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Vortex shedding in the flow around two side-by-side circular cylinders of different diameters*

Xiang Qiu (邱翔)[1], Zhen-xiao Bi (毕贞晓)[2], Jian-ping Luo (罗剑平)[2], Yu-lu Liu (刘宇陆)[3]
1. *School of Science, Shanghai Institute of Technology, Shanghai 201418, China, E-mail: emqiux@163.com*
2. *School of Mechanical Engineering, Shanghai Institute of Technology, Shanghai 201418, China*
3. *Shanghai Institute of Applied Mathematics and Mechanics, Shanghai University, Shanghai 200072, China*

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Abstract: In this paper, the 3-D turbulent flow around two side-by-side circular cylinders of different diameters, at sub-critical Reynolds number $(Re = 3\,900)$, is numerically simulated by the large eddy simulation (LES). The spacing ratios (T/D) between the two cylinders are considered in four cases ($T/D = 1.2$, 1.5, 1.8 and 2.7) to study the vortex shedding and turbulent properties in the flow field. The main results are focused on the drag and lift coefficients, the vortex shedding frequency, the coherent structure, and the scale properties. It is shown that when T/D is equal to 1.2, the vortex shedding of the main cylinder is strongly suppressed by the small cylinder, the drag and lift coefficients of the main cylinder are smaller than those in other three cases. While T/D is equal to 1.5, the vortex shedding of the main cylinder can be improved, the drag and lift coefficients of the main cylinder are larger than those in other three cases. The empirical mode decomposition (EMD) method is applied to decompose the velocity signals traced by the LES. It is shown that there is a linear relationship between the mean period and the mode in the semi-log coordinates. The vortex shedding period of the main cylinder is consistent with the period of the restructured coherent structures quantitatively.

Key words: Large eddy simulation (LES), drag and lift coefficients, vortex shedding frequency, empirical mode decomposition (EMD)

Introduction

The flow around multiple cylinders were studied theoretically in fluid mechanics and extensively in engineering applications. As a classical model of the multiple-cylinder system, the case of two side-by-side circular cylinders attracted much attention. Experimental studies show that there are three flow patterns for the configuration of two side-by-side cylinders at different spacing ratios, including the single-bluff-body behavior, the parallel vortex streets and the biased flow pattern[1-3]. Related studies on drag and lift coefficients show that except for the biased flow regime, the mean drag coefficient is close to that of a single circular cylinder, and the mean lift coefficient is close to zero. At very small spacing ratios, a negative lift force is on the two cylinders. Within the biased flow regime, the two cylinders are mutually expelled with positive lift coefficients[4,5].

With the development of computer technology, the flows around multiple cylinders were widely studied numerically in recent years. Kravchenko and Moin[6] studied the flow around a single circular cylinder using the large eddy simulation method at $Re =$ 3 900. It was found that the results of the dynamic Smagorinsky sub-grid scale (SGS) model and the center discrete format are closer to the experimental results, and the density of the grid around the cylinder affects the length of the recirculation. Zhang et al.[7] use the large eddy simulation (LES) to obtain the flow past a finite circular cylinder with a height-to-diameter ratio of 1.5 and an infinite circular cylinder of the same diameter at a Reynolds number $Re = 3\,900$. Ali and Sheldon[8] investigated the effects of Reynolds numbers and spacing ratios on the flow characteristics and the hydrodynamic forces on the two side-by-side arranged cylinders of the same diameter. Cross-flows arou-

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Biography: Xiang Qiu (1978-), Male, Ph. D., Professor nd two, three and four circular cylinders in tandem, side-by-side, isosceles triangle and square arrangements are simulated using the incompressible lattice Boltzmann method with a second-order accurate curved boundary condition[9]. Vedat et al.[10] found that the asymmetric flow behavior of two side-side circular cylinders downstream can be suppressed with a splitter plate in a shallow water. Zeng et al.[11] examine the water wave radiation by arrays of truncated circular cylinders. Based on the eigenfunction expansion and Graf's addition theorem for Bessel functions, an analytical method that includes the effects of evanescent modes is developed to analyze such arrays of cylinders. With respect to the turbulent signal analysis, Huang and Lu[12] analyzed the velocity signal at a point behind the cylinder, using the EMD method at $Re = 152$. The large energy-containing modes were found to have a clear physical meaning, and an obvious intra-wave frequency modulation was found at the corresponding instantaneous frequency.

