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PIV measurements of the wake behind a rotationally oscillating circular cylinder

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Abstract

The near-wake behind a circular cylinder undergoing rotational oscillatory motion with a relatively high forcing frequency has been investigated experimentally. Experiments were carried out varying the ratio of the forcing frequency f_f to the natural vortex shedding frequency f_n in the range of 0.0 (stationary) to 1.6 at an oscillation amplitude of $\theta_A = 30^\circ$ and Reynolds number of $\mathrm{Re} = 4.14 \times 10^3$. Depending on the frequency ratio ($F_R = f_f/f_n$), the near-wake flow could be divided into three regimes—non-lock-on ($F_R = 0.4$), transition ($F_R = 0.8,\ 1.6$) and lock-on ($F_R = 1.0$) regimes—with markedly different flow structures. When the frequency ratio was less than 1.0 ($F_R \leqslant 1.0$), the rotational oscillatory motion of the cylinder decreased the length of the vortex formation region and enhanced the mutual interaction between large-scale vortices across the wake centerline. The entrainment of ambient fluid seemed to play an important role in controlling the near-wake flow and shear-layer instability. In addition, strong vortex motion was observed throughout the near-wake region. The flow characteristics changed markedly beyond the lock-on flow regime ($F_R = 1.0$) due to the high frequency forcing. At $F_R = 1.6$, the high frequency forcing decreased the size of the large-scale vortices by suppressing the lateral extent of the wake. In addition, the interactions between the vortices shed from both sides of the cylinder were not so strong at this forcing frequency. As a consequence, the flow entrainment and momentum transfer into the wake center region were reduced. The turbulent kinetic energy was large in the region near the edge of the recirculation region, where the vortices shed from both sides of the cylinder cross the wake centerline for all frequency ratios except for the case of $F_R = 1.6$. The temporally resolved quantitative flow information extracted in the present work is useful for understanding the effects of open-loop active flow control on the near-wake flow structure.

Keywords: Rotational oscillation; Forcing frequency; Cylinder wake; Dynamic PIV; Flow control; Shear-layer instability; Fluid entrainment

1. Introduction

The wake behind a circular cylinder has been a major research topic for many years due to the simple geometry and interesting flow characteristics of this system. Williamson (1996) reviewed works on the vortex dynamics in the two-dimensional wake behind a circular cylinder, and more recently, Williamson and Govardhan (2004) summarized what is known about vortex formation behind stationary and oscillating cylinders. When vortices are shed from the upper and

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lower sides of a cylinder, the flow pattern is maintained for some distance downstream. Due to the capacity of circular cylinders to shed large-scale vortices, the cylinder wake has many practical engineering and scientific applications.

Several active flow control techniques have been used to control the flow behind a circular cylinder. A representative active flow control technique is to apply a rotational oscillatory motion to the circular cylinder. In this technique, the interaction between the rotationally oscillating body and the surrounding fluid modifies the near-wake structure significantly by accelerating and decelerating the fluid around the cylinder according to the direction of rotation (Baek and Sung, 1998). When the adjacent fluid is accelerated by the cylinder rotation, flow separation is delayed or suppressed and the large-scale vortices formed previously are pushed downstream. In contrast, when the adjacent fluid is decelerated, the separated shear layer starts to roll up and large-scale vortices are formed. Therefore, the near-wake flow and vortex structure can be controlled considerably by applying a rotational oscillatory motion to the cylinder.

In terms of the net effect of flow control, open-loop active flow control without auxiliary devices is preferred as an effective scheme. Therefore, it is important to investigate the role of rotary oscillation with open-loop control on the near-wake flow characteristics with varying the forcing condition.

Rotational oscillatory motion can be easily applied and manipulated using simple electrical and mechanical devices. Although this type of flow control is a promising and effective method, it has been investigated in only a limited number of studies. For instance, Tokumaru and Dimotakis (1991) investigated the wake behind a rotationally oscillating cylinder at the high Reynolds number of $\mathrm{Re} = 15\,000$. They found that the wake has four distinct flow modes depending on the forcing condition, and that the drag is reduced by about 80% at high forcing frequency. Taneda (1978) visualized the periodic shedding of vortices behind a rotationally oscillating cylinder for Reynolds numbers in the range $30 \leqslant \mathrm{Re} \leqslant 300$ and Strouhal numbers of $0 \leqslant \mathrm{St}_f(= f_f D/U_o) \leqslant 55$. The dead water region behind a cylinder disappeared at high forcing frequency. Filler et al. (1991) observed large velocity fluctuations and high response peaks at frequencies near the Karman frequency of the test cylinder. Moreover, they observed a phase difference of approximately 180° between the cylinder motion and the vortex shedding when the forcing frequency crossed the natural Karman frequency. Recently, Lee and Lee (2006) used hot-wire anemometry to investigate the modification of the near-wake behind a rotationally oscillating cylinder. They classified the wake patterns into five flow regimes and showed that the vortex shedding frequency was notably different in each flow regime. In addition, through a detailed study of the lock-on flow regime, they identified the threshold amplitude of oscillation (θ_t) at which the lock-on phenomenon occurs only at $F_R = 1.0$.

In a numerical study of the wake behind a rotationally oscillating cylinder, Baek and Sung (1998) investigated the temporal variation of vortex formation with varying oscillation frequency ($0.110 \leqslant S_f \leqslant 0.220$) and angular amplitude ($\theta_{\max} = 15^\circ$, 30° and 60°) at $\mathrm{Re} = 110$. The vortex formation mode changed when the forcing frequency approached the natural shedding frequency and relevant phase change (π-change) occurred across the natural shedding frequency. Mahfouz and Badr (2000) found that the lock-on phenomenon occurred when the forcing frequency was close to the natural shedding frequency, and that the lock-on frequency range widened as the oscillation amplitude was increased. Shiels and Leonard (2001) observed that the drag was reduced as a result of separation delay due to the presence of multipole vorticity structures in the boundary layer around an oscillating cylinder, and that the rotational oscillation method for drag reduction was effective only at high Reynolds numbers ($\mathrm{Re} \geqslant 3000$). Dennis et al. (2000) and Poncet (2004) investigated the temporal variation of the large-scale vortex structure behind a rotationally oscillating cylinder at moderate Reynolds numbers with varying forcing conditions. They found that the near-wake flow structure and aerodynamic forces acting on the cylinder were varied significantly depending on the forcing conditions, especially the forcing frequency and oscillation amplitude. In addition, the flow patterns were distinctly different according to the flow regime, and the mutual interaction between vortices was strong for large Reynolds numbers and oscillation amplitudes.

However, there have been few experimental studies on the variation of the flow structure behind a rotationally oscillating cylinder at high Reynolds numbers. The main objective of the present study was to investigate the flow structure of the near-wake behind a rotationally oscillating circular cylinder experimentally, in particular the effect on the vortex structure of varying the frequency ratio ($F_R = f_f/f_n$, where f_f and f_n are the forcing frequency and the natural vortex shedding frequency, respectively). To mimic the conditions encountered in practical applications, the experiments were carried out under high forcing frequencies at a relatively high Reynolds number. Although the variation of velocity profiles in the near-wake behind a rotationally oscillating cylinder was examined by Lee and Lee (2006) using a point wise measurement technique, information on the modification of the whole flow field in the near-wake is required to understand the flow characteristics in detail. Therefore, in the present work, the temporal evolution of vortex structure and the variation of mean flow characteristics were investigated using a dynamic particle image velocimetry (PIV) velocity field measurement system. The effect of the active flow control technique was evaluated by comparing the experimental results obtained using a rotationally oscillating cylinder with those obtained using a stationary cylinder.