



## Proposing Immersed Boundary-Lattice Boltzmann-Lattice Spring Algorithm for Simulation of 2-D Deformable Plate in Steady Flow

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**ABSTRACT:** An immersed boundary-lattice Boltzmann method along with a lattice spring configuration is proposed. Fluid-solid interaction was accounted for by an additional force density in the lattice Boltzmann equation enhanced with the split-forcing approach. To analyze deformation of a flexible body, a robust lattice spring model is implemented. In this way, solid body is considered by collection of linear springs which are connected regularly inside the body. To reduce instabilities and limitation in selection of lattice spring length and time step, for the first time, we extended an implicit approach based on lattice Boltzmann-lattice spring method. Finally, flow and solid solvers are respectively validated by simulation of flow over a rigid plate and deformation of cantilever beam under axial and bending forces. Then, a deformable plate which is fixed in the middle is simulated. Results are also compared with the results of COMSOL's software which show accuracy of the presented hybrid method. It is also shown that decreasing of the rigidity of the plate causes reduction of drag coefficient and retardation in initiation of the unsteady conditions.

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Thin plate  
Critical Reynolds number

### 1- Introduction

Deformable objects immersed in viscous fluid occur in different problems such as motion of Red Blood Cells (RBCs) [1] and interactions between heart leaflets and body fluid in biological systems [2].

There are different models for simulating the deformable body motion under the influence of viscous flow with some success. For example, Buxton et al. [3] simulated breathing-mode behavior of elastic shell that is filled by fluid using combination of Lattice Boltzmann and Lattice spring model. Aidun [4] also applied External Body Force method (EBF) – Lattice Boltzmann Method (LBM) joined with Lattice Spring configuration (LSM) to track RBCs deformation suspended in fluids. They simulated 120 deformable RBCs at 47% volume fraction that led to significant changes of the effective viscosity of the suspension at a constant shear rate. In the hybrid models that are noted above, the fluid and solid motion are separately evaluated, whereas there are conventional approaches that solve two-phase flows, concurrently [2]. Combination of Lattice Boltzmann and Immersed Boundary method (IB) has significant advantage for solving the Fluid Structure Interaction (FSI) problems, which was first attempted by Feng and Michaelides [5]. Mohd-Yusof [6] introduced a new type of IB method that does not require choosing arbitrary parameters and forcing terms. In this approach (so-called direct-forcing method), a forcing term is added to the discretized equations that implicitly imposes the non-slip boundary condition in the immersed boundary method. In this study, a suitable immersed boundary-Lattice Boltzmann method along with

a robust Lattice spring arrangement has been developed and used to simulate the behavior of deformable vertical plate in a laminar cross-flow. To solve the flow field, the split forcing LBM is implemented to increase the numerical accuracy.

### 2- Numerical methods

In this study, the immersed boundary-lattice Boltzmann method based on the split forcing scheme with a robust lattice spring model is developed for simulation of flow around deformable bodies. The present immersed boundary method relies on a direct momentum forcing [7]. The force is distributed on the Eulerian nodes (in the fluid domain) by a simple interpolation based on the four point diffuse delta functions. Using this approach, the required boundary conditions on the Lagrangian nodes at the boundary of the deformable immersed body are satisfied. To compute the deformation of solid body due to the boundary forces, a set of springs inside the body is used. The deformed configuration of the elastic body at each time step is generated by the movements of spring links. The solid elastic body is modeled by a collection of 2D Square network as shown in Fig. 1.

