ON THE DEVELOPMENT OF A GPU-BASED IMPLICIT FORCING IMMERSED BOUNDARY METHOD FOR SIMULATING FLUID FLOW PAST A SOLID BODY

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Abstract. In this research, the simulated fluid flow using the newly proposed implicit forcing immersed boundary (IFIB) method is not seem to penetrate the solid. By using the method of the weighted averaging, one can properly simulate the effect of the no-slip condition near the solid body. Therefore, the IFIB method can be properly applied to simlute the flowfield near the solid body with a higher accuracy.

1 INTRODUCTION

In this work, a new implicit forcing immersed boundary (IFIB) method is proposed to deal with the problem involving complex stationary/moving bodies or complex flow domains. The main difference between the IFIB method and other immersed boundary (IB) methods [1, 2] is that in the IFIB method, the forcing term and the pressure term will be coupled and solved repeatedly. Therefore, the velocity field will satisfy the velocity boundary condition and the continuity equation. Moreover, with the use of the IFIB method, the fluid flow will not penetrate the solid region so that the velocity inside the body is precisely equal to zero. The newly proposed IFIB method can be applied to simulate the velocity of the fluid flow in complex boundary. Moreover, the IFIB method is highly data independent. Therefore, one can exploit the power of the GPU to accelerate computing. In this study, the GPU accelerated IFIB method will be combined with the previously proposed multiple GPU accelerated IMLE method to simulate fluid flow in complex physical domain.

2 NUMERICAL METHODS

After the three dimensional velocities u^* within the computational domain are computed by the IMLE method [3], the IFIB method will be applied to correct flow field inside and near the solid body. To apply the IFIB method in computational domain, the cells will be first divided into three parts which are the solid cell, the fluid cell, and the interface cell. The cell which is entirely located inside the solid boundary is the solid cell, while the cell which is situated wholly outside the solid boundary is the fluid cell. The interface cell is the cell containing only part of the solid body.

The main equation in the IFIB method is

$$\mathbf{u}^{n+1} = \mathbf{u}^* - \frac{\Delta t}{\rho}\nabla p^{n+1} + \Delta t \mathbf{f}^{\,n+1}$$

To make sure the velocity field satisfies the continuity equation, a modified pressure Poisson equation (MPPE) will be applied which leads to

$$\frac{\rho}{\Delta t}\nabla \cdot \mathbf{u}^* = \nabla^2 p^{n+1} - \rho \nabla \cdot \mathbf{f}^{\,n+1}$$

Besides, in solid cells, the velocity boundary condition will be used to correct the velocity within the body by means of

$$\mathbf{u}^{n+1}_{body} = \mathbf{u}^* - \frac{\Delta t}{\rho}\nabla p^{n+1} + \Delta t \mathbf{f}^{\,i-1}$$

After getting the solutions in solid and the fluid cells, in the interface cell, the weighted averaging procedure $\mathbf{u}^i = (1-\phi)\mathbf{u}_{fluid} + \phi \mathbf{u}_{solid}$ is adopted to compute the velocity of the interface cell. However, the velocity of the $\mathbf{u}_{fluid}$ near the solid may not satisfy the velocity boundary condition. An iterative algorithm will be used to correct the velocity near the boundary. The proposed iterative algorithm is summarized in Algorithm 1

3 ALGORITHM

Algorithm 1 Algorithm of the IMLE-IFIB method

1: $\mathbf{u}^* = \mathbf{u}^n + \Delta t \nu \nabla^2 \mathbf{u}^2$
2: $\mathbf{r}^* = \mathbf{r}^n + \Delta t \mathbf{u}^*$
3: MLS interpolation: $\mathbf{u}^*_{particle} \to \mathbf{u}^*_{grid}$
4: $f^0 = f^n, i = 0$
5: **loop**
6: i = i + 1
7: Solve $\nabla^2 p^i = \frac{\rho}{\Delta t} \nabla \cdot \mathbf{u}^* + \rho \nabla \cdot \mathbf{f}^{\,i-1}$
8: $\mathbf{u}^{**} = \mathbf{u}^* - \frac{\Delta t}{\rho} \nabla p^i + \Delta t \mathbf{f}^{\,i-1}$
9: $\mathbf{u}^i = (1 - \omega_{IFIB}\phi)\mathbf{u}^{**} + \omega_{IFIB}\phi \mathbf{u}^{n+1}_{body}$
10: $\delta \mathbf{f}^{\,i} = \frac{\mathbf{u}^i - \mathbf{u}^{**}}{\Delta t} = \omega_{IFIB}\phi \frac{\mathbf{u}^{n+1}_{body} - \mathbf{u}^{**}}{\Delta t}$
11: $\mathbf{f}^{\,i} = \mathbf{f}^{\,i-1} + \delta \mathbf{f}^{\,i}$
12: **if** $||\mathbf{u}^i - \mathbf{u}^{i-1}|| < \varepsilon_{IFIB}$ and $||p^i - p^{i-1}|| < \varepsilon_{IFIB}$ and $||\mathbf{f}^{\,i} - \mathbf{f}^{\,i-1}|| < \varepsilon_{IFIB}$ **then**
13: $\mathbf{u}^{n+1} = \mathbf{u}^i$, $p^{n+1} = p^i$, $\mathbf{f}^{\,n+1} = \mathbf{f}^{\,i}$,exit
14: **end if**
15: **end loop**

