Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **11**, No. 3, pp. 608-618

DOI: 10.4208/aamm.2018.s05
June 2019

Direct Numerical Simulation of a Freely Falling Thick Disk

Pan Zhang[1,2], Zhenhua Xia[3] and Qingdong Cai[2,*]

[1] *Software Center for High Performance Numerical Simulation, Institute of Applied Physics and Computational Mathematics, Beijing 100088, China*
[2] *State Key Laboratory for Turbulence and Complex Systems, Center for Applied Physics and Technology, College of Engineering, Peking University, Beijing 100871, China*
[3] *Department of Engineering Mechanics, Zhejiang University, Hangzhou 310027, Zhejiang, China*

Received 22 August 2018; Accepted (in revised version) 6 December 2018

Abstract. In this paper, a thick disk with aspect ratio greater than 1/10 is directly simulated by adaptive mesh refinement-immersed boundary-lattice Boltzmann flux solver (AMR-IB-LBFS). The AMR-IB-LBFS model is a combination of the adaptive mesh refinement (AMR) technique and immersed boundary-lattice Boltzmann flux solver (IB-LBFS). Four different aspect ratio disks are numerically simulated, and the numerical results are in good agreements with theoretical results. In addition, these disks with different aspect ratios are compared with trajectories and gestures.

AMS subject classifications: 35R37, 74F10
Key words: Moving boundary, freely falling disk, immersed boundary-lattice Boltzmann flux solver, adaptive mesh refinement.

1 Introduction

A flow field caused by a freely falling or rising body under the effect of gravity contains very complicated unsteady characteristics. A disk is a simple object in the freely falling or rising body, and its geometry is simple and symmetrical. The disk freely falling motion is related to these parameters, which are disk diameter d, thickness h, density ρ_s, fluid density ρ_f and kinematic viscosity ν. Willmarth et al. [1] systematically studied the stable and unstable motions and the wakes of freely falling disk using experimental methods in 1964, and summarized the relationship between its motion and the following three dimensionless numbers. They are the aspect ratio,

$$\lambda=\frac{h}{d},$$

*Corresponding author.
Emails: zhpan@pku.edu.cn (P. Zhang), xiazh@pku.edu.cn (Z. H. Xia), caiqd@pku.edu.cn (Q. D. Cai)

the dimensionless moment of inertia,

$$I^*=\frac{\pi\rho_d}{64\rho_f}\cdot\frac{h}{d}$$

and the Reynolds number,

$$Re=\frac{U_\infty d}{\nu},$$

where, U_∞ is the average falling velocity, which is usually estimated by

$$U_\infty\approx\sqrt{(\rho_d/\rho_f-1)gh}.$$

Willmarth et al. [1] observed the disk motion exhibited a variety of different models and found its motion depended on the dimensionless numbers I^* and Re. Thereafter, Smith [2] measured more experimental data about I^* and Re. And, Field et al. [3] summarized the past literatures data and generalized four main motion modes, including steady, flutter, tumble and chaotic. In addition, the range of I^* and Re for different motion modes was given.

About the wake of a free moving object, Ern et al. [4] summarized the relationship between the state of understanding of the path oscillations of freely moving bodies and the dynamics of the body wake. And, Auguste et al. [5] used direct numerical simulation to investigate the wake dynamics of a thick disk. For the study of a freely falling disk, it was generally simplified to solve the two-dimensional problem. But, Zhong [6] experimentally studied the path of disk and observed that the freely falling path could result in a transition from zigzag type to spiral by slightly changing the location of a disk's center of mass. And Zhong et al. [7] first obtained the change of the six degrees of freedom of the disk with time in the experimental method in 2011. It was also found that when I^* was reduced, the trajectory of motion changes from being in one plane to not being in one plane, while the spiral motion modality was observed. What's more, Zhong et al. [8] experimentally investigated the effect of Reynolds number on the planar zigzag motion in terms of amplitude, horizontal oscillation, body tilt angle and Strouhal number. Lee et al. [9] experimentally studied the transition of the freely falling motion of a thin disk from zigzag to spiral with accurate about the six degrees of freedom. And, Auguste [10] numerically investigated the dynamics of thin disks falling under gravity in a viscous fluid medium at rest at infinity. JONES [11] modeled the separated flow of an inviscid fluid around a falling flat plate using a boundary integral formulation for the complex conjugate velocity field.

For the study of moving boundary problems, the immersed boundary method (IBM) is a very effective method. The usual IBM is to take a non-uniform Cartesian mesh of uniform meshes around the object, which would reduce the computational accuracy of some areas due to the narrow mesh. In order to overcome the above drawbacks and efficiently simulate the flow with complex geometries and moving boundary, Zhang et al. [12] presented the adaptive mesh refinement-immersed boundary-lattice Boltzmann