Cheng, Yongguang; Zhang, Hui

Immersed boundary method and lattice Boltzmann method coupled FSI simulation of mitral leaflet flow. (English) Zbl 1242.76372

Comput. Fluids 39, No. 5, 871-881 (2010).

Summary: Coupling the immersed boundary (IB) method and the lattice Boltzmann (LB) method might be a promising approach to simulate fluid-structure interaction (FSI) problems with flexible structures and moving boundaries. To investigate the possibility for future IB-LB coupled simulations of the heart flow dynamics, an IB-LB coupling scheme suitable for rapid boundary motion and large pressure gradient FSI is proposed, and the mitral valve jet flow considering the interaction of leaflets and fluid is simulated. After analyzing the respective concepts, formulae and advantages of the IB and LB methods, we first explain the coupling strategy and detailed implementation procedures, and then verify the effectiveness and second-order accuracy of the scheme by simulating a benchmark case, the relaxation of a stretched membrane immersed in fluid. After that, the diastolic filling jet flow between mitral leaflets in a simplified 2D left heart model is simulated. The model consists of the simplified transmitral passage of the heart and two curvilinear leaflets. In the simulation, the atrial and ventricular pressure histories of normal human are specified as boundary conditions, and the leaflets are treated as fibers that interact with the fluid to define their deformations and movements. The resulting opening and closing movements of the leaflets and the flow patterns of the filling jet are qualitatively reasonable and compare well with existing numerical and measured data. It is shown that this IB-LB coupling method is feasible for treating flexible boundary FSI problems with rapid boundary motion and large pressure gradient, the results of the mitral leaflet flow are valuable for understanding the transmitral FSI dynamics, and it is possible to simulate the more realistic 3D heart flow by the scheme in the future.

MSC:

76Z05 Physiological flows
76M28 Particle methods and lattice-gas methods
76M25 Other numerical methods (fluid mechanics) (MSC2010)
92C10 Biomechanics
74F10 Fluid-solid interactions (including aero- and hydro-elasticity, porosity, etc.)

Keywords:

lattice Boltzmann method; immersed boundary method; fluid; structure interaction; mitral leaflet flow; coupling

Full Text: DOI

References:

[1] Peskin CS. Flow patterns around heart valves: a digital computer method for solving the equations of motion, vol. 378. PhD thesis, Albert Einstein College of Medicine; Univ. Microfilms; 1972. p. 72-102.

[2] Peskin, C.S.; McQueen, D.M., ()

[3] McQueen, D.M.; Peskin, C.S., A three-dimensional computer model of the human heart for studying cardiac fluid dynamics, Comp graph, 34, 56-60, (2000)

[4] Lemmon, J.D.; Yoganathan, A.P., Three-dimensional computational model of left heart diastolic function with fluid – structure interaction, J biomech eng, 122, 109-117, (2000)

[5] Lemmon, J.D.; Yoganathan, A.P., Computational modeling of left heart diastolic function: examination of ventricular dysfunction, J biomech eng, 122, 297-303, (2000)

[6] Miller, L.A.; Peskin, C.S., When vortices stick: an aerodynamic transition in tiny insect flight, J exp biol, 207, 3073-3088, (2004)

[7] Mitta R, Dong H, Bozkurttas M, Loebbecke A. Analysis of flying and swimming in nature using an immersed boundary method. In: 36th AIAA fluid dynamics conference and exhibit, San Francisco, California; 2006.

[8] Fauci, L.J.; Peskin, C.S., A computational model of aquatic animal locomotion, J comp phys, 77, 85-108, (1988) · Zbl

0641.76140

[9] Zhu, L.D.; Peskin, C.S., Simulation of a flapping flexible filament in a flowing soap film by the immersed boundary method, J comp phys, 179, 452-468, (2002) · Zbl 1130.76406

[10] Zhu LD. An immersed boundary method by the lattice Boltzmann approach in three dimensions. In: The sixth international conference on mesoscopic methods in engineering and science, Guangzhou, China; July 2009.

