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Harmonic oscillations of laminae in non-Newtonian fluids: A lattice Boltzmann-Immersed Boundary approach

Alessandro De Rosis

Department of Agricultural Sciences (DIPSA), University of Bologna, 40127 Bologna, Italy

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A B S T R A C T

In this paper, the fluid dynamics induced by a rigid lamina undergoing harmonic oscillations in a non-Newtonian calm fluid is investigated. The fluid is modelled through the lattice Boltzmann method and the flow is assumed to be nearly incompressible. An iterative viscosity-correction based procedure is proposed to properly account for the non-Newtonian fluid feature and its accuracy is evaluated. In order to handle the mutual interaction between the lamina and the encompassing fluid, the Immersed Boundary method is adopted. A numerical campaign is performed. In particular, the effect of the non-Newtonian feature is highlighted by investigating the fluid forces acting on a harmonically oscillating lamina for different values of the Reynolds number. The findings prove that the non-Newtonian feature can drastically influence the behaviour of the fluid and, as a consequence, the forces acting upon the lamina. Several considerations are carried out on the time history of the drag coefficient and the results are used to compute the added mass through the hydrodynamic function. Moreover, the computational cost involved in the numerical simulations is discussed. Finally, two applications concerning water resources are investigated: the flow through an obstructed channel and the particle sedimentation. Present findings highlight a strong coupling between the body shape, the Reynolds number, and the flow behaviour index.

1. Introduction

An accurate prediction of the flow physics induced by the motion of solid bodies which are immersed in a viscous fluid represents an attractive and interesting challenge for scientists involved in the study of computational fluid dynamics (CFD). Moreover, a huge attention is devoted to CFD by the industrial context, since a lot of practical applications can be covered. For example, in the design of offshore platforms, the oil pipes can undergo large oscillations due to the underwater streams or an approaching storm. In aeronautics, the motion of a flapping wing can be significantly modified by a stream flow. In naval engineering, the impact between the sea waves and the ship hulls may generally generate impulsive forces, thus inducing considerable vibrations and local structural damages on the ship due to stress concentrations and fatigue phenomena. Another interesting aspect is related to the non-Newtonian fluids, whose properties are very popular especially in geophysics and hydrology [1–4]. In the last decades, the flow of a non-Newtonian fluid has received a huge attention due to its important application in petroleum industry, environmental remediation, chemical engineering and biological processes. For example, the injection of iron particles has been investigated for the remediation of aquifers [5,6]. Liquid pollutants, bitumen, greases and even slurries can filtrate through the subsurface and contaminate groundwater and underground reservoirs [7,8]. In oil industry, the oil recovery process is usually enhanced by adopting non-Newtonian fluids, as chemical additives and foams, which are often added to the injected water in order to the improve the overall stability [9–11]. Polymer solutions can be even adopted for NAPL recovery [12]. Concerning mining engineering, in low-permeability formations non-Newtonian fracturing agents are often employed [13–15]. Finally, studies on non-Newtonian fluids arose to model blood flow, biomaterials and even dental tissues, [16–19]. It is worth to remark that such kind of fluids exhibits behaviours depending on the stress acting upon these. As a consequence, if a solid body is immersed in a non-Newtonian fluid, the forces acting upon the body are strongly related to the fluid–solid mutual interaction.

As well known, the CFD numerical simulations can be performed by solving the macroscopic-based Navier–Stokes equations. Although well consolidated, such approach is affected by several drawbacks. For example, moving meshes are required if a fluid–structure interaction (FSI) problem is simulated, thus involving a huge computational effort. In opposition to this methodology, in the last decades the lattice Boltzmann (LB) method arose as a

E-mail address: alessandro.derosis@unibo.it

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powerful tool showing that it recovers the solution of the Navier–Stokes equations with a second-order accuracy [20]. The LB method solves the mesoscopic-based Boltzmann's transport equation on an Eulerian grid, which is kept fixed during the overall analysis. Such method has proved to be an effective alternative to classical CFD for solving several problems. In particular, phenomena involving multiphase flows [21–24], transport in porous media [25,26], shallow waters [27], mechanics [28–30], industrial applications [31] and even flapping wings [32,33] have been successfully modelled. Moreover, non-Newtonian fluids have been investigated [34–39], showing that the non-Newtonian feature can be accounted for by simply modifying the local viscosity via the shear rate.

In this paper, the LB method is adopted to predict the fluid dynamics induced by the harmonic motion of a rigid lamina which is immersed in a non-Newtonian fluid. An implicit strategy is developed to properly compute the shear rate-dependent viscosity and its accuracy and convergence properties are evaluated. In order to account for the presence of a solid body in the fluid lattice background, the Immersed Boundary (IB) method [40,41] is employed, following an implicit velocity-correction based strategy [42]. According to a partitioned staggered explicit coupling algorithm recently devised by the author [30], the LB and IB methods are combined within a proper strategy, whose effectiveness has been widely evaluated. Notice that the LB and IB methods have been used to solve FSI problems involving Newtonian fluids by several authors [43–46]. A numerical campaign is performed, which devotes a special attention to the dependence of the forces acting upon the solid on the non-Newtonian feature of the encompassing fluid. A transverse harmonic motion is imposed to a rigid lamina and the time history of the drag coefficient is investigated for different values of the flow behaviour index and for prescribed values of the Reynolds and Keulegan–Carpenter numbers. Moreover, the added mass experienced by the lamina is discussed by computing the hydrodynamic function according to [47]. In addition, some considerations on the involved computational effort are carried out. Finally, two applications concerning water resources are discussed. In the former, the development of the flow of a non-Newtonian fluid in a channel obstructed by a sequence of sharp-edged slats is investigated, aiming at simulating the flow in a fractured tortuous medium. In the latter, the sedimentation process of a cylindrical particle is dissected. All the tests confirm a strong dependence of the flow physics on the Reynolds number, the flow behaviour index and the body shape, as discussed.

