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Study on dynamic behaviors of liquid-filled flexible multibody systems under low-gravity environment

Weizhen Kong Qiang Tian

School of Aerospace Engineering
Beijing Institute of Technology

Email: weizhen_kong@aliyun.com

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3 Cases

4 Conclusions

Introduction

Rigid body

Spacecraft

Liquid fuel

Flexible attachments

motion

Rigid-liquid-flexible coupled spacecraft system

sloshing

Spacecraft flight stability

In-orbit spacecraft attitude control

Introduction

Methods of liquid sloshing

- Volume of fluid (VOF) method
- Finite element method (FEM)
- Boundary element method (BEM)
- Smoothed particle hydrodynamics（SPH）method

With large amplitude

Sloshing + low-gravity ?

Modeling of flexible attachments

Absolute nodal coordinate formulation (ANCF) is popular to study flexible multibody systems

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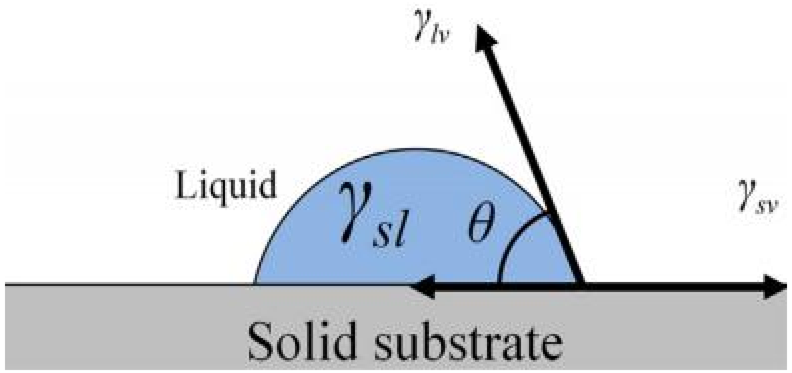
Method

Liquid sloshing dynamics under a low gravity field experiences different problems from those encountered under regular gravitational field. These problems include the reorientation of the liquid in its container and difficulty of moving and handing it, since the body forces are almost negligible. In a low gravity field, the surface tension is dominant.

CSF model[1]: $$\frac{d\mathbf{v}_i^{(s)}}{dt} = -\frac{\alpha_i}{m_i}\kappa_i \nabla c_i$$

Contact angle quantifies the wettability of solid surface by a liquid, and it is usually considered in aerospace field [2]



[1] Adami S, Hu X Y, Adams N A. A new surface-tension formulation for multi-phase SPH using a reproducing divergence approximation[J]. Journal of Computational Physics, 2010, 229(13):5011-5021.

[2] Breinlinger T, Polfer P, Hashibon A, et al. Surface tension and wetting effects with smoothed particle hydrodynamics[J]. Journal of Computational Physics, 2013, 243(12):14-27.

Method

Governing equations

Continuity equation: $$\frac{d\rho}{dt} = -\rho\nabla\cdot\boldsymbol{v}$$

Momentum equation: $$\frac{d\boldsymbol{v}}{dt} = \boldsymbol{g} + \frac{1}{\rho}\left[-\nabla p + \boldsymbol{F}^{(v)} + \boldsymbol{F}^{(s)}\right]$$

$$\rho_i = m_i \sum_j W_{ij}$$

$$\frac{d\boldsymbol{v}_i^{(p)}}{dt} = -\frac{1}{\rho_i}\nabla p_i = -\frac{1}{m_i}\sum_j \left(V_i^2 + V_j^2\right)\frac{\rho_i p_j + \rho_j p_i}{\rho_i + \rho_j}\nabla_i W_{ij}$$

$$\frac{d\boldsymbol{v}_i^{(v)}}{dt} = \nu_i \nabla^2 \boldsymbol{v}_i = \frac{1}{m_i}\sum_j \frac{2\eta_i\eta_j}{\eta_i + \eta_j}\left(V_i^2 + V_j^2\right)\frac{\boldsymbol{v}_{ij}}{r_{ij}}\frac{\partial W}{\partial r_{ij}}$$

$$\frac{d\boldsymbol{v}_i^{(s)}}{dt} = -\frac{\alpha_i}{m_i}\kappa_i \nabla c_i$$

Equation of state: $$p = \frac{c^2\rho_0}{\gamma}\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] + p_b$$

Renormalized Gaussian kernel function: $$W(\boldsymbol{r},h) = \begin{cases} \alpha_n\left[\dfrac{e^{-(\boldsymbol{r}/h)^2} - C_0}{1 - C_1}\right] & \text{if } \mathrm{r} \le 3\mathrm{h} \\ 0 & \text{otherwise} \end{cases}$$

Method

The modified prediction-correction time-stepping scheme [1]

1, the prediction step

$$\begin{cases} \rho_i^{n+1/2} = m_i \sum_j \left(W_{ij}\right)^n \\ \boldsymbol{v}_i^{n+1/2} = \boldsymbol{v}_i^n + \dfrac{\Delta t}{2}\left(\dfrac{d\boldsymbol{v}}{dt}\right)_i^n \\ \boldsymbol{r}_i^{n+1/2} = \boldsymbol{r}_i^n + \dfrac{\Delta t}{2}\boldsymbol{v}_i^{n+1/2} \end{cases}$$

2, the correction step

$$\begin{cases} \rho_i^{n+1} = m_i \sum_j \left(W_{ij}\right)^{n+1/2} \\ \boldsymbol{v}_i^{n+1} = \boldsymbol{v}_i^n + \Delta t\left(\dfrac{d\boldsymbol{v}}{dt}\right)_i^{n+1/2} \\ \boldsymbol{r}_i^{n+1/2} = \boldsymbol{r}_i^n + \Delta t \boldsymbol{v}_i^{n+1} \end{cases}$$

Boundary condition

Pressure of the wall particles is obtained by summation of all contributions of fluid particles f

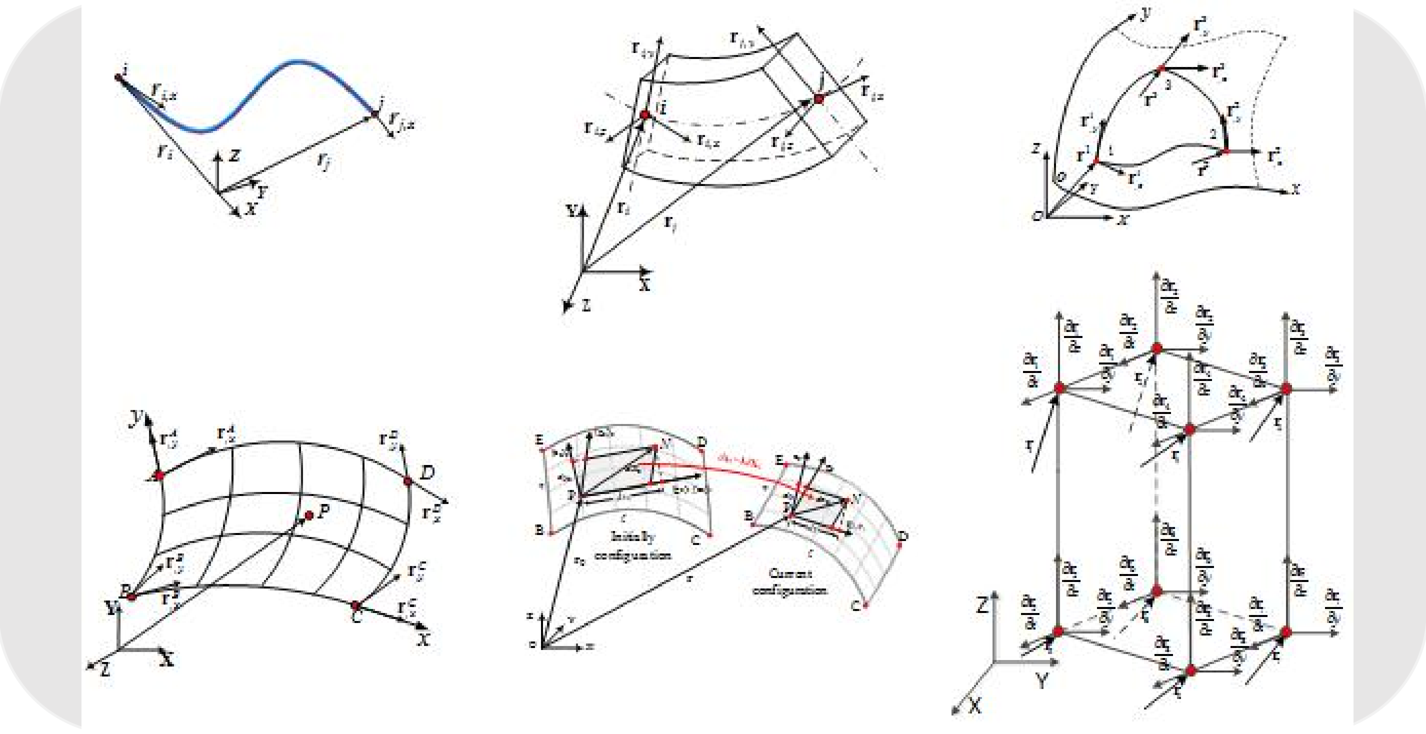
$$p_w = \frac{\sum_f p_f W_{wf} + (\boldsymbol{g} - \boldsymbol{a}_{\boldsymbol{w}}) \cdot \sum_f \rho_f \boldsymbol{r}_{\boldsymbol{wf}} W_{wf}}{\sum_f W_{wf}}$$

[1] Zhang A, Sun P, Ming F. An SPH modeling of bubble rising and coalescing in three dimensions[J]. Computer Methods in Applied Mechanics & Engineering, 2015, 294:189-209.

Method

Absolute Nodal Coordinate Formulation（ANCF）

1、An accurate and non-incremental finite element method initially proposed by Shabana
2、Higher-order shape functions of being able to describe large displacements
3、Position vector defined in the global frame of coordinates
4、A constant mass matrix and no explicit centrifugal and Coriolis forces

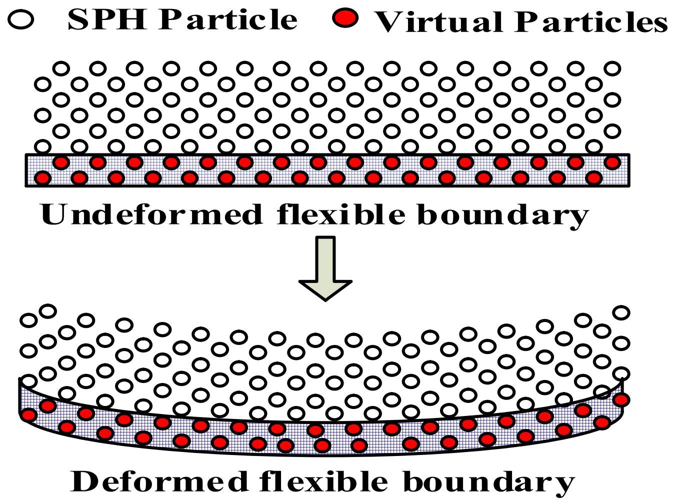


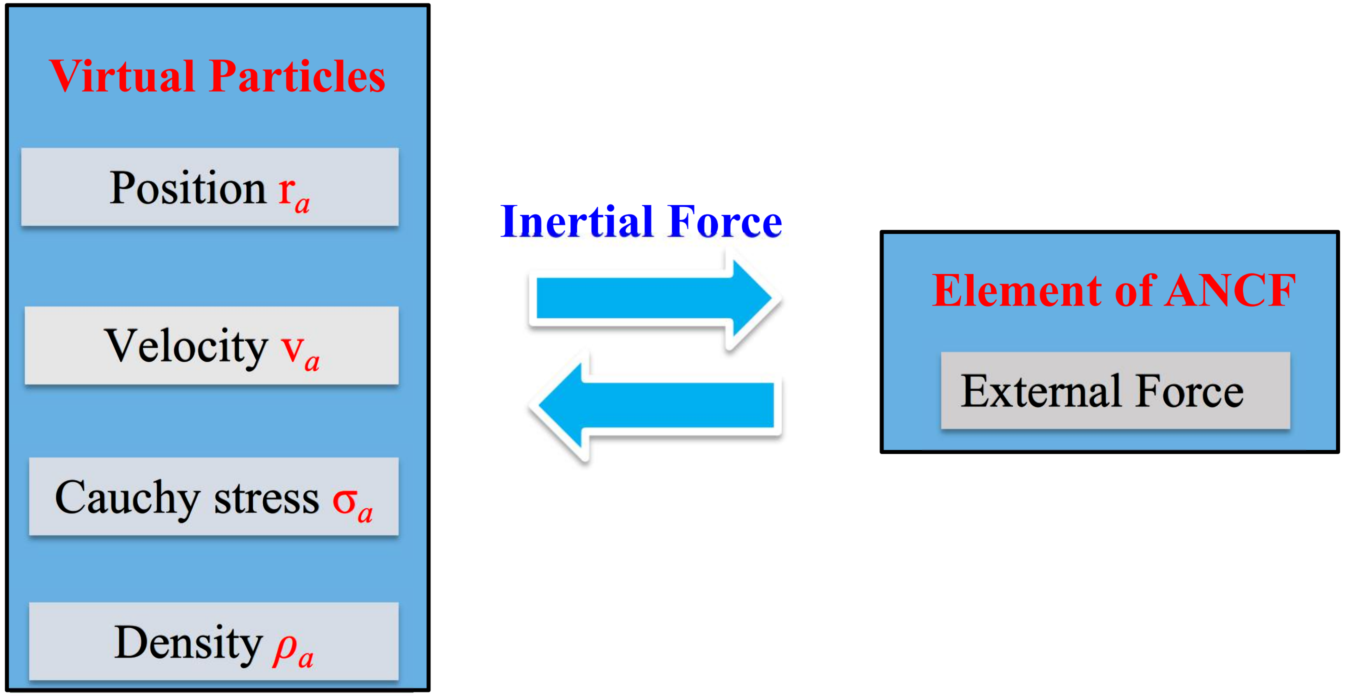
Method

Coupling for finite elements of ANCF and particles of SPH [1]

Transfer force

Prevent particles penetrate the border





[1]Hu W, Tian Q, Hu H. Dynamic simulation of liquid-filled flexible multibody systems via absolute nodal coordinate formulation and SPH method[J]. Nonlinear Dynamics, 2014, 75(4):653-671.

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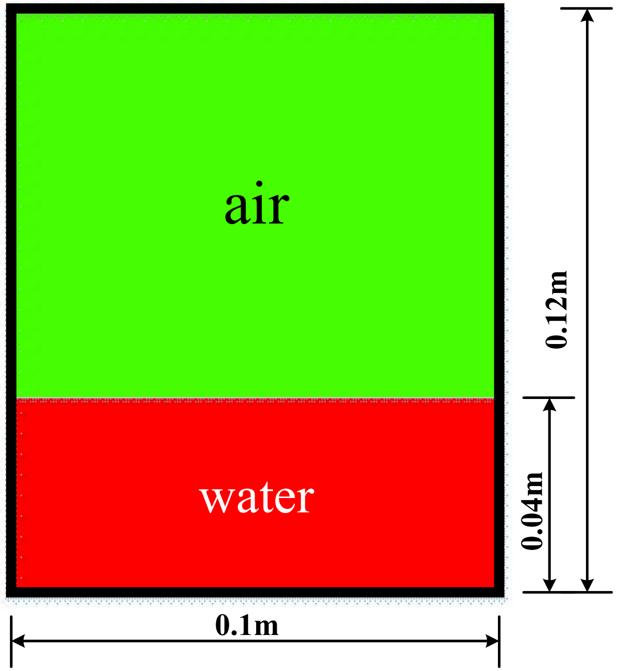
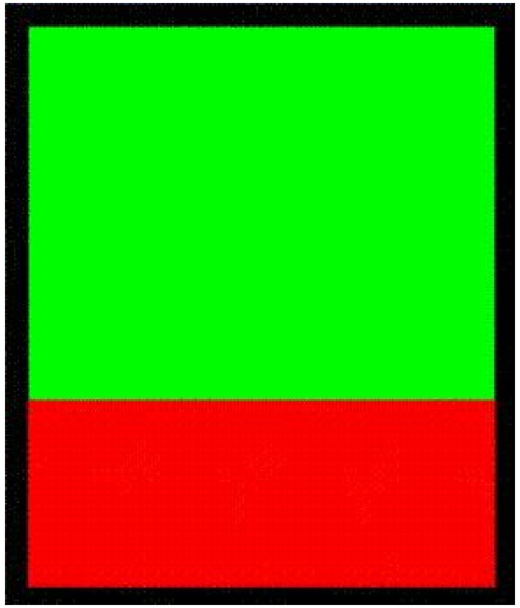
Cases

Case 1: 2D Flow induced by wall adhesion





water	1000kg/m³ / 1.002e-3
air	1.293kg/m³ / 1.709e-5
Surface tension coefficient	0.0727
Contact angle	5°
Initial spacing	0.001m
Gravity acceleration	0

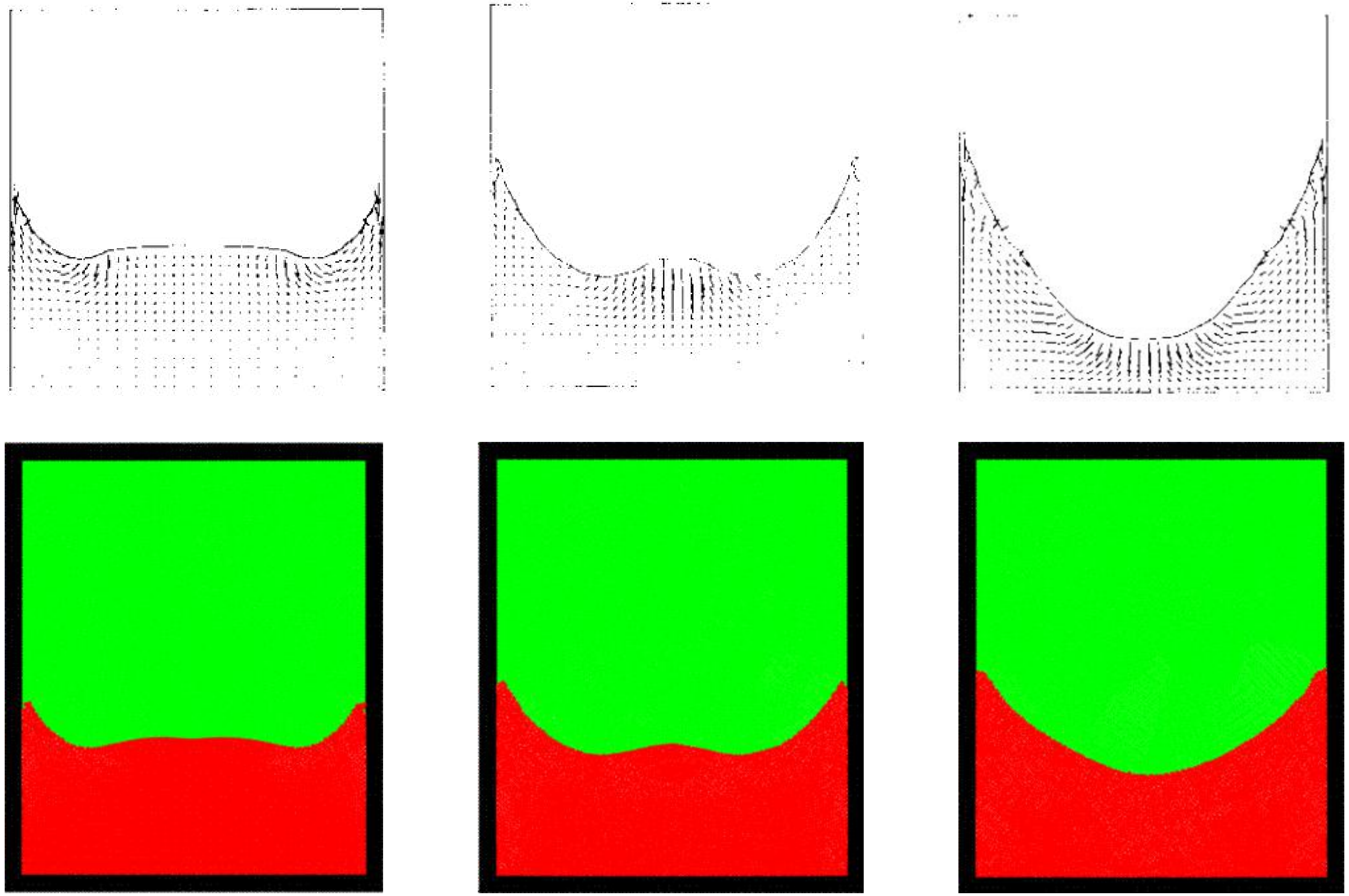
Water particles	4000
Air particles	12000
Boundary particles	2300
Time step(s)	1e-5
Simulation time(s)	3

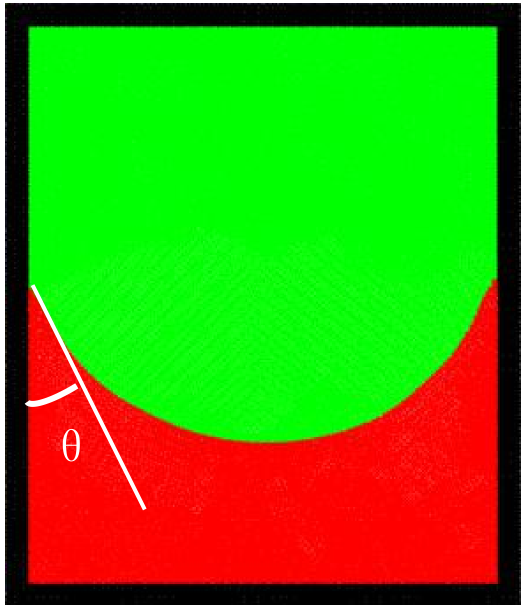
Cases

Case 1: 2D Flow induced by wall adhesion

VOF

SPH





θ >5°

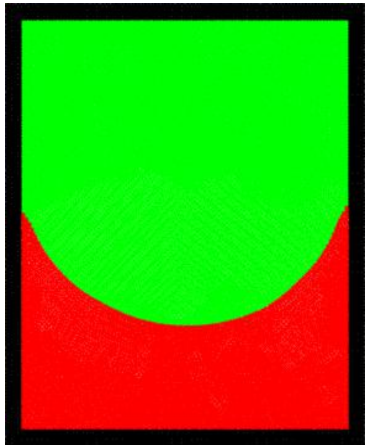
SPH has difficulties to describe the sparse contact regions。

Brackbill J U, Kothe D B, Zemach C. A continuum method for modeling surface tension [J]. Journal of Computational Physics, 1992, 100(2):335-354.

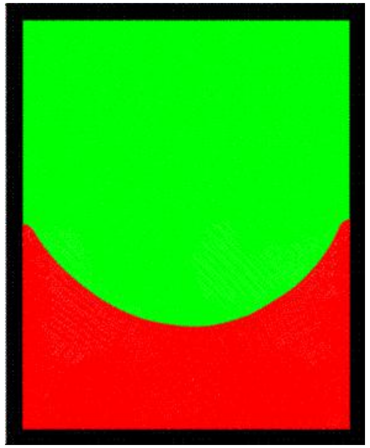
Cases

Case 1*: Comparison under different gravity

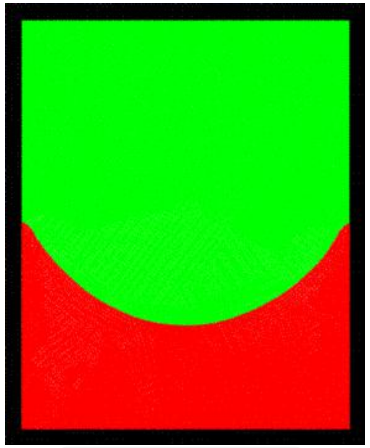
$g=\alpha * 9.81$



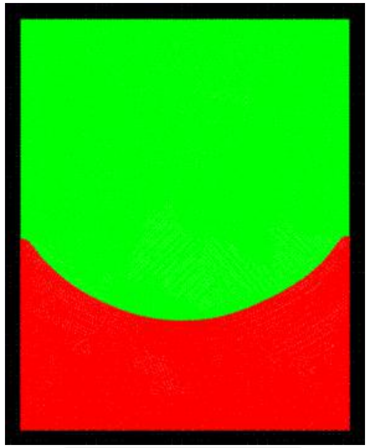
$\alpha=0$



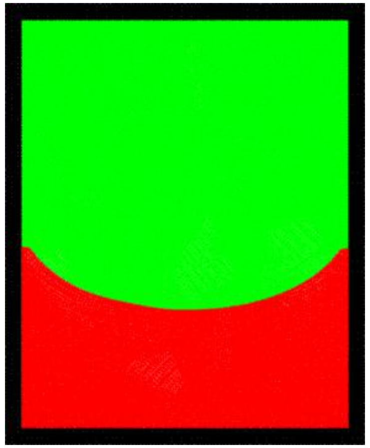
$\alpha=1e-5$



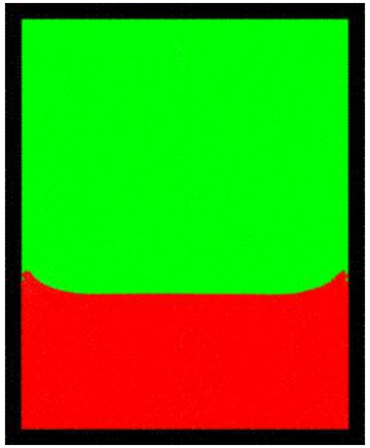
$\alpha=1e-4$