Note that lines 1-3 account for the IMLE method which is used to simulate the flow within the boundary. Lines 5-15 describe the IFIB iterative method. It is worth to note that in this study, the simulation is mainly focused on the stationary solid problem, u^{n+1}_{body} equals 0. Therefore, line 9 can be modified as $\mathbf{u}^i = (1 - \omega_{IFIB}\phi)\mathbf{u}^{**}$ and line 10 is $\delta \mathbf{f}^{\,i} = \omega_{IFIB}\phi \frac{-\mathbf{u}^{**}}{\Delta t}$.

4 RESULTS

In the validation study, a classical benchmark problem for an uniform flow past a stationary cylinder is conducted. With the use of the newly proposed IFIB method, it is possible to get zero velocity within the solid body, as shown in figure 1.

It is worth to note that the streamlines near the solid body are slightly different using the IB method and the IFIB method. The difference is due to the velocity in the body cell that can approach zero in the IFIB method and the velocity of the interface cell is calculated by means of weighted averaging. Therefore, the results simulated by IFIB method are much more accurate than those by the IB method.

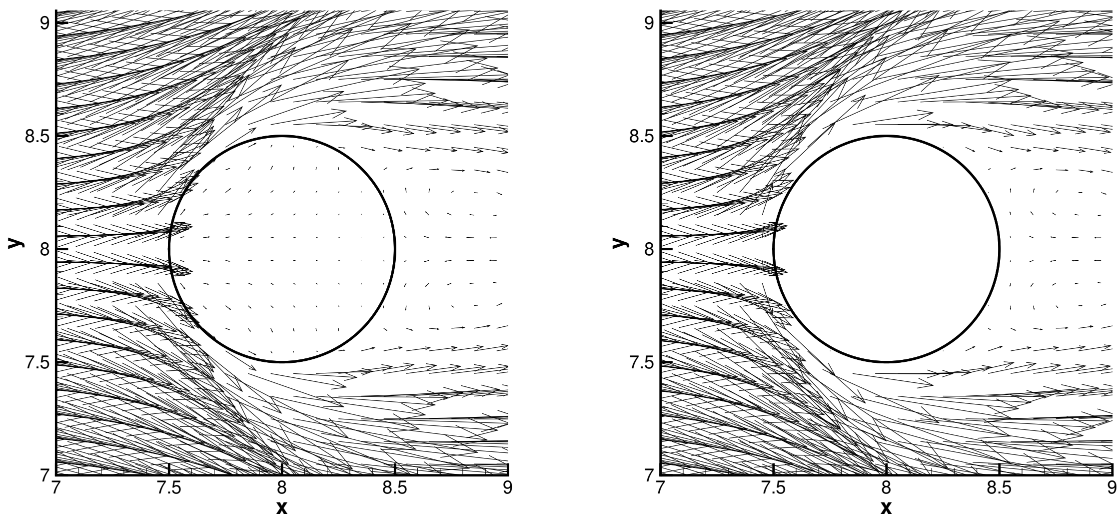

Figure 1: The simulated streamlines and velocity vectors for the case of Re = 20. The left figure is obtained from the IB method and the right figure is obtained from the IFIB method

5 SUMMARY

Due to the zero velocity within the body cell, the IFIB method can more accurately simulate the interface cell. Besides, the execution of the IFIB method is highly data independent. Therefore, the proposed method can be parallelized and the computer code can be executed in multiple GPUs.

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