Ocean Engineering 169 (2018) 253–269

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Numerical analysis of flow past an elliptic cylinder near a moving wall

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ARTICLE INFO

Keywords:
Elliptic cylinder
Vortex shedding
Moving wall
Lattice Boltzmann method

ABSTRACT

A large eddy simulation based on the lattice Boltzmann method is used in this study to develop a computation program for fluid flow past an elliptic cylinder near a moving wall. The flow field around the elliptic cylinder as it approaches the moving wall is simulated for different axis ratios at Reynolds numbers of 200 and 400. The effects of the gap ratio, axis ratio, and Reynolds number on the flow field, force coefficient, and Strouhal number are investigated. The moving wall inhibits the normal velocity and stabilizes the flow, thereby suppressing vortex shedding. This study focuses on the mechanisms that various parameters influence the vortex shedding of flow past an elliptic cylinder near a moving wall. The calculation results show that decreasing the gap and axis ratios both suppress vortex shedding, while the increase in Reynolds number effectively alleviates the complete suppression of vortex shedding. A decreased axis ratio increases the gap ratio for vortex shedding suppression, and an increased Reynolds number significantly lowers the gap ratio for complete vortex shedding suppression. As the gap ratio decreases, owing to the interaction between the positive vortex separated from the lower side of the cylinder and the negative vortex separated from the moving wall, the strength of the positive vortex formed at the lower side of the cylinder gradually decreases downstream. This interaction is more prominent at small axis ratios. When the Reynolds number increases, the interaction between the positive vortex separated from the lower side of the cylinder and the negative vortex separated from the moving wall is noticeably weaker, and the positive vortex maintains its strength for a longer distance downstream. The computed results are in good agreement with the limited experimental data published in literature.

1. Introduction

Flow around blunt bodies, considered a fundamental classic problem that has attracted much attention from fluid dynamics scientists, is commonly encountered in scientific research and engineering practices. To understand the mechanism of this type of flow, researchers have performed much theoretical and experimental work on the topic (Tian et al., 2013; Jiang et al., 2015; Bai et al., 2016; Xu et al., 2016; Strandenes et al., 2017; Gao et al., 2017; Stadler et al., 2017). Typical blunt bodies such as circular, square, and elliptic cylinders play very important roles in various constructions, including high-rise buildings, bridges, and marine risers. Unsteady flow past blunt bodies is often related to complex flow phenomena such as flow separation, separation bubbles, and vortex shedding, the last of which is specifically related to negative effects such as vortex-induced vibration and noise.

Many flow problems occur near flat walls or the ground, which substantially effect fluid flow. These scenarios are more complex because the flow is not only influenced by the relative thickness δ/D, but also the relative position δ/G (where δ is the boundary layer thickness, D is the cylinder diameter, and G is the shortest distance from the cylinder to the wall). The shear stress on the wall and small amount of flow in the gap will suppress vortex shedding, creating a type of problem that attracts widespread interest from researchers. Bailey et al. (2002) performed a simulation of flow around a square cylinder near a stationary wall to analyze three-dimensional turbulent flows at different gap ratios (G/D), and their results showed that the number of vortex dislocations is closely related to changes in the oblique shedding angle. The probability of vortex dislocation increases when the gap ratio is less than 0.7 and decreases when the gap ratio is close to that of vortex shedding suppression ($0.5 < G/D < 0.7$). Mahir (2009) calculated the flow around two- and three-dimensional square cylinders near a fixed wall, specifically analyzing flow structures at different Reynolds numbers and gap ratios, and their results showed that when $Re = 250$, B type secondary vortices form in the wake region; however, at $Re = 175$ and 185, a transition from A type to fully periodic B type vortices was observed when the cylinder was brought closer to the wall. Abrahamsen Prsic et al. (2016) used large eddy simulation (LES) to simulate flow past a circular cylinder near a horizontal flat wall at subcritical Reynolds numbers, and observed that the gap ratio significantly influenced the forces on the cylinder as well as the

