Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **6**, No. 4, pp. 461-477

DOI: 10.4208/aamm.2013.m395
August 2014

Lattice Boltzmann Study of a Vortex Ring Impacting Spheroidal Particles

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Received 4 November 2013; Accepted (in revised version) 21 February 2014

Available online 28 May 2014

Abstract. Interaction of vortex rings with solid is an important research topic of hydrodynamic. In this study, a multiple-relaxation time (MRT) lattice Boltzmann method (LBM) is used to investigate the flow of a vortex ring impacting spheroidal particles. The MRT-LBM is validated through the cases of vortex ring impacting a flat wall. The vortex evolution due to particle size, the aspect ratio of a prolate particle, as well as Reynolds (Re) number are discussed in detail. When the vortex ring impacting a stationary sphere, the primary and secondary vortex rings wrap around each other, which is different from the situation of the vortex ring impacting a plate. For the vortex ring impacting with a prolate spheroid, the secondary vortex ring stretches mainly along the long axis of the ellipsoid particle. However, it is found that after the vortex wrapping stage, the primary vortex recovers along the short axis of the particle faster than that in the long axis, i.e., the primary vortex ring stretches mainly along the short axis of the particle. That has never been address in the literature.

AMS subject classifications: 76D17

Key words: Vortex interaction, lattice Boltzmann method, spheroid, particle.

1 Introduction

The study of vortex ring interactions with solid bodys has attracted much attention. The possible reasons are that the experiments are easy to carry out and the results would give physical insights to more complicated flow fields dominated by vorticities.

The simplest interaction between a vortex and a solid body may be a vortex ring impacting on a flat wall. This case is helpful to understand the topological changes in evolving vortex structures [1]. This topic has been studied extensively through experiment and numerical simulations [1–5]. For example, Chu [5] studied the vortex structure

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and the associated surface force with $500 \leq Re \leq 2000$ numerically and experimentally. In the literature, the following procedure is identified [1, 5]. When the vortex ring approaches the wall, a boundary layer with vortices of opposite signs will form, which is a viscous response in the vicinity of the wall [6, 7] due to the non-slip wall boundary condition. In the procedure, the toroidal radius of the vortex ring would expand. Due to vortex stretching, the vortex core shrinks but its vorticity is intensified [1]. Finally, a secondary vortex and even a tertiary vortex ring may be generated from the boundary layer and leave the boundary.

There are also some numerical studies on the interaction of the ring with an inclined wall. Liu [8] used the vortex particle-in-cell method and a hybrid Eulerian-Lagrangian method to simulate the unsteady shear flow induced by a vortex ring impacting a flat wall with angle 38.5°. Liu [8] proved that the helical winding of vortex lines behaved more prominent and the secondary vortex core is thicker at a high Re. Cheng et al. [1] studied a vortex ring impacting a flat wall with an angle of $0 \leq \theta \leq 40$ and $100 \leq Re \leq 1000$. He observed the development of the primary vortex ring and the pattern of the secondary vorticity generation, and made a investigation on the effect of θ and Re.

On the other hand, vortex interaction with a stationary and rotating spheroidal particle, which probably represents the simplest interaction of a vortex with a body, receives less attention [9, 10]. To the best of our knowledge, the following two works were carried out in the literature. One is the experimental study of a vortex ring impacting a sphere [9]. In the experiment, a neutrally buoyant sphere was free to move in response to the impulse delivered by a vortex ring in water. The other work is a numerical study of the vortex interaction with a stationary sphere [10] using the implicit fourth-order compact finite difference schemes for solving the flow with Re=2000. Paulo analyzed the vortex dynamics of the ring as it approached the sphere surface [10]. He identified that the boundary layer formed on the surface of the sphere undergoes separation to form a second vortex ring, which grow rapidly as it interact with the primary ring. However, most of the previous studies are restricted to a flat or a sphere. The vortex ring interaction with an ellipsoidal particle and particle's size effect on the evolution of the vortices have never been addressed in the literature.

In this work, we will investigate three-dimensional flow structure of a vortex ring impacting an ellipsoidal particle with different ellipticity (ratio between the major axis and the minor axis) and Reynolds numbers by using the lattice Boltzmann method (LBM) [11]. Lattice Boltzmann equation is able to recover the macroscopic Navier-Stokes equation, it looks like an artificial compressibility method (ACM) for solving the N-S equation [12]. However, in terms of spatial and temporal discretization, LBM is different from the ACM. For transient flows, the LBM may be more accurate for capturing the pressure waves than the ACM [12]. In the LBM, the Poisson equation is not required to solve. The LBM is an explicit scheme and the code is easy to be parallelized.

Here, through LBM simulations, we try to understand the mechanisms of the interaction between vortex ring and ellipsoidal particle. The effects of the ellipticity and Re are investigated.