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SIMULATION OF FLUID-STRUCTURE INTERACTIONBASED ON AN IMMERSED-SOLID METHOD

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ABSTRACT

A new method for studying the interaction between an elastic object and a fluid has been developed. The fluid phase including solid interface is solved by our immersed solid method of body-force type. In the present study, the fluid-solid interaction force is incorporated into the finite-element method. This process is done by a superposition of the hydrodynamic force field with the solid internal force field. The inter-phase momentum exchange is implemented through the distributed force field shared by both Eulerian and moving Lagrangian references. In this paper, we demonstrate the recent results of our conservative momentum exchange algorithm for the fluid flow bounded by elastic walls. Examples include two-dimensional flows through a gap between modeled vocal cords, and some three-dimensional demonstrations.

***Keywords*: C**omputational mechanics; finite difference method; finite element method, deformable solid, multiphase flow.

INTRODUCTION

In the early stage of computational fluid dynamics (CFD), some pioneering methods or fluid-structure interaction were developed on the basis of the Cartesian coordinate system by approximating the object shape as an assembly of cuboids. Then, approaches employing a body-fitted grid system with generalized curvilinear coordinates were extensively studied, as this improves the resolution for the boundary layer with a small increase in the total number of grid points. For more complicated boundary geometries and a larger number of objects, the choice of an unstructured grid system has gained popularity. Besides the unstructured grids, a number of methods have been proposed to deal with more complex systems: multi-block, over-set, etc. However, it is not always easy to generate a high-quality mesh which facilitates efficient and accurate computation and, at the same time, reduces the computational resources. Therefore, simulation methods without the mesh generation procedure are desired, and recently the use of a fixed Cartesian grid system has been focused on again. The immersed boundary (IB) method (Mittal & Laccarino, 2005; Peskin, 1977) is one of those which have attracted considerable attention, and this trend has inspired many researchers to propose a number of improved methods. In this article, we introduce our method for the direct numerical simulation of multiphase flows and fluid–structure interaction.

OUTLINE OF COMPUTATIONAL METHOD

Fixed Cartesian Grid Method

The early versions of the family of IB methods include the original IB method developed (Peskin, 1977), which uses an approximated delta function for communication between the Lagrangian and Eulerian frames, and the feedback IB procedure (Goldstein, Handler, & Sirovich, 1993). Employing the assumption of a solid structure of connected elastic fibers permeated with the same fluid both inside and outside, the method has been successfully applied to biological systems (Peskin, 2002). Later, higher-order delta functions were proposed by many researchers (Cortez & Minion, 2000; Peskin & McQueen, 1995), and a feedback IB procedure with a smaller number of adjustable parameters is proposed by (Huang & Sung, 2009). A fully-implicit algorithm of Lagrangian tracking is studied by (Mori & Peskin, 2008).

Direct forcing methods employ an external force directly at a grid point adjacent to the solid surface. The external force is determined so that the interpolated or extrapolated velocity at the intersection satisfies an appropriate boundary condition. The method proposed by (Verzicco, Mohd-Yusof, Orlandi, & Haworth, 2000) gives the external force at the first grid point outside the solid boundary. On the other hand, (Kim, Kim, & Choi, 2001) applied an external force at the first grid point inside the solid. Then, they proposed a method to reasonably reconstruct the divergence-free flow field. (Ikeno & Kajishima, 2007) independently proposed an improved discretization of the pressure equation to adjust this enforcement.

