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Numerical investigation of fluid flow past circular cylinder with multiple control rods at low Reynolds number

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ABSTRACT

Laminar flow past a circular cylinder with multiple small-diameter control rods is numerically investigated in this study. The effects of rod-to-cylinder spacing ratio, rod and cylinder diameter ratio, cylinder Reynolds number, number of control rods and angle of attack on the hydrodynamics of the main circular cylinder are investigated. Four different flow regimes are identified based on the mechanism of lift and drag reduction. The range of rod-to-cylinder spacing ratio where significant force suppression can be achieved is found to become narrower as the Reynolds number increases in the laminar regime, but is insensitive to the diameter ratio. The numerical results for the case with six identical small control rods at Re=200 show that the lift fluctuation on the main cylinder can be suppressed significantly for a large range of spacing ratio and various diameter ratios, while the drag reduction on the main cylinder is also achieved simultaneously. The six-control-rod arrangement has shown better performance in flow control than the arrangements with less control rods, especially in terms of force reduction at various angles of attack.

1. Introduction

Fluid flow over a circular cylinder is of great importance for fluid dynamics and various practical applications. The flow characteristics and hydrodynamic forces for laminar flow past an isolated stationary circular cylinder have been well understood (Williamson, 1989; Henderson, 1995, 1997; Norberg, 2003; Baranyi and Lewis, 2006). A stable wake flow regime with a vortex pair starts at around Re=6.2 (Dennis and Chang, 1970; Sen et al., 2009), while the alternate vortex shedding appears as the Reynolds number becomes greater than about 46–47 (Norberg, 2001; Kumar and Mittal, 2006; Cantwell and Barkley, 2010). The Kármán vortex street remains two-dimensional (2-D) until the Reynolds number reaches 170–190 (Williamson, 1996). Barkley and Henderson (1996) suggested that the two-dimensional wake loses stability at a critical

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Nomenclature

C_D^A	amplitude of drag coefficient
C_D^M	time-averaged mean drag coefficient
C_D^{rms}	Root Mean Square value of drag coefficient
C_L^A	amplitude of lift coefficient
C_L^M	time-averaged mean lift coefficient
C_L^{rms}	Root Mean Square value of lift coefficient
C_t	empirical safe coefficient used for numerical calculation
d	uniform diameter of the attached control rods C1–C6
D	diameter of the main cylinder C0
$f_{p\text{-lift}}$	peak frequency of the lift fluctuation
f_s	vortex shedding frequency
F_x	dimensional drag force exerted on unit length of the circular cylinder
F_y	dimensional lift force exerted on unit length of the circular cylinder
G	surface-to-surface distance between main cylinder and control rods
n	number of control rods
N	number of mesh cells on the main cylinder
p	pressure
Re	Reynolds number $Re = UD/\upsilon$
S_e	area of individual computational mesh cell
St	Strouhal number
t	time
u_e	velocity at the center of a computational mesh cell
u_i	the ith velocity component corresponding to the ith Cartesian coordinates, $u_1 = u$ and $u_2 = v$
U	free-stream velocity
x_i	the ith Cartesian coordinate with $x_1 = x$ and $x_2 = y$
β	angle formed by the main circular cylinder and the two adjacent control rods
θ	angle of attack
μ	dynamic viscosity of the fluid
υ	kinematic viscosity of the fluid
ω	vortices
Δt	time step used for numerical discretization

Reynolds number of $Re = 188.5 \pm 1.0$, which is referred to as “Mode A” instability. The corresponding spanwise wavelength in Mode A is 3.96 ± 0.02 diameters. With the increase in Reynolds number up to 259, the two-dimensional wake becomes linearly unstable, giving rise to a “Mode B” with a wavelength of instability of 0.822 diameters.

Due to the alternate vortex shedding and consequently large amplitude lift fluctuations, vortex-induced vibrations (VIV) of cylindrical structures are generally design concerns for engineers. Many methods have been proposed in order to suppress VIV responses, which include active flow control methods, such as the feedback rotationally oscillating cylinders (Lu et al., 2011; Fujisawa et al., 2001), and passive methods, such as helical strake (Zhou et al., 2011; Korkischko and Meneghini, 2010), small rods (Strykowski and Sreenivasan, 1990; Zhao et al., 2005, 2007), splitter plates (Sudhakar and Vengadesan, 2012; Wu and Shu, 2011), and rotating circular cylinders (Mittal and Kumar, 2003; Nobari and Ghazanfarian, 2009). As for cylindrical drilling risers in offshore oil and gas engineering, they are generally attached by several auxiliary lines, such as choke and kill lines, blowout preventer lines and rotary lines. These facilities can be referred to as control rods, i.e., the secondary, much smaller cylinders placed near the main cylinder. These control rods may reduce VIV response of the risers if their arrangement is optimized. Therefore, the lift and drag reduction, the wake interaction and the response of the system are the interesting topics in the study of fluid flow past multiple circular cylinders.

The closely relevant problems that have been addressed extensively are the steady flow past two identical circular cylinders in tandem (in-line), side-by-side (transverse) or generally staggered arrangements (Mittal et al., 1997; Meneghini and Saltara, 2001; Singha and Sinhamaahapatra, 2010; Sumner et al., 2000; Lee and Yang, 2009). For two cylinders in a tandem arrangement, a large range of Reynolds number from 8.7×10^3 to 5.2×10^4 and wide span of center-to-center distance/diameter ratio ranging from 1.03 to 5.0 were examined experimentally (Igarashi, 1981). Eight different flow regimes were identified, and the fluid forces were confirmed to be greatly dependent on the Reynolds number and the spacing ratios. The detailed numerical investigation (Sharman et al., 2005) at a low Reynolds number of $Re = 100$ suggested the existence of a critical spacing of between 3.75 and 4.0 diameters, at which significant jumps in the fluctuating forces and the Strouhal number occur. The drag force on the downstream cylinder was found to be negative when the gap ratio is small. The flow patterns around the twin cylinders in tandem at low Reynolds number were also examined by experimental observations and two different modes of the vortex shedding were identified (Tasaka et al., 2006). The mode transition was found to be hysteretic, giving rise to a complicated bifurcation in the vicinity of the threshold condition for instability.

The experimental results of flow past twin cylinders in a side-by-side arrangement in the laminar flow regime suggests that the vortex-shedding synchronization occurs either in phase or in anti-phase as the gap between the cylinders exceeds a critical value, while the asymmetric vortex shedding with harmonic modes was observed at small gap ratios (Williamson, 1985). The numerical simulations by Vakil and Green (2011), which covered a fairly wide range of gap-to-diameter ratio from 0.1 to 30, indicated that even under the extremely low Reynolds numbers of $1 \le Re \le 20$, the flow patterns are significantly different from the case of an isolated circular cylinder. The wake interference leads to distinct variations in lift coefficient with spacing ratio, which is highly dependent on the Reynolds number. In order to interpret the mechanisms of the different configurations of the coupled wakes, a theoretical model was proposed by Peschard and Le Gal (1996), where the dynamic interaction was modeled by two coupled Landau equations with the coefficients determined from experimental observations.