A general formulation for deformation of the elastic body is also suggested in the present model in which the position of the LSM nodes (inside the body) can be updated implicitly at each time step:

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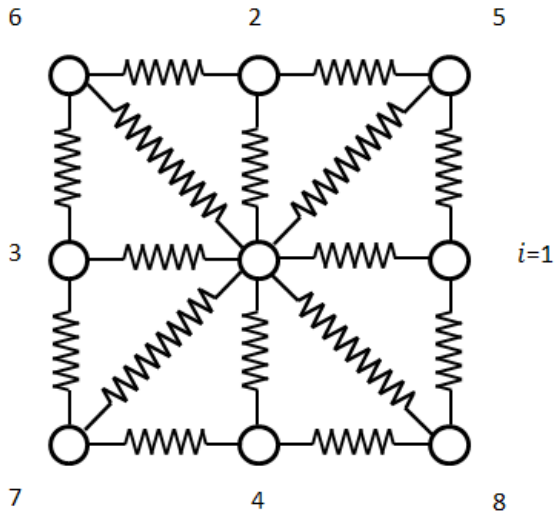


Figure 1. Two-dimensional square lattice

$$\vec{r}_i = \frac{1}{4} \left( \frac{\vec{F}_{ij}^{ext} + \vec{F}_{ij}^{boundary}}{k_n + k_{n-n}} + \frac{k_n}{k_n + k_{n-n}} \sum_{j=1}^4 \frac{a_0}{|\vec{r}_{ij}|} \vec{r}_{ij} + \frac{k_{n-n}}{k_n + k_{n-n}} \sum_{j=5}^8 \frac{\sqrt{2}a_0}{|\vec{r}_{ij}|} \vec{r}_{ij} \right) \quad (1)$$

### 3- Validation and Results

IB-LB method is validated by comparing of drag coefficients of a flat plate with earlier works [8, 9] in Fig. 2. It was found that for low Reynolds numbers ( $Re < 50$ ) and when the middle of the plate is fixed, reducing the capillary number led to a decrease in the drag coefficient as shown in Fig. 3. In the present case, since the thin plate is perpendicular to the flow direction, the projected area is reduced. Therefore, the total drag is reduced with decreasing the capillary numbers.

