ARTICLE IN PRESS

Computers and Mathematics with Applications ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

journal homepage: www.elsevier.com/locate/camwa

Central-moment lattice Boltzmann schemes with fixed and moving immersed boundaries

Alessandro De Rosis *, Emmanuel Lévêque

Univ Lyon, CNRS, Laboratoire de Mécanique des Fluides et d'Acoustique, Ecole Centrale de Lyon, F-69134 Ecully cedex, France

ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 18 July 2016
Accepted 20 July 2016
Available online xxxx

Keywords:
Lattice Boltzmann scheme
Immersed boundary method
Fluid–structure interaction

ABSTRACT

Lattice Boltzmann (LB) schemes based on the relaxation of central moments have recently proved valuable in simulating flows with an improved stability with respect to the original single-relaxation-time BGK formulation, while preserving the accuracy of the latter. This has been assessed mainly for flows in simple geometries, *e.g.* in periodic domains or with fixed rigid straight boundaries. In the present study, the properties of central-moment LB schemes have been investigated against flow configurations involving arbitrarily-shaped, possibly moving, boundaries within the framework of the so-called immersed boundary (IB) method. Namely, the presence of boundaries is accounted by an external force acting on the fluid that is encompassed in the central-moment LB algorithm. Accuracy and stability issues are examined in comparison with existing results from the literature and LB simulations based on the original BGK scheme. Our results show that central-moment LB schemes accompanied by the IB method provide an efficient tool for fluid–structure interaction simulations.

© 2016 Elsevier Ltd. All rights reserved.

1. General context and motivations

The lattice Boltzmann (LB) method [1] has attracted a progressively larger interest during the last twenty years. The number of related studies has grown exponentially [2] and, nowadays, it should be recognized that it represents a meaningful approach to computational fluid dynamics. Therefore, the fluid is viewed as populations of fictitious particles that collide, re-distribute and propagate along the different links of a discrete Cartesian lattice. The LB method expresses the space-and-time evolution of these populations, from which the effective fluid dynamics can be rebuilt by summing up the different contributions. The physics of the fluid is introduced essentially through the modelling of the collision process. In this respect, the so-called BGK approximation, which refers to the relaxation (with the same rate) of all populations to their values at absolute statistical equilibrium, has been originally adopted [3]. Since macroscopic fluid dynamics is eventually sought, it is indeed assumed that most details hidden in the collision process may be disregarded and that a handier expression, retaining only the features pertaining at macroscopic scale, can be used. Within this single-relation-time approximation, the LB scheme is proved to be consistent with the Navier–Stokes equations with a second-order accuracy and third-order corrections in the Mach number. This original formulation may be considered as the *orthodox* LB approach [1,4], which has been assessed by a very large number of studies. Nevertheless, the BGK formulation suffers from numerical instability, unless the lattice spacing is dramatically reduced, related to the growing of spurious high-frequency modes when strong velocity gradients develop in the flow.

* Corresponding author.
E-mail address: alessandro.de-rosis@ec-lyon.fr (A. De Rosis).

http://dx.doi.org/10.1016/j.camwa.2016.07.025
0898-1221/© 2016 Elsevier Ltd. All rights reserved.

Please cite this article in press as: A. De Rosis, E. Lévêque, Central-moment lattice Boltzmann schemes with fixed and moving immersed boundaries, Computers and Mathematics with Applications (2016), http://dx.doi.org/10.1016/j.camwa.2016.07.025

Moment-based LB schemes rely on a map between the local set of particle populations propagating along the different links of the lattice and some resulting velocity moments. Hence, the idea is to relax the moments rather than the populations with parameters that can be chosen judiciously to damp spurious modes while ensuring the correct dynamics of physical modes [5]. The stability of this multi-relaxation-time (MRT) formulation is improved. However, since fluid dynamics is intrinsically non-linear, the arbitrary damping of some moments leads to some irreducible coupling artefacts in the dynamics of physical modes [6]. Therefore, the level of accuracy is essentially problem-dependent and requires a specific optimization for each flow configuration [7,8]; the choice of velocity moments and relaxation parameters is not unique. More recently, Geier et al. proposed to consider the relaxation of a basis of moments in the frame of reference of the moving fluid [9–11] rather than in the rest frame, as done previously. This allows us to remove the insufficient degree of Galilean invariance of previous formulations and reduces the coupling artefacts between spurious and physical modes. The velocity moments that are computed in the moving frame are called central moments.

