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A Variable Correction-Based Immersed Boundary Method for Compressible Flows over Stationary and Moving Bodies

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Abstract. In this paper, a variable correction-based immersed boundary method (IBM) for simulating viscous compressible flows over stationary and moving bodies is presented. It is the extension of the implicit velocity correction-based IBM proposed by Wu and Shu (J. Comput. Phys., 228 (2009), pp. 1963–1979). Since the incompressible flow was studied in their work, only the fluid velocity field was needed to be corrected by enforcing the no-slip boundary condition. But for compressible flow problems, other flow variables around the boundary also should be corrected or updated. To simulate the flow field without the effect of immersed boundary firstly, the open source code OpenFOAM is utilized in this work. After performing the velocity correction then, the density is corrected by resolving the continuity equation with the corrected fluid velocity. After that, the temperature surrounding the boundary is corrected from the given temperature condition, which is similar to the velocity correction. Finally, the pressure is updated by using the corrected density and temperature through the equation of state. In such way, all the flow variables have been corrected and the given physical boundary conditions can be accurately implemented. To validate the proposed method, the flows over a stationary circular cylinder, a stationary airfoil and a transversely oscillating circular cylinder at different Mach and Reynolds numbers are simulated. Compared to the results in the literature, good agreement can be achieved. To further illustrate the potential of current method for dealing with com-

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plex problems, the flow over a rotating cylinder in front of a stationary cylinder is also simulated.

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1 Introduction

Phenomena of flows over bodies can be frequently observed in engineering applications [1]. Examples include the movement of aircraft and high-speed train in the air. In computational fluid dynamics, conventional techniques need to use the body-fitted mesh to discretize the computational region, and then the boundary conditions are directly implemented. However, mesh generation for configurations with complex geometry is still one of the most difficult jobs. Additionally, even a body with simple geometric shape performing simple motion also requires dynamic mesh, and it would consume more computing time because the mesh has to change every updating time. To overcome the drawback of body-fitted mesh methods, the use of non-body-fitted mesh methods is a reasonable choice. Among them, a special technique is the so-called immersed boundary method (IBM), which was firstly proposed by Peskin [2] to simulate the blood flow in the heart. The advantage of IBM is that the fixed Cartesian (Eulerian) mesh is applied to discretize the computational domain, and any complex objects could be represented by a series of Lagrangian points. As a result, no more body-fitted mesh or dynamic mesh is required.

Following the pioneer work of Peskin, some improvements of IBM have been made. For example, Glowinski et al. [3] proposed a Lagrangian multiplier based fictitious-domain method for simulation of particulate flows. Cheny and Botella [4] developed a variant of IBM in which the boundary was represented by the level-set function. Goldstein et al. [5] came up with a virtual boundary method, which applied the feedback forcing computed directly from fluid and boundary velocities to represent the effect of solid body. Obviously, computing the force term is the critical issue in the IBM. A penalty method was firstly proposed by Peskin [2], which was related to the spring parameters. Fadlun et al. [6] developed a direct forcing method, in which the force term was computed at boundary nodes. Moreover, a momentum exchange scheme, which was based on the lattice Boltzmann method, was proposed by Niu et al. [7] to calculate the body force. Recently, an implicit velocity correction-based IBM was presented by Wu and Shu [8]. In this method, the body force was set as unknown and could be computed after the velocity correction. This idea was also adopted by Constant et al. [9] in the platform of OpenFOAM. It should be noted that the information communication between Eulerian mesh and Lagrangian points in these IBM methods is completed by using the delta