A Numerical Approach to Investigate the Influence of Deformable Blockages on Blood Flow in an Elastic Vessel

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Abstract

In this work, we presented a new numerical approach to study the deformation of blockages and fluid properties in an elastic blood vessel. In computational hemodynamics, only few of the current numerical models considered the elasticity of vessels, and those models were difficult to extend to other topics like the deformation of blockages in elastic blood vessels. In addition, the approach that we employed is especially effective on visualization. A validation for the present method is carried out by comparing the simulation results with a theoretical prediction of the deformation of the pulmonary blood vessel in a steady flow. Subsequently, the method is applied to study the relationship between the fluid properties and the deformation of blockages.

Introduction

Last decade, cardiovascular diseases were the major causes of death for both males and females in the world [1]. Since experimental studies are relatively difficult, computational fluid dynamics (CFD) for modeling cardiovascular system has become an innovative and popular field [2]. A lattice Boltzmann method (LBM) is a modern approach in CFD and two reasons have explained its high efficiency. First, the LBM solved the Boltzmann equation to obtain fluid behaviors. In other words, it avoided solving the nonlinear Navier-Stokes equations directly [3]. Secondly, the architecture of the LBM is particularly suitable for GPU parallel computing. However, most researchers still use the traditional finite element method or finite difference method in hemodynamics when the elasticity of vessels is considered. Only a few authors used the LBM to deal with blood flows in an elastic pulmonary artery. For example, Fang et al. [4], Descovich et al. [5], and Leitner [6] presented some numerical results of the deformation of vessel walls by using the LBM, and their predictions for the deformation were based on a given pressure-radius relationship [8]. Consequently, their methods cannot be extended to the other deformable objects such as carotid plaques because the vessel walls do not have any structure in their models. In order to overcome the drawback, the lattice spring model (LSM) is employed to provide structures to the solid bodies such as vessels and blockages. Besides, the lattice Boltzmann method is used to capture blood behavior, and the immersed-boundary method (IBM) is applied to couple the LBM and LSM. Hence, the purpose of this work is to demonstrate that the method is able to handle a variety of deformable solid bodies and elastic blood vessels, which proves that this method is suitable for simulations of hemodynamics.

Acknowledgment

The authors acknowledge travel support from US National Science Foundation to attend ICMMES-2015, held in CSRC, Beijing, July 20 — 24, under the Grant CBET-1549614. Tai-Hsien Wu also appreciates the scholarship from the Graduate College in Western Michigan University, which helps him to finish this work. The authors also acknowledge the use of computer cluster in the Center for Advanced Vehicle Design and Simulation, Western Michigan University.

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Methods

In this method, the **lattice Boltzmann method**[1] is used to capture fluid behavior, and the **lattice spring model**[2] is employed to mimic the deformation of the blood vessel and blockages while the **immersed-boundary method**[3] is applied to deal with the fluid-solid interaction.

[1]Lattice Boltzmann method (LBM):

Lattice Boltzmann method is a relatively new computational fluid dynamics method. In this method, fluid domain is represented by a series of regularly arranged nodes and each node has several particle distribution functions (see Figure 1). All macroscopic fluid properties such as fluid densities, velocities, and pressures can be derived from the distribution functions. Moreover, the architecture of the LBM is particularly suitable for GPU parallel computing which is a promising technology in the follow decades.

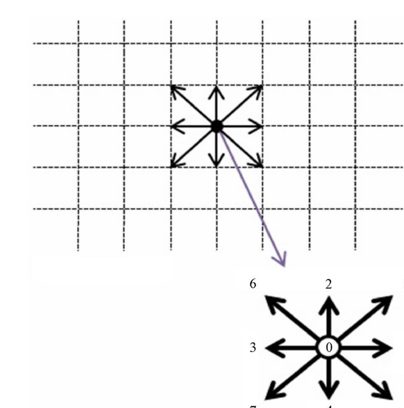

Figure 1. In LBM, a fluid domain is represented by a series of regularly arranged nodes and each node has several distribution functions. The sketch is an example that presents a node would has 9 distribution functions in 9 directions. Also, the macroscopic fluid properties can be calculated from the distribution functions.

[2]Lattice spring model (LSM):

The lattice spring model uses plenty of particles to represent a solid body like a vessel. Harmonic spring and angular bonding potential energies exist between the two neighboring particles and the two adjacent springs, respectively. Once both potential energies have been calculated on a solid particle, the elastic force can be evaluated to update the position and velocity of the solid particle. Since every solid particle has different positions and velocities, the movement and deformation of entire solid body can be expressed.

