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Numerical investigations on the vortex-induced vibration of moving square cylinder by using incompressible lattice Boltzmann method

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ABSTRACT

Vortex-induced vibrations (VIV) phenomena related to self-excited energy harvesters consisting of square cylinders have been investigated numerically by using the BGK incompressible lattice Boltzmann method. In the present work, such a harvester is placed inside a channel flow and is allowed to oscillate without a structural restoring force in a direction normal to the flow. Currently the half-way bounce-back boundary and interpolations method are being used to model the moving boundary. The numerical results of the periodical and non-periodical oscillations and the frequency content of the longitudinal and lateral forces acting on the square cross section harvester are discussed in detail. The numerical technique was validated by computing the flow around a fixed cylinder. The results are compared favorably with the results obtained by classical CFD methods.

1. Introduction

Vortex-induced vibration (VIV) is a self-sustained vibration, generally appeared in nature and in phenomena related to flag fluttering, cable swing, and tree waving in the wind. Understanding the physical mechanisms and interactions in VIV is important to several industries, such as offshore structures, bridges, submarines, heat exchangers and other applications. Recently, VIV is used in a family of energy harvesters consisting of a cantilever beam with a bluff body at its tip [1–3]. In energy harvesting, the self-sustained vibration of the oscillator is expected to be periodic for a stable energy transfer.

There are many published works in the literatures on experimental and numerical investigations of the VIV phenomena [4–11]. Due to the complex, non-linear interactions between the structural motions and the vortex-shedding [4], it is very difficult to predict the vortex-induced vibration in modeling the flow field, structural vibration and fluid–structure interaction [12]. In most of previous works the traditional CFD numerical methods are used to solve the VIV problems. Bishop and Hassan [13] studied the effect of the transverse force to the oscillation of the circular cylinder and found that a jump phase occurs when the oscillation frequency approached the shedding frequency. The so called “lock-in” phenomenon is traditionally referred to the resonance between the flow and structure [9], i.e. the frequency superposition of the Strouhal shedding and structure vibration, and it is generally associated with VIV. In addition, there always exists a frequency doubling relationship between cross-flow and in-line response under lock-in conditions [4]. Meneghini and Bearman [14] adopted a discrete vortex method incorporating viscous diffusion to simulate the flow about an oscillating circular cylinder and an asymmetric mode of shedding was observed. Vortex shedding from a transversely oscillating circular cylinder in a uniform flow has been studied by solving the two-dimensional unsteady Navier–Stokes equations with a primitive-variable formulation by Lu and Dalton [15].

Similar to above mentioned circular cylinder cases, the VIV involving square cylinder was also studied by experiments [6,7,16] and numerical simulations [10,11]. The effects of axial applied tension on the vibration properties during vortex-induced vibration of a horizontally mounted square cylinder was studied experimentally in the Reynolds number range ($Re = 1000" - "16,000$) [6]. Experiments focusing on the effects of the angle of attack, relatively to the incoming flow of a square cylinder on the cylinder’s flow-induced vibration were performed by András Nemes et al. [7]. Alam et al. [16] performed a comprehensive experimental study of the wake of two side-by-side square cylinders. The wake of the fixed square cylinder was simulated numerically by using a standard centered and second-order-accurate finite-difference scheme on a staggered Cartesian mesh to solve the incompressible, two-dimensional N–S equations [10].

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In this study, the inversion phenomenon of the vortex street and its position characteristics were discussed in detail. Generally, the cylinder oscillation is due to the alternative change of the sign of forces (i.e. lift force) due to the vortex shedding in the wake, which is dominated by the incoming flow velocity or Reynolds number. That is to say, self-sustained oscillation is related directly to the vortex shedding. Sánchez-sanz and Velazquez [11] used the mixed implicit-explicit relaxation-based pseudo-compressibility formulation to simulate the vortex-induced oscillation of a square section cylinder placed inside a two-dimensional channel flow. The oscillation modes (periodic and non-periodic) related to the mass/density ratios of the cylinder and fluid were discussed in details under a Reynolds range $Re = 50" - "200$. A detailed review of the traditional numerical simulations about the flow past a cylinder associated with VIV can be found in references [5,8,17,18].

The lattice Boltzmann method (LBM) is an effective alternative of the traditional CFD with some advantages. There are few numerical investigations on VIV by using LBM [19–21]. Breuer et al. [19] investigated the laminar flow past a fixed square cylinder by using lattice Boltzmann and finite-volume method under the Reynold number less than 300. Islam et al. [20] used incompressible lattice Boltzmann method to studied numerically a uniform flow past a fixed rectangular cylinder with different aspect ratios. Flow across a row of transversely oscillating square cylinders was simulated numerically by using the lattice Boltzmann method with a peculiar process, which means that the flow is oscillating with respect to the cylinders by avoiding the actual movement of the cylinders with respect to the computational grid [21].

