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Numerical simulation of flow past twin near-wall circular cylinders in tandem arrangement at low Reynolds number

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Abstract

Fluid flow past twin circular cylinders in a tandem arrangement placed near a plane wall was investigated by means of numerical simulations. The two-dimensional Navier-Stokes equations were solved with a three-step finite element method at a relatively low Reynolds number of $Re = 200$ for various dimensionless ratios of $0.25 \leq G/D \leq 2.0$ and $1.0 \leq L/D \leq 4.0$, where D is the cylinder diameter, L is the center-to-center distance between the two cylinders, and G is the gap between the lowest surface of the twin cylinders and the plane wall. The influences of G/D and L/D on the hydrodynamic force coefficients, Strouhal numbers, and vortex shedding modes were examined. Three different vortex shedding modes of the near wake were identified according to the numerical results. It was found that the hydrodynamic force coefficients and vortex shedding modes are quite different with respect to various combinations of G/D and L/D. For very small values of G/D, the vortex shedding is completely suppressed, resulting in the root mean square (RMS) values of drag and lift coefficients of both cylinders and the Strouhal number for the downstream cylinder being almost zero. The mean drag coefficient of the upstream cylinder is larger than that of the downstream cylinder for the same combination of G/D and L/D. It is also observed that change in the vortex shedding modes leads to a significant increase in the RMS values of drag and lift coefficients.

Keywords: Navier-Stokes equations; Finite element method; Circular cylinder; Vortex shedding mode; Hydrodynamic force coefficient

1. Introduction

Steady fluid flows past circular cylinders near a plane wall are highly significant to ocean currents over submarine pipelines. Actual pipelines may be close to one another in a tandem arrangement, due to special engineering requirements, leaving a certain center-to-center distance between them. The gap between the pipelines and the plane wall can also be formed by either an uneven seabed or local scour below submarine pipelines, which can be measured using the distance from the seabed to the lowest surface of pipes. These suspended pipelines are subjected to oscillating fluid forces induced by vortex shedding, which may give rise to severe vortex-induced vibration and even strengthen the undesirable local scour. Hence, an understanding of hydrodynamic characteristics is important to practical pipeline design, even if the flow is limited to a rather low Reynolds number (*Re*).

Investigations of fluid flow past a pair of cylinders in tandem, side-by-side, or staggered arrangements have been carried out in the past, and these investigations have mainly focused on situations in which the cylinders were immersed in an open space and the effect of wall boundaries could be ignored. Zdravkovich (1977, 1987) showed that when more than one body is placed in a fluid flow, the resulting hydrodynamic force coefficient and vortex shedding mode may be completely different from those on a single body at the same Reynolds number. Hence, a variety of vortex shedding modes,

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characterized by the different characteristics of near wakes, should be discerned under different arrangements of the circular cylinders or spacings between two circular cylinders.

Flow past two circular cylinders of an identical diameter in a side-by-side configuration was studied by Bearman and Wadcock (1973), Williamson (1985), and Kim and Durbin (1988). Their results showed that only one vortex shedding mode was observed when the distance ratio $L/D \leq 2.0$, where L is the center-to-center distance between the two cylinders, and D is the cylinder diameter. Early experimental studies on the flow past circular cylinders in a tandem arrangement, for example, Ishigai et al. (1972), Kostić and Oka (1972), Tanida et al. (1973), and King and Johns (1976), showed that there were two major flow regimes. For cylinders separated from one another at small values of L/D, the flow is separated from the upstream cylinder and reattaches to the downstream one, while when the values of L/D are large, vortices are shed from both the cylinders. Meneghini et al. (2001) and Jester and Kallinderis (2003) studied the flow past two cylinders in tandem and side-by-side arrangements. Meneghini et al. (2001) observed negative drag coefficients of the downstream cylinder for $L/D \leq 4.0$ and $Re = 200$ when the two cylinders were in a tandem arrangement. Mittal et al. (1997) conducted numerical simulations to study fluid flows past two cylinders in tandem and staggered arrangements. They found that, for the two cylinders in a tandem arrangement, the hydrodynamic force coefficient and vortex shedding mode were greatly dependent on the Reynolds number, in comparison to fluid flow past an isolate cylinder.

