Immersed Boundary Method for Stationary and Moving-body Problems

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The immersed boundary method has been successfully applied to stationary-body problems covering various biological and practical complex geometries. However, it produces oscillations in the force on a solid body when applied to moving-body problems. We identify two sources of these force oscillations. One is from the pressure discontinuity across the immersed boundary and the other is from the velocity discontinuity in time nearby the immersed boundary. It is found that the force oscillations are reduced more with decreasing grid size and increasing time step size, but depend more on the grid than on the time step. For a flexible slender body, we propose a new immersed boundary method which shows good performances for a flexible beam in a flowing stream and other example problems.

One of the most important issues in computational fluid dynamics (CFD) is how to efficiently and effectively simulate flow around/inside a complex geometry. Especially, flow around a flexible body moving with a prescribed motion or by fluid-solid interaction becomes a hot issue in CFD these days.

The immersed boundary method (IB method) has been known as a promising tool for flow over/inside a complex geometry and most studies have been successfully conducted for stationary-body problems.[(1)] Examples range from flow around a simple body such as the cylinder or sphere to flow over/inside a biological or practical geometry such as an insect, fish and vehicle. However, it is generally known that there exist artificial oscillations in the force on a solid body when an IB method is applied to moving-body problems in the inertial reference frame. These force oscillations may significantly degrade the credibility of numerical solution. To avoid this problem, one may use a non-inertial reference frame for single moving-body problems,[(2)] but this method is not applicable to multi-body problems. Therefore, in the present study, we identify two main sources of these artificial force oscillations and discuss how one can reduce the oscillations.

The no-slip boundary condition on the immersed boundary is satisfied by applying momentum forcing in the momentum equation according to the IB method. Since momentum forcing applied inside the solid works as a sort of pressure gradient, a discontinuity in the pressure occurs across the immersed boundary. In moving-body problems, some grid points locate in solid at time step n and in fluid at next time step n+1, as the solid body moves. Then the non-physical pressure gradient existing inside the solid body at time step n contaminates the flow field by working on the fluid part at n+1. We show that this pressure discontinuity can be alleviated by applying mass source in the continuity equation by Kim et al.[(3)] or field extension strategy by Yang and Balaras .[(4)]

The other source of force oscillations comes from the velocity discontinuity in time. When a grid point locates in solid from in fluid due to the movement of solid body, momentum forcing is applied to that grid point and the velocity there is suddenly changed. This abrupt change in the velocity is originated from the assumption in the IB method that the velocities near the IB are linearly distributed. This velocity discontinuity is reduced more with smaller grid size.

As examples of showing the sources of artificial force oscillations, we consider flow around an in-line oscillating cylinder, flow over a rectangular cylinder moving at a constant speed, and flow over a flapping wing. It is shown that the force obtained from the coarse mesh artificially oscillates in time, even though the overall flow is similar to that from the dense mesh. On the other hand, the oscillations become larger with smaller time step when the same grid resolution is used. However, the oscillations are still reduced with the constant CFL number where the time step size is decreased proportionally to the grid size. This indicates that the grid size is more critical to the force oscillations than to the time step size.

Next, we propose a new IB method for the simulation of flow around a flexible slender body such as the biological locomotion. The method is based on the IB method by Kim et al.[(3)] together with the coupling of elastic body motion. The flexible slender body is assumed as a thin flexible beam. The flexible body is segmented by consecutive blocks. Each block is moved by the hydrodynamic force obtained from a flow field, the elastic force determined by relative distances between neighboring blocks, the bending force dependent upon the bending stiffness and curvature, and the buoyancy force. We simulate flow around a fluttering beam in a flowing stream,[(5)] flow around a flexible ring, and flow around a flexible flapping wing. The flow details obtained by the present method agree well with those from previous studies.

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