In the present work, VIV phenomena of the flow around a rigid-body cylinder (oscillator) with square section moving in cross-flow direction in the channel flow were simulated numerically by using BGK incompressible lattice Boltzmann method. The half-way bounce-back boundary and interpolations method were used to process the square cylinder motion relative to the computational grid. In particular, we have investigated the flow around a square cylinder undergoing forced oscillations in a Poiseuille flow. Three different cases were considered in our investigations. First, the case of a stationary square cylinder in a Poiseuille flow was investigated with the objective to validate the numerical method; second the case of a moving square cylinder in a quiescent flow was computed to establish the self-induced vortex interaction by the motion of the cylinder in the absence of cross Poiseuille flow. Last the case of a moving square cylinder inside a Poiseuille flow was investigated and compared with existing results.

2. Numerical methods

2.1. LBM method

The lattice Boltzmann equation with Bhatnagar–Gross–Krook (BGK) single relaxation time (SRT) is used in current research

$$f_i(t+\delta_t, \mathbf{x}+\mathbf{e}_i\delta_t) = f_i(t,\mathbf{x}) + \frac{1}{\tau}(f_i^{eq}(t,\mathbf{x}) - f_i(t,\mathbf{x})),$$
$$i = 0, 1, 2 \ldots 8 \tag{1}$$

$$f_i^{eq}(f) = H_i^{eq}(\rho(f), \mathbf{u}(f))$$

Here, $f_i(t, \mathbf{x})$ is the mesoscopic variable, indicating the probability density distribution of i-component of the discretization velocity space at time t and position $\mathbf{x}$. The discrete time-step δ_t is set equal to unity as well as the lattice spacing δ_x ($\delta_t = \delta_x = 1$). The equilibrium values, H_i^{eq}, are obtained through the following:

$$H_i^{eq}(\rho, \mathbf{u}) = w_i\rho\left(1 + c_s^{-2}\mathbf{e}_i\cdot\mathbf{u} + \frac{c_s^{-4}}{2}(|\mathbf{e}_i\cdot\mathbf{u}|^2 - c_s^2\mathbf{u}^2)\right) \tag{2}$$

where, $\mathbf{u}$ and ρ is the fluid velocity and density. $\mathbf{e}_i$ is the velocity component in the lattice velocity space, which is dependent on the velocity discretization model, for D2Q9 model (as shown in Fig. 1)

$$\mathbf{e}_i = \begin{cases} 0 & \text{for } i = 0 \\ c(\cos((i-1)\pi/4), \sin((i-1)\pi/4)) & \text{for } i = 1" - "4 \\ \sqrt{2}c(\cos((i-1)\pi/4), \sin((i-1)\pi/4)) & \text{otherwise.} \end{cases}$$

Accordingly weighted parameters w_i are given as

$$w_i = \begin{cases} 4/9 & \text{for } i = 0 \\ 1/9 & \text{for } i = 1" - "4 \\ 1/36 & \text{otherwise.} \end{cases}$$

The macroscopic variables, i.e., the fluid density and momentum are

$$\rho = \Sigma_i f_i = \Sigma_i f_i^{eq}, \quad \rho\mathbf{u} = \Sigma_i \mathbf{e}_i f_i = \Sigma_i \mathbf{e}_i f_i^{eq} \tag{3}$$

And the relationship of the viscous and relaxation time is

$$\nu = (2/\zeta - 1)\delta_x \cdot c/6 \tag{4}$$

Here, $\zeta \equiv \delta_t/\tau$, $c = \delta_x/\delta_t = 1$. The pressure was obtained through the equation of state: $p = c_s^2\rho$, here c_s is the sound speed, in D2Q9 model, $c_s = c/\sqrt{3}$. That is to say the density is related to the pressure even if the flow is incompressible, i.e., the compressibility effects are embeded in LBM. To reduce or to eliminate the compressible effect, we use the He–Luo model [22], in which the equilibrium values are calculated through

$$H_i^{eq}(\rho, \mathbf{u}) = w_i\left(\rho + \rho_0\left(c_s^{-2}\mathbf{e}_i\cdot\mathbf{u} + \frac{c_s^{-4}}{2}(|\mathbf{e}_i\cdot\mathbf{u}|^2 - c_s^2\mathbf{u}^2)\right)\right) \tag{5}$$

Here, ρ_0 is the constant density. ρ is only related to pressure $p = c_s^2\rho$ and the velocity is $\rho_0\mathbf{u} = \Sigma_i\mathbf{e}_i f_i$. An additional condition must be satisfied [22],

$$|\mathbf{u}| \ll c_s, T \gg L/c_s$$

where, T and L is time and length scale of the macroscopic change, respectively.

2.2. Boundary conditions

The computational domain and boundary conditions are shown as in Fig. 2. The left boundary is velocity specified inflow boundary condition [23] with Poiseuille flow profile, and the right outflow boundary is zero-extrapolation boundary, the top and bottom boundaries are solid boundary by using the on-site bounceback boundary method. The moving boundaries of the cylinder are processed by using the interpolations method recommended by [24]. For the velocity specified boundary (in Fig. 3 a), the relationship between the populations and macrovariables are there,

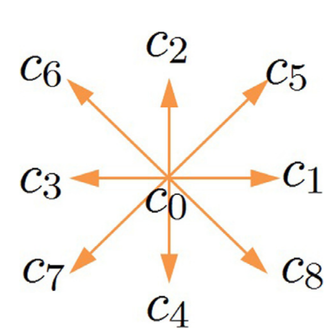

Fig. 1. Velocity components of the D2Q9 model.