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A weak-coupling immersed boundary method for fluid–structure interaction with low density ratio of solid to fluid

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ABSTRACT

We present a weak-coupling approach for fluid–structure interaction with low density ratio (ρ) of solid to fluid. For accurate and stable solutions, we introduce predictors, an explicit two-step method and the implicit Euler method, to obtain provisional velocity and position of fluid–structure interface at each time step, respectively. The incompressible Navier–Stokes equations, together with these provisional velocity and position at the fluid–structure interface, are solved in an Eulerian coordinate using an immersed-boundary finite-volume method on a staggered mesh. The dynamic equation of an elastic solid-body motion, together with the hydrodynamic force at the provisional position of the interface, is solved in a Lagrangian coordinate using a finite element method. Each governing equation for fluid and structure is implicitly solved using second-order time integrators. The overall second-order temporal accuracy is preserved even with the use of lower-order predictors. A linear stability analysis is also conducted for an ideal case to find the optimal explicit two-step method that provides stable solutions down to the lowest density ratio. With the present weak coupling, three different fluid–structure interaction problems were simulated: flows around an elastically mounted rigid circular cylinder, an elastic beam attached to the base of a stationary circular cylinder, and a flexible plate, respectively. The lowest density ratios providing stable solutions are searched for the first two problems and they are much lower than 1 ($\rho_{\min} = 0.21$ and 0.31, respectively). The simulation results agree well with those from strong coupling suggested here and also from previous numerical and experimental studies, indicating the efficiency and accuracy of the present weak coupling.

1. Introduction

Fluid–structure interactions occur in various fields such as mechanical, aerospace, and biomedical engineering. So far, many numerical methods for fluid–structure interaction have been developed and they may be classified into monolithic and partitioned approaches, respectively [1]. The monolithic approach simultaneously solves the governing equations for fluid and structure by combining them into a single system, whereas the partitioned one uses separate solvers for fluid and structure, respectively. Thus, the latter approach facilitates taking advantage of a suitable solution algorithm for each governing equation of fluid and structure motions [2].

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In fluid–structure interaction problems, the no-slip boundary condition should be satisfied on the fluid–structure interface when the equations for fluid flow are solved, and the hydrodynamic forces on the interface should be provided when the structure equation is solved. For this purpose, it is necessary to transfer variables such as the velocity, velocity gradient, and pressure on the interface from fluid to structure, or vice versa, through strong or weak coupling. Strong coupling implicitly transfers variables on the interface and simultaneously (or iteratively until convergence) solves the governing equations for fluid and structure at each time step. Strong coupling guarantees the temporal accuracy of fluid and structure time integrators [2], but usually requires an iterative process which increases the computational cost per time step [3]. Also, strong coupling may lead to unstable solutions for the problems with low density ratio (ρ) of solid to fluid [4]. To obtain stable solutions for those problems, block-Gauss–Seidel methods with an under-relaxation scheme [4–11] and block-Newton methods [12–15] have been applied together with strong coupling. On the other hand, weak coupling is performed in a staggered manner where the governing equations for fluid and structure are alternatively solved at each time step without iteration. Weak coupling is easier to implement and requires less computational cost per time step than strong coupling. However, weak coupling degrades the temporal accuracy at least one order lower than those of fluid and structure time integrators, and even severely restricts the stability limit for low-density-ratio problems [16].

In weak coupling, a predictor is used as a tool to prevent the degradation of temporal accuracy. Piperno et al. [17] suggested implicit schemes for fluid and structure (called implicit/implicit scheme), respectively, with the position and velocity of the interface determined from the previous time step, and thus their temporal accuracy was first order. Farhat et al. proposed an implicit/implicit [18], explicit/explicit, and implicit/explicit schemes [19] for compressible fluid–structure interaction problems, together with predictor and corrector schemes for the interface position and hydrodynamic force, thus satisfying a second-order accuracy. Farhat et al. [19] also showed that the order of temporal accuracy depends on predictor and corrector schemes. Dettmer and Perić [20] suggested a predictor using a second-order linear extrapolation and a corrector using a weighted average on the hydrodynamic force for incompressible fluid–structure interaction problems, and obtained a second-order accuracy. However, their method was unstable for a problem with $\rho = 1$. Yang et al. [21] showed that weak coupling using a semi-implicit/explicit scheme (without a predictor) produces unstable solutions for the interaction of incompressible flow and a rigid body with $\rho = 1.07$, whereas strong coupling using Hamming's fourth-order predictor-corrector method provides stable solutions but does not much increase the number of iterations even if the number of degrees of freedom of the structure increases.

For fluid–structure interaction problems with $\rho < 1$, the numerical stability of weak coupling is restricted by the added-mass effect [22–24]. The added mass of incompressible flow approaches a constant within a very small time interval after the interface is accelerated or decelerated, because the displacement of the interface affects the entire flow field [24]. Thus, weak coupling for incompressible flow with low ρ shows unstable solutions even for a sufficiently small size of computational time step. On the other hand, the added mass of compressible flow is proportional to the time interval because the displacement of the interface affects local flow field only [24]. Förster et al. [23] derived an instability condition of weak coupling with a predictor, and compared the lowest possible ρ's for different predictors. However, the velocity predictor suggested by Förster et al. [23] had a first-order temporal accuracy. Therefore, it should be useful to find a predictor providing a second-order temporal accuracy for fluid–structure problems with low ρ's.

To handle an arbitrarily moving interface, Peskin [25] suggested an immersed boundary (called IB hereafter) method. This method is convenient and efficient, because it allows the use of a non-body-fitted or structured mesh such as the Cartesian or cylindrical mesh and does not require mesh regeneration for a moving interface problem. This IB method is called continuous forcing [26] in that momentum forcing is provided along the IB, and has been developed by many investigators [25,27–31]. Another IB method is called discrete forcing in which forcing is applied at the grid points (or cell surfaces) [32,33]. The discrete-forcing IB method sharply expresses IB and allows a high Courant–Friedrichs–Lewy (CFL) number [32–34]. Thus, this method has been also widely used to simulate flow around an elastic body [10,35,36] as well as a rigid body [21,34,37,38]. Here, we use a discrete-forcing IB method to satisfy the no-slip condition at the fluid–structure interface [33].

In the present study, we develop a weak coupling method with predictors for fluid–structure interface position and velocity, together with a discrete-forcing IB method. To preserve a second-order temporal accuracy, an explicit two-step method as a predictor is used to obtain a provisional velocity distribution on the fluid–structure interface, and then the implicit Euler method is applied to predict its position from the provisional velocity obtained. We consider both rigid and elastic bodies with $\rho < 1$: flows around an elastically mounted rigid circular cylinder, an elastic beam attached to the base of a stationary circular cylinder, and a flexible plate. The results are compared with those by strong coupling suggested in this study and by previous numerical and experimental studies. We provide a numerical method in Sec. 2, and apply it to three different fluid–structure problems in Sec. 3, followed by conclusions in Sec. 4.

2. Numerical method

The governing equations for incompressible flow are solved in an Eulerian coordinate, whereas the dynamic equation for the motion of a rigid or elastic body is solved in a Lagrangian coordinate. To satisfy the no-slip condition and exert the hydrodynamic force on the interface, flow and structure variables such as the displacement, velocity, velocity gradient and pressure are transferred from the Eulerian to Lagrangian coordinates, and vice versa.