Oral presentation | Numerical methods

Numerical methods-II

Tue. Jul 16, 2024 4:30 PM - 6:30 PM Room A

[6-A-03] A generic balanced-force algorithm for multiphase flows with moving bodies on polyhedral unstructured grids

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Keywords: Multiphase flow, Unstructured grids, Balanced-force algorithm, Fluid-structure interaction

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A generic balanced-force algorithm for multiphase flows with moving bodies on polyhedral unstructured grids

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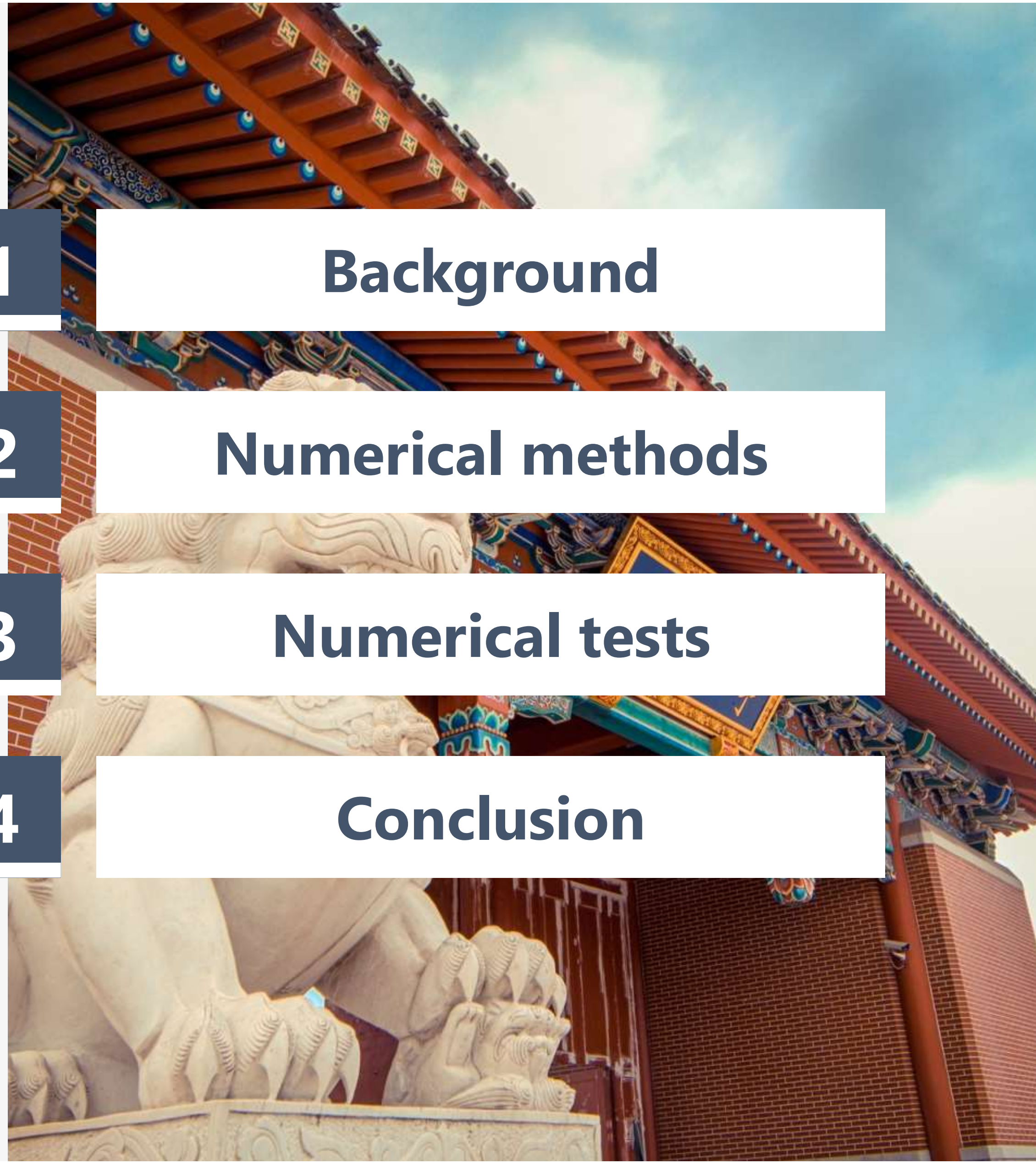
Contents

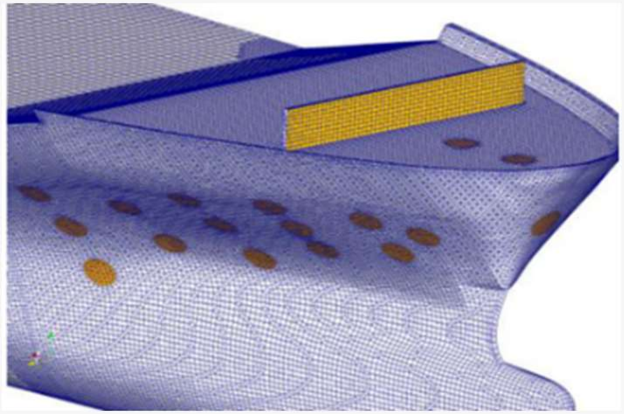


Background

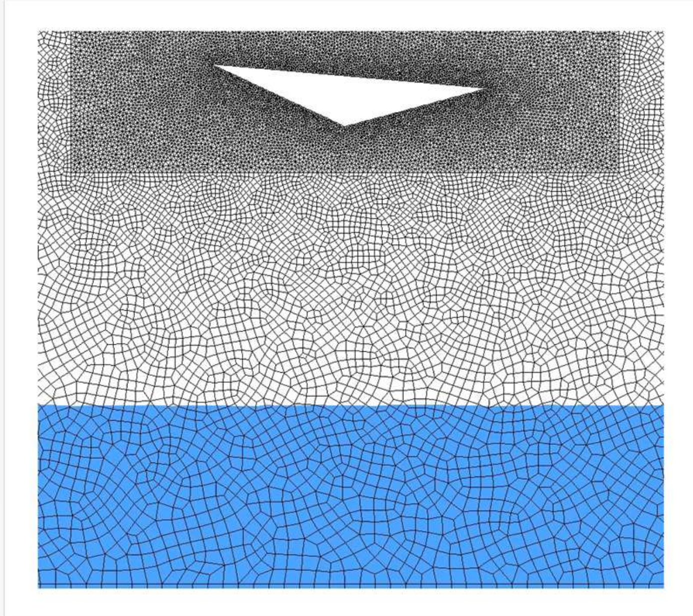
Challenges of multiphase fluid-structure interaction (FSI) simulations with the arbitrary Lagrangian-Eulerian (ALE) method

- Large fluid density ratio (usually 10^3)
- Severe deformation and distortion of the unstructured grid
- Strong nonlinearity during the fluid-structure coupling

(a) Filming of ship navigation



(b) Polyhedral unstructured grids for ship modeling



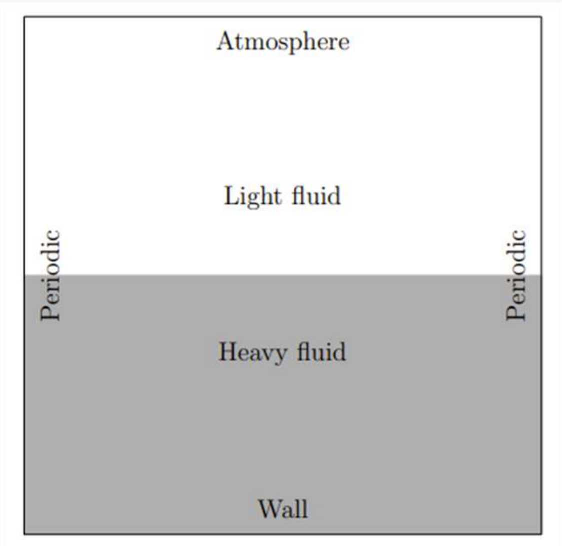
(c) Simulation of wedge free falling

Background

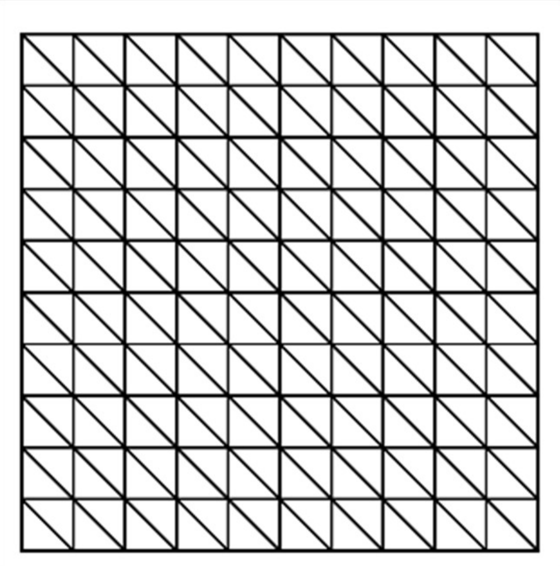
Example: **Stationary** water tank (only gravity)

- Density ratio $\rho_{\mathrm{H}}/\rho_{\mathrm{L}} = 10^3$
- Non-orthogonal unstructured grid in the entire domain