Central-moment LB schemes offer an improved stability and promise to be an effective approach to simulate fluid flows in the regime of high Reynolds numbers (Re). This approach is also referred to as *cascaded* lattice Boltzmann method because of the pyramidal dependence of increasing-order central moments. It has been argued in [12] that the cascaded collision operator may be recast as the relaxation to some *generalized local equilibrium* in the frame at rest. Let us also mention that a variant is the factorized cascaded LB formulation [13,14], which introduces a minor correction in the collision operator in order to ensure a better stability. Very recently, a new scheme based on cumulants has been introduced as a relevant generalization in three dimensions [15]. All these schemes share the common features of considering the relaxation of central moments, *i.e.* particle-velocity moments in the frame of the moving fluid.

Systematic thorough studies have shown that central-moment schemes exhibit essentially the same level of accuracy and convergence as the original BGK formulation but outperform the limited stability of the latter [15,16]. Comparisons with the MRT approach have also been carried out, indicating a superiority of central-moment LB schemes in terms of stability and accuracy in most situations [15]. However, up to now, these properties have only been elucidated against problems involving periodic domains or rigid fixed straight walls, *e.g.* a Taylor–Green vortex in a periodic domain, a Poiseuille flow or a lid-driven cavity flow. The feasibility and performance of the method for scenarios involving arbitrarily-shaped possibly moving boundaries have not been demonstrated yet.

This paper aims at proposing a numerical method relying on central-moment LB schemes to handle flows in complex geometries. Among the possible choices for taking into account a solid boundary, the so-called immersed boundary (IB) method [17–19] has been extensively adopted within the lattice Boltzmann community and has already been used successfully in a rich variety of applications [20–23]. An attractive feature of the IB method lies in its generality, *i.e.* it applies independently of the shape of the solid body. The method can also handle deformable body [24,25]. With respect to classical interpolated bounce-back rules, the IB method leads generally to a more stable algorithm [26].

In the following, an implementation of the IB method within central-moment LB schemes is developed and tested against three canonical problems in two dimensions. Firstly, the harmonic motion of a blade in a quiescent fluid is considered and compared to literature results. Secondly, attention is paid to the flow induced by the harmonic motion of a cylinder; accuracy and stability issues are examined in details. Finally, the drag coefficient, lift coefficient and Strouhal number experienced by a cylinder in a stream flow is estimated for different values of the Reynolds number and compared with a comprehensive database. The remainder of the paper is organized as follows. In Section 2, the numerical scheme is presented with a focus on the implementation of the immersed-boundary force within the cascaded LB scheme. In Section 3, numerical results for three complementary test cases are discussed and compared with reference data from the literature and LB simulations based on the original BGK scheme. Finally, some conclusions are drawn in Section 4, and some insight about possible applications in the general context of fluid–structure interactions is given.

2. Immersed-boundary method within central-moment LB scheme

The method is introduced in two dimensions and relies on the cascaded LB scheme originally introduced by Geier [9]. The generalization to three dimensions and application to variants such the factorized central-moment LB scheme [13] or the cumulant LB scheme [15] are conceptually straightforward. Nevertheless, for the sake of clarity and facilitating extensive comparisons with existing results, the approach is here presented in two dimensions and with the original central-moment formulation.

The flow physics arises from the evolution in space and time of the so-called particle distribution functions $f_0(\boldsymbol{x}, t), \dots, f_8(\boldsymbol{x}, t)$ of particles that move respectively with velocities $\mathbf{c}_0, \dots, \mathbf{c}_8$. The D2Q9 lattice with nine possible velocities ($\mathbf{c}_0 = \mathbf{0}$) is here adopted. It is sketched in Fig. 1.

The evolution of the distribution functions $f_0, \dots, f_8$ is discretized as

$$f_j(\boldsymbol{x} + \mathbf{c}_j \Delta t, t + \Delta t) = f_j(\boldsymbol{x}, t) + \Omega_j(\boldsymbol{x}, t) + a_j S_j(\boldsymbol{x}, t) \quad \text{for } j = 0, \dots 8 \tag{1}$$

where Ω_j refers to the collision operator, $a_0 = 1/9$ and $a_{1\dots8} = 1/36$ are constant factors and S_j accounts for an external force acting on the fluid. With an abuse of notation, the dependence on the node position $\boldsymbol{x}$ and time t will be ignored in the following. In the framework of the IB method, the external force will be adjusted so as to ensure the no-slip condition on

Download English Version:

https://daneshyari.com/en/article/4958708

Download Persian Version:

https://daneshyari.com/article/4958708

Daneshyari.com