[11] Zhang, J.; Johnson, P.C.; Popel, A.S., An immersed boundary lattice Boltzmann approach to simulate deformable liquid capsules and its application to microscopic blood flows, Phys biol, 4, 285-295, (2007)

[12] Zhang, J.; Johnson, P.C.; Popel, A.S., Red blood cell aggregation and dissociation in shear flows simulated by lattice Boltzmann method, J biomech, 41, 47-55, (2008)

[13] Dillon, R.; Fauei, L.J.; Fogelson, A.L.; Gaver, D., Modeling biofilm processes using the immersed boundary method, J comp phys, 129, 57-73, (1996) · Zbl 0867.76100

[14] Kim, Y.; Peskin, C.S., 2-D parachute simulation by the immersed boundary method, SIAM J sci comp, 28, 2294-2312, (2006) · Zbl 1126.76043

[15] Kim, Y.; Peskin, C.S., 3-D parachute simulation by the immersed boundary method, Comp fluids, 38, 1080-1090, (2009) · Zbl 1242.76242

[16] Peskin, C.S., The immersed boundary method, Acta numer, 11, 479-517, (2002) · Zbl 1123.74309

[17] Chen, S.; Doolen, G.D., Lattice Boltzmann method for fluid flows, Annu rev fluid mech, 30, 329-364, (1998) · Zbl 1398.76180

[18] Zheng, H.W.; Shu, C.; Chew, Y.T., A lattice Boltzmann model for multiphase flows with large density ratio, J comp phys, 218, 353-371, (2006) · Zbl 1158.76419

[19] Pan, C.X.; Luo, L.S.; Miller, C.T., An evaluation of lattice Boltzmann schemes for porous medium flow simulation, Comp fluids, 35, 898-909, (2006) · Zbl 1177.76323

[20] Chen, S.; Chen, H.D.; Martinez, D.; Matthaeus, W., Lattice Boltzmann model for simulation of magnetohydrodynamics, Phys rev lett, 67, 3776-3779, (1991)

[21] Aidun, C.K.; Lu, Y.N., Lattice Boltzmann simulation of solid particles suspended in fluid, J stat phys, 81, 49-61, (1995) · Zbl 1106.82342

[22] Zhang, R.; Shan, X.; Chen, H., Efficient kinetic method for fluid simulation beyond the navier – stokes equation, Phys rev E, 74, 046703, (2006)

[23] Gan, Y.B.; Xu, A.G.; Zhang, G.C.; Yu, X.J.; Li, Y., Two-dimensional lattice Boltzmann model for compressible flows with high Mach number, Physica A, 387, 1721-1732, (2008)

[24] Feng, Z.G.; Michaelides, E.E., The immersed boundary-lattice Boltzmann method for solving fluid – particles interaction problems, J comp phys, 195, 602-628, (2004) · Zbl 1115.76395

[25] Peng, Y.; Shu, C., Application of multi-block approach in the immersed boundary-lattice Boltzmann method for viscous fluid flows, J comp phys, 218, 460-478, (2006) · Zbl 1161.76552

[26] Shu, C.; Liu, N.; Chew, Y.T., A novel immersed boundary velocity correction – lattice Boltzmann method and its application to simulate flow past a circular cylinder, J comp phys, 226, 1607-1622, (2007) · Zbl 1173.76395

[27] Dupuis, A.; Chatelain, P.; Koumoutsakos, P., An immersed boundary-lattice Boltzmann method for the simulation of the flow past an impulsively started cylinder, J comp phys, 227, 4486-4498, (2008) · Zbl 1136.76041

[28] Niu, X.D.; Shu, C.; Chew, Y.T.; Peng, Y., A momentum exchange-based immersed boundary-lattice Boltzmann method for simulating incompressible viscous flows, Phys lett A, 354, 173-182, (2006) · Zbl 1181.76111

