Multiphysics simulation of fluid–structure interaction

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ABSTRACT

Fluid–structure interaction (FSI) underpins the life and locomotion of living organisms, as well as the behavior of engineering systems. It encapsulates many complex physical phenomena in the coupled dynamics of solids immersed in fluids. Simulations have been an attractive complement to studying FSI, enabling us to uncover scientific discoveries that are inaccessible via theory or experiment. However, simulating FSI is a nontrivial task. The fundamental challenge lies in how to computationally represent both solids and fluids. As solid stress is induced by strain, solids are naturally modeled in a Lagrangian framework; while fluids are often described in an Eulerian framework, given that fluid stress is induced by strain rate. In addition to this natural dichotomy in the preferred discretization framework for solids and fluids, modeling multi-body interactions or capturing the material and geometric nonlinearity in solids further complicates FSI simulations. In this thesis, we explore the development of multiphysics simulation of FSI from three perspectives: experimental, numerical, and artistic.

In Chapter 2, we examine the one-way FSI in the context of cryo-plunging experiments. We simulate plunge freezing for sample preparation in cryogenic electron microscopy and develop a computational framework to create three-dimensional (3D) "digital twins" of sample vitrification in liquid ethane. By integrating experimental protocols, adaptive mesh refinement, and parallelization, our 3D simulations provide a lens to visualize heat transfer during cryo-plunging and quantify the effects of plunging protocols on cooling rates. Validated against experimental data, this framework lays the groundwork for engineering fluid dynamics to improve cryo-vitrification.

In Chapter 3, we focus on the method development for simulating two-way FSI. We extend the lattice Boltzmann (LB) method to model finite-strain solids on one fixed Eulerian grid with the reference map technique (RMT). We introduce a new Eulerian boundary condition to model multiple moving deformable solids with different densities. The resulting LBRMT is fully explicit, and therefore suitable for parallelization. It is validated against benchmark problems and applied to simulate multi-body interactions between soft solids and fluids such as rotating and mixing. This general method offers a new computational approach to the LB community for simulating many-body FSI problems involving hundreds of deformable solids in fluids, using modest computational resources.

In Chapter 4, we explore an ancient art form, marbling, and examine how the use of thin tools to craft stable and intricate artwork on a viscosified fluid surface constitutes an intriguing FSI problem. Through a showcase of various marbling patterns, we uncover a physical explanation of the workings of marbling and the roles of interfacial tension, surfactants, and viscosity. Additionally, we introduce a basic computational framework for capturing sharp color interfaces inspired by the reference map technique.

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To my Māma and Bàba.

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