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Aeroacoustic Simulations Using Compressible Lattice Boltzmann Method

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Abstract. This paper presents a lattice Boltzmann (LB) method based study aimed at numerical simulation of aeroacoustic phenomenon in flows around a symmetric obstacle. To simulate the compressible flow accurately, a potential energy double-distribution-function (DDF) lattice Boltzmann method is used over the entire computational domain from the near to far fields. The buffer zone and absorbing boundary condition is employed to eliminate the non-physical reflecting. Through the direct numerical simulation, the flow around a circular cylinder at $Re=150$, $M=0.2$ and the flow around a NACA0012 airfoil at $Re=10000$, $M=0.8$, $\alpha=0^\circ$ are investigated. The generation and propagation of the sound produced by the vortex shedding are reappeared clearly. The obtained results increase our understanding of the characteristic features of the aeroacoustic sound.

AMS subject classifications: 65M10, 78A48

Key words: Lattice Boltzmann method, compressible flow, double-distribution-function, direct numerical simulation, aeroacoustics.

1 Introduction

Computational aeroacoustics (CAA) is a very useful way to predict the generation of noise through numerical methods. At present, there are two major categories of CAA [1, 2]. The first one is the hybrid method in which the flow field is simulated first to find the acoustic source strength of the flow and then the acoustic field is calculated in the surrounding domain. The hybrid method had a weakness that the feedback effects of sound to flow is not considered. The direct method in which the acoustic field is a natural part of the flow field has no such problem. Compared with the hybrid method, computational

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cost of the direct method is high to provide the details of sound generating mechanisms. With the development of the computer technology, the direct method has become popular [3–5].

Lattice Boltzmann (LB) method is now a very powerful tool of computational fluid dynamics (CFD). Different with the traditional Navier-Stokes equations based CFD methods, LB method is a mesoscopic approach based on kinetic theory of fluids and can bring more information of complex flow behavior [6, 7]. After the introduction of the Bhatnagar-Gross-Krook (BGK) model [8], LB method also has simpler mathematical expressions. Through the Chapman-Enskog expansion, Navier-Stokes equations can be derived from LB model [9]. Thus many scholars consider LB model as an alternative numerical scheme to solve Navier-Stokes equations. Over the past twenty years, LB method has emerged as a competitive scheme for simulating nearly incompressible flows [10]. In order to expend LB method to the simulation of compressible flow, various of compressible LB models have been proposed. In 1993, Alexander et al. [11] and Qian [12] proposed multi-speed (MS) model respectively. Yan et al. [13, 14] constructed a multi-speed and multi-energy-level model. Sun [15, 16], Shi et al. [17], Kataoka et al. [18, 19], and Watari [20] devised several models that introduced an extra energy into the definition of total internal energy. He et al. [21] proposed the first double-distribution-function (DDF) model in 1998. On this basis, Guo et al. [22] and Li et al. [23] developed a total energy DDF model and potential energy DDF model respectively.

LB method was first used to study the wave propagation by Buick et al. [24, 25]. In 2001, Haydock and Yeomans [26] investigated sound-boundary of acoustic streaming for different geometries. Since then, the studies on the application of LB method to acoustics are becoming more and more popular. The accuracy and low-dissipative capability of LB model for acoustic computations were indicated by Marié et al. [27, 28]. Xu and Sagaut [29] proposed a dispersion-relation-preserving LB model to reduce the dispersion and dissipation errors in CAA simulations. Kang et al. [30], Tsutahara et al. [31], Laffite and Pérot [32] simulated the acoustic sounds generated by uniform flow around a circular cylinder. Tamura and Tsutahara [33] calculated the noises caused by blade-vortex interaction using a finite difference LB method. A LB model with a very large eddy simulation approach was used to investigate the noise generated during the interactions between the flow and the rod-airfoil structure [34]. Kusano et al. [5] simulated airfoil self-noise using a multi-scale LB model. So far, most of the applications of LB method to CAA are low Mach number cases. For the higher Mach number flows, the ordinary LB model, which can only handle weakly compressible flows, is not available. In this paper, the potential energy DDF LB model [23] is applied to computationally investigate the aeroacoustic behavior of the transonic flow around a NACA0012 airfoil directly.

The rest of the paper is organized as follows. The compressible LB model and numerical methods are described in Section 2 and Section 3, respectively. Section 4 presents selected numerical simulations including the simulations of the low speed flow around a circular cylinder and the higher speed flows around a NACA0012 airfoil. Finally, some remarks concluded from this study are grouped in Section 5.