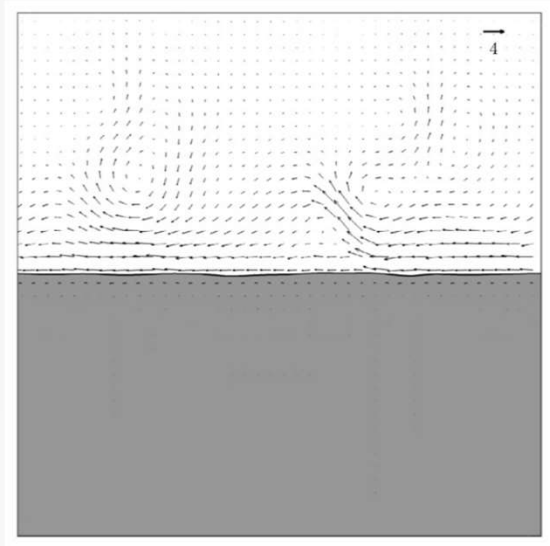
Spurious currents generated by unbalanced algorithm:



(a) Sketch



(b) Non-orthogonal grid



(c) Simulation by unbalanced algorithm

Unphysical

Background

Balanced-force algorithm

- Devise a specific discretization to **enforce the exact balance** between pressure gradient and external forces
- Francois et al. (*J. Comput. Phy. 213 (2006) 141-173*) proposed a balanced-force algorithm on **structured** grids

ELSEVIER

Journal of Computational Physics
Volume 213, Issue 1, 20 March 2006, Pages 141-173

A balanced-force algorithm for continuous and sharp interfacial surface tension models within a volume tracking framework

Marianne M. Francois [a], Sharen J. Cummins [a], Edward D. Dendy [a], Douglas B. Kothe [a], James M. Sicilian [a], Matthew W. Williams [b]

Cited by (687)

Three dimensional interface normal prediction for Volume-of-Fluid method using artificial neural network
2024, European Journal of Mechanics, B/Fluids
Show abstract

On polytope intersection by half-spaces and hyperplanes for unsplit geometric volume of fluid methods on arbitrary grids
2024, Computer Physics Communications
Show abstract

A locally redistributed level-set method for numerical simulation of thin interface structures
2024, Computers and Fluids
Show abstract

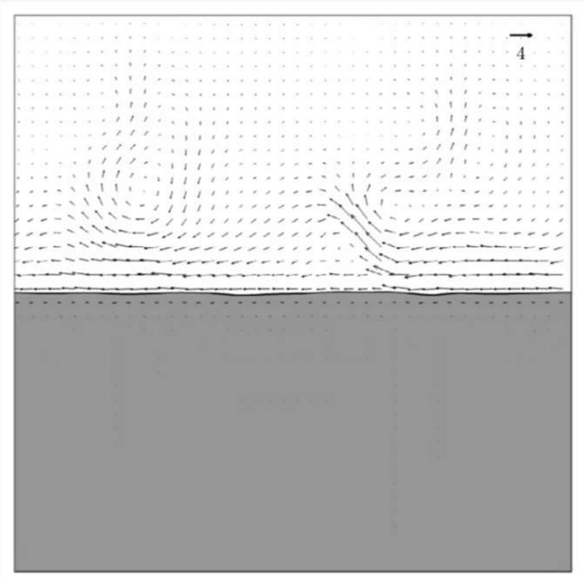
A robust phase-field method for two-phase flows on unstructured grids
2024, Journal of Computational Physics

Achieve force balance by identical discretization of gradient operators at the same location ? → Structured grid ✓ Unstructured grid ?

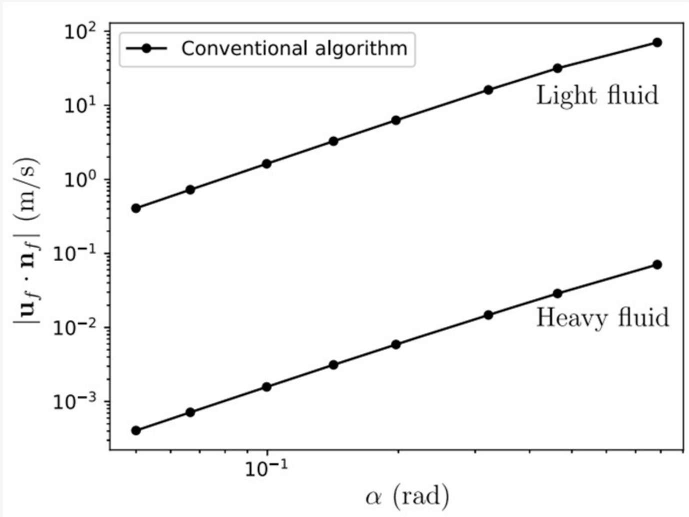
Background

Defect of conventional balanced-force algorithm (*J. Comput. Phy. 213 (2006) 141-173*)

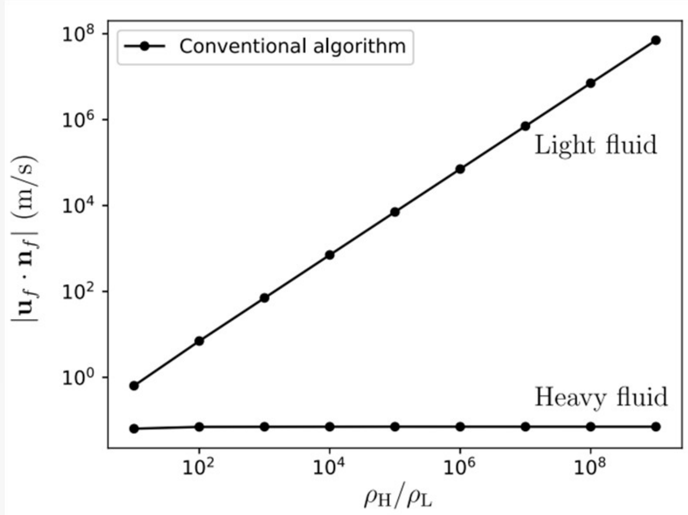
- can **NOT** achieve force balance on non-orthogonal grids and generate severe **spurious currents**
- **Spurious velocity escalates** with larger **non-orthogonality angle** and higher **fluid density ratio**



(a) **Spurious currents** generated by conventional model



(b) Velocity vs mesh angle ($\rho_H/\rho_L = 1000$)

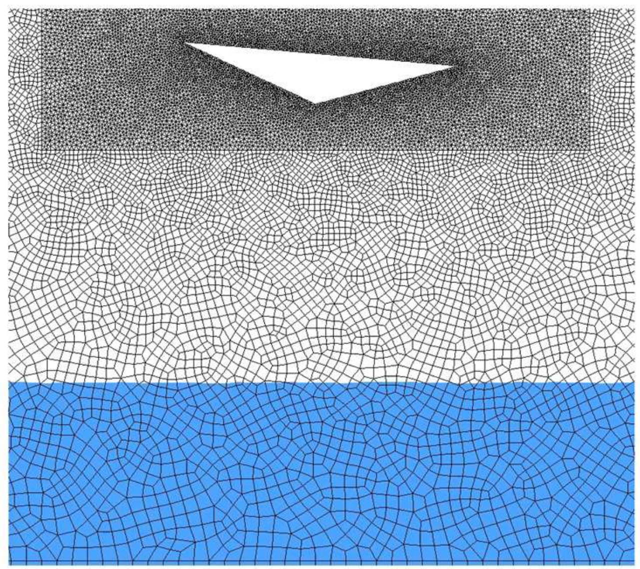


(c) Velocity vs density ratio ($\alpha = 26.6°$)

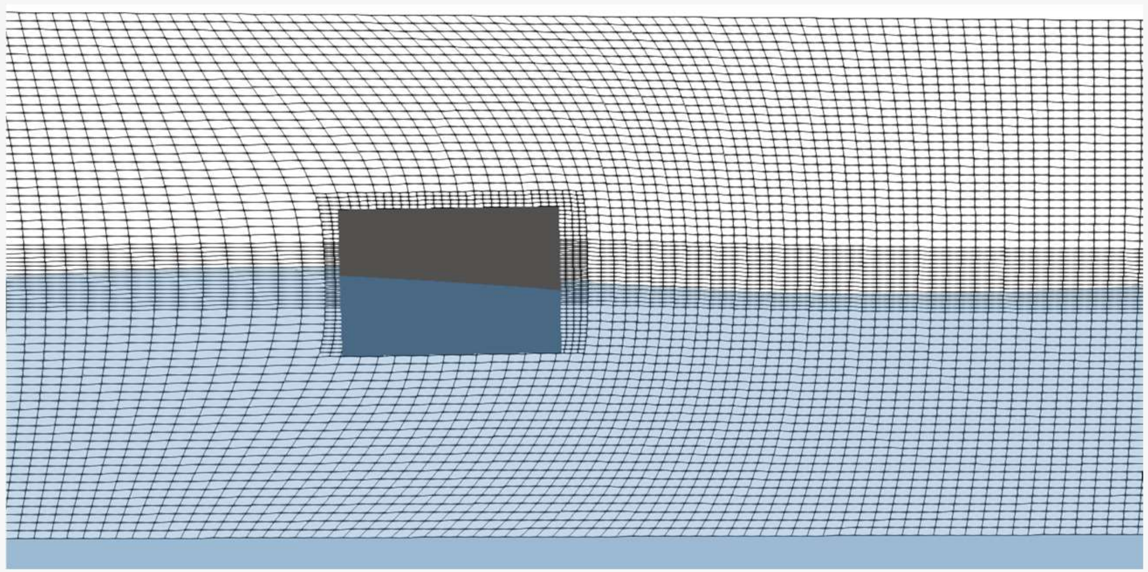
Background

Objective: Balanced-force algorithm for fluid-structure interaction (FSI)