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https://doi.org/10.1016/j.oceaneng.2018.09.033
Received 6 May 2018; Received in revised form 16 August 2018; Accepted 16 September 2018
0029-8018/

development of flow in the wake. At $G/D = 0.2$, both the primary and secondary separation bubbles were long and nearly stationary; however, $G/D = 0.6$ yielded a slightly asymmetric wake with long shear layers. The cylinder shear layers and wall boundary layer separate periodically when $G/D = 1$. Shaafi et al. (2017) applied the second-order accurate immersed boundary method to numerically simulated laminar flow past a rotating cylinder near a wall and observed a flow pattern similar to those past non-rotating cylinders near walls that could be classified into three regimes: regular Karman vortex shedding, irregular vortex shedding, and complete vortex suppression.

Translational movements of blunt bodies near stationary planes are both important in engineering and frequently observed in real life, such as in fluid flows past car wheels and the influence of the ground on racing cars. In direct simulations, blunt body positional changes over time complicate the study of the flow field characteristics; however, if the blunt body is fixed in a Cartesian coordinate system, the problem will be transformed to one of a stationary blunt body and moving plane. The latter model was developed in this study. Such problems are relatively simple, as no boundary layer is formed on the wall, and have been the subject of theoretical and experimental research. Taneda (1965) pioneered the visualization of the translational motion of a cylinder near a wall and observed vortex shedding at a Reynolds number of 170 and gap ratios of 0.6 and 0.1. When the gap rate was 0.1, a single row vortex street was shed and formed near the wall before rapidly breaking down. Nishino et al. (2007) set their bottom boundary as a moving plane with the same speed as the incoming flow, giving the bottom boundary layer negligible influence, but still found a reduction in drag as G/D decreased from 0.5 to 0.35. Zheng et al. (2012) employed the lattice Boltzmann method to simulate the flow around a cylinder near a moving wall to develop an accurate and comprehensive determination of the critical gap ratio and discovered the flow characteristics were quite different between different gap ratio regimes. Both lift and drag increase significantly relative to isolated cylinders, and vortex shedding was suppressed by the wall. Rao et al. (2013) analyzed the flow field around a moving circular cylinder above a non-slip wall boundary at $Re \le 200$, and found a steady two-to three-dimensional transition first occurred at the gap ratio $G/D \le 0.25$, beyond which the initial transition was to unsteady flow. At $G/D = 0.3$, the critical Reynolds number required for the onset of three-dimensional flow rose sharply. Zhang and Shi (2016) discussed the flow around a circular cylinder with a splitter near a moving wall, with results showing that the Strouhal number relevant to vortex shedding frequency first increased and then decreased when the splitter-fitted cylinder moved close to the wall, implying the wall and splitter exercise significant control over the flow and can suppress the vortex and reduce drag. D' Souza et al. (2016) studied the hydrodynamic properties of flow around two tandem circular cylinders near a moving wall and noted an early transition from reattachment to co-shedding during their calculation. For tandem circular cylinders with Reynolds numbers of 200 and gap ratios of 0.5, a parallel double-vortex row formed in the co-shedding regime due to the combined wake interference and wall proximity effects.