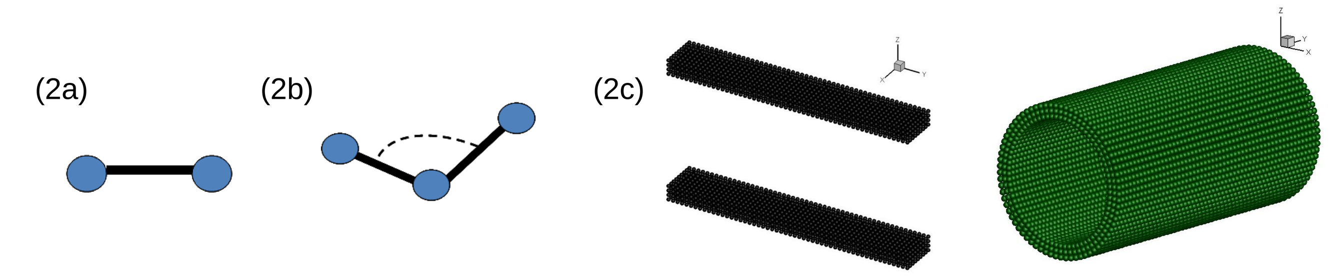

Figure 2. (2a) A bond potential energy exists between two nodes. (2b) An angular bonding potential energy exists between two bonds. (2c) An advantage of the LSM is that the solid bodies can be easily constructed in any shapes.

[3]Immersed-boundary method (IBM):

Since the fluid nodes are Eulerian points, a solid particle (Lagrangian point) may not coincide with its adjacent fluid node. There are three steps in the IBM to deal with the fluid-solid interaction.

Step 1. The discrete Dirac delta function is used to extrapolate a fluid velocity from the fluid nodes surrounding the solid particle.

Step 2. The interaction forces can be calculated based on the non-slip boundary condition.

Step 3. The discrete Dirac delta function is used again to distribute the interaction forces to the fluid nodes.

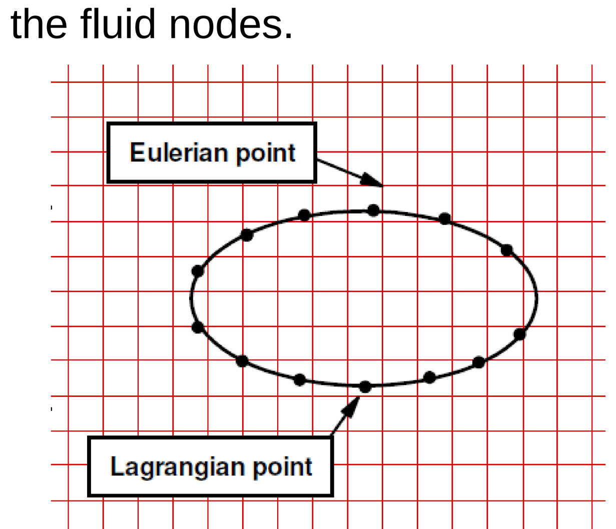

Figure 3. An Eulerian point represents a fluid node whereas a Lagrangian point represents a solid particle. In general, the immersed-boundary method can be utilized to deal with the fluid-solid interaction, which means combining the LBM and LSM.

Results

Validation:

To validate the present method, a fluid flow in an elastic pulmonary blood vessel is simulated. The flow is driven by a pressure gradient, and the width D (see Figure 4) of the elastic vessel is reduced in the downstream due to a pressure drop and deformation of the vessel walls. The comparison between the simulation and the theory results is given in Figure 4, where the red line and blue circles represent the analytical and simulation results respectively.

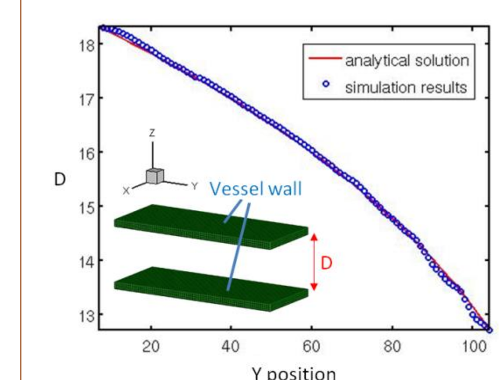

Figure 4: The comparison between the analytical solution (red line) and the simulation results (blue circles) in pulmonary blood vessel. A sketch is also given to describe the simulation geometry and to define the width in the simulation.

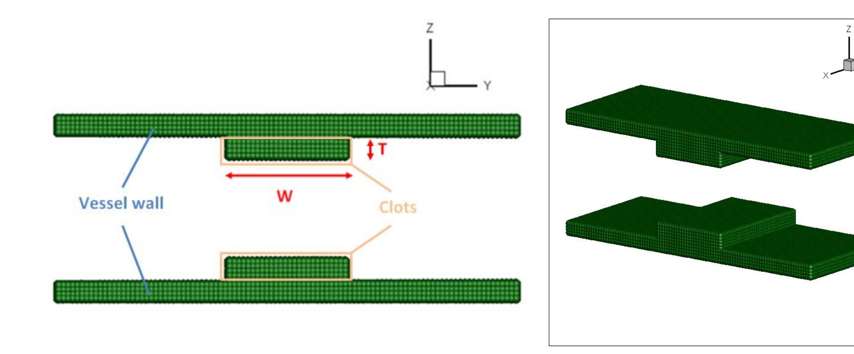

Figure 5: A sketch is to defined the thickness T and the width W of the blockages in YZ-plane.

