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Simulation of Turbulent Flows Using a Finite-Volume Based Lattice Boltzmann Flow Solver

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Abstract. In this study, the Lattice Boltzmann Method (LBM) is implemented through a finite-volume approach to perform 2-D, incompressible, and turbulent fluid flow analyses on structured grids. Even though the approach followed in this study necessitates more computational effort compared to the standard LBM (the so called stream and collide scheme), using the finite-volume method, the known limitations of the stream and collide scheme on lattice to be uniform and Courant-Friedrichs-Lewy (CFL) number to be one are removed. Moreover, the curved boundaries in the computational domain are handled more accurately with less effort. These improvements pave the way for the possibility of solving fluid flow problems with the LBM using coarser grids that are refined only where it is necessary and the boundary layers might be resolved better.

AMS subject classifications: 76M12, 76M28, 76D99, 76F99

Key words: Lattice Boltzmann Method, finite-volume approach, turbulent flows.

1 Introduction

The LBM is a fairly new numerical method to simulate fluid flows and can be considered as an alternative to the classical Navier-Stokes (NS) equations based methods. The LBM originated from the Lattice-Gas Automata (LGA) method which can be thought as a simple Molecular Dynamics model. The purpose of the LGA method is to simulate the behavior and interaction of particles in a gas as simple as possible [1]. For this purpose, the gas is modeled as a cluster of solid spheres moving along a uniform lattice. Each solid sphere has a discrete set of possible velocities and the collision between separate particles is handled by a set of elastic collision rules. Macroscopic quantities, such as particle

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density and velocity at each lattice node, can be computed using the microscopic quantities, making it possible to study the macroscopic behavior of a fluid flow. Even though the idea is simple, the method still provides similar solutions as the NS equations based methods do. Beyond being simple, it has the advantage of low memory requirement. The method is also highly parallelizable because of the locality of the data access pattern. However, numerically, the LGA method suffers the statistical noise caused by the averaging procedure to obtain the macroscopic properties from the microscopic properties.

To remedy the statistical noise that the LGA method suffers, the LBM was developed. Being a derivative of the LGA method, the LBM basically relies on the same idea. But, instead of handling single particles, the LBM handles particle distributions. This removes the need for averaging to obtain the macroscopic properties from the microscopic properties, so the statistical noise is also removed. Even though the LBM is more memory intensive compared to the LGA method since it is based on particle distributions that are in floating point numbers, it retains some of the advantages that LGA method has, such as being simple and having a high degree of parallelization potential. In addition to above mentioned advantages, the solution of computationally expensive Poisson equation, which is required when using NS equations based methods, is not needed when using the LBM. Also, since no pressure-velocity coupling is needed, unlike the NS equations based methods; one does not have to use complex staggered-grid systems. Furthermore, the equations solved when using the LBM are linear, so the solution time is reduced significantly since the solution procedure does not necessitate any iterative algorithm. These properties make the LBM an attractive method, and there is an increasing interest for the LBM in the Computational Fluid Dynamics (CFD) community. As a result, the progress in developing and employing the LBM is rapid. The recent applications range from multiphase flow simulations [2] to aero-acoustic simulations [3], from high resolution turbulence simulations [4] to biological flow simulations [5].

Even though the LBM in its standard form, which basically consists of streaming and collision steps, looks very attractive as mentioned above, the method is strictly restrictive about the uniformity of the computational grid. This restriction is inherited from the LGA method in which the particles modeled have to move to the next link after a time step. This shortcoming in turn dictates that the CFL number has to be equal to one. These are the major handicaps on widespread use of LBM in engineering problems. So, a lot of research has been going on to improve these aspects of LBM. One of the first efforts toward improving standard LBM is the work of He et al. [6]. In that work, an interpolation based approach is applied at every time step to obtain the distribution function at points of a non-uniform grid. Since the interpolation procedure is very time consuming and the accuracy of the method highly depends on the interpolation scheme used, this method is not very practical comparing to the standard LBM. Another approach proposed by Filippova and Hanel [7] is based on the idea of grid refinement method. With this approach, a coarser background grid is generated and a local refinement is performed in critical regions. Even though it is less complicated, an interpolation scheme is still needed for this method to transfer data from different levels of grid. The last approach, which is also