Eulerian-Lagrangian Approach for Interactions between Fluids and Multiple Deformable Swelling Objects using Mass-Spring Model

Niku GUINEA, Graduate School of Engineering, Kyoto University
Daisuke TORIU, ACCMS, Kyoto University
Satoru USHIJIMA, ACCMS, Kyoto University
E-mail : guinea.niku.25w@st.kyoto-u.ac.jp

A computation method was proposed for the interactions between Newtonian fluids and deformable solid objects which swell by absorbing the surrounding fluids. The direct-forcing immersed boundary method and mass-spring model are used to estimate the fluid-solid interactive forces and deformations of the solid. The swelling of the object is simulated by changing the natural lengths of the spring models. In addition, the solid-solid interaction is treated by utilizing the distinct element method. The proposed method was applied to three numerical experiments. As a result, it was shown that the basic behaviors of the swelling-deformable objects are reasonably calculated with the present method.

1. Introduction

The main target in this study is on the computational method for the interactions between Newtonian fluids and swelling deformable solid objects. In the proposed method, the direct-forcing immersed boundary (DF/IB) method[1)] is employed, in which Lagrangian points located on the solid surface are utilized to estimate the fluid-solid interactive forces. On the other hand, the deformable object is modeled with a mass-spring model using the Lagrangian points by adding new supporting springs. The swelling of the object is simulated by changing the natural lengths of the spring models. In addition, the solid-solid interaction is treated by setting CDS (contact detection sphere) at each Lagrangian point, which corresponds to a DEM to detect particle collisions.

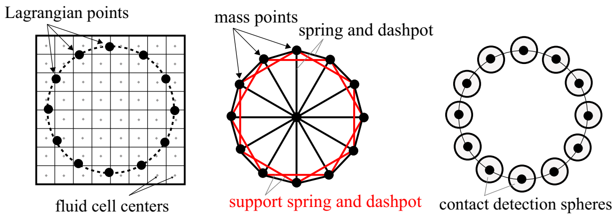
2. Numerical Method

The fluid is assumed to be incompressible, and the momentum equations are given by

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho_f}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2} + f_i + \lambda_i, \qquad (1)$$

where u_j is the averaged velocity component in x_j direction in two-dimensional Cartesian coordinates, t is time, x_i is the component of the Cartesian coordinate system, ρ_f is density, ν is kinematic viscosity, and p is pressure. In addition, u_i is the velocity component, f_i and λ_i are the external and fluid-solid interaction forces in x_i direction.

The schemes for DF/IB, mass-spring model, and contact detection spheres used in the computation can be seen in Figs. 1 (a), (b), and (c) respectively. For the swelling scheme, the size increase is proposed by utilizing the natural spring length $\|x^0_{AB}\|$ used in the mass-spring model. A fixed value of density is proposed, resulting in the increase of the mass of the object as the volume of the object increases.



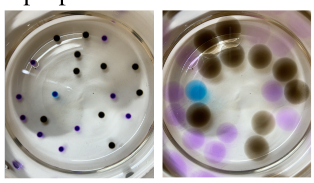
(a) DF/IB scheme (b) MSM scheme (c) DEM scheme

Fig. 1 Schematic of (a) fluid cells and Lagrangian points for DF/IB, (b) mass-spring model, and (c) CDS

3. Applications

(1) Experiments and Computation on Swelling Behavior of Hydrogel Particles

In this section, the diameter growth of hydrogel particles is experimentally observed as shown in Fig. 2 and implemented into the proposed method.



(a) $t = 0$ [hrs] (b) $t = 9.7$ [hrs]

Fig. 2 Experiment of hydrogel particles in water

The calculated results in Fig. 3 show a smooth curve from the computation, with a good agreement with the experimental data and the expected growth.

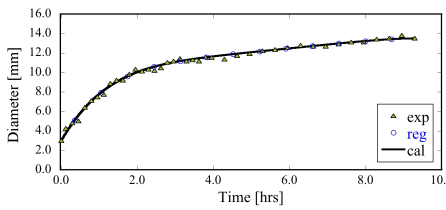


Fig. 3 Computed diameter of hydrogel particle (cal) compared to experiments (exp) and predicted results (reg)

(2) Sedimentation of a Single Particle in Fluid

It is important to confirm that the proposed method will give the same results as the original DF/IB for rigid bodies[1]. The proposed method is applied to a case of sedimentation of a single particle in fluid, and compared with results computed with the original DF/IB for rigid bodies and references as shown in Fig. 4. The time histories of velocity from the proposed method a good agreement with the original DF/IB method and references.