The rest of the paper is organized as follows. In Section 2, the numerical methods are recalled and the iterative viscosity-correction based strategy is presented. In Section 3, numerical results are discussed. Finally, in Section 4 some conclusions are drawn.

2. Numerical methods

The problem is governed by the Navier–Stokes equations for an incompressible flow and viscous fluid. Specifically, such equations read as follows:

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla(p) + \nu \nabla^2 \mathbf{u}, \tag{2}$$

where $\mathbf{u}$ is the flow velocity, t is the time, ρ and p are the fluid density and pressure, respectively, and ν is the fluid kinematic viscosity. For a non-Newtonian fluid, the viscosity depends on the shear rate $\dot{\gamma}$ by the following relation,

$$\nu(\dot{\gamma}) = m\dot{\gamma}^{n-1}, \tag{3}$$

where m and n are the consistency and the flow behaviour indexes, respectively. The first index, m, relates the tangential stress to the velocity gradient. Specifically, increasing values of the tangential stress arise as m grows, for a given velocity gradient. The second index, n, leads to classify non-Newtonian fluids in two groups. The former exhibits shear thinning (or pseudoplastic) properties which arise if $n < 1$. The latter is characterized by $n > 1$ and it includes shear thickening (or dilatant) fluids, whose viscosity increases with the shear rate.

Concerning the definition of the problem, the fluid is initially at rest and the no-slip boundary condition is enforced at the fluid–solid interface. The LB and the IB methods are adopted to predict the fluid dynamics and to account for the presence of an immersed solid body, respectively. In the following, these methods are briefly recalled.

2.1. The lattice Boltzmann method for non-Newtonian fluids

The lattice Boltzmann method is adopted to predict the fluid dynamics. The two-dimensional lattice Bhatnagar–Gross–Krook equation [48] is solved on a fixed square grid and the evolution of the particle distribution functions f_i are computed by

$$f_i(\boldsymbol{x} + \Delta t\,\mathbf{c}_i, t + \Delta t) = f_i(\boldsymbol{x}, t) + \frac{1}{\tau(\boldsymbol{x})}[f_i^{eq}(\boldsymbol{x}, t) - f_i(\boldsymbol{x}, t)] \tag{4}$$

being $\boldsymbol{x}$ the position, t the time (with an abuse of notation with respect to Eq. (2)), τ the relaxation parameter and Δt the time step. The particle distribution functions are forced to move along prescribed directions i with velocities $\mathbf{c}_i$ defined as

$$\mathbf{c}_i = 0, \quad \text{if } i = 0, \tag{5}$$

$$\mathbf{c}_i = [\cos((i-1)\pi/4), \sin((i-1)\pi/4)], \quad \text{if } i = 1, 3, 5, 7, \tag{6}$$

$$\mathbf{c}_i = \sqrt{2}[\cos((i-1)\pi/4), \sin((i-1)\pi/4)], \quad \text{if } i = 2, 4, 6, 8. \tag{7}$$

The equilibrium particle distribution functions f_i^{eq} are derived in the form of a second-order expansion in the local Mach number, as described in [49]. The macroscopic fluid density ρ and the flow velocities $\boldsymbol{v}$ are computed as:

$$\rho(\boldsymbol{x}, t) = \sum_i f_i(\boldsymbol{x}, t), \quad \boldsymbol{v}(\boldsymbol{x}, t) = \frac{\sum_i f_i(\boldsymbol{x}, t)\mathbf{c}_i}{\rho(\boldsymbol{x}, t)}, \tag{8}$$

respectively. Notice that the relaxation parameter τ is strictly related to the fluid viscosity as $\nu = (\tau - 1/2)c_s^2$, being $c_s^2 = \sum w_i \mathbf{c}_i^2 = 1/3$ with w_i a set of 9 weights defined as $w_0 = 4/9$, $w_1 = w_2 = w_3 = w_4 = 1/9$ and $w_5 = w_6 = w_7 = w_8 = 1/36$ in the adopted D2Q9 model [50]. The problem is solved in lattice units, where the lattice spacing Δx and the time step Δt are set to $\Delta x = \Delta t = 1$.

In order to account for the non-Newtonian behaviour of the fluid, the viscosity (i.e. τ) should be properly modified. Specifically, a power-law model is adopted allowing to define the viscosity as a function of the shear rate $\dot{\gamma}$, i.e. Eq. (3), where $\dot{\gamma} = 2\sqrt{D_{II}}$. The second invariant D_{II} of the strain rate tensor $\boldsymbol{S}$ is computed as $D_{II} = \boldsymbol{S} : \boldsymbol{S}$. At each lattice node the strain rate tensor is readily available through the following relation,

$$\boldsymbol{S}(\boldsymbol{x}, t) = -\frac{3}{2\tau(\boldsymbol{x})}\sum_i [f_i(\boldsymbol{x}, t) - f_i^{eq}(\boldsymbol{x}, t)]\mathbf{c}_i \otimes \mathbf{c}_i. \tag{9}$$

As it is possible to observe, the problem is strictly non-linear. Specifically, the strain rate tensor $\boldsymbol{S}$ is computed through a viscosity that is different from the one computed by Eq. (3). Thus, at each lattice site $\boldsymbol{x}$ the following iterative procedure is adopted to achieve a proper value of the relaxation parameter to be used in Eq. (4):