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Rotating elliptic cylinders in a uniform cross flow

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ABSTRACT

Numerical simulation of flow past a two-dimensional rotating cylinder of different thickness ratios at $Re = 200$ has been carried out to investigate how incremental changes in the cross-section of a cylinder from a circle to a thin ellipse affect their lift and drag characteristics as well as flow structures. In contrast to past studies, the present work considers velocity ratios up to 2.5, where vortex shedding of a circular cylinder completely ceases. Results show that a decreasing thickness generally leads to lower mean lift magnitude, but a non-monotonic change in mean drag with a local minimum at a thickness ratio of approximately 0.375. Interestingly, at velocity ratio 2.5, such minimum drag changes sign and turns into a positive thrust; this event occurs at a much smaller velocity ratio than the case of a circular cylinder. Detailed analysis on vorticity contours and surface pressure distributions reveals that the thrust generation is a result of the competition between a prevailing negative pressure below the cylinder due to rotational motion, and a suction effect from a "hovering vortex" formed above the cylinder. Additionally, as the thickness reduces, the wake transits from a von-Kármán type to a separated flow dictated by the two edges of the elliptic cylinder. And the crests and troughs in the transient aerodynamic forces become highly related to the instantaneous geometric angle of attack, which can be attributed to a projection effect.

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1. Introduction

As one of the most fundamental flows, the flow past a rotating circular cylinder has been studied extensively over the past three decades (see Badr et al., 1990; Chen et al., 1993; Kang et al., 1999; Stojkovic et al., 2002). Early papers focused on the forces and moments generated by the cylinder, especially the side force or lift due to velocity difference between the upper and lower surfaces of the cylinder, which, in the case of inviscid flow, is also known as the Magnus effect. However, the presence of viscosity makes the flow much more complex. For example, Chew et al. (1995) carried out viscous simulations and showed a convergence of lift coefficient (C_l) towards the 4π inviscid limit proposed by Prandtl (1925), whereas Mittal and Kumar (2003) later proved that C_l can exceed 4π when the velocity ratio (α, tip speed of the cylinder over the freestream speed) is higher than 3.5. The wake structure is also found to be highly dependent on the velocity ratio. As the cylinder rotates faster in a viscous flow, the von Kármán vortex street formed by alternatively shed vortices is deflected more by the rotation, before vortex shedding ceases at approximately $\alpha > 1.9$. According to Mittal and Kumar (2003), there exists another flow regime, which lies in a narrow range of higher α between 4.4 to 4.8, where vortex shedding occurs on one side of the cylinder with a substantially lower frequency.

In recent years, research on rotating cylinder has switched to the study of three-dimensional instability. It is found that apart from the two well-known instability modes (mode A and mode B) for a non-rotating circular cylinder, much more modes exist due to the asymmetry introduced by the rotational motion. For example, Rao et al. (2013a, b) discovered up to mode F in their Floquet analysis for a wide range of velocity ratio up to 7. A review summarizing these studies can be found in Rao et al. (2015). In another paper, Navrose et al. (2015) carried out three-dimensional direct numerical simulations and linear stability analysis, and found several new instability modes (mode H to K) for Reynolds number (Re) in the range of $200 \le Re \le 350$ and $4 \le \alpha \le 5$.

As a bluff body, the flow past a rotating circular cylinder is clearly distinct from the flow past a rotating flat plate or thin airfoil; the latter is associated with intense separation at both the leading and trailing edges and circulatory forces at high angles of attack. While a rotating cylinder in cross flow experiences Magnus effect, a rotating plate in cross flow does not. Instead, the lift generated on a rotating plate is usually attributed to the "Kramer effect", i.e. a wing experiencing lift enhancement above stalled value when it rotates from low to high angles of attack (Kramer, 1932). The Kramer effect also serves as an explanation for the "rotational circulation" or "rotational lift" that is observed on insect flapping wings near stroke reversal, when extra circulation is generated to re-satisfy the Kutta condition due to deviation of the stagnation point from the trailing edge during rotation (Shyy et al., 2008). Hence, understanding the flow behavior of a rotating plate, and the flow transition from a rotating circular cylinder to a rotating flat plate is important to the phenomenon associated with flapping wings as well as autorotating leaves and seeds (see Lentink et al., 2009). Some of the past work on a rotating elliptic cylinder that resembles a flat plate is highlighted as follows.

Lugt and Ohring (1977) computed the viscous flow around a rotating elliptic cylinder in a parallel freestream. They found that when the rotating velocity was low ($\alpha = 0.5$), a pair of vortices was shed from the two tips of the elliptic cylinder every time its major axis was normal to the incoming flow. At higher rotation velocity ($\alpha = 2$), one of the vortices was pushed by the cylinder and paired up with another vortex formed in the next half-cycle to form a dipole. Due to computing limitations, their simulations were limited to several cycles of rotation only. Iversen (1979) analyzed free flight and wind tunnel measurement data on a rotating flat plate and found that the lift and drag coefficients are functions of velocity ratio, aspect ratio and Re based on the chord length and plate thickness. Using similar flow conditions as in Lugt and Ohring (1977), Lua et al. (2010) conducted DPIV measurement on a rotating elliptic cylinder and discovered the existence of a "hovering vortex" located above the cylinder at high rotation rate. Unfortunately, Lua et al. (2010) were unable to measure the corresponding transient forces on the cylinder due to a technical constraint of their experimental facility, i.e. entanglement of the wires of the load cell due to continuous spinning of the cylinder. More recently, Thompson et al. (2014) performed numerical simulation on stationary elliptic cylinders normal to the freestream with a range of thickness ratios, and focused primarily on wake transition. Hu (2015) numerically studied the three-dimensional flow past a rotating wing at $Re = 200$ and considered the effect of span-to-chord aspect ratio. His results confirmed the existence of the hovering vortex at high α. More recently, Naik et al. (2017) simulated a 2D rotating cylinder with three α (0.5, 1.0 and 1.5) and five thickness ratios (0.1, 0.3, 0.5, 0.7 and 1.0) at $Re = 100$. They claimed that the merger of trailing edge vortices (TEVs) was important to the formation of hovering vortex. Surprisingly, they still attributed the lift generated on a thin elliptic cylinder to the Magnus effect even though past experimental study by Walker (2002) indicated otherwise. Notwithstanding the above shortcoming, some of the results of Naik et al. (2017) have provided insights into the flow characteristics of a rotating cylinder. Unfortunately, their study is limited to α values within the periodic vortex shedding regime only. As to how the flow behaves when α values go beyond the vortex shedding regime (i.e. $\alpha > 1.9$) is not clear. In particular, how do the flow characteristics of a rotating circular cylinder transit to those of a rotating thin elliptic cylinder (resembling a flat plate) in this steady-state regime? Our desire to answer this question motivates the present numerical investigation.

The remainder of this paper is organized as follows: Section 2 provides a brief description of the current problem and numerical methods, and Section 3 presents our numerical results in the form of vorticity contours, surface pressure distribution and time-history of the forces acting on the cylinders. The conclusions are presented in Section 4.