論文 / 著書情報
Article / Book Information

題目(和文)	運動量保存型弱圧縮性二相流の大規模 GPU 計算ソルバー
Title(English)	A Momentum-conserving Weakly Compressible Navier-Stokes Solver for Large-scale Two-phase Flow Simulation on GPUs
著者(和文)	YangKai
Author(English)	Kai Yang
出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第12521号, 授与年月日:2023年9月22日, 学位の種別:課程博士, 審査員:青木 尊之,末包 哲也,奥野 喜裕,大西 領,門永 雅史
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第12521号, Conferred date:2023/9/22, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	論文要旨
Type(English)	Summary

（博士課程）
Doctoral Program

論 文 要 旨

THESIS SUMMARY

系・コース： Department of, Graduate major in	機械　系 機械　コース	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of　（ 工学 ）
学生氏名： Student's Name	YANG Kai	審査員主査： Chief Examiner	青木　尊之

要旨（英文800語程度）
Thesis Summary (approx.800 English Words)

This thesis addresses the challenge of simulating violent two-phase flows with high density ratios by proposing novel methods for numerical computations of the weakly compressible Navier-Stokes equations. These methods are validated through various benchmarking problems, and their scalability and performance on multi-GPU clusters are evaluated. The proposed consistent and conservative formulation for mass and momentum transport in the context of simulating incompressible two-phase flows using weakly compressible methods ensures high accuracy and robustness. Furthermore, the implementation of spatially sparse grid structures, including adaptive mesh refinement and spatial hash-based sparse grids, provides an effective way to reduce the computational cost while maintaining high-fidelity simulations, making it suitable for large-scale simulations.

Chapter 1: Introduction

In order to make the best use of the increasing computing performance of modern processors, new demand on scalability is put forward for the numerical methods. In the simulation of incompressible two-phase flow, a pressure Poisson equation is required to be solved implicitly. However, iterative methods such as Jacobi, Gauss-Seidel, and SOR are known for their slow convergence rates when applied to two-phase flows with a high density contrast. To address this challenge, Krylov methods and multigrid preconditioners are used to efficiently solve the Poisson equation with variable coefficients. Despite their effectiveness, the complexity of these algorithms presents significant implementation challenges, particularly on large-scale multi-node clusters. This fact motivates researchers to turn attention to explicit methods for nearly incompressible flow. Under low Mach number and isothermal conditions, an independent pressure evolution equation can be derived and explicitly integrated over time. And its spatial discretization depends only on a local and compact stencil. The simple numerical scheme used for calculating the pressure evolution equation is flexible and can be readily applied to both unstructured and adaptive Cartesian grids. This thesis is devoted to studying weakly compressible flow simulation for violent two-phase flows with high density ratio.

Chapter 2: Weakly Compressible Navier-Stokes Solver

First, an evolving pressure projection method for numerical computations of the weakly compressible Navier-Stokes equations is proposed. Fully explicit time integration is achieved using an independent pressure evolution equation. To damp the acoustic wave in a weakly compressible fluid flow, the pressure evolution equation is iteratively computed and coupled with a projection step. Due to the simplicity and locality of this iteration procedure, it does not increase the computational amount too much. The computation is performed on a staggered Cartesian grid. By introducing the phase field model for interface capturing, this solver can be directly applied to two-phase flow simulations using a one-fluid model. Exact mass conservation is ensured by a finite-volume formulation of the conservative phase field equation. Various benchmarking problems are simulated to validate accuracy. The stability of a two-phase flow with high Reynolds number is demonstrated in a three-dimensional dam break simulation. Numerical results show that the proposed method for weakly compressible Navier-Stokes equations can prevent oscillations of pressure and velocity.

Chapter 3: Momentum Conservation for Two-phase Flow

Next, a consistent and conservative formulation for mass and momentum transport is proposed in the context of simulating incompressible two-phase flows by using weakly compressible method. Combined with the evolving pressure projection method to prevent oscillation of the solution induced by the acoustic wave, this solver aims at a robust and accurate computation of violent two-phase flows with a high density ratio, while taking advantage of fully explicit time integration of the

weakly compressible Navier-Stokes equations. Coupled with the volume of fluid method for capturing interfaces, the mass and momentum fluxes are evaluated in a consistent manner using the finite volume method. In addition, a special implementation of the pressure projection is devised to avoid velocity-pressure decoupling on a collocated grid. The momentum conserving property of the solver is demonstrated by solving realistic two-phase flow problems, including the dam break and the liquid jet simulations.

Chapter 4: Multi-GPU Scalability

Then, to address the demand for high-performance large-scale simulation of two-phase flows, the scalability and performance of two conservative weakly compressible solvers on the multi-GPU cluster are evaluated. Following the principle of consistent transport, the phase-field model and VOF method are coupled with the momentum equation, respectively. Factors affecting the performance and scalability of multi-GPU computing, including domain partitioning, communication hiding, and solver choice, are discussed and analyzed. After demonstrating the superior mesh convergence and accuracy of the conservative weakly compressible solver with PLIC-VOF and height function methods through simulations of the Rayleigh-Taylor instability and the droplet oscillation, this solver is used for largescale simulations of milk crown, dam break and liquid jet atomization problems. In these two-phase flow computations with high density ratio and high Reynolds number, high-fidelity results are presented with detailed reproduction of the complex interface structures.

Chapter 5: Spatially Sparse Grid Structure on GPU

Finally, spatially sparse grid structures including adaptive mesh refinement and spatial hash based sparse grid are implemented on GPU. The data structures are designed to have a flexible topology and efficient data access for fluid simulations. In this thesis, a parallel algorithm of tree-based block-structured adaptive mesh refinement (AMR) is developed for GPU computing, with special considerations on the memory management and conservation of interpolation for cell-centered data. Droplet splashing on thin liquid film and dam breaking on a wet bed are simulated to demonstrate the capability of the interface-adapted solver. On the other hand, sparse grid allocates a uniform grid to the region of interest. It is free of any spatial interpolation and the traversal of complex tree structure. Each block is stored as an entry in the hash table. These features make the sparse grid particularly suitable for simulation in an open domain. A numerical example of smoke simulation by using the sparse grid on GPU is presented, where the fluid flow is simply driven by the Boussinesq approximation of the buoyancy. Both AMR and sparse grid can effectively reduce the amount of grid cells for storage and computation, hence minimize the need for computing resources.

Chapter 6: Conclusions

In conclusion, this thesis presents novel weakly compressible Navier-Stokes solvers for simulating violent two-phase flows with high density ratios. The proposed methods provide high accuracy and robustness through a consistent and conservative formulation for mass and momentum transport. Among various interface capturing and curvature estimation methods, the combination of PLIC and height function exhibits the best accuracy and performance for multi-GPU computing. Moreover, the implementation of spatially adaptive and sparse grid structures reduces computational costs while maintaining high-fidelity simulations, making it promising for large-scale simulations. These contributions provide valuable insights into the simulation of complex two-phase flows and can be applied to a wide range of engineering and scientific fields.