- Propose a generic balanced-force (GBF) algorithm for multiphase flows on unstructured grids
- Employ the GBF algorithm for multiphase FSI problems to enhance the stability and accuracy of simulations



(a) Wedge falling



(b) Wave induced motion of a 3d floating box

Numerical methods

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Governing equations in the ALE description

$$\frac{\partial \phi}{\partial t} + \nabla \cdot \left(\phi(\mathbf{u} - \mathbf{u}_{\mathrm{g}})\right) = \phi \nabla \cdot \mathbf{u},$$
$$\nabla \cdot \mathbf{u} = \mathbf{0},$$
$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left(\rho(\mathbf{u} - \mathbf{u}_{\mathrm{g}}) \otimes \mathbf{u}\right) = (\nabla \cdot (\mu \nabla \mathbf{u}) + \nabla \mathbf{u} \cdot \nabla \mu) - \nabla p - (\mathbf{g} \cdot \mathbf{x})(\rho_{\mathrm{H}} - \rho_{\mathrm{L}}) \nabla \phi + \sigma \kappa \nabla \phi.$$

where ϕ $(\mathbf{x}, t)$ represents the volume fraction separating two immiscible fluids, $\mathbf{u} = (u, v, w)$ is the velocity field, p the dynamic pressure, ρ the fluid density and μ the fluid dynamic viscosity. $\mathbf{g}$ is the gravitational acceleration, σ the surface tension coefficient and κ the curvature of fluid interface. $\mathbf{u}_{\mathrm{g}}$ is the grid velocity.

$$\phi(\mathbf{x}, t) = \begin{cases} 1, & \text{Heavy fluid} \\ 0, & \text{Light fluid} \\ 0 < \phi < 1. & \text{Fluid interface} \end{cases}$$

The material properties of fluids：

$$\rho = \rho_{\mathrm{H}} \phi + \rho_{\mathrm{L}}(1 - \phi)$$
$$\mu = \mu_{\mathrm{H}} \phi + \mu_{\mathrm{L}}(1 - \phi)$$

where subscripts H and L represent heavy and light fluid respectively.

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Numerical methods

Solution procedure

(1) Calculate the dynamics and displacement of moving body with 6 DOF motion equations. Update the grid to time step $n+1$ and calculate the grid velocity $\mathbf{u}_{\mathrm{g}}^{n+1}$.

(2) Solve the advection equation of mass and convection equation of momentum simultaneously:

$$\frac{\partial \phi}{\partial t} = -\nabla \cdot \left(\phi\left(\mathbf{u} - \mathbf{u}_{\mathrm{g}}^{n+1}\right)\right) + \phi \nabla \cdot \mathbf{u},$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} = -\nabla \cdot \left(\rho \mathbf{u} \otimes \left(\mathbf{u} - \mathbf{u}_{\mathrm{g}}^{n+1}\right)\right) + \left(\nabla \cdot (\mu \nabla \mathbf{u}) + \nabla \mathbf{u} \cdot \nabla \mu\right),$$

to obtain ϕ^{n+1} and $\mathbf{u}^*$, and update ρ^{n+1} and μ^{n+1} with ϕ^{n+1}.

(3) Solve the following **pressure Poisson equation** for pressure field p^{n+1}:

$$\nabla \cdot \left(\frac{1}{\rho} \nabla p^{n+1}\right) = \frac{\nabla \cdot \mathbf{u}^*}{\Delta t} - \nabla \cdot \underbrace{\left(\frac{\mathbf{g} \cdot \mathbf{x}}{\rho}(\rho_{\mathrm{H}} - \rho_{\mathrm{L}}) \nabla \phi^{n+1}\right)}_{\text{Gravity force}} + \nabla \cdot \underbrace{\left(\frac{\sigma \kappa}{\rho} \nabla \phi^{n+1}\right)}_{\text{Surface tension force}},$$

⬅ **Balanced-force algorithm**

where the gravity and surface tension forces are incorporated to derive a balanced-force formulation.

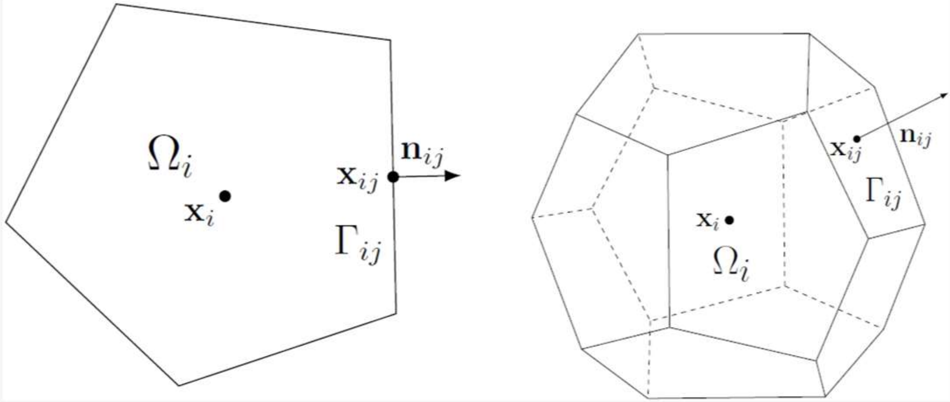
(4) Correct the intermediate velocity $\mathbf{u}^*$ to $\mathbf{u}^{n+1}$ by the projection step.

$$\frac{\mathbf{u}^{n+1} - \mathbf{u}^*}{\Delta t} = -\frac{\mathbf{g} \cdot \mathbf{x}}{\rho}(\rho_{\mathrm{H}} - \rho_{\mathrm{L}}) \nabla \phi^{n+1} + \frac{\sigma \kappa}{\rho} \nabla \phi^{n+1} - \frac{1}{\rho} \nabla p^{n+1}.$$

The updated velocity field $\mathbf{u}^{n+1}$ should satisfy the divergence-free condition.

Numerical methods

Pressure equation actually solved in the numerical methods



- Discrete pressure Poisson equation with FVM:

$$\sum_{j=1}^{J}\left(\frac{\Delta t|\boldsymbol{\Gamma}_{ij}|}{\rho_{ij}}\left(\nabla p_{ij}^{n+1}\cdot\mathbf{n}_{ij}\right)\right)=\sum_{j=1}^{J}\left(|\boldsymbol{\Gamma}_{ij}|\left(\overline{\mathbf{u}}_{ij}^{*}\cdot\mathbf{n}_{ij}\right)+\frac{\Delta t|\boldsymbol{\Gamma}_{ij}|}{\rho_{ij}}\left(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\left(\nabla\phi_{ij}^{n+1}\cdot\mathbf{n}_{ij}\right)\right).$$

- For **stationary** flows, $|\mathbf{u}|=0$:

$$\boxed{\sum_{j=1}^{J}}\left(\frac{\Delta t|\boldsymbol{\Gamma}_{ij}|}{\rho_{ij}}\left(\nabla p_{ij}^{n+1}\cdot\mathbf{n}_{ij}\right)\right)=\boxed{\sum_{j=1}^{J}}\left(\frac{\Delta t|\boldsymbol{\Gamma}_{ij}|}{\rho_{ij}}\left(-(\mathbf{g}\cdot\mathbf{x}_{\mathrm{ij}})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\left(\nabla\phi_{ij}^{n+1}\cdot\mathbf{n}_{ij}\right)\right). \quad (1)$$

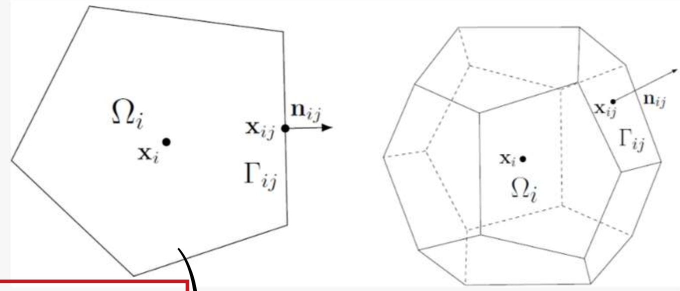
Necessary but **insufficient** condition

Pressure equation required by a balanced-force algorithm

$$-\nabla p_{ij}=\left(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\nabla\phi_{ij}. \quad (2)$$

Merely solve Eq. (1) for p^{n+1} but meet Eq. (1) and (2) simultaneously ➡ **Not** all numerical scheme can achieve force balance