Flow past a circular cylinder near a plane wall has also been widely studied in the past few decades. Investigations have shown that the vortex shedding can be suppressed with very small gaps between the cylinder and the plane wall. Under the condition of high Reynolds numbers in the sub-critical regime, Bearman and Zdravkovich (1978), Grass et al. (1984), and Lei et al. (1999) confirmed that the vortex shedding can be suppressed when the gap ratio $G/D < 0.3$, although different experimental techniques were employed. Price et al. (2002) experimentally studied the fluid flow past a circular cylinder near a plane wall for Reynolds numbers between 1 200 and 4 960. Their study indicated that, for very small values of G/D, the vortex shedding was suppressed or extremely weak, and no regular vortex was shed from the cylinder. Angrilli et al. (1982) investigated the effects of G/D on the Strouhal number at $Re = 2\,860$, 3 820, and 7 640. They found that, when $G/D < 0.5$, the gap ratio G/D had a fairly strong effect on the Strouhal number. Bearman and Zdravkovich (1978) investigated the fluid flow over a cylinder close to a plane wall at higher Reynolds numbers of $Re = 2.5 \times 10^4$ and 4.8×10^4. They found that regular vortex shedding occurred when $G/D > 0.3$, and the Strouhal number was independent of G/D. Cheng et al. (1994) conducted flow visualization measurements to examine the flow past a cylinder close to a plane wall at $Re = 500$. They concluded that the Strouhal number increased with the decrease of G/D when $0.2 < G/D < 0.625$. Lei et al. (2000) found that vortex shedding was suppressed at small gap ratios, and the critical gap ratio, at which the vortex shedding is suppressed, varies with the thickness of the boundary layer that develops on the plane wall.

It is well known that vortex shedding from a circular cylinder becomes three-dimensional when $Re > 200$ (Williamson, 1988, 1989) and turbulent at higher Reynolds numbers. Both the three-dimensional and turbulent effects give rise to a considerable increase in computational requirements. However, two-dimensional simulations at low Reynolds numbers can be used to generate some insights into the vortex dynamics in the wake (Lei et al., 2000; Meneghini et al., 2001). Hence, the numerical investigations of this study were restricted to a limiting Reynolds number of $Re = 200$, which allows us to solve the two-dimensional laminar Navier-Stokes equations with fairly acceptable computational efforts.

The numerical simulations were conducted for $G/D = 0.25$, 0.50, 0.75, 1.00, 1.50, and 2.00 and L/D values ranging from 1.0 to 4.0 with an interval of 0.25. The effects of L/D and G/D on the hydrodynamic force coefficients, Strouhal numbers, and vortex shedding modes were investigated in this study.

2. Governing equations and numerical method

The governing equations are the non-dimensional continuity equation and the non-dimensional time-dependent incompressible Navier-Stokes equations for viscous Newtonian fluid:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

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

where u_i is the velocity component in the x_i direction ($i = 1, 2$ for the present two-dimensional numerical model with $x_1 = x$ and $x_2 = y$ in this study), p is the pressure, t is time, and Re is defined as $Re = U_0 D/\nu$, with U_0 being the free-stream speed, and ν being the kinematic viscosity of the fluid.

The governing equations are solved using a three-step finite element method (Jiang and Kawahara, 1993), which shows high-order accuracy and strong performance for convection-diffusion problems. Using the method, the momentum equation is discretized as follows:

$$u_i^{n+1/3} = u_i^n + \frac{\Delta t}{3}\left(\frac{1}{Re}\frac{\partial^2 u_i^n}{\partial x_j \partial x_j} - u_j^n \frac{\partial u_i^n}{\partial x_j} - \frac{\partial p^n}{\partial x_i}\right) \tag{3}$$

$$u_i^{n+1/2} = u_i^n + \frac{\Delta t}{2}\left(\frac{1}{Re}\frac{\partial^2 u_i^{n+1/3}}{\partial x_j \partial x_j} - u_j^{n+1/3} \frac{\partial u_i^{n+1/3}}{\partial x_j} - \frac{\partial p^n}{\partial x_i}\right) \tag{4}$$

$$u_i^{n+1} = u_i^n + \Delta t\left(\frac{1}{Re}\frac{\partial^2 u_i^{n+1/2}}{\partial x_j \partial x_j} - u_j^{n+1/2} \frac{\partial u_i^{n+1/2}}{\partial x_j} - \frac{\partial p^{n+1}}{\partial x_i}\right) \tag{5}$$

where Δt denotes the time increment between the nth and $(n+1)$th time levels, and superscripts $n + 1/3$, $n + 1/2$, and $n + 1$ represent the time instants of $(n + 1/3)\Delta t$, $(n + 1/2)\Delta t$,