not change much with increasing rotation rate.

Stojković et al. (2002) simulated flow around a rotating circular cylinder at higher rotation rates and observed a second vortex shedding regime in the rotation rate range of $4.8 \leq \alpha \leq 5.15$ for $Re = 100$, which was characterized by the shedding of one vortex from one side of the cylinder in one vortex shedding period. The second vortex shedding regime was also reported by Pralits et al. (2010). Mittal and Kumar (2003) and Lu et al. (2011) found that the wake flow remained steady for the rotation rates in the range of $1.91 \leq \alpha \leq 4.34$, whereas it became unstable at $\alpha \approx 4.35$ when $Re = 200$. The vortex shedding disappeared again as the rotation rate exceeded 4.8. Lam (2009) studied flow past a rotating cylinder for $Re = 3600$–5000 and $\alpha \leq 2.5$ using flow visualization and particle image velocimetry (PIV) measurements. Lam (2009) found that the wake became increasingly narrow and deflected sideways with increasing cylinder rotation speed and that the formation length of the vortices decreased with increasing α, leading to a slight increase in the vortex shedding frequency.

Mittal (2004) performed numerical simulations to study the three-dimensionality of flow past a rotating cylinder at $Re = 200$ and a range of α from 0 to 5. It was found that the centrifugal instabilities were present along the entire span for the rotation rate α of 5. Furthermore, it was observed that the no-slip condition on the side walls and the aspect ratio between length and diameter greatly influenced the flow separation. Rao et al. (2013) performed a systematic study of flow past a rotating cylinder at Reynolds numbers $Re < 400$ and nondimensional rotation rates of $\alpha \leq 2.5$. Rao et al. (2013) observed that the three-dimensionality in the wake of a rotating cylinder resembled its stationary counterpart for $\alpha \leq 1$. In addition to the wake flow modes A and B that are similar to those identified in the nonrotating cylinder case (Williamson and Roshko, 1988), there were other steady and unsteady modes that were dependent on Reynolds number and rotation rate α. Moreover, the three-dimensional flow at high rotation rates became increasingly complex and moved the critical Reynolds number for three-dimensional transition to a higher value. A similar conclusion was drawn by El Akoury et al. (2008) using three-dimensional direct numerical simulation (DNS). They found that the critical Reynolds number is increased to 219.8 for $\alpha = 0.5$.

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