Numerical methods



Discrete pressure Poisson equation with FVM

$$\sum_{j=1}^{J}\left(\frac{\Delta t|\boldsymbol{\Gamma}_{ij}|}{\rho_{ij}}\boxed{(\nabla p_{ij}^{n+1}\cdot\mathbf{n}_{ij})}\right)=\sum_{j=1}^{J}\left(|\boldsymbol{\Gamma}_{ij}|(\overline{\mathbf{u}}_{ij}^{*}\cdot\mathbf{n}_{ij})+\frac{\Delta t|\boldsymbol{\Gamma}_{ij}|}{\rho_{ij}}(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij})\boxed{(\nabla\phi_{ij}^{n+1}\cdot\mathbf{n}_{ij})}\right).$$

Conventional balanced-force formulation

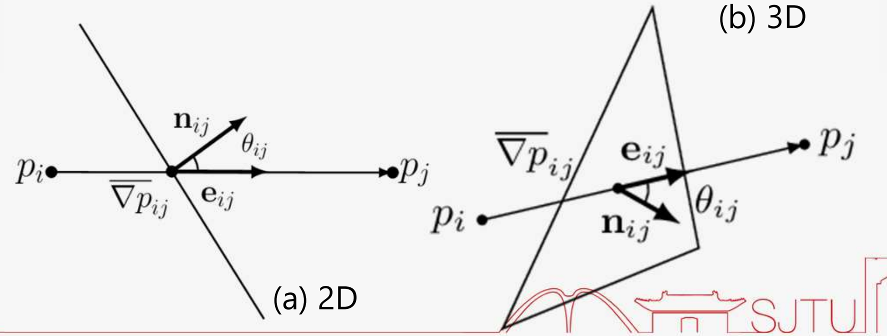
Calculate $\nabla\varphi_{ij}^{n+1}\cdot\mathbf{n}_{ij}$ $\varphi\in(p,\phi)$ with the **same** face gradient scheme

$$\underbrace{\sum_{j=1}^{J}\alpha_{ij}(p_j^{m+1}-p_i^{m+1})}_{\text{Implicit central difference term}}=\sum_{j=1}^{J}(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij})\alpha_{ij}(\phi_j^{n+1}-\phi_i^{n+1})$$

$$+\sum_{j=1}^{J}\boldsymbol{\beta}_{ij}\cdot(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij})\overline{\nabla\phi}_{ij}^{n+1}\quad\underbrace{-\sum_{j=1}^{J}\boldsymbol{\beta}_{ij}\cdot\overline{\nabla p}_{ij}^{m}}_{\text{Explicit non-orthogonal correction term}}\quad+\sum_{j=1}^{J}|\Gamma_{ij}|(\overline{\mathbf{u}}_{ij}^{*}\cdot\mathbf{n}_{ij})$$

where the averaged face gradients $\overline{\nabla\varphi_{ij}}$ = linear interpolation($\nabla\varphi_i$) ($\varphi\in(\phi,p)$), and $\nabla\varphi_i$ can be calculated with Gauss's theorem or the least square method.

Face gradient scheme	α_{ij}	$\boldsymbol{\beta}_{ij}$
Edge-normal scheme	$\frac{\Delta t\lvert\boldsymbol{\Gamma}_{ij}\rvert}{\rho_{ij}\lvert\mathbf{r}_{ij}\rvert}(\mathbf{n}_{ij}\cdot\mathbf{e}_{ij})$	$\frac{\Delta t\lvert\boldsymbol{\Gamma}_{ij}\rvert}{\rho_{ij}}(\mathbf{n}_{ij}\cdot\mathbf{e}_{ij}^{\perp})\mathbf{e}_{ij}^{\perp}$
Face-tangent scheme	$\frac{\Delta t\lvert\boldsymbol{\Gamma}_{ij}\rvert}{\rho_{ij}\lvert\mathbf{r}_{ij}\rvert}\frac{1}{(\mathbf{n}_{ij}\cdot\mathbf{e}_{ij})}$	$-\frac{\Delta t\lvert\boldsymbol{\Gamma}_{ij}\rvert}{\rho_{ij}}\frac{(\mathbf{t}_{ij}\cdot\mathbf{e}_{ij})}{(\mathbf{n}_{ij}\cdot\mathbf{e}_{ij})}\mathbf{t}_{ij}$



(a) 2D (b) 3D

Numerical methods

Present balanced-force formulation

Express the averaged face gradient of pressure $\overline{\nabla p_{ij}}$ into the sum of external forces and a novel pressure correction term $\nabla \hat{p}$:

$$\begin{aligned}\overline{\nabla p_{ij}} &= \left(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\overline{\nabla\phi_{ij}} + \left(-\left(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\cdot\overline{\nabla\phi_{ij}}+\overline{\nabla p_{ij}}\right)\\ &= \left(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\overline{\nabla\phi_{ij}}+\overline{\nabla\hat{p}_{ij}}\\ \overline{\nabla p_{ij}^m} &= \left(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\overline{\nabla\phi_{ij}^{n+1}}+\overline{\nabla\hat{p}_{ij}^m}\end{aligned}$$

- Calculate $\nabla\hat{p}_i^m$ with the Eq. (6)， and linear interpolate to $\overline{\nabla\hat{p}_{ij}^m}$

$$\nabla\hat{p}_i^m = \left(\sum_{j=1}^{J}\boldsymbol{\Gamma}_{ij}\otimes\mathbf{n}_{ij}\right)^{-1}\cdot\sum_{j=1}^{J}\left(\left(\nabla p_{ij}^m\cdot\mathbf{n}_{ij}\right)-\left(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\left(\nabla\phi_{ij}^{n+1}\cdot\mathbf{n}_{ij}\right)\right)\boldsymbol{\Gamma}_{ij} \qquad (6)$$

- Present semi-implicit pressure Poisson equation:

$$\underbrace{\sum_{j=1}^{J}\alpha_{ij}\left(p_j^{m+1}-p_i^{m+1}\right)}_{\text{Implicit central difference term}} = \sum_{j=1}^{J}\left(-(\mathbf{g}\cdot\mathbf{x}_{ij})(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\alpha_{ij}\left(\phi_j^{n+1}-\phi_i^{n+1}\right) \underbrace{-\sum_{j=1}^{J}\boldsymbol{\beta}_{ij}\cdot\overline{\nabla\hat{p}_{ij}^m}}_{\text{Explicit non-orthogona correction term}} + \sum_{j=1}^{J}\left|\Gamma_{ij}\right|\left(\overline{\mathbf{u}}_{ij}^*\cdot\mathbf{n}_{ij}\right)$$

