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An Improved Immersed Boundary Method with New Forcing Point Searching Scheme for Simulation of Bodies in Free Surface Flows

Bin Yan[1], Wei Bai[2,*] and Ser Tong Quek[1]

[1] *Department of Civil and Environmental Engineering, National University of Singapore, Kent Ridge, Singapore 117576, Singapore.*
[2] *School of Computing, Mathematics and Digital Technology, Manchester Metropolitan University, Chester Street, Manchester M1 5GD, UK.*

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Abstract. An improved immersed boundary method is proposed and applied to simulate fluid-structure interactions by combining a level set method for free water surface capturing. An efficient Navier-Stokes equation solver adopting the fractional step method at a staggered Cartesian grid system is used to solve the incompressible fluid motion. A new efficient algorithm to search forcing points near the immersed body boundary is developed. The searching schemes for forcing points located both inside and outside the solid phase with the linear interpolation schemes for the determination of velocities at forcing points are presented and compared via the case of dam break over obstacles. The accuracy and effectiveness of the proposed forcing point searching schemes are further demonstrated by the study of wave propagation over a submerged bar and more challenging cases of wedge with prescribed velocity or falling freely into the water. By the extensive comparison of present numerical results with other experimental and numerical data, it suggests that the present improved immersed boundary method with the new forcing point searching scheme has a better performance and is very promising due to its accuracy, efficiency and ease of implementation. Furthermore, the present numerical results show that the outside forcing scheme is superior over the inside forcing scheme.

AMS subject classifications: 65, 76

Key words: Immersed boundary method, level set method, forcing point searching scheme, dam break, free fall wedge.

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*Corresponding author. *Email addresses:* `w.bai@mmu.ac.uk` (W. Bai), `binyan@u.nus.edu` (B. Yan), `ceeqst@nus.edu.sg` (S. T. Quek)

1 Introduction

Fluid-structure interaction (FSI) is a classical hydrodynamic problem and has a wide range of applications in many ocean and coastal engineering problems. Numerical simulations gain its popularities to handle the FSI problems. However, numerical simulation of fluid-structure interactions is extremely complicated, especially when involving moving objects with irregular boundaries and complex free surface evolutions. With the rapid advance in computing technology, more researchers and engineers have paid extensive attentions to the development of efficient numerical methods to study fluid-structure interactions. Traditionally, the problems can be solved by the boundary-fitted method [25, 26], which generates the curvilinear structured or unstructured grids conforming to the body boundary. However, grid regeneration is entailed with a heavy cost in computational time as well as manpower. The drawback of the method due to its inapplicability to the multi-grid acceleration solver is also obvious.

Over the last few decades, Immersed Boundary Method (IBM) becomes increasingly popular among the numerical methods to simulate bodies in fluid domain. It introduces a body force to the momentum equations at certain points in the domain, without the necessity of performing the mapping procedures, aiming to simulate the effect of the investigated body in the flow. As a result, generation of grids is greatly simplified. The immersed boundary method was firstly proposed by [19], based on which [8, 20] introduced a feedback forcing mechanism to enforce the desired boundary condition at the immersed boundary. It can be implemented into an existing Navier-Stokes solver with relative ease due to its advantage of being formulated relatively independent of the spatial discretization. However, this technique may induce high-frequency spurious oscillations and restrict the computational time step, which makes the simulation of flow fields in complex domains very expensive.

To address the issue of too small time step, [17] proposed a discrete-time immersed boundary method combining with a B-spline spectral method, which allows the implementation of complex moving geometries in the pseudo spectral codes. Due to the expense of calculating the B-spline coefficients at each time step, it requires much memory so that the availability is restricted. [7] applied the discrete-time forcing scheme on a staggered grid and compared with the feedback forcing scheme proposed by [8, 20]. The comparison indicated that the discrete-time forcing scheme is more efficient than the feedback forcing scheme. In addition, [7] imposed the forcing term inside the flow field while in [17] the momentum forcing was applied only on the body surface or inside the body. [7] also tested the three interpolation procedures, stepwise geometry, volume fraction and linear interpolation. It was shown that linear interpolation can yield most accurate solution.

[11] developed a new immersed boundary method by introducing a mass source/sink as well as a momentum forcing applied on the body surface or inside the body. Although [11] adopted both the linear and bilinear interpolation schemes, no comparison was given to determine which scheme is better. Furthermore, the combination of the im-