Overriding an Immersed Solid

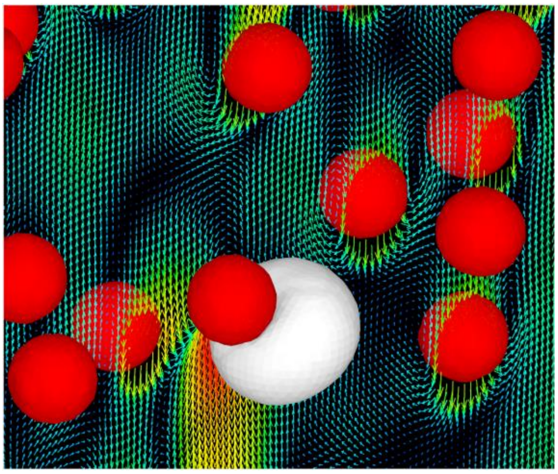
The present authors have proposed another hybrid Lagrangian-Eulerian fixed-grid method of body-force type (Kajishima & Takiguchi, 2002; Kajishima, Takiguchi, Hamasaki, & Miyake, 2001) for solid objects immersed in a fluid. This method is characterized by the concept of a “velocity-field overridden by immersed solid (VOIS)”. First, the whole domain is time-updated as a single continuum (irrespective of the material occupying the cell) obeying the Navier-Stokes equation. Then, in the region which the solid object occupies, the velocity field is overridden with the velocities obtained separately in a Lagrangian way. This process is done by applying an interaction term (volume force) which is proportional to the local solid volume fraction and the relative velocity between the fluid and the solid velocity. The significant feature of our method is the property of “conservative momentum exchange (CMX)”. This immersed solid approach was successfully applied to the direct numerical simulations of turbulent flow induced by the vortex shedding and the collective behaviors of more than 1000 solid particles (Kajishima et al., 2001). The method has been reformulated to allow arbitrary geometry for solid objects (Yuki, Takeuchi, & Kajishima, 2007). This method also exhibits a strong compatibility with a finite-element formulation, which has enabled analysis of the strong interaction problem between fluid and deformable solid structures (Takeuchi, Yuki, Ueyama, & Kajishima, 2010).

EXAMPLES

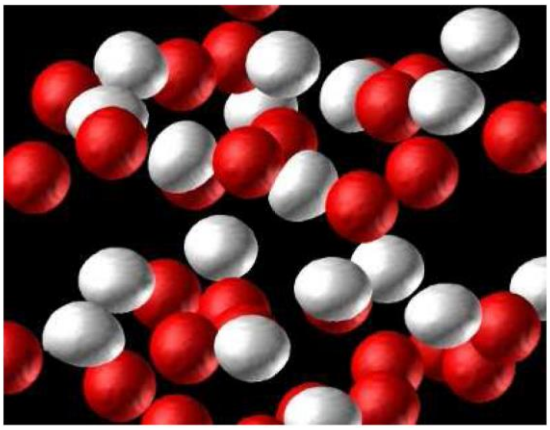
We present some recent numerical examples of flows incorporating a deformable nature into the solid material or multiple species of immiscible fluids. We choose our immersed solid approach as the basis of the FSI analysis, considering the advantage of no-leakage in the momentum exchange between fluid and solid. The algorithm is found to show good compatibility with those incorporated methods, without any essential modification to the existing computer code developed for studying the large population of solid suspension problems (Kajishima & Takiguchi, 2002; Kajishima et al., 2001).

Three-phase Flows

For capturing the interface of multiple immiscible fluids, the volume of fluid (VOF) method is employed together with an interface reconstruction scheme. The details of the coupling procedure of VOF and the immersed solid approach are found in (Iwata, Takeuchi, & Kajishima, 2010). The treatment for a moving solid boundary in a single fluid established in the above immersed solid method is fully applicable to a system involving a fluid–fluid interface. The applicability of the present method is demonstrated in 3-D flow fields with a total of 1024 mono-sized particles moving under the effect of gravity. Snapshots of the flow field around the bubble and particle are shown in Figure 1. The detailed analysis of the motion of the falling particles suggests that the particle rotation is strongly influenced by the behavior of the rising bubble, giving rise to a snap reversal of the rotating directions of the particles due to the flow induced by the bubble, which is a finite-size effect of particles on the angular momentum transfer.