Most previous studies focused on circular (elliptic cylinders with an axis ratio of 1) or square cylinders, with few investigating the flow around elliptic cylinders with different axis ratios ($AR < 1$) near moving walls. There are many practical applications for the present configuration of elliptic cylinders near a moving wall. Firstly, this effect has a great relationship with flows where the interactions of wall-particle are significant, such as sedimentation tanks involved in the chemical and mining industries, cells in blood vessels, and micro-carrier beads in bioreactors. Secondly, in engineering practice, especially in the automation industry, it is very common to see the elliptic cylinders move transversely along the stationary plate. Therefore, in this study, the lattice Boltzmann method (LBM) was used to simulate the flow around elliptic cylinders with different axis ratios near a moving wall. The LBM, owing to its use of molecular kinetic theory, has made considerable progress in theoretical and applied complex flow simulation research, including turbulence flow (Yun et al., 2014; Jin et al., 2015a,b; Gehrke et al., 2017; Eshghinejadfard et al., 2017), multiphase and multicomponent flow (Gupta et al., 2015; Liu et al., 2016; Zudrop et al., 2017; Fakhari et al., 2017), and porous media flow (Parmigiani et al., 2011; Jin et al., 2015a,b, 2017; Suga et al., 2017), showing promise as a numerical simulation method. In previous studies, appropriate laminar flow models were generally used when the Reynolds number was below 400. However, according to the works of Sumer and Fredsøe (1997) and Zhang and Shi (2016), wake flows are turbulent at $300 < Re < 3 \times 10^5$ (subcritical flow regime) despite the laminar flow at the surface boundary layer of the cylinder. In this study, LBM-based LES was used to more accurately simulate fluid flow. A multi-relaxation-time (MRT) model was adopted to improve numerical stability.

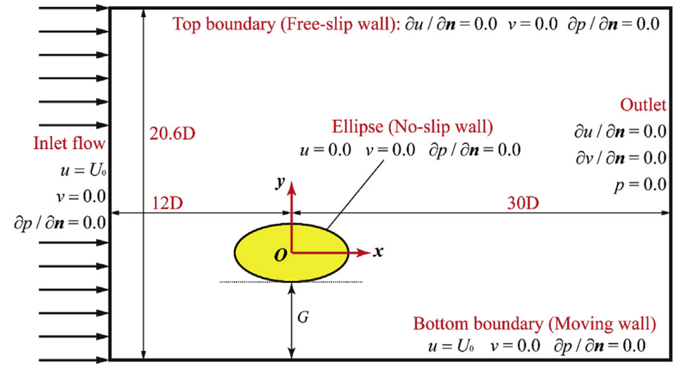

Fig. 1. Computational domain and boundary conditions.

Table 1
Comparison of mean drag coefficients and Strouhal numbers with literature values.

Case	References	$\overline{C}_d$	Difference %	S_t	Difference %
$Re = 200$	Present	1.3847	–	0.1751	–
	Benson et al. (1989)	1.45	−4.50	0.17	3.00
	Ding et al. (2004)	1.327	4.35	0.164	6.77
	Tian et al. (2011)	1.43	−3.17	0.163	7.42
	Cui et al. (2017)	1.34	3.34	0.167	4.85
$Re = 400$	Present	1.4794	–	0.2203	–
	Jordan and Fromm (1972)	1.23	20.28	0.20	10.15
	Gresho et al. (1984)	1.78	−16.89	0.22	1.36
	Borthwick (1986)	1.50	−1.37	–	
	Zhang and Shi (2016)	1.4680	0.78	0.2272	−3.04

2. Numerical method

2.1. MRT lattice Boltzmann method

The French scholar d'Humieres proposed a generalized lattice Boltzmann equation (GLBE) model (d'Humières, 1994).Lallemand and Luo (2000) performed a detailed theoretical analysis of the model and found it had considerable advantages in terms of its physical principle, parameter selection, and numerical stability. The primary difference between this and the traditional lattice Bhatnagar–Gross–Krook (LBGK) model is its introduction of multiple relaxation times (i.e., the so-called MRT-LBE model) expressed as

$$\boldsymbol{f}_i(\boldsymbol{x} + e_\alpha \delta t,\ t + \delta t) - \boldsymbol{f}_i(\boldsymbol{x},\ t) = -\Lambda_{ij}[f_j(\boldsymbol{x},\ t) - f_j^{(eq)}(\boldsymbol{x},\ t)],\ i = 1,2,\ \cdots, b \tag{1}$$

in which $-\Lambda_{ij}$ is the collision matrix. A number (b) of moments, $\boldsymbol{m}_k = \boldsymbol{f} \cdot \phi_k$, are defined according to the distribution function $\boldsymbol{f}$, where $k = 1,2,\ \cdots, b$, and ϕ_k represents the linearly correlated polynomial