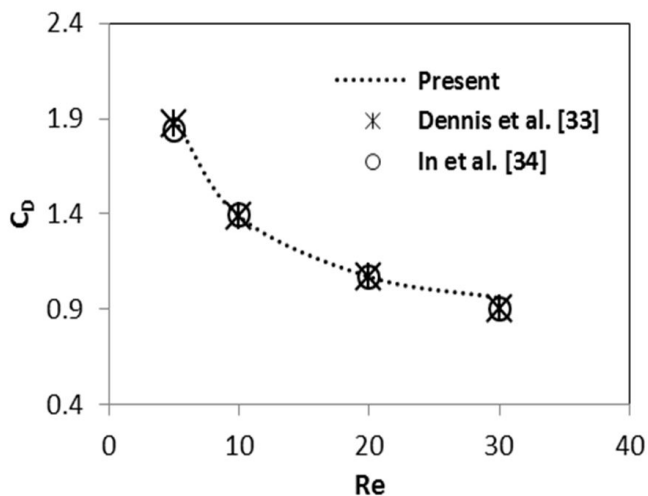


Figure 2. Drag coefficient vs Reynolds number

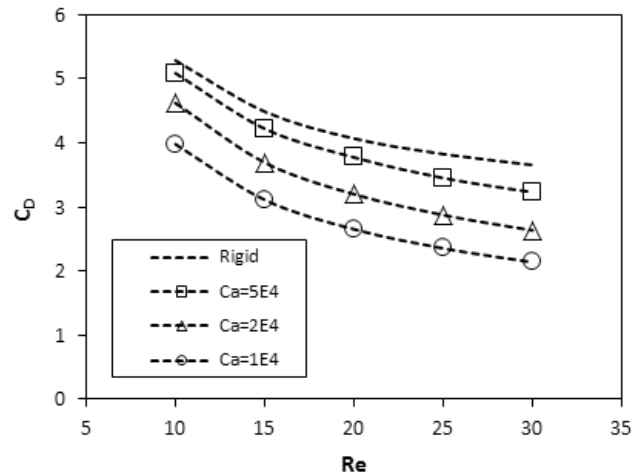
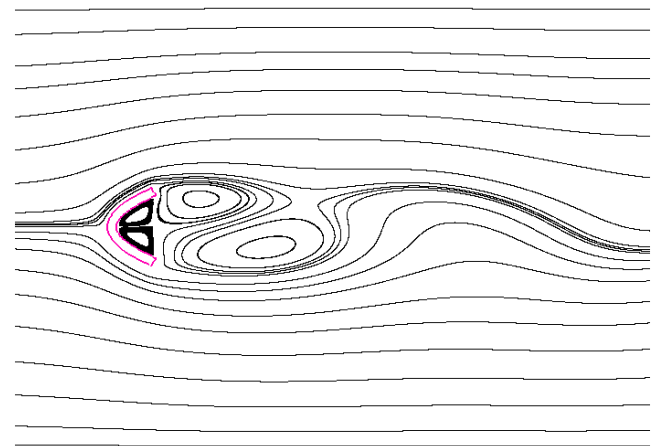
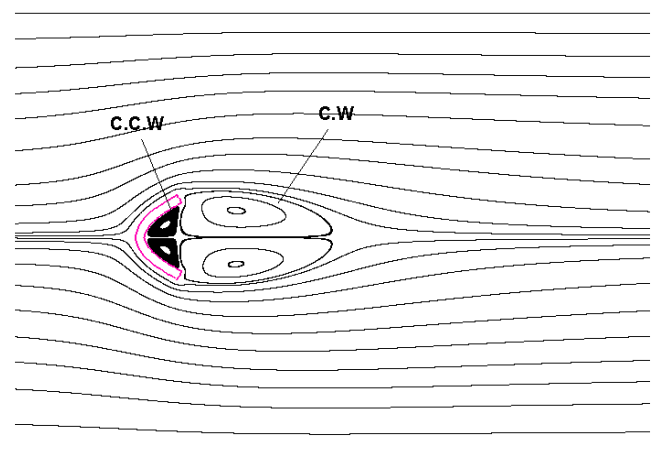


Figure 3. The variations of drag coefficient with Reynolds number for different capillary numbers

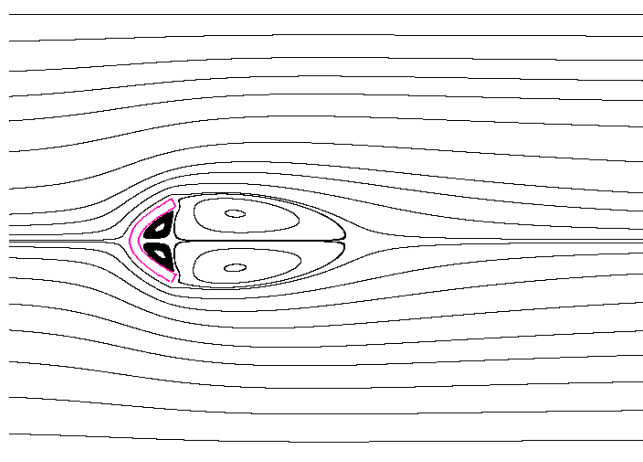
Also in Fig. 4, patterns of flow have been demonstrated. It is obvious that by increasing Reynolds number of flow in a constant Capillary number, deformation of plate increase. Consequently, increase in plate deformation length lead to some fluctuations behind the plate.



(a)



(b)



(c)

**Figure 4. stream line of flow over a flexible plate in Capillary number of 10000 and Reynolds number of (a) 30, (b) 35 and (c) 50.**

#### 4- Conclusion

An immersed boundary-lattice Boltzmann method along with a robust lattice spring configuration for modeling fluid-elastic body interactions was developed. To include the effects of viscous flow forces on the deformation of a flexible body, rotational invariant springs were connected regularly inside the deformable body through the square lattices. Fluid-solid interaction was accounted for by an additional force density in the Lattice-Boltzmann equation enhanced with the split-forcing approach. The accuracy of the proposed method is checked by solving several test cases including steady cross flow around a deformable vertical plate. It is shown that reduction in capillary number leads to a delay in the beginning of the unsteady conditions.

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