FEMまたはVOF法を組み込んだ埋込境界法による可変形境界を有する多相流の解析

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Motivation

- Multiphase flows
  - Effects of microscopic parameters on macroscopic flows
- Flow-structure interaction
  - Multiple flexible structures
- Parameters to be considered
  - Non-spherical particles, Deformable particles
  - Interfacial phenomena
  - Inter-particle forces (remote and/or contact)
  - Liquid film, Liquid bridge
  - High Knudsen number effect
  - Heat and mass transfer, Phase change

Multifunctional Immersed Boundary Method

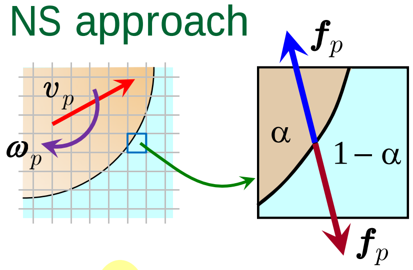
- Based on IB Method of body force type
  - Kajishima & Takiguchi (2001, 2002)
- IB-VOF (Volume-of-Fluid) Method
  - Three-phase flows (R. Iwata, M. Taniguchi)
- IB-FEM (Finite-Element Method)
  - Deformable particles (A. Ueyama, K. Tamura)
- IB-DEM (Discrete-Element Method)
  - Particle agglomerate (T. Yukimoto)
- IB-LES (Large-Eddy Simulation)
  - Flow in rod-bundle (T. Ikeno)

IBM method by fortified NS approach

- Volume-averaged velocity

$$\boldsymbol{u} = (1-\alpha)\boldsymbol{u}_f + \alpha \boldsymbol{u}_p$$

$$\boldsymbol{u}_p = \boldsymbol{v}_p + \boldsymbol{\omega}_p \times \boldsymbol{r}$$



$$\frac{D\boldsymbol{u}}{Dt} = -\frac{\nabla p}{\rho} + \nabla \cdot \left[\nu\left(\nabla \boldsymbol{u} + \boldsymbol{u}\nabla\right)\right] + \boldsymbol{f}_p$$

$$\boldsymbol{f}_p = \alpha \frac{\boldsymbol{u}_p - \boldsymbol{u}}{\Delta t}$$

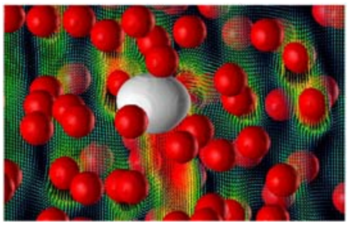
Momentum transfer in the interface cell

- Equation for motion and rotation

$$\frac{d(m_p \boldsymbol{v}_p)}{dt} = -\int_{V_p} \boldsymbol{f}_p dV + \boldsymbol{G}_p$$

$$\frac{d(\boldsymbol{I}_p \cdot \boldsymbol{\omega}_p)}{dt} = -\int_{V_p} \boldsymbol{r} \times \boldsymbol{f}_p dV + \boldsymbol{T}_p$$

Surface integrals are rewritten in volume integral forms.

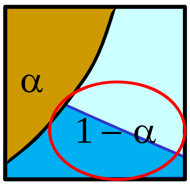


Combination of
Immersed-Boundary Method
and
Volume-of-Fluid Method

R. Iwata
M. Taniguchi

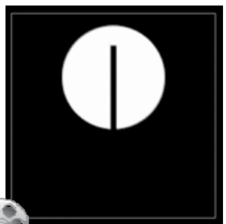
IB-VOF

IB-VOF combination



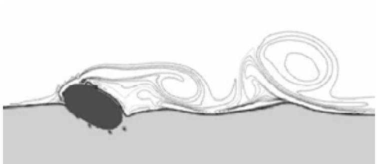
$$\frac{\partial F}{\partial t} + \boldsymbol{u} \cdot \nabla F = 0$$

- VOF method
  - Advection scheme
    - EI-LE (Eulerian-implicit Lagrangian-explicit scheme) based on PLIC (Piecewise Linear Interface Calculation) (Aulisa, Manservisi, Scardovelli & Zaleski, 2003)
  - Interface reconstruction
    - MYC (Mixed Young's and centered) method (Aulisa, Manservisi, Scardovelli & Zaleski, 2007)
  - Surface tension
    - Continuum surface force model (Brackbill, Kothe & Zemach, 1992)