(a) Instantaneous flow field around a bubble and particles



(b) Multiple bubble and particles

Figure 1. Interaction between bubbles (bright color) and solid particles (dark color).

Interaction of Fluid with Deformable Objects

The second attempt with our immersed solid approach is a coupling with the finite element method (FEM) for interaction problems of a deformable object with a fluid. The difficulty lies in the way of incorporating an elastic effect into the dynamics of the fluid, and there exist a number of approaches on this point, including a full-Eulerian approach (Ii, Sugiyama, Takeuchi, Takagi, & Matsumoto, 2011; Nagano et al., 2010; Sugiyama, Ii, Takeuchi, Takagi, & Matsumoto, 2010, 2011). In the present study, a hybrid Eulerian-Lagrangian coupling approach on a fixed grid system is presented. In the hybrid approach, the interaction force that appears in the immersed solid approach is incorporated into FEM through a superposition of the interaction-force field with the solid internal force field. This process does not cause major changes in the algorithm for the time-advancement of the velocity field of one-fluid formulation and, again, the computation is efficient. The details of the method are found in (Takeuchi et al., 2010). With this approach, the full-scale simulation of the interaction between multiple elastic objects and a fluid is carried out in a two-dimensional open space. Figure 2 is a snapshot of settling deforming particles and induced vortices.

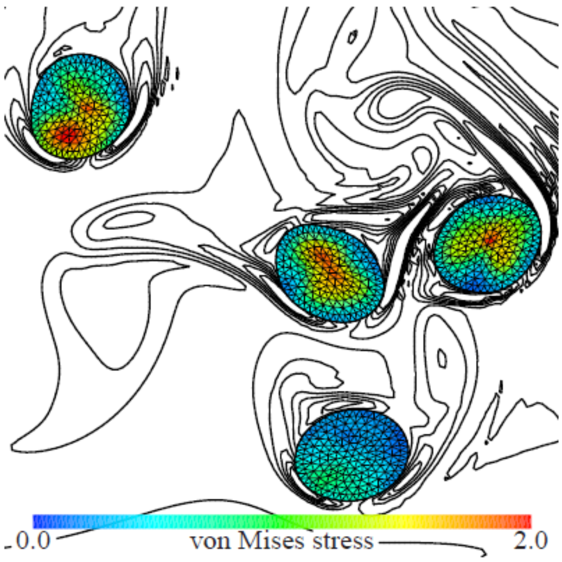


Figure 2. Settling of elastic particles in a rising flow.
(Color: von Mises stress. Contours: vorticity)

The particles were found to tumble as a pair/cluster at a faster speed than a single particle, and they were observed to exhibit the typical deformed shapes depending on the positions in the cluster; the particles at the front of the cluster were stressed most and exhibit oblate shapes. Due to the lubrication effect between particles, inter-particle collision was not dominant for the cases attempted. Further detailed analysis suggested that the difference in neutral shape of the particles (circular and elliptic of different ellipticity) affects the (translating and rotating) behaviors and mean drag forces working on the particles. Also, a three-dimensional simulation is attempted with a thin object flapping in a uniform flow, as shown in Figure 3. Through those simulation results, the effects of solid deformability on the fluid flow and solid behaviors have been studied.

