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Fluid-Structure Interaction Simulation of Heart Valve Flows by a Hybrid Immersed-Boundary/ Body-Fitted-Grid Method

Jingyang Wang[1], Chunhua Zhou[1,*] and Zhendong Xu[1,2]

[1] *Department of Aerodynamics, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, China*
[2] *Shanghai Electro-Mechanical Engineering Institute, Shanghai 201109, China*

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Abstract. In this paper, a hybrid Immersed-Boundary/Body-Fitted-Grid method is extended to simulate the complex fluid-structure-interaction (FSI) problems involved in the flows through a bileaflet mechanical heart valve (BMHV). The background grid is discretized with a body-fitted gird while the freely-rotating leaflets are treated by an immersed boundary method named the local domain-free-discretization (DFD) method. For simulation of turbulence involved in BMHV flows, the wall-modelled large eddy simulation is implemented in the DFD framework. In order to address the instability issue associated with low-mass structures, the strong coupling (SC) strategy is employed. To accelerate the convergence of SC-FSI sub-iteration, we adopt the under-relaxion scheme with an optimal relaxion coefficient and Hamming's 4th-order predictor-corrector scheme. To validate the SC schemes for low-mass structures, numerical experiments on the vortex induced vibration of an elastically mounted cylinder are carried out. Finally, the present method is applied to simulate and investigate the pulsatile flows through a BMHV at physiologic conditions, in which complex fluid-structure interactions are involved. The computed results agree well with the published numerical or experimental data.

AMS subject classifications: 74F10, 76F65

Key words: Fluid-structure interaction, immersed boundary method, body-fitted-grid method, heart valve flows, large eddy simulation.

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1 Introduction

Native heart valves need to be replaced with prosthetic valves when encountering with congenital birth defects or disease. Bileaflet mechanical heart valve (BMHV) is one of

*Corresponding author.
Email: chzhou@nuaa.edu.cn (C. Zhou)

the most popular prosthetic valve designs. Both native valves and prosthetic valves operate under a very complex flow environment. Heart valve flow is driven by pulsating pressure gradient. The resulting flow phenomena involve transition to turbulence, subsequent relaminarization and fluid-structure interaction. For simplicity, some studies ignore the effects of fluid-structure interaction (FSI) and the leaflet motion are prescribed by the experimental measurements [1–5]. The numerical study of heart valve flows still faces great challenges, especially when the blood-leaflet FSI is considered.

The techniques handling the moving boundaries in FSI problems available for the current numerical simulation of the heart valve flows can be classified into two categories: moving grid methods and fixed grid methods. Traditional moving grid methods [6,7] are more accurate in the prediction of cardiac mechanics and the flow field near the blood-leaflet interface. But they are computational expensive due to the displacement and deformation of mesh at each time step and frequent remeshing must also be conducted to ensure a well-conditioned mesh. The fixed grid methods, such as the immersed boundary (IB) methods, solve moving-boundary problems on a fixed grid. Therefore, they behave well in computational efficiency and can robustly handle the large displacements or deformations of the valve leaflets.

The IB methods have been widely applied in the simulation of heart valve flows [8–10]. Peskin and McQueen [11–14] proposed the classical IB method to study blood flow through elastic leaflets. In the classical IB method, the sharp blood-leaflet interface is absent and the effect of moving leaflets is transmitted to blood through a body forcing term. To account for the effect of the moving structure boundary as a sharp interface and the consequent structural force, various sharp interface methods have been proposed. Yang et al. [15] used a sharp-interface IB method to simulate the pulsatile flow through a BMHV implanted in the simplified straight aorta, in which both the aorta and the valve are immersed in a Cartesian grid. Ge et al. proposed a Curvilinear immersed boundary (CURVIB) method [16], which combines an IB method with a curvilinear body-fitted grid (BFG). This method has been successfully applied to subsequent numerical investigations of BMHV flows [5, 8, 17, 18] and bioprosthetic-valve flows [9, 19], where the stationary boundaries are treated by the BFG method. Transformation from physical space to computational space is needed in the CURVIB method due to the employment of finite difference discretization. Using a sharp-interface IB method, Tullio et al. [10] conducted a direct numerical simulation BMHV flows with a realistic geometry of the aortic root and investigated the production and spatial distribution of shear stresses in the flow field.

The strategies for solving FSI problems can be categorized into the partitioned coupling approach and the monolithic coupling approach. The partitioned coupling approach, served as the most widely adopted FSI algorithm, has two separate fluid and structure solvers. The separate solvers are coupled in time to achieve kinematic and dynamic equilibrium at the interface. According to the coupling strategies (explicit or implicit), there exist loose coupling (LC) and strong coupling (SC). LC-FSI often experiences stability and robustness difficulties because of its explicit nature, especially for the low-mass structures. As analyzed by Borazjani et al. [5], the instability of LC-FSI is