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A CUDA-Based Implementation of a Fluid-Solid Interaction Solver: The Immersed Boundary Lattice-Boltzmann Lattice-Spring Method

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Abstract. The immersed boundary lattice-Boltzmann lattice-spring method (IBLLM) has previously been implemented to solve several systems involving deformable and moving solid bodies suspended in Navier-Stokes fluids, but these studies have generally been limited in scope by a lack of computing power. In this study a Graphics Processing Unit (GPU) in CUDA Fortran is implemented to solve a variety of systems, including a flexible beam, stretching of a red blood cell (RBC), and an ellipsoid under shear flow. A series of simulations is run to validate implementation of the IBLLM and analyze computing performance. Results demonstrate that an Intel Xeon E5645 fitted with an NVIDIA Tesla K40 graphics card running on a GPU improves computational speed by a maximum of over 80-fold increase in speed when compared with the same processor running on a CPU for solving a system of moderately sized solid and fluid particles. These studies represent the first report on using a single GPU device with CUDA Fortran in the implementation of the IBLLM solver. Incorporation of a GPU while solving with the versatile IBLLM technique will expand the range of complex fluid-solid interaction (FSI) problems that can be solved in a variety of fields.

AMS subject classifications: 68U20, 74S30, 76Z99, 92C99

Key words: Lattice Boltzmann method, lattice spring model, immersed boundary method, CUDA, red blood cell, fluid-solid interaction.

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1 Introduction

Recent advances in numerical techniques have resulted in the solution of a diversity of fluid-solid interaction (FSI) problems, including problems in engineering [1,14] and biology [3–5]. Conducting experiments involving FSI has proven to be extremely challenging, and so computers have been used to simulate FSI and predict fluid dynamics and movement of the solid under flow. Computer simulation has proven particularly useful in problems involving deformable solids, including biological materials and flexible fibers, as present in the paper industry. Advantages of using computer simulations have led to rapid growth of these calculations to study FSI in the past decade.

An FSI simulation model, also known as an FSI solver, consists of three main elements: a fluid, a solid, and an interaction between the solid and fluid. Complexity of direct solution of the Navier-Stokes equations has contributed to the popularity of more straightforward solver methods, including the lattice Boltzmann method (LBM), which solves the Boltzmann equation to simulate fluid behavior. It has been previously demonstrated that the LBM is equivalent to solution of the Navier-Stokes equations for Mach numbers below 0.3 [6]. The LBM allows us to avoid solving nonlinear partial differential equations [6–14], while allowing for greatly improved efficiency when compared to the classic computational fluid dynamics (CFD) approaches such as the finite difference method (FDM) and the finite element method (FEM).

The structure of the LBM allows for seamless integration of Graphics Processing Unit (GPU) parallel computing in Compute Unified Device Architecture (CUDA). CUDA is a GPU parallel computing platform developed by NVIDIA Corporation. Due to its simplicity, CUDA has quickly gained remarkable attention and, therefore, has been widely used in CFD, particularly for solutions using the LBM. In 2008, J. Tolke and M. Krafczyk reported use of CUDA on a desktop PC to implement the LBM and obtain TeraFLOP computing speed for the first time [15]. Later, J. Habich *et al.* presented optimization approaches with D3Q19 based on J. Tolke's strategy [16]. Furthermore, many authors have studied other implementation strategies of CUDA for use in the LBM calculations [17–20]. For an FSI system with low solid concentration, the computing load is primarily occupied by solution of the fluid element. As shown in these studies, LBM calculations have been greatly accelerated due to improvements in computational power. However, when systems have a solid concentration that is very high, such as a simulation of red blood cells in blood flow where the interfaces of fluid and solids are more prevalent, FSI solvers using these methods are much slower. As a result, the efficiency of the entire solver is prohibitively limited, and there is a need for improvement of computational power to facilitate the solid and interaction elements.

In recent publications, we have presented an FSI solver, combining the LBM, lattice spring model (LSM) [21,22], and immersed boundary method (IBM) [23], called the immersed boundary lattice-Boltzmann lattice-spring method (IBLLM). The IBLLM is composed of the LBM for fluid dynamics, the LSM for solid movement, and the IBM for the