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Three-dimensional simulation of vortex shedding flow in the wake of a yawed circular cylinder near a plane boundary at a Reynolds number of 500

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ABSTRACT

Flow past a yawed circular cylinder in the vicinity of a plane boundary is investigated numerically by solving the three-dimensional Navier–Stokes equations using the Petrov–Galerkin finite element method. Simulations are carried out at a constant Reynolds number of 500, two gap ratios of 0.4 and 0.8 and six cylinder yaw angles (α) ranging from 0° to 60° with an increment of 15°. The gap ratio is defined as the ratio of the gap between the cylinder and the plane boundary to the cylinder diameter. The focus of the study is on the effects of α and the gap ratio on the vortex shedding flow and the hydrodynamic forces of the cylinder. It is found that increasing the cylinder yaw angle weakens three-dimensionality of the flow. The root mean square lift coefficient decreases at $\alpha = 60^\circ$, indicating that the vortex shedding is suppressed more than that at small yaw angles. The independence principle, which states that the drag and lift coefficients based on the velocity component perpendicular to the cylinder axis are independent on the yaw angle of the cylinder, applies to the flow at the gap ratio of 0.8 better than that at the gap ratio of 0.4. Because of the strong influence from the plane boundary on the flow, the force coefficients for the gap ratio of 0.4 do not follow the independence principle if the yaw angle is greater than $\alpha > 30^\circ$.

1. Introduction

Flow around circular cylinders has been studied extensively due to its engineering importance. It has been well known that vortex shedding starts to appear when the Reynolds number is approximately above 40. The flow transition from two-dimensional (2D) laminar flow to three-dimensional (3D) turbulent flow occurs at a Reynolds number of about 140–190 (Roshko, 1954; Tritton, 1959; Zhang et al., 1995; Eisenlhr and Eckelmann, 1989; Williamson, 1988, 1989). Miller and Williamson (1994) found that the laminar regime for parallel vortex shedding can be extended up to Re = 194 and even beyond 200 for a short period of time if there is no end effect. The vortex shedding modes in the transition regime of the Reynolds number are classified into mode A and mode B. Mode A is characterized by the inception of vortex loops and the formation of streamwise vortex pairs due the deformation of the primary vortices in the wake of the cylinder and mode B is characterized by the dominance of the streamwise vortex pairs spaced by a distance of about one cylinder diameter. Barkley and Henderson (1996) and Robichaux et al. (1999) used the Floquet stability analysis method to study the transition modes of the flow. Scarano and Poelma (2009) measured the wake flow field using PIV and presented the transition flow using the three-dimensional iso-surfaces of the vorticity. The flow transition was also successfully predicted by three-dimensional numerical simulations (Karniadakis and Triantafyllou, 1992; Zhang and Dalton, 1998; Zhao et al., 2013). The hydrodynamic forces on the circular cylinder oscillate with time due to the vortex shedding. Schewe (1983) presented experimental results of the drag and lift coefficients over a wide range of Reynolds numbers. It was reported that the force coefficients and vortex shedding frequency are not sensitive to Reynolds number in the subcritical regime ($300 < \text{Re} < 3 \times 10^5$).

In offshore oil and gas engineering, cylindrical structures such as subsea pipelines are generally laid on seabed. Due to the unevenness of the seabed or the erosion of the sediment, a gap between a subsea pipeline and the seabed surface occurs. Flow around a subsea pipeline has been modeled as flow past a circular cylinder near a plane boundary in many studies. When a circular cylinder is located near a plane boundary, vortex shedding flow depends not only on the Reynolds number but also on the gap ratio e/D, with e being the gap between the bottom surface of the

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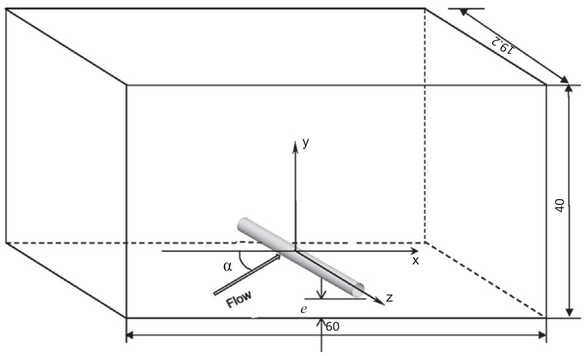

Fig. 1. Non-dimensional computational domain for flow past a circular cylinder near a plane boundary at oblique attack.

cylinder and the plane boundary and D being the cylinder diameter as shown in Fig. 1. Due to its engineering relevance, flow around a cylinder close to a plane boundary has been well studied over the past few decades (Taneda, 1965; Bearman and Zdravkovich, 1978; Grass et al., 1984; Taniguchi and Miyakoshi, 1990; Lei et al., 1999). Many of the existing studies are based on experimental measurements at Reynolds numbers in the sub-critical regime, where the vortex shedding is relatively insensitive to the Reynolds number (Schewe, 1983). Bearman and Zdravkovich (1978), Grass et al. (1984), Lei et al. (1999) and Cheng and Su (2012) reported that the vortex shedding from both top and bottom sides of the cylinder close to a plane boundary was fully suppressed as e/D is less than 0.3. The experimental study by Wang and Tan (2008) demonstrated that the effects of the plane boundary on the flow were weak if e/D is exceeds 0.8. When vortex shedding is fully suppressed, the flow becomes static and the oscillation of the flow-induced force disappears. Akoz et al. (2010), Lin et al. (2009) and Zang et al. (2013) studied flow characteristic of circular cylinders close to a plane boundary using the particle image velocimetry technique. Lin et al. (2009) found the occurrence of a recirculating eddy formed on the plane boundary upstream of the circular cylinder for the gap ratio less than 0.5. Using the swirling strength analysis, Zang et al. (2013) found that, the lee-wake patterns for flow past two cylinders of different diameters are affected by the arrangement of the two cylinders.

