GPU-Accelerated Lattice Boltzmann Method for Complex Free Surface Flows

李, 旭晖

https://doi.org/10.15017/1785434

出版情報：九州大学, 2016, 博士（工学）, 課程博士
バージョン：
権利関係：全文ファイル公表済

氏　　名　: 李 旭晖　(Li Xuhui)

論 文 名　: GPU-Accelerated Lattice Boltzmann Method for Complex Free Surface Flows（GPUを用いた格子ボルツマン法による複雑自由表面流れの数値解析）

区　　分　: 甲

論文内容の要旨

In the historical development of the fluid dynamics in ocean engineering applications, three branches have been going ahead together: experimental fluid dynamics (EFD), potential flow theory and computational fluid dynamics (CFD). In the EFD, model experiments can provide reliable and accurate results for parameters optimization and risk assessment while the huge expenditure, long period and the scale-effect prevent it from convenient and low-cost execution. The inviscid potential flow theory based on the boundary element method (BEM) using the complex Green function or Rankine source on the body surface, free surface with some far-field boundary condition plays pivotal role in the linear physical problems and some nonlinear physical problems. This method, however, cannot be used for most fully nonlinear problems. The traditional CFD tools such as finite difference method (FDM), finite volume method (FVM) have remarkable achievements in the ocean engineering applications. Unfortunately, due to the time-consuming property, researchers have been making efforts to develop an efficient alternative CFD tool. The well-suited and intrinsic parallelism of the lattice Boltzmann method (LBM) and the coming of the era of GPU parallel computation make it possible to develop an extremely efficient and even real-time numerical simulation tool.

As a young CFD branch, LBM has not yet practically applied into complicated free surface problems in the ocean engineering field. The work described in the present thesis is devoted to investigate the potential of the lattice Boltzmann method in ocean engineering applications. It is well known that the wave-body interaction such as ship and platform motion in waves, as a typical ocean engineering problem usually involves two major numerical difficulties for LBM: moving solid boundary and complicated free surface. The present work is devoted to handle these two topics. The main results are as follows.

(1) For the moving solid boundary, the difficulty is the spurious pressure oscillation in the treatment of moving fluid-solid boundary, which is systematically investigated in this study. It is found that firstly the fundamental collision model in the lattice Boltzmann method causes intrinsic pressure fluctuation. Secondly the re-initialization algorithm for the fresh fluid node that just emerged from the solid region remarkably affects the oscillation of the force exerted on the moving body immersed in the fluid domain. Moreover, the force evaluation approach (such as various momentum exchange methods, stress integration method, immersed boundary method) is also relevant to the pressure calculation accuracy and the oscillation of the force on the moving body. To improve the accuracy of force evaluation of the moving boundary, a bi-quadratic ghost fluid immersed boundary method has been proposed. To suppress the pressure oscillation issue, a new refilling scheme for the fresh fluid node has been

developed.

(2) For the free surface, two approaches have been explored to model the violent free surface flow: the single-phase free surface model and the high-density ratio multiphase model. To develop a stable, accurate and efficient free surface capture algorithm is a key challenge for both of them. In the present study, a VOF (volume-of-fluid) type algorithm is applied and improved to capture the free surfaces in the single-phase free surface model which ignores the gas phase and model the atmosphere pressure as dynamic boundary condition on the free surface. The classical engineering applications such as dam breaking, dam breaking with obstacle, water entry and exit of circular cylinder with constant speed, water entry of circular cylinder with free falling have been successfully simulated. Meanwhile, the multiphase lattice Boltzmann models which are capable of high-density ratio and high Reynold number simulations have also been investigated and compared. The mass conservative phase-field interface tracking equation has been applied to treat the interfacial dynamics. The up-to-date mass-conservative multiphase lattice Boltzmann model developed by Abbas & Martin & Lee has been applied in this thesis. The bubble dynamics including single bubble behavior, bubble-bubble interactions and vortex ring bubble have been investigated deeply.

(3) To efficiently implement the numerical code of different LB solvers, the modern GPU accelerated technique has been realized and equipped to the present programs. In order to achieve the large-scale three-dimensional numerical simulation, the multi-GPU technique has been also developed due to the limited device memory on single GPU card. The accelerated program has fulfilled the speed-up ratio up to several hundreds, which dramatically decreases the simulation time and improve the research efficiency.

The dissertation is organized as follows. Chapter 1 is the introduction of the thesis. Basic theory, collision model, boundary condition, turbulence model and unit transformation are stated in chapter 2. In chapter 3, the hardware architecture of GPU device, CUDA programming platform, GPU implementation with single device and multi-devices in the lattice Boltzmann simulation are elaborated. In chapter 4, a bi-quadratic ghost fluid immersed boundary lattice Boltzmann method is proposed and the accuracy and pressure oscillation feature of the fluid-solid interaction is deeply investigated. In chapter 5, the single phase free surface lattice Boltzmann model is described and applied to simulate the water entry and water exit problem. In chapter 6, the features of four multiphase lattice Boltzmann models are investigated and compared. The Abbas-Martin-Lee model is applied to bubble dynamics. Chapter 7 is the conclusion of the thesis.