NUMERICAL SIMULATION OF FLUID-STRCTURE INTERACTIONS WITH A DIRECT-FORCING FICTITIOUS DOMAIN METHOD

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Summary A direct-forcing fictitious domain method is proposed for the simulation of the interactions between fluids and flexible bodies, as an improved version of the Distributed-Lagrange-Multiplier based Fictitious Domain method previously proposed by Yu [J. Comput. Phys. 207 (2005), 1-27]. Firstly, it is demonstrated that the Lagrange multiplier problem can be more efficiently solved with a direct-forcing scheme instead of the original Uzawa iterations without the sacrifice of the accuracy. The type of the interpolation function (i.e. smoothed delta function) for the transfer of the quantities between the Eulerian and Lagragian frames is shown not to affect the results significantly. Secondly, the accuracy of the code is verified via test problems. Thirdly, the new fictitious domain method is applied to various problems, including the passive propulsion of a flexible foil in the wake of a D-section cylinder, the flapping of a 3D flexible plate in a uniform flow, and the deformation of tri-leaflets at opening stage.

INTRODUCTION

Numerical simulation of interactions between fluids and flexible bodies with large deformation is a computationally challenging problem. Various methods for the simulations of fluid-structure interactions have been proposed in the literature. They can be classified into two types: the boundary-fitted methods and the non-boundary-fitted methods, according to whether the mesh is fitted to the boundary of the solid body or not. The boundary-fitted methods such as the arbitrary Lagrangian Eulerian (ALE) finite element method[1] are the traditional methods and better suited to the small or moderate deformation problems, whereas, the non-boundary-fitted methods such as the immersed boundary method[2] and the fictitious domain method[3,4] are better suited to the large deformation problems. For the non-boundary fitted method, the no-slip velocity condition needs to be satisfied on the fluid-structure interface or in the solid domain. In the immersed boundary method and the fictitious domain method mentioned above, a pseudo body force is introduced for this purpose. An important feature of the pseudo-body-force based methods is that the hydrodynamic force on the solid boundary is not required to determine the motion of the solid. For the body-force based methods, the time scheme for the no-slip condition can be different. In the traditional immersed boundary method of Peskin [2], the flexible body moves at the same velocity as the local fluid, and then affects the fluid motion through an elastic force (i.e. the pseudo body force) that is calculated with the known deformation of the body. By contrast, in the DLM/FD method, the no-slip velocity constraint is imposed as an equation for the Lagrange multiplier, and the fluid and solid velocities are obtained simultaneously. Baaijens solved the coupled system with the fully implicit scheme[3]. Yu decoupled the original system into the fluid, solid and Lagrange multiplier sub-problems with the fractional step scheme[4], following the DLM/FD time scheme for the rigid body problem[5]. The resulting Lagrange multiplier sub-problem was solved the Uzawa iteration. It was shown that a non-iterative scheme for this sub-problem is the same as the direct-forcing scheme previously used in the immersed boundary method for the rigid boundary problem[6].The direct-forcing scheme was also proposed in the earlier version of Yu[4], but not reported in the published version. Shi and Phan-Thien[7] later used the direct-forcing scheme for the fluid/flexible-body interactions. In the present study, we demonstrate that the direct-forcing scheme is as accurate as the Uzawa iterative scheme. The main aim of this study is to present a 3D direct-forcing fictitious domain method for the fluid/flexible-body interactions.

PRINCIPLE of FICTITIOUS DOMAIN METHOD

Yu[4] extended the FD formulation of Glowsinki et al.[5] for the rigid particles to the case of flexible bodies. The key idea for the method is that the interior of the solid is assumed to be filled with the fluid and the fictitious fluid is constrained to move at the same velocity with the solid by a pseudo body force (i.e. Lagrange multiplier). The reader is referred to Yu[4] for the detailed derivation of the FD formulation. Due to the page limitation, the description of the numerical scheme is not presented here. The reader is referred to Yu & Shao[6] for the direct-forcing scheme for the rigid body problem.