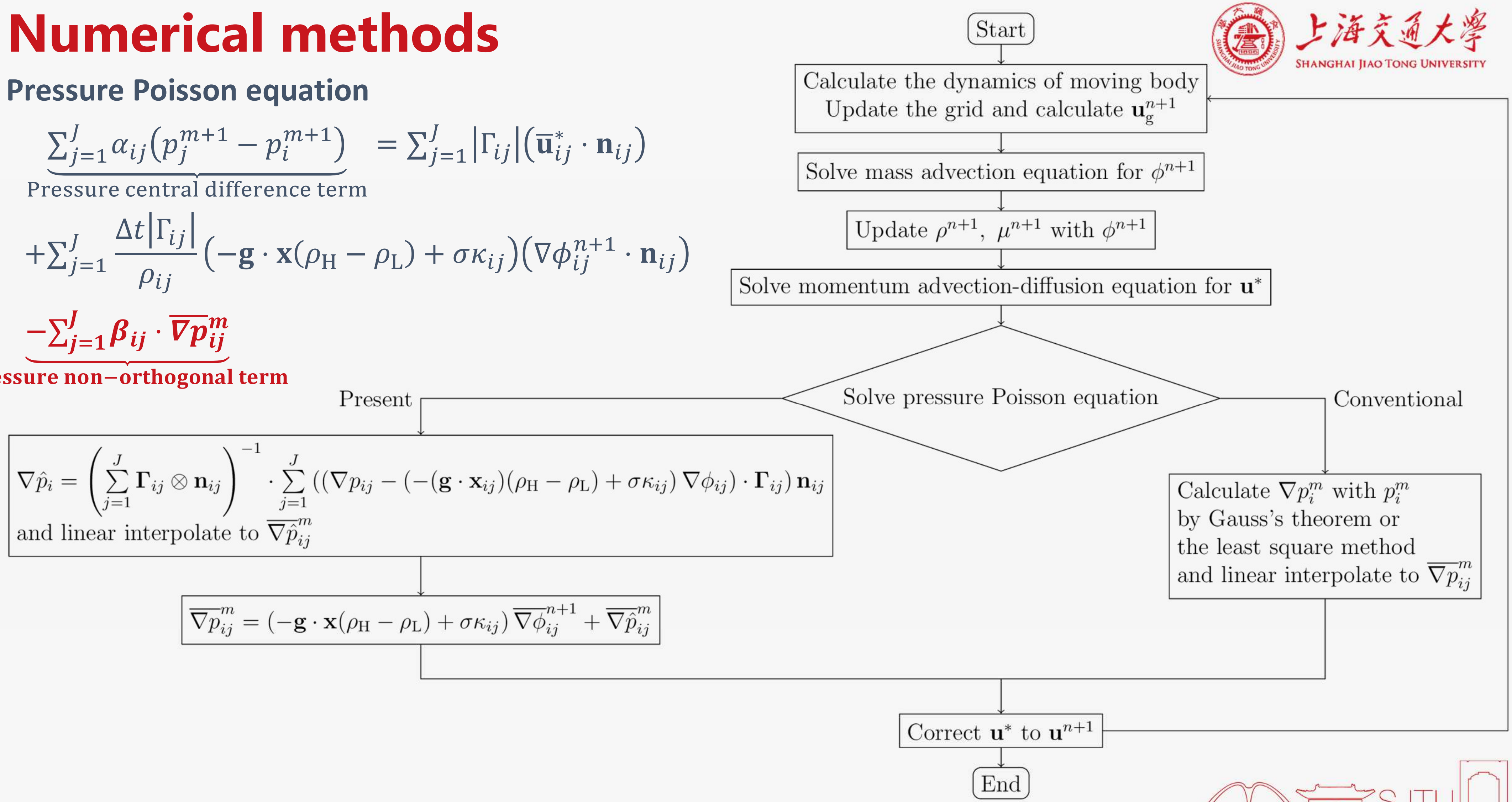
Numerical methods

Pressure Poisson equation

$$\underbrace{\sum_{j=1}^{J}\alpha_{ij}\left(p_j^{m+1}-p_i^{m+1}\right)}_{\text{Pressure central difference term}} = \sum_{j=1}^{J}\left|\Gamma_{ij}\right|\left(\overline{\mathbf{u}}_{ij}^{*}\cdot\mathbf{n}_{ij}\right)$$

$$+\sum_{j=1}^{J}\frac{\Delta t\left|\Gamma_{ij}\right|}{\rho_{ij}}\left(-\mathbf{g}\cdot\mathbf{x}(\rho_{\mathrm{H}}-\rho_{\mathrm{L}})+\sigma\kappa_{ij}\right)\left(\nabla\phi_{ij}^{n+1}\cdot\mathbf{n}_{ij}\right)$$

$$\underbrace{-\sum_{j=1}^{J}\boldsymbol{\beta}_{ij}\cdot\overline{\nabla p}_{ij}^{m}}_{\text{Pressure non–orthogonal term}}$$



Numerical methods

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Numerical schemes

- Based on finite volume method for polyhedral unstructured grids
- Interface capturing scheme: **THINC/QQ** (The **T**angent of **H**yperbola for **IN**terface **C**apturing method with **Q**uadratic surface representation and Gaussian **Q**uadrature)
- Velocity discretization scheme: **FVMS3** (The **F**inite **V**olume method based on **M**erged **S**tencil with **3**rd-order reconstruction)
- **MLP** (**M**ulti-dimensional **L**imiting **P**rocess) and **BVD** (**B**oundary **V**ariation **D**iminishing)
- Generic balanced-force algorithm
- Time scheme: Third-order TVD Runge–Kutta scheme
- 6DoF body motions: Newmark's method

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Numerical tests

3D stationary water tank

Suppress the spurious velocity due to unbalance between pressure gradient and gravity force on unstructured grids

Equation: $\nabla p = -\mathbf{g}\cdot\mathbf{x}(\rho_H - \rho_L)\nabla\phi$

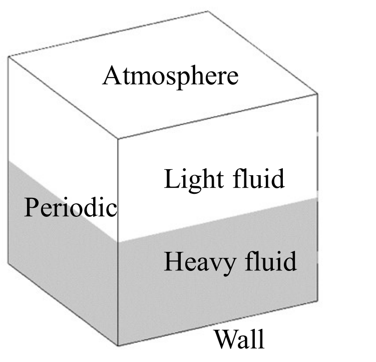
Computational domain: $[0,1]^3$

Fluid density ratio: $\rho_H/\rho_L = \mathbf{10^6}$

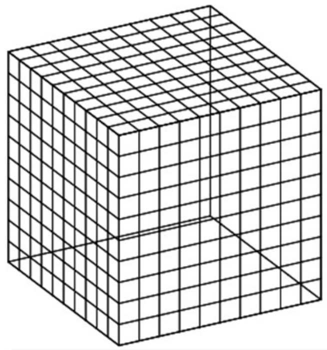
Theoretical solutions:

$\mathbf{u} = \mathbf{0}$

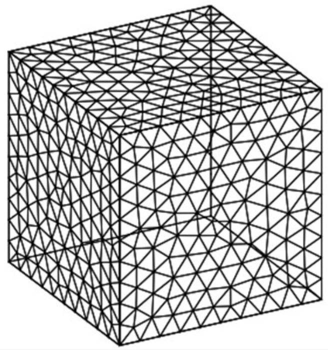
$$p = \begin{cases} \rho_L |g|(1-z), & y \ge 0.5 \\ 0.5\rho_L + \rho_H(1-y). & y < 0.5 \end{cases}$$



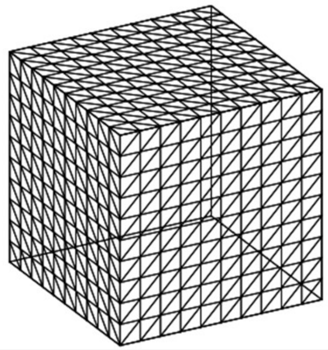
Sketch



grid A

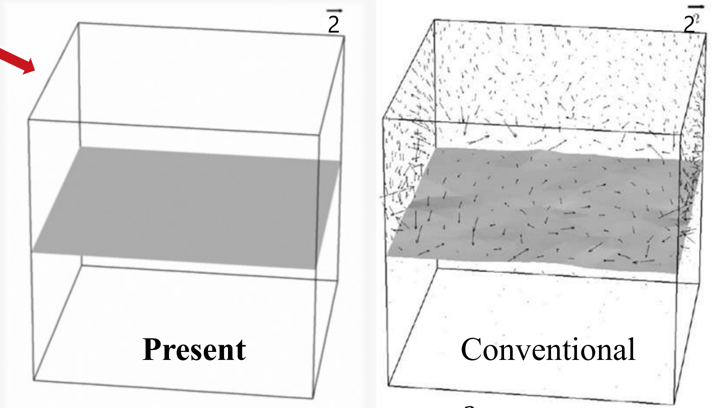


grid B



grid C

The spurious velocity is restraind to 10^{-8}



Animation of $\rho_H/\rho_L = 10^3$, CFL = 0.5

Numerical errors of velocity and pressure after 50 time steps with $\Delta t = 10^{-4}$.

Errors	Δx	Present balanced-force algorithm			Conventional balanced-force algorithm		
		grid A	grid B	grid C	grid A	grid B	grid C
$L_\infty(\|\mathbf{u}\|)$	1/10	8.1267×10^{-11}	4.1897×10^{-8}	2.1938×10^{-9}	4.4166×10^{-11}	×	×
	1/20	9.6185×10^{-11}	1.7489×10^{-8}	3.4444×10^{-9}	9.6248×10^{-11}	×	×
	1/40	5.1181×10^{-10}	1.2987×10^{-8}	7.9295×10^{-9}	4.7424×10^{-10}	×	×
$L_2(p)$	1/10	5.2401×10^{-12}	4.0276×10^{-11}	2.3894×10^{-11}	1.2639×10^{-11}	×	×
	1/20	2.0837×10^{-12}	3.5804×10^{-12}	1.6252×10^{-11}	1.6878×10^{-12}	×	×
	1/40	8.5730×10^{-13}	1.3232×10^{-12}	2.1425×10^{-12}	8.2874×10^{-13}	×	×

where × denotes that the computation **diverges** and **compels to terminate halfway**.

Numerical tests

Suppress the spurious velocity due to unbalance between pressure gradient and surface tension force on unstructured grids

3D static drop in equilibrium

Equation: $\nabla p = \sigma\kappa\nabla\phi$

Drop radius: $R = 2$

Computational domain: $[0, 8]^3$

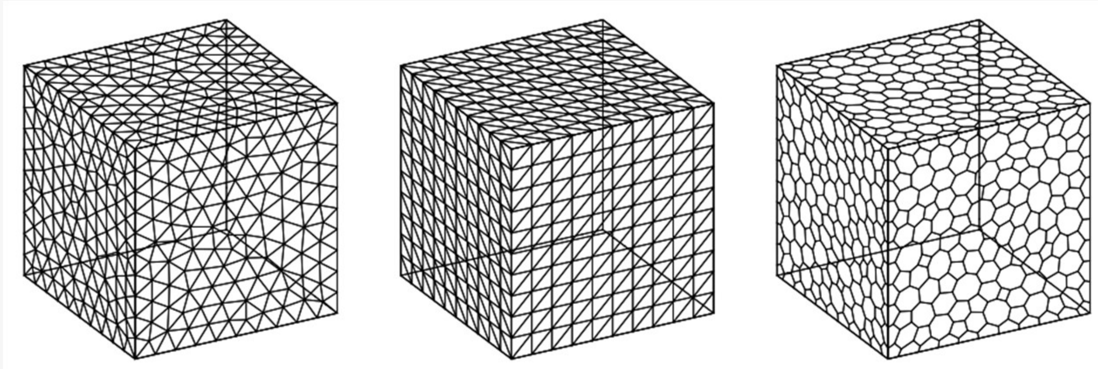
Fluid density ratio: $\rho_H/\rho_L = \mathbf{10^6}$

Surface tension coefficients: $\sigma = 73$

Theoretical solutions：

$\mathbf{u} = \mathbf{0}$

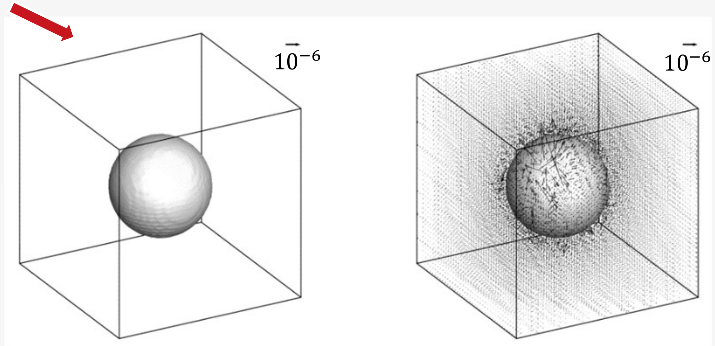
$\Delta p = 2\sigma/R$



The spurious velocity is restraind to 10^{-1}

Numerical errors of velocity and pressure after 1 time step with $\Delta t = 10^{-4}$.