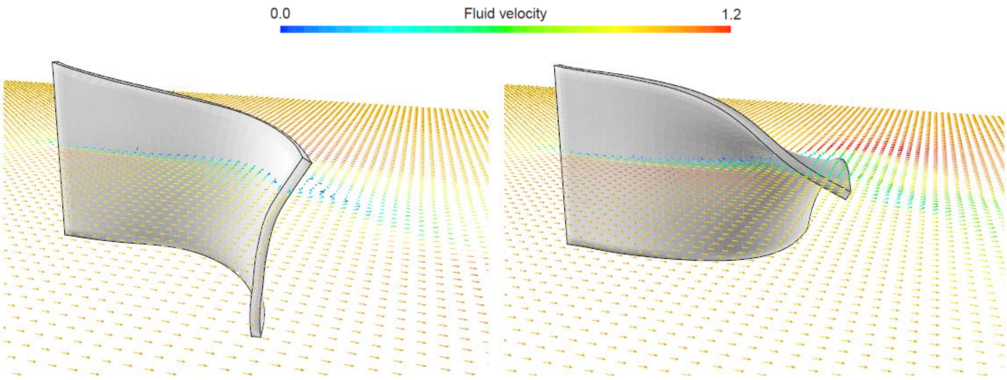
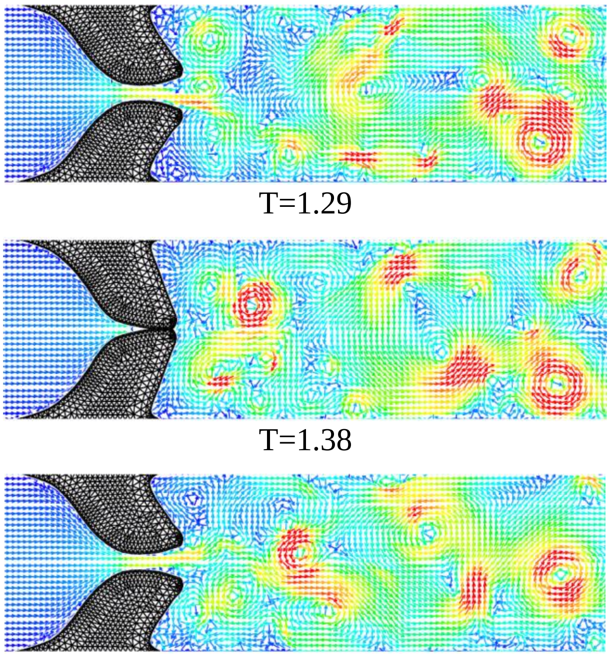


Figure 3. Snapshots of a flexible plate flapping in a uniform stream.

Flow through a Vocal Cord Model

For the understanding of the phonation mechanism and for the design of an artificial vocal cord, we developed a computational method for the fluid–structure interaction, including the elastic walls and membranes (Miyauchi, Omori, Takeuchi, & Kajishima, 2011). A robust and efficient method is required to deal with large deformation of biological materials and high frequency vibration. To this end, we applied our immersed solid method. The flow through a two-dimensional channel including a pair of flexible structures, which is a simplification of a vocal cord, is simulated. The elastic solid is modeled by the St. Venant-Kirchhoff material and its motion is simulated by FEM, where the contact of the vocal cord is taken into account by a Lagrange multiplier method. The incompressible fluid flow is computed by a finite difference method.



T=1.29

T=1.38

T=1.51

Figure 4. Time evolution of the two-dimensional flow through the vocal cord.

A vocal cord is composed of several layers of different properties. In our simulation, we use a vocal cord model consisting of two layers (cover and body) of different Young's moduli. In the present results, the deformation of the structure and the frequency of the pulsating flow are reasonably reproduced. The typical Reynolds number of the air passage of human vocal cords is known to be less than 2000. As for the frequency of the vocal cord vibration, our results give 1.6Hz, 16Hz, 250Hz at Re=10, 100, 1500, respectively. The result reasonably agrees with 100～150Hz of males and 200～300Hz of females. Figure 4 shows examples of the instantaneous flow field through the vocal cord. The considerable number of vortices may be one of the major reasons for the significant dissipation of the kinetic energy of the fluid flow.

CONCLUSIONS

Finally, let us point out some urgent issues in the fields of multiphase flow and/or the fluid-structure interaction. A key issue in dispersed three-phase flows is the effect of interfacial physics: for instance, surface tension, wettability, phase change, chemical reaction, etc. Numerical treatment for topological change of the interfaces has also lagged behind. In addition, as for the numerical resolution, the development of the method to deal with the flow through a narrow passage or the flow past a very thin object is quite important.

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