[29] Cheng, Y.G.; Li, J.P., Introducing unsteady non-uniform source terms into the lattice Boltzmann model, Int J num meth fluids, 56, 629-641, (2008) · Zbl 1130.76061

[30] Peskin, C.S.; Printz, B.F., Improved volume conservation in the computation of flows with immersed elastic boundaries, J comp phys, 105, 33-46, (1993) · Zbl 0762.92011

[31] Lee, L.; LeVeque, R.J., An immersed interface method for incompressible navier – stokes equations, SIAM J sci comp, 25, 832-856, (2003) · Zbl 1163.65322

[32] Xu, S.; Wang, Z.J., An immersed interface method for simulating the interaction of a fluid with moving boundaries, J comp phys, 216;454-493, (2006) · Zbl 1220.76058

[33] Oertel, H., Prandtl's essentials of fluid mechanics, (2004), Springer Press New York

[34] Courtois, M.; Kovacs, S.J.; Ludbrook, P.A., Transmitral pressure – flow velocity relation: importance of regional pressure gradients in the left ventricle during diastole, Circulation, 78, 661-671, (1988)

[35] Ebbers, T.; Wigstroem, L.; Bolger, A.F.; Wranne, B.; Karlsson, M., Noninvasive measurement of time-varying three-dimensional relative pressure fields within the human heart, J biomech eng, 124, 288-293, (2002)

[36] Saber, N.R.; Wood, N.B.; Gosman, A.D.; Merrifield, R.D.; Yang, G.Z.; Charrier, C.L., Progress towards patient-specific computational flow modeling of the left heart via combination of magnetic resonance imaging with computational fluid dynamics, Ann biomed eng, 31, 1, 42-52, (2003)

[37] Nakamura, M.; Wada, S.; Mikami, T.; Kitabatake, A.; Karino, T., Computational study on the evolution of an intraventricular vortical flow during early diastole for the interpretation of color M-mode Doppler echocardiograms, Biomech model mechanobiol, 2, 59-72, (2003)

[38] Jacob, M.J.; Pernille, T.A., Evaluation of a 2D model of the left side of the human heart against magnetic resonance velocity mapping, Cardiovasc eng, 1, 2, 59-76, (2001)

[39] McQueen, D.M.; Peskin, C.S.; Yellin, E.L., Fluid dynamics of the mitral valve physiological aspects of a mathematical model, Am J physiol, 242, H1095-H1110, (1982)

[40] Watton, P.; Luo, X.; Wang, X.; Bernacca, G.; Molloy, P.; Wheatley, D., Dynamic modelling of prosthetic chorded mitral valves using the immersed boundary method, J biomech, 40, 3, 613-626, (2007)

[41] d'Humires, D.; Ginzburg, I.; Krafczyk, M.; Lallemand, P.; Luo, L.S., Multiple-relaxation-time lattice Boltzmann models in three dimensions, Philos trans roy soc A, 360, 437-451, (2002) · Zbl 1001.76081

[42] Newren EP. Enhancing the immersed boundary method: stability, volume conservation and implicit solvers. PhD dissertation of the University of Utah, USA; 2007.

[43] Mittal, R.; Iaccarino, G., Immersed boundary methods, Annu rev fluid mech, 37, 226-239, (2003)

[44] Griffith, B.E.; Peskin, C.S., On the order of accuracy of the immersed boundary method: higher order convergence rates for sufficiently smooth problems, J comp phys, 208, 75-105, (2005) · Zbl 1115.76386

[45] Le, G.; Zhang, J., Boundary slip from the immersed boundary lattice Boltzmann models, Phys rev E, 79, 2, 026701, (2009)

[46] Lallemand, P.; Luo, L.S., Theory of the lattice Boltzmann method: dispersion, dissipation, isotropy, Galilean invariance, and stability, Phys rev E, 61, 6, 6546-6562, (2000)