VALIDATION OF DIRECT-FORCING SCHEME

The direct-forcing scheme is simpler than the Uzawa iterations for the Lagrange multiplier problem. We first examine whether the direct-forcing scheme is equally accurate as the Uzawa iterations. The test problem is the flapping of a 2D plate in a uniform flow. The characteristic velocity is the mainstream velocity, and the characteristic length is the plate length. The computation domain is a rectangular domain with the length of 4 and the width of 1. The aspect ratio of the plate is 40. The control parameters are: (Re, $\overline{G}$, ρ_r) =(500, 125,11). The *y*-positions of the free end of the flapping plate

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obtained with the Uzawa iterations and direct-forcing scheme are compared in Fig. 1. The two results agree excellent with each other, indicating that the direct-forcing scheme is as accurate as the Uzawa iterative scheme. In addition, Fig. 1 shows that the results from the bi-linear function and the 4-point smoothed delta function do not differ significantly, although the agreement is not as good as the one between the direct-forcing scheme and Uzawa iterations. We use the direct-forcing scheme and the tri-linear function for our 3D code.

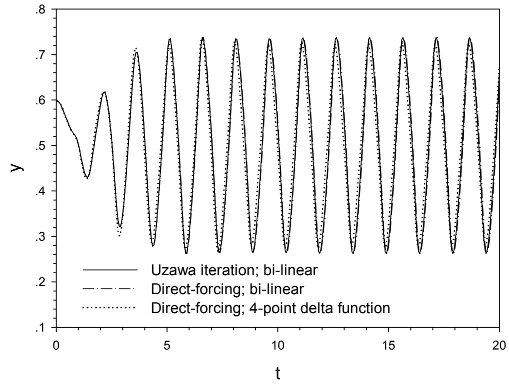

Fig. 1 The *y*-positions of the free end of a 2D flapping plate in a uniform flow obtained with the Uzawa iterations and direct-forcing scheme.

NUMERICAL RESULTS ON THE OPENING OF TRI-LEAFLETS

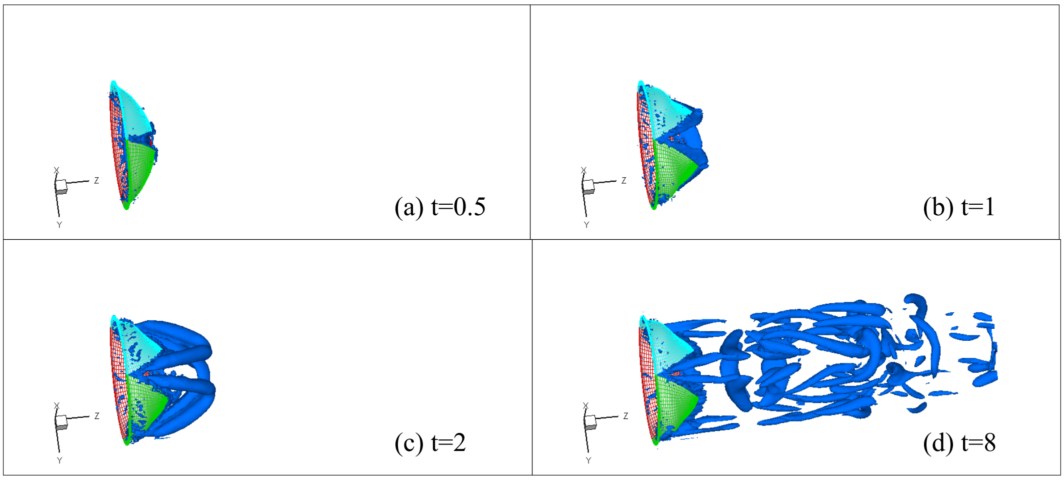

Fig. 2 Snapshots of the vortex structures for the flow over three flexible leaflets in a pipe. (Re, $\overline{G}$, ρ_r, R/h) =(500, 50,1,50).

The interactions between three leaflets and fluids in a pipe at opening stage are simulated with our method. The undisturbed Poiseuille flow is imposed on the inlet of the pipe. We take the maximum velocity at the tube axis and the radius of the pipe as the characteristic velocity and length, respectively. The aspect ratio of the leaflet (i.e. the ratio of the radius and the thickness of the plate) is set to be 50. Fig. 2 shows the vortex structures at different times for Re=500. When the leaflets stop opening at time being around 1, the vortex sheets begin to emanate from the edges of the leaflets. The strong hair-pin vortices subsequently form in the wake and develop into streamwise vortices. At stable state, a pair of weak streamwise vortices exist between the neighboring leaflets, and there are more smaller scale vortices, compared to the initial opening stage. Other numerical tests and applications are not shown here due to page limitations.

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