	Loop	Δx	grid B $L_\infty(\lvert\mathbf{u}\rvert)$	grid B $L(\lvert\Delta p\rvert)$	grid C $L_\infty(\lvert\mathbf{u}\rvert)$	grid C $L(\lvert\Delta p\rvert)$	grid D $L_\infty(\lvert\mathbf{u}\rvert)$	grid D $L(\lvert\Delta p\rvert)$
Present	$m = 2$	1/10	6.0776×10^{-16}	2.4334×10^{-14}	3.4870×10^{-16}	2.7760×10^{-13}	4.5167×10^{-16}	7.9425×10^{-14}
		1/20	9.9517×10^{-16}	4.2243×10^{-14}	1.5055×10^{-16}	9.7724×10^{-14}	2.7619×10^{-16}	1.7715×10^{-14}
		1/40	9.8247×10^{-16}	2.8616×10^{-14}	2.7417×10^{-16}	8.4681×10^{-14}	5.7589×10^{-16}	1.0512×10^{-14}
Conventional	$m = 2$	1/10	1.6535×10^{-3}	3.8227×10^{-2}	5.6383×10^{-4}	5.5466×10^{-2}	3.4066×10^{-5}	2.3645×10^{-3}
		1/20	2.8578×10^{-3}	4.5069×10^{-2}	2.7807×10^{-3}	7.4548×10^{-2}	5.2566×10^{-5}	4.8507×10^{-3}
		1/40	7.6344×10^{-3}	7.6461×10^{-2}	5.5937×10^{-3}	1.1431×10^{-1}	2.4797×10^{-4}	1.0910×10^{-2}
	$m = 10$	1/10	2.9079×10^{-5}	6.6186×10^{-4}	2.2748×10^{-6}	2.1645×10^{-4}	3.4560×10^{-11}	5.8241×10^{-10}
		1/20	2.4094×10^{-4}	2.5389×10^{-3}	1.0332×10^{-5}	8.6706×10^{-4}	2.1788×10^{-12}	1.4114×10^{-10}
		1/40	1.0873×10^{-3}	7.6657×10^{-3}	3.5426×10^{-5}	1.1219×10^{-3}	5.3945×10^{-12}	2.1383×10^{-10}



Numerical tests

2D water entry of an inclined free-falling

Restrain the instability and divergence induced by strong nonlinearity during FSI

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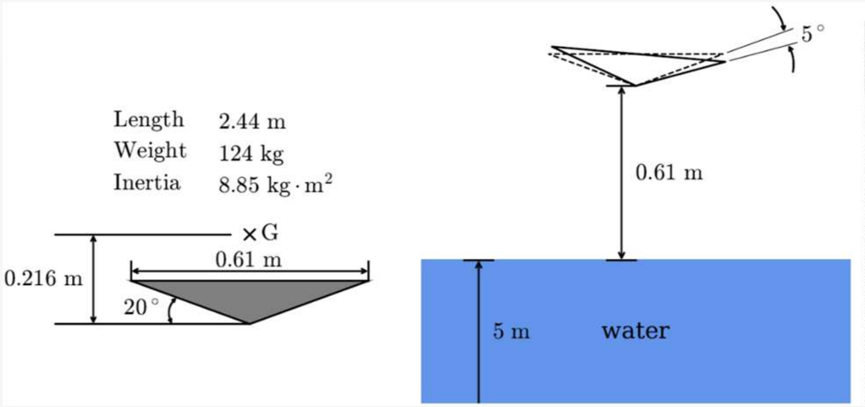
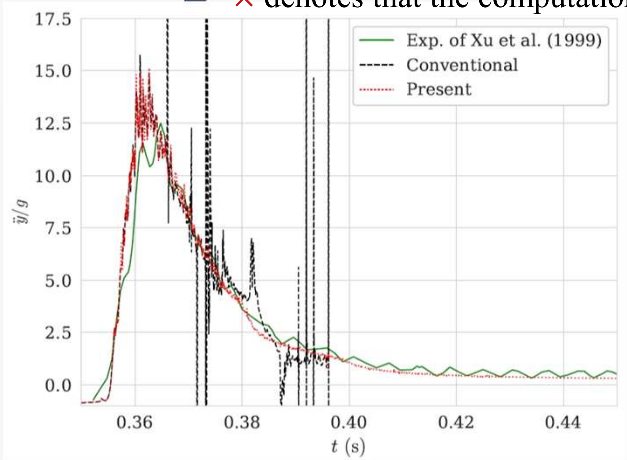
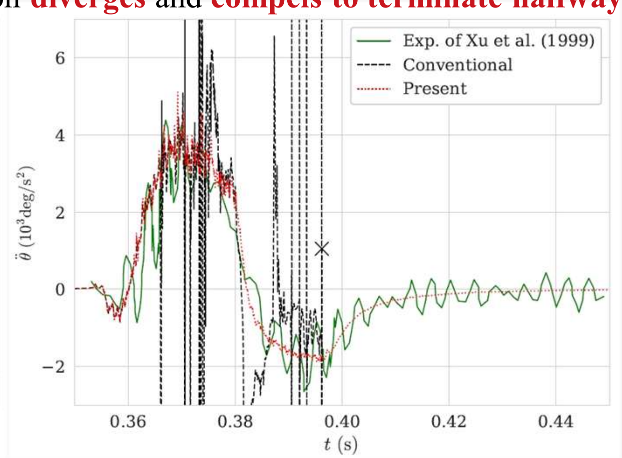
× denotes that the computation **diverges** and **compels to terminate halfway**