At present, the flows around two side-by-side circular cylinders of different diameters were not well studied. Dalton et al.[13] and Zhao et al.[14] found that the vortex street exists behind the cylinders only at very small spacing ratios for the two cylinders. Dalton et al.[13] showed that both the drag and the lift coefficients of the main cylinder were reduced because of the existence of a small cylinder. Zhao et al.[14] simulated the flow around two side-by-side circular cylinders at $Re = 500$ and at the diameter ratio of 0.25. It was found that the spacing ratio has little effect on the mean drag coefficient of the small cylinder, while has a great influence on the wake of the main cylinder and the mean drag and lift coefficients. Yang et al.[15] showed the effects of the piggyback cylinder on the drag and lift coefficients of the main cylinder in an oscillatory flow.

In the present work, the flow around two side-by-side circular cylinders of different diameters is investigated numerically by the LES method, based on the dynamic Smagorinsky SGS model. and the EMD method is used to analyze the suppression mechanism of the vortex shedding. The primary coverage is focused on the effects of the two side-by-side cylinders of different diameters on the vortex shedding behind two cylinders and the force on the main cylinder.

1. Computational details

1.1 *Governing equation and numerical method*

The basic idea of the LES is to calculate large scale eddies directly by solving the filtered Navier-Stokes equations, and to simulate the small scale eddies by a SGS model. The governing equations used for the LES in this paper are as follows:

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

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial \overline{u_i u_j}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_j \partial u_j} - \frac{\partial \overline{\tau_{ij}}}{\partial x_j} \tag{2}$$

where $\overline{u_i}$ and $\overline{u_j}$ are the filtered mean velocity components, $\overline{p}$ is the mean pressure, ρ is the water density, ν is the kinematic viscosity of the water, $\overline{\tau_{ij}}$ denotes the mean SGS stress resulting from the filtering operation, which is unknown and is modeled as

$$\tau_{ij} = \frac{1}{3}\tau_{kk}\delta_{ij} - 2\nu_t \overline{S_{ij}} \tag{3}$$

where τ_{kk} is incorporated in the pressure, resulting in a modified pressure term, ν_t is the SGS kinematic viscosity, $\overline{S_{ij}}$ is the rate-of-strain tensor, and can be modeled as

$$\overline{S_{ij}} = \frac{1}{2}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) \tag{4}$$

The most basic SGS model was built by Smagorinsky and then further developed by Lilly. In the Smagorinsky-Lilly model, the sub-grid kinematic viscosity ν_t is modeled by

$$\nu_t = L_s^2 \left|\overline{S_{ij}}\right| \tag{5}$$

where L_s is the mixing length for the SGS, and $\left|\overline{S_{ij}}\right| = \sqrt{2\overline{S_{ij}}\,\overline{S_{ij}}}$, L_s can be computed by

$$L_s = \min(\kappa y, C_S \Delta^{1/3}) \tag{6}$$

where $\kappa = 0.42$ is the von Karman constant, y is the distance to the nearest wall, Δ is the volume of the computational cell. C_S is the Smagorinsky constant. Good results for a wide range flows were obtained when the Smagorinsky constant $C_S = 0.1 - 0.14$ [16]. All computations in this paper are carried with $C_S = 0.1$.

In the present simulation, the finite volume method (FVM) applied on the structured grids is used to discrete the unsteady Navier-Stokers equations, the SIMPLE algorithm is used for the pressure-velocity coupling between the momentum and continuity equations, the bounded central differencing is used for the