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An Immersed Boundary Method Based on Volume Fraction

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Abstract

The immersed boundary method(IBM) was rapid developed in recent years, because of the ability for the complex configurations and moving bodies simulations. Most of the research on the IBM were focused on the low Mach number flow, few researchers applied this method to the high Mach number flow problems. A new IB method developed in current paper, which applied the volume fraction to get the cut cell average variables. The values of the variables in the cells that located in the body was determined by the ghost cell method, and the value located in the flow field were gained by power law interpolation. The cases that transonic flow round airfoil and Ma 1.3 shock wave cross wedge were simulated, which showed that the new method could captured the shock wave, expansion wave, shock-vortex interaction, shock reflection, and this method is suitable for the high-speed flow problems.

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Keywords: Immersed Boundary Method; Power-law interpolation; Volume fraction; Direct forcing method

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1. Introduction

Researchers paid more and more attention to the unsteady flow that affected by the moving boundary. The numerical method for the moving boundary problems became an important direction in CFD research and application. The method which based on the non-body conformal grid, such as the immersed boundary (IB) method[1]-[4], Cartesian grid method[5],[6] , begin to expose their tremendous potential for moving boundary numerical simulations.

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The immersed boundary method was introduced by Peskin[0] for blood flow simulation. There are two key factors that affect the IB method, one is how to get the force term, and the other is how to disperse the force near the wall. During the early stage of the IB method, researcher used the continuous force approach[0] or feedback force method[0] to gain the analytic force term, then distributed the volume force to the boundary by distributed functions. The bottleneck of these kinds of method was the numerical stability, especially for the rigid body flowfield simulation. The discrete forcing method that developed by Yusof[4], which derive the forcing from the numerical solution, accelerated the development of the IB method. To gain the discrete forcing term, the flow variables in the cells near the boundary should be interpolated form cells nearby. The bilinear interpolating method (trilinear interpolation for 3D)was the most common method for the low-speed flow problems. The boundary layer velocity profile in the cases that with low mach number or low Reynolds number flow was nearly linear, which made the bilinear(trilinear) interpolation widely used in the IB method for these cases. Choi et al.[8] suggested the power-law interpolation for the turbulent boundary layer simulation, and the second-order tangential velocity correction was also used. Keistler[0] extended the method to the supersonic flow simulation, which is one of the few studies on the supersonic IB method.

Some researchers ranked the Cartesian grid method to the IB method, because most of the IB methods were based on the Cartesian grid. The regular Cartesian grid method, such as ghost cells method, cut-cell method, could not avoid the complex treatment for the cells splitting or combination, which prevented the Cartesian grid method development in the cases with complex configurations.

The method developed in current paper combined the Choi's power-law interpolation and the ghost cell method, and used the volume fraction to compute the variable average value located in the cut cells. The transonic airfoil cases and the diffraction of a Ma 1.3 shock wave past a wedge case were employed for the method test. The result showed that the method could capture flow details, such as the shock wave, expansion wave, the shock-vortex interaction, shock reflection. This method could be easily applied to any complex configurations, and could extended to 3D case or dynamic process simulation expediently.

2. Numerical Method

2.1. Governing equation

The integral form 2D N-S equation, which considered the volume force, could be written as follow:

$$\iiint \frac{\partial}{\partial t}\mathbf{W}d\Omega + \iiint \nabla \mathbf{F} d\Omega = \iiint \left(\nabla \mathbf{F}_v + \rho f\right) d\Omega \tag{1}$$

Where:

$$\mathbf{W} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \mathbf{F} = \begin{bmatrix} \rho u & \rho v \\ \rho u^2 + p & \rho v u \\ \rho u v & \rho v^2 + p \\ u(e+p) & v(e+p) \end{bmatrix}, \mathbf{F}_v = \begin{bmatrix} 0 & 0 \\ \tau_{xx} & \tau_{xy} \\ \tau_{xy} & \tau_{yy} \\ \varphi_x & \varphi_y \end{bmatrix} \tag{2}$$

$$\tau_{x_i x_j} = \mu\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] + \lambda \frac{\partial u_k}{\partial x_k}\delta_{ij}, \qquad \varphi_{x_i} = -q_{x_i} + u_j \tau_{x_i x_j} \tag{3}$$

The variable ρ, p, e, T and k stand for density, static pressure, internal energy, temperature and heat conduction coefficient.; u, v are the Cartesian components of the velocity vector $\vec{\mathbf{V}}$. The heat conduction term q_{x_i} equal to $-k\,\partial T/\partial x_i$, and the dynamic viscosity is given by Surtherland equation.