Numerical method is also popularly used to predict flow past a cylinder near a plane boundary. Lei et al. (2000) studied flow past a circular cylinder by solving the 2D Navier–Stokes equations for Reynolds numbers up to 1000 and found that the critical gap ratio decreased with an increase in the Reynolds number. By conducting 2D numerical simulation, Bimbato et al. (2013) found that the fluid viscosity and Venturi effect were responsible for the increase in the lift force and the decrease in the drag force of a cylinder close to a plane boundary. Ong et al. (2010, 2012) investigated flow past a marine pipeline using two-dimensional $k-\varepsilon$ turbulence model and obtained good prediction of the flow, although there were some difference between the model results of the forces and the experimental data. Jiang and Lin (2012) and Lin et al. (2013) investigated flow and flow-induced vibrations of two tandem cylinders between two plane walls and found that the distance between the two walls affected the critical spacing between the cylinders for vortex shedding from the upstream cylinder. Camarri and Giannetti (2010) investigated the three-dimensional stability of the wake behind a cylinder confined in two lateral walls with a blockage ratio of 1/5 and found that the transition to a three-dimensional state has the same space-time symmetries of the unconfined case.

When a cylinder is placed in a fluid flow at an inclined angle to the flow, the independence principle is commonly used in practical applications to estimate the vortex shedding frequency and hydrodynamics forces on the cylinder. The independence principle states that the force coefficients and the Strouhal number, which are normalized by the velocity component perpendicular to the cylinder, are approximately independent on the inclination angle of the cylinder. Hereafter, the yaw angle is defined as the angle between the incoming flow and a plane perpendicular to the cylinder axis as shown in Fig. 1 with the zero-degree angle corresponding to the case where the cylinder is perpendicular to the flow direction. In case of flow past an inclined cylinder of finite length, it was found that the wake vortices far from the upstream end of the cylinder are approximately parallel to the cylinder and the vortices near the upstream end of the cylinder are aligned at an angle larger than the cylinder yaw angle (Ramberg, 1983; Thakur et al., 2004). The numerical study by Zhao et al. (2009) showed that the error of independence principle increases with increasing yaw angle. The experimental study of Zhou et al. (2010) also showed that the independence principle is valid up to a yaw angle of about 40°. Lam et al. (2010) reported that the flow past a yawed circular cylinder followed the independence principle for yawed angles up to 45°. The numerical simulation of flow past a yawed cylinder at large yaw angles of 60° and 70° by Lucor and Karniadakis (2003) showed that the vortices in the wake of the cylinder were not exactly parallel to the cylinder. By conducting three-dimensional numerical simulations of flow past an inclined square cylinder at low Reynolds numbers, Yoon et al. (2012) found that the effects of the Reynolds number are weak on the mean flow and the Strouhal number and strong on the lift coefficient.

The study of flow past a yawed circular cylinder close to plane boundary is relatively rare. Kozakiewicz et al. (1995) found that the independence principle can be applied to stationary cylinders in the vicinity of a plane boundary for a yaw angle between 0° and 45°. It is expected that both the yaw angle and the gap ratio affect the transition of the flow in the low Reynolds number regime. In the present study, flow past a yawed circular cylinder at yaw angles in the range of 0°–60° was investigated numerically at a Reynolds number of 500. The focus of this study is to examine the influence of the yaw angle and gap ratio on the vortex shedding flow at a relatively low Reynolds number. A relatively low Reynolds number in the turbulent flow regime is chosen based on the following considerations. Firstly, the wake flow at $\mathrm{Re}=500$ is in the turbulent flow regime based on previous studies (Williamson, 1988, 1989). Three-dimensional vortex shedding flow occurs at $\mathrm{Re}=500$ for an isolated cylinder with zero yaw angle. Secondly, the effect of the yaw angle on the vortex shedding suppression is one of the aims of this study, which is stronger at this relative low Reynolds number than at higher Reynolds numbers. Finally, a relatively low Reynolds number allows the direct numerical simulations (DNS) to be conducted at an affordable computational time.

2. Numerical method

The incompressible Navier–Stokes (NS) equations are solved for simulating the flow. The non-dimensional NS equations are written as

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}+\frac{\partial p}{\partial x_i}-\frac{1}{\mathrm{Re}}\frac{\partial^2 u_i}{\partial x_j^2}=0, \tag{1}$$

$$\frac{\partial u_i}{\partial x_i}=0, \tag{2}$$

where $(x_1, x_2, x_3)=(x, y, z)$ are the Cartesian coordinates, u_i is the fluid velocity component in the x_i direction and p is the pressure.