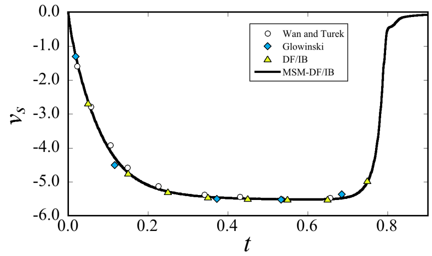


Fig. 4 Time histories of v_s with D = 0.25 and references

In addition, the sedimentation of a swelling particle (D = 0.25 to 0.50) is calculated and the velocity is compared with the case of sedimentation of non-swelling particle (D = 0.25 and D = 0.50). The relations between particle diameter and time in each case is shown in Fig. 5 and the computation results of the sedimentation of a swelling particle can be seen in Fig. 6. The time history of the velocity for the swelling particle at case C fits between cases A and B as it can be seen in Fig. 7, showing reasonable results for the computation. Additionally, the particle in case C never reached its terminal velocity as the size is keep increasing until it hits the bottom side.

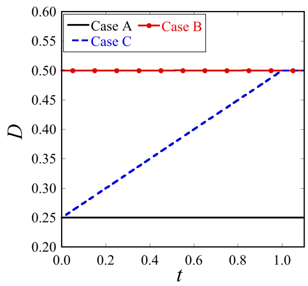
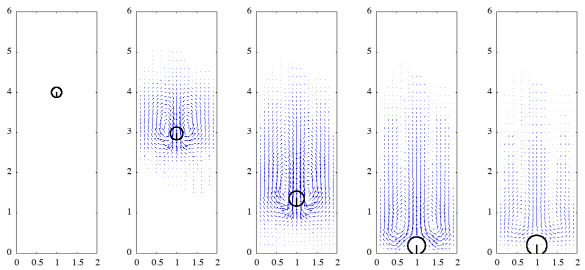


Fig. 5 Diameter of particles for case A, B, and C with respect to time (left)



(a) t = 0.0 (b) t = 0.25 (c) t = 0.50 (d) t = 0.75 (e) t = 1.00

Fig. 6 Sedimentation of single swelling particle in fluid for case C (velocity vectors and particle outline)

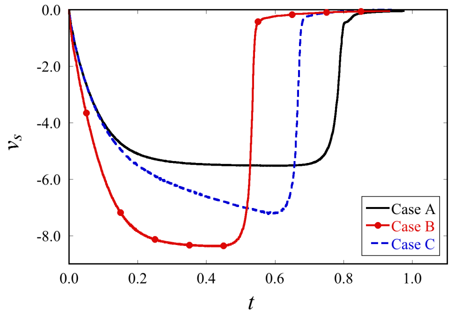
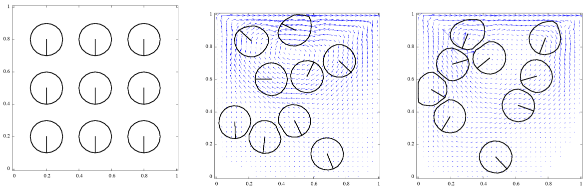


Fig. 7 Time histories of particle velocity v_s for case A (D = 0.25), case B (D = 0.5), and case C (D = 0.25 to 0.50) (right)

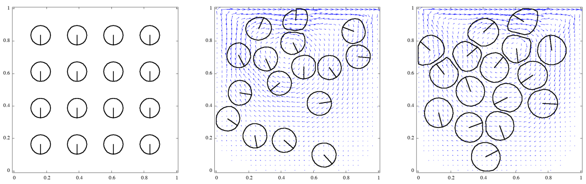
(3) Lid-Driven Cavity Flow with Multiple Objects

Multiple deformable solid objects are arranged inside the 2D computational area filled with the fluid, then two types of condition is calculated with non-swelling objects and swelling objects as it can be seen in Figs. 8 A) and B) respectively. In both cases, k_s is set at 100.



(a) t = 0 (b) t = 30 (c) t = 60

A) Non-Swelling Deformable Objects



(a) t = 0 (b) t = 50 (c) t = 100

B) Swelling Deformable Objects

Fig. 8 Cavity flow with A) non-swelling and B) swelling deformable objects

The deformation can be observed in both computations with non-swelling and swelling objects, especially closer to the moving top wall where velocity is higher and when the solid-solid and solid-wall contacts occur. Additionally, for the swelling objects, as the objects get transported by the fluid flow, the objects become larger and fill the computational area, causing slower movements.

References

1) Uhlmann, M.: An immersed boundary method with direct forcing for the simulation of particulate flows, *J. Comput. Phys.*, Vol. 209, pp. 448–476, 2005.