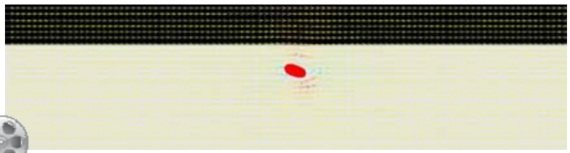


Effect of interface reconstruction

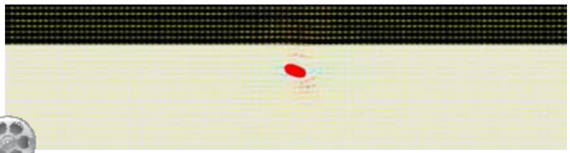
Lifting body on the interface



VOF (Donor-Acceptor) method



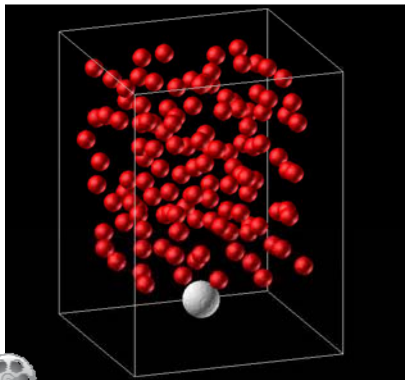
VOF (EI-LE/MYC) method



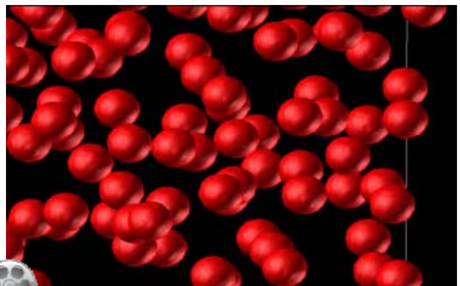
Collision of bubble and particles $N_p = 125$

$N_x \times N_y \times N_z$	$160 \times 120 \times 120$
D_b / Δ	20
D_p / Δ	10

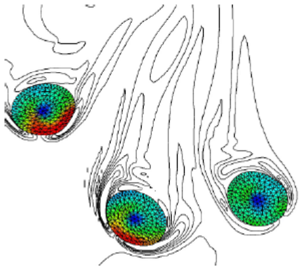
$Re = \rho_l U_b D_b / \mu_l$	20
$We = \rho_l U_b^2 D_b / \sigma$	2
$\rho_g / \rho_l, \rho_s / \rho_l$	1/1000, 2.5
μ_g / μ_l	1/100



Sphere



Spheroid



Combination of
Immersed-Boundary Method
and
Finite Element Method

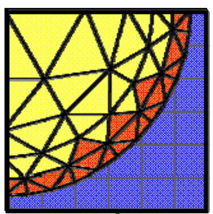
A. Ueyama
K. Tamura

IB-FEM

IB-FEM combination

- Use interactive forces for BC in FEM method of linear elastic objects
  - Directly incorporating the body forces of IBM into the external force term of the FEM

$$M\ddot{z} + Kz = F$$

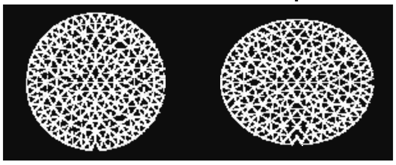


$$F = \sum_e \int_{V_e} N^T f_p dV$$

$$\boldsymbol{f}_p = \alpha \frac{\boldsymbol{u}_p - \boldsymbol{u}}{\Delta t}$$

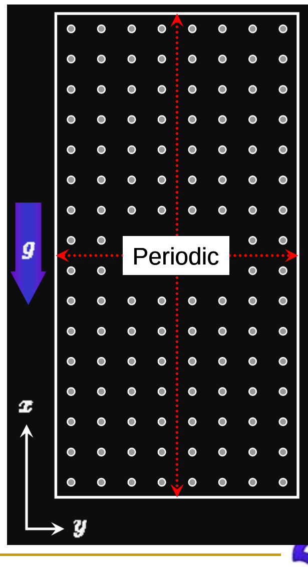
2D simulation of particle-laden flow $N_p = 128$

Circular Elliptic



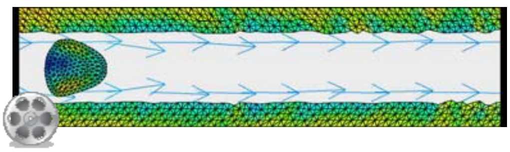
(Ellipticity=1.2)

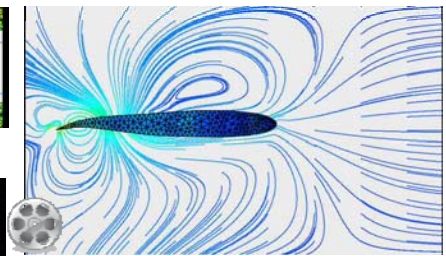
$N_x \times N_y$	4096×2048
N_e	324 / particle
D_p / Δ	20
$E / \rho_f U_0^2$	10, 50, 100
$Re_p = \rho_f U_0 D_p / \mu_f$	200
ρ_p / ρ_f	5

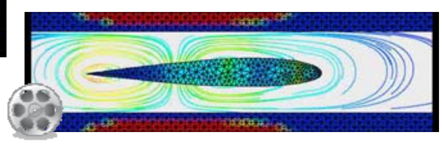


Deformable objects and walls (2D)

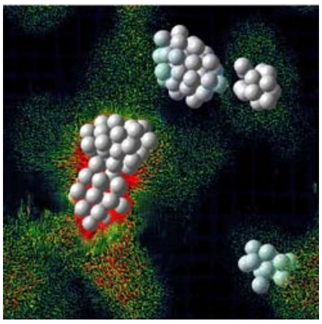
- Deformable objects in elastic channel
- Fish locomotion in narrow passage







Colors: von Mises stress distribution



Combination of
Immersed-Boundary Method
and
Discrete-Element Method

T.Yukimoto

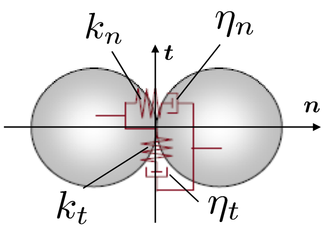
IB-DEM

Particle-particle interactions

- van der Waals force

$$F_{vlm} = \frac{A_h}{6}\left[-\frac{D^2 r_{lm}}{(r_{lm}^2 - D^2)^2} - \frac{D^2}{r_{lm}^3} + \ln\frac{2r_{lm}}{r_{lm}^2 - D^2} - \frac{2}{r_{lm}}\right]$$

- Contact force (DEM)



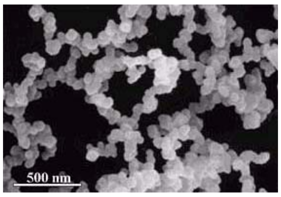
Contact force : $\boldsymbol{f}_C = \boldsymbol{f}_{C_n} + \boldsymbol{f}_{C_t}$

Normal force: $\begin{cases} \boldsymbol{f}_{C_n} = -k_n \boldsymbol{d}_n - \eta_n \boldsymbol{v}_n \\ \boldsymbol{v}_n = (\boldsymbol{v}_r \cdot \boldsymbol{n})\boldsymbol{n} \end{cases}$

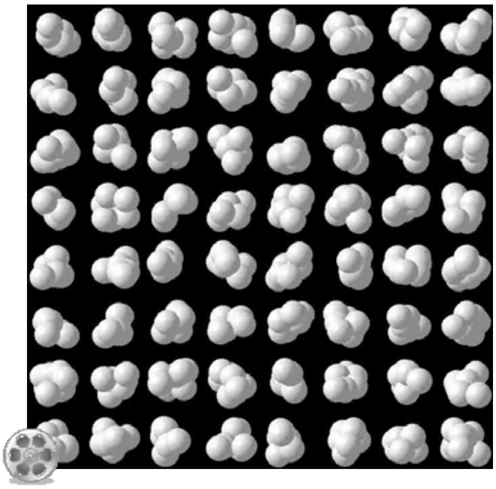
Tangential force: $\begin{cases} \boldsymbol{f}_{C_t} = -k_t \boldsymbol{d}_t - \eta_t \boldsymbol{v}_t \\ \boldsymbol{v}_t = \boldsymbol{v}_r - \boldsymbol{v}_n \end{cases}$

Agglomerating van der Waals particles

$N_x \times N_y \times N_z$	$180 \times 180 \times 180$
D_p / Δ	10
N_p	512
ρ_g / ρ_f	2



Soot



Conclusions

- Immersed Boundary Method
  - Enhanced by IB-FEM, IB-VOF, IB-DEM
    - Especially suited for multiple objects in fluid flows
  - Problems
    - Resolution for thin layers
      - Local refinement, Overlapped grid ???
      - Wall function model, Liquid film model
  - Ongoing works
    - Nonlinear FEM
    - Heat transfer and phase change