Elastic vessel with blockages:

Both of the deformation of blockages (see Figures 6 and 7) and the influence of blockages in an elastic blood vessel on fluid properties (see Figures 8 and 9) are investigated by using the validated method. In the simulations, the stenosis of the blockages is varied in three different degrees: 18:2% (case 1), 36:4% (case 2), and 54:6% (case 3).

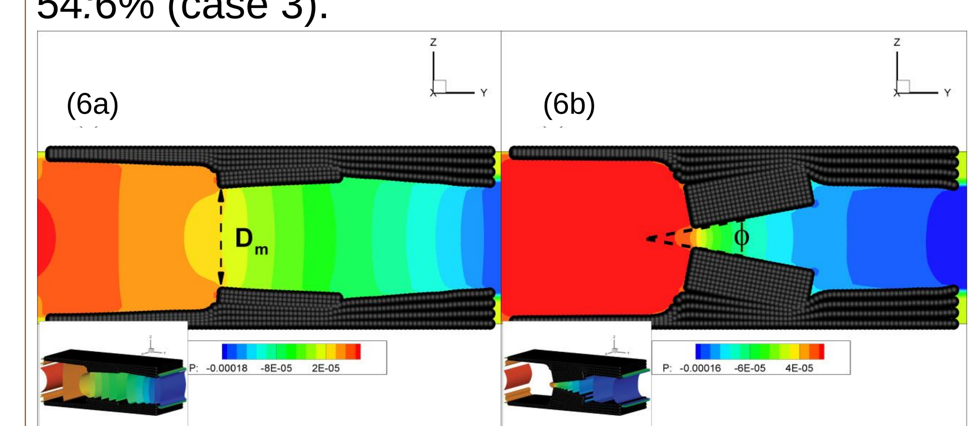

Figure 6. The black particles represent the vessel and blockages. It shows that the gap became more narrow as the blockage thickness increases due to a large deformation. The minimum gap distance D_m is defined in (6a), and the inclined angle ϕ is defined in (6b).

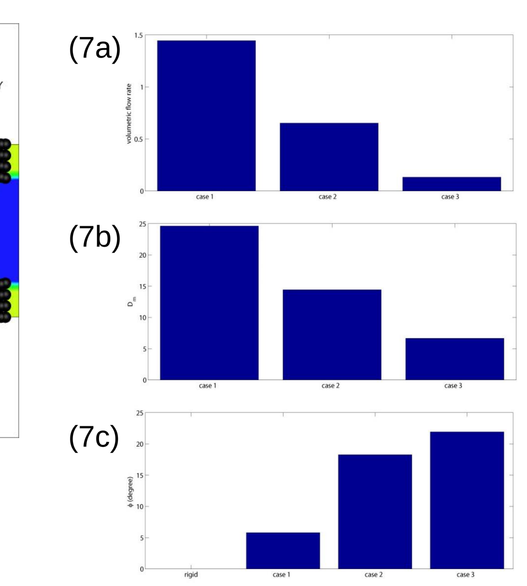

Figure 7. (7a) The minimum distances D_m, (7b) The inclined or rotation angle ϕ, (7c) The comparing blood flow rates among cases 1, 2, and 3.

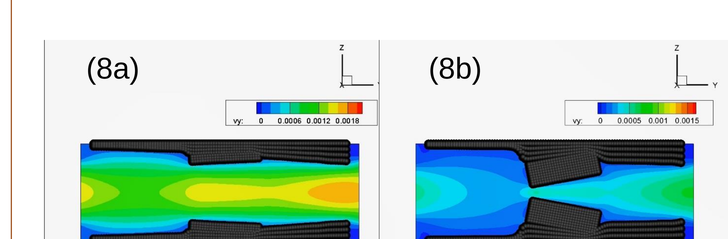

Figure 8. The velocity in Y-direction at steady state for (8a) case 1 and (8b) case 3.

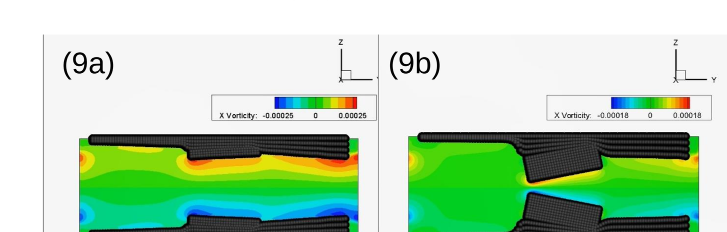

Figure 9. The vortices in X-direction at steady state for (9a) case 1 and (9b) case 3.

Conclusion

In this work, the lattice-Boltzmann lattice-spring method (LBLSM) is reported to simulate the deformation of blockages in an elastic blood vessel. The method is validated by comparing the simulation results with the theory of radiuses of a pulmonary blood vessel. Subsequently, the method is applied to model the fluid properties when the thickness of blockages is varied at three different levels. It is found that the top and the bottom blockages are rotated in two opposite directions and expanded to the vessel central area. In conclusion, as the thickness increases, the left gap between the top and the bottom blockages, fluid velocity, and flow rate decrease, and the inclined angles of blockages increase. Therefore, the results indicated that the deformation of blockages enhances the resistant of fluid flowing.