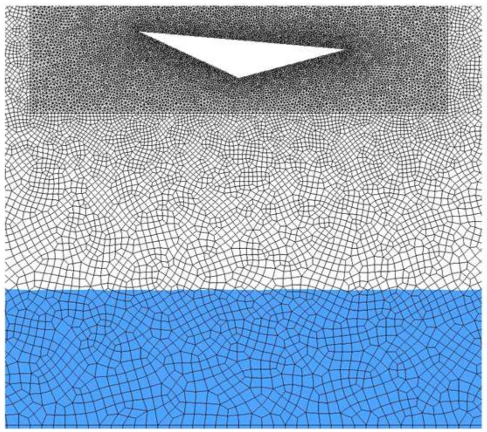
Sketch at $t = 0$



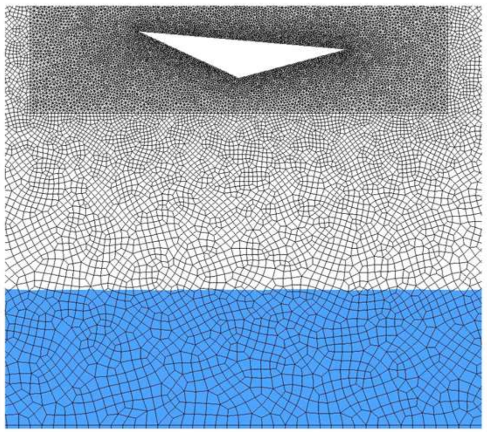
Vertical acceleration



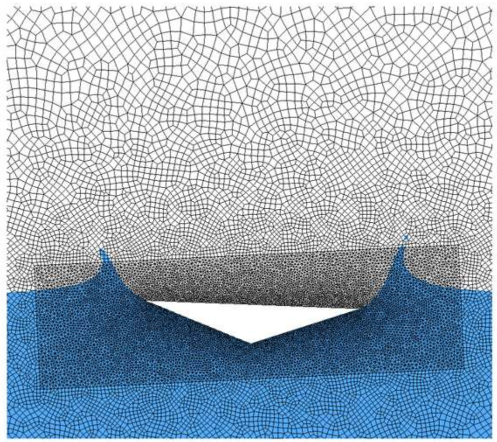
Angular acceleration



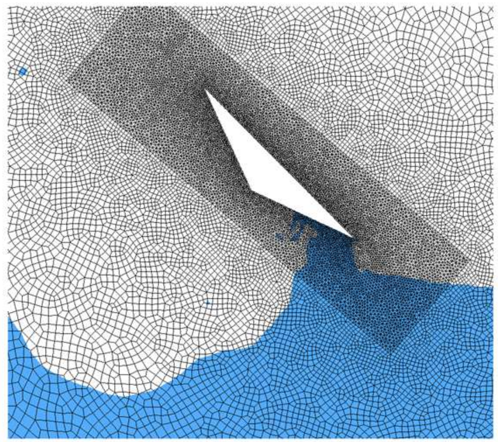
Present



Conventional



Present at $t = 0.45$

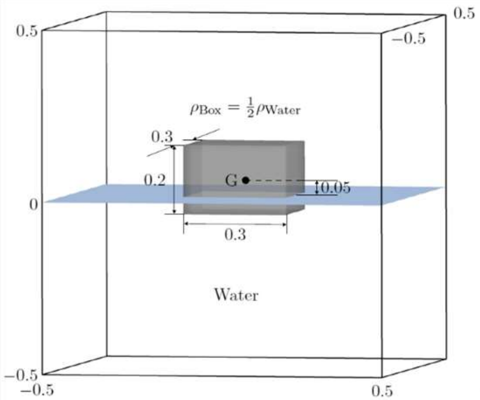


Conventional at $t = 0.4$

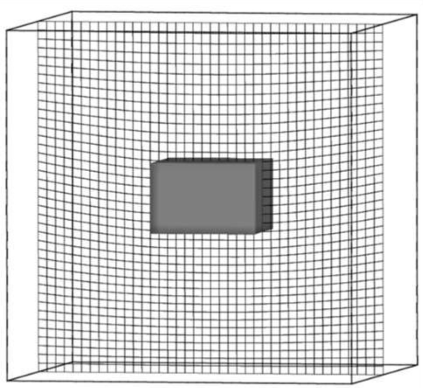
Numerical tests

3D floating box

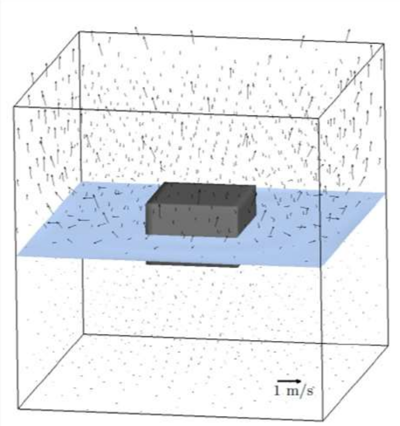
Suppress the spurious velocity due to mesh movement and deformation



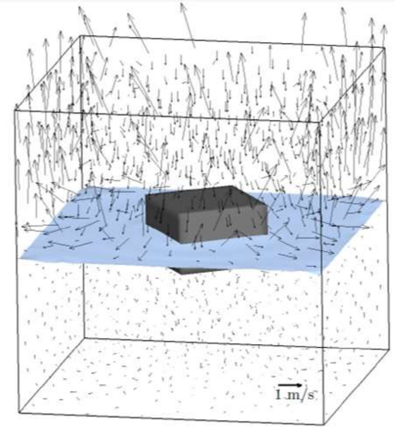
Sketch at $t = 0$



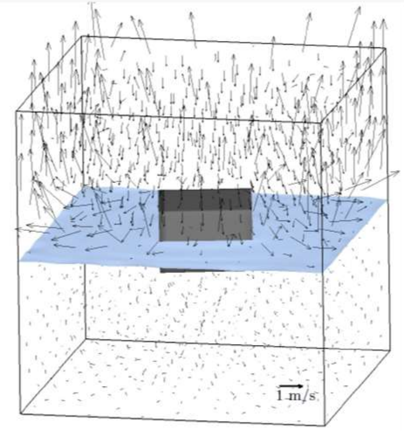
Mesh at position of equilibrium



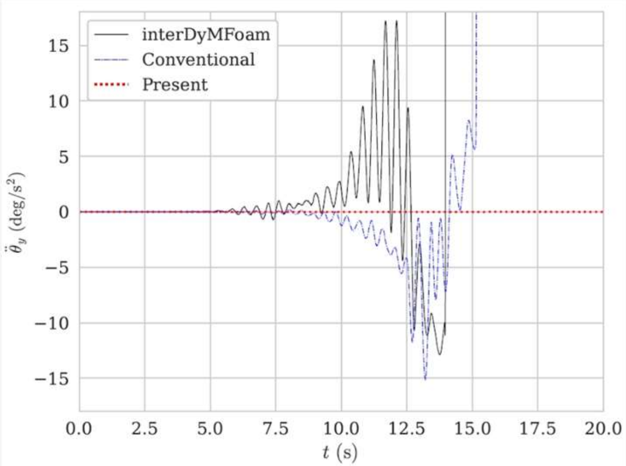
Present



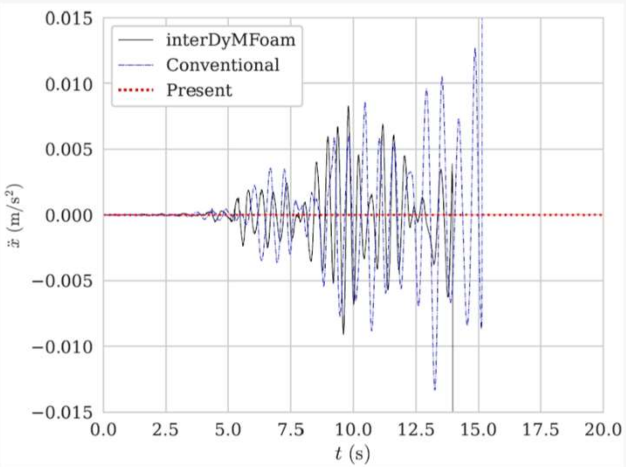
Conventional



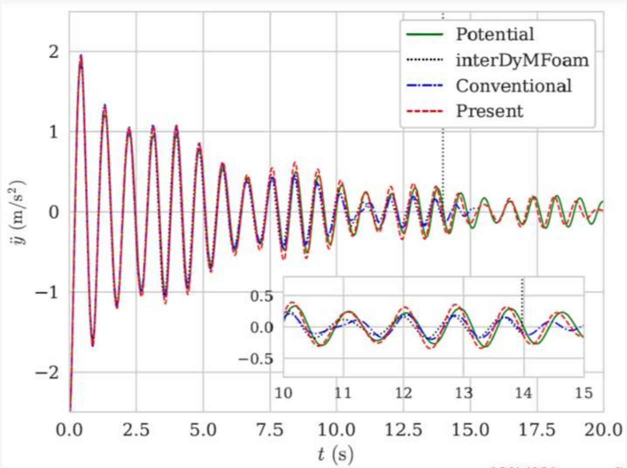
interDyMFoam



Angular acceleration in y-direction



Velocity acceleration in x-direction



Velocity acceleration in y-direction

The computations of conventional algorithm and interDyMFoam solver **diverge and compel to terminate halfway.**

Numerical tests

Provide more accurate and robust predictions for multiphase FSI

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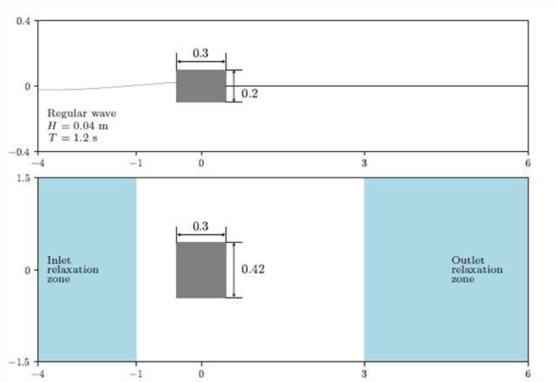
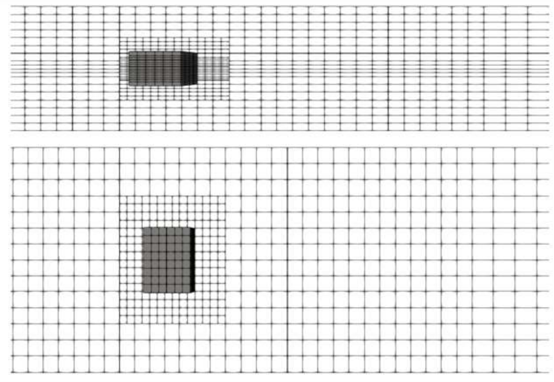
3D wave-induced motions of a floating body

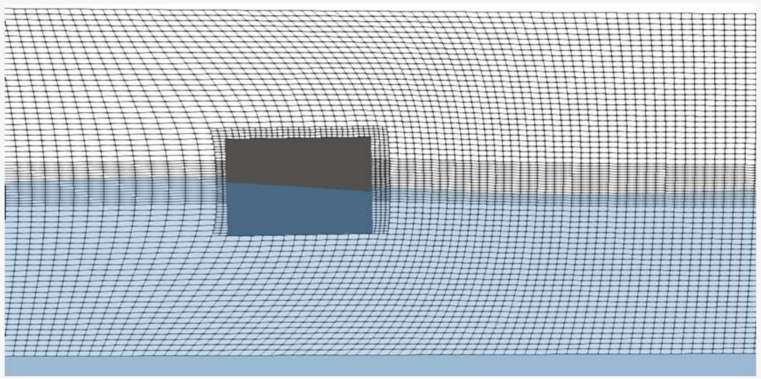
- Regular wave: $H = 0.04$ m, $T = 1.2$ s



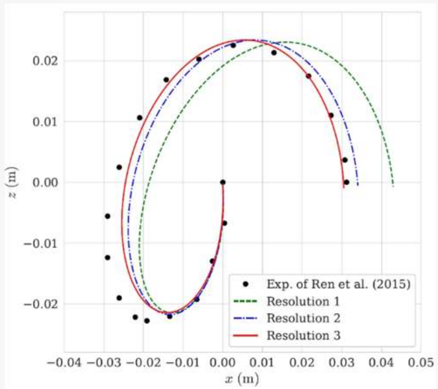
Sketch at $t = 0$



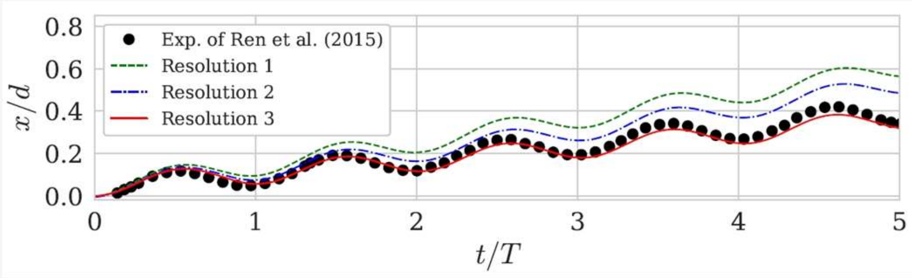
Mesh at $t = 0$



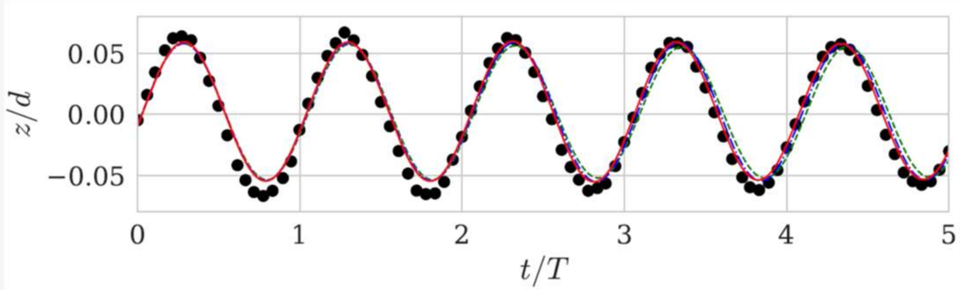
Object motion in $2T$



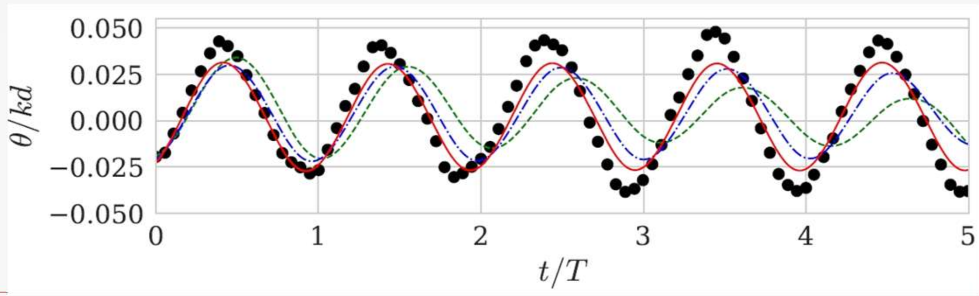
Centroid trajectories in $1T$



Sway



Heave



Roll

Numerical tests

Provide more accurate and robust predictions for practical applications

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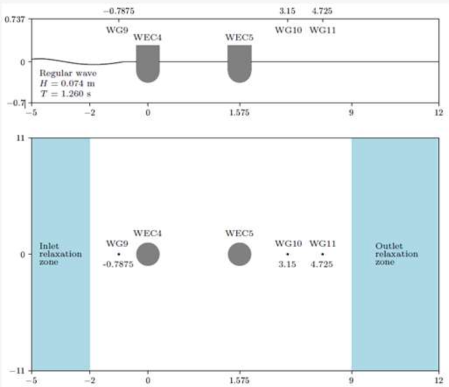
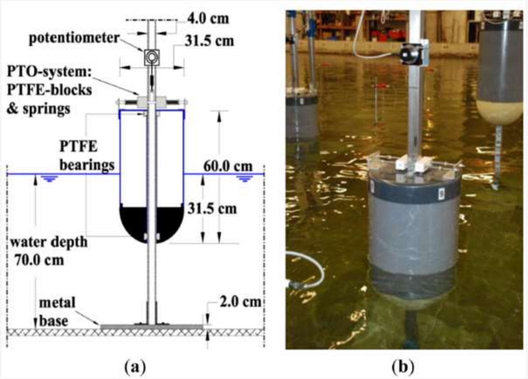
Two wave energy converters interaction with regular waves

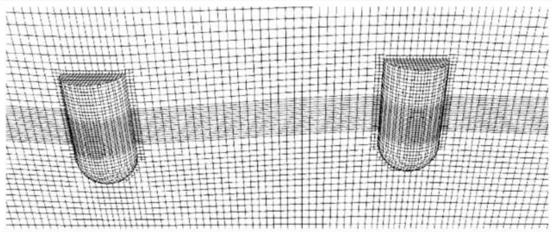
- Regular wave: $H = 0.074$ m, $T = 1.26$ s
- $F_{\mathrm{PTO}} = -\mu F_{\mathrm{Spring}} \mathrm{sign}(w(t)) = -\mu(4k_{\mathrm{Spring}} \mathrm{d}l)\mathrm{sign}(w(t))$
- $F_{\mathrm{Bearing}} = -\mu \mathrm{abs}(F_{\mathrm{Surge}}(\mathrm{t}))\mathrm{sign}(w(t))$
- $F_{\mathrm{Linear}} = -c_{\mathrm{Damping}} w(t)$



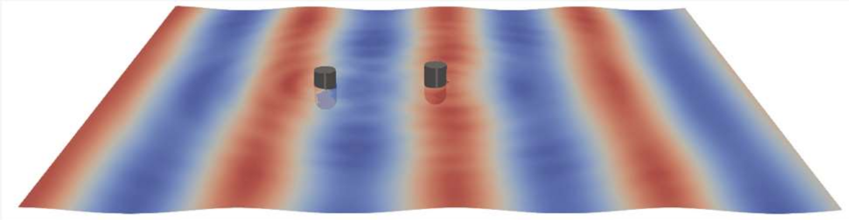
Sketch at $t = 0$



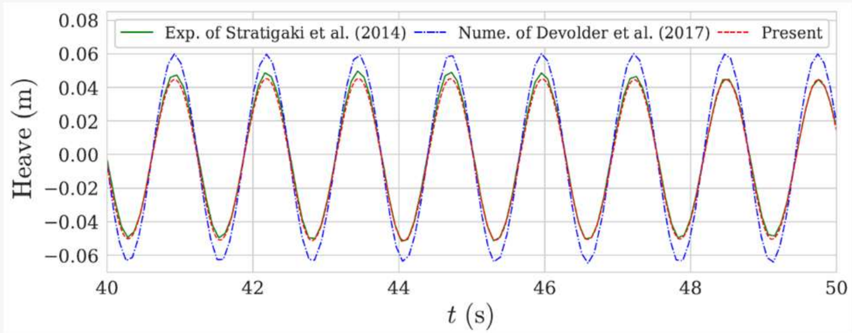
Experiment from Stratigaki el al. (*Energies. 2014; 7(2):701-734*)



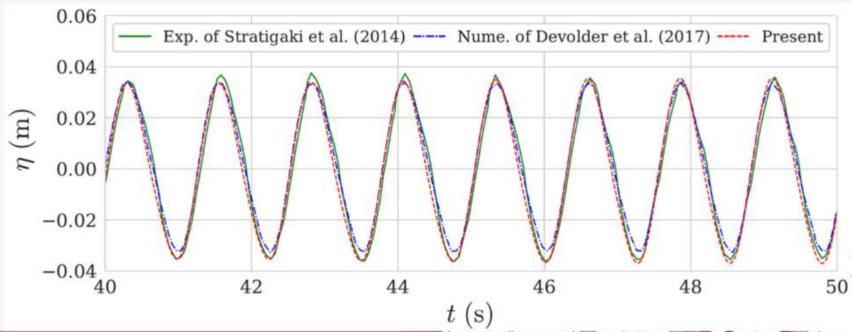
Mesh at $t = 40$ s



Heave of WEC4



Surface elevation



Conclusion

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A generic balanced-force algorithm for FSI problems

- considerably **suppresses the spurious velocity** due to the mesh non-orthogonality for multiphase flows in moving mesh configurations
- effectually **restrains the instability and divergence** induced by large mesh deformation and non-linearity during FSI simulations
- offers a promising platform to provide **more accurate and robust predictions** for practical multiphase flow simulations involving strong fluid-structure interactions

https://doi.org/10.1016/j.jcp.2023.112010

http://dx.doi.org/10.2139/ssrn.4668121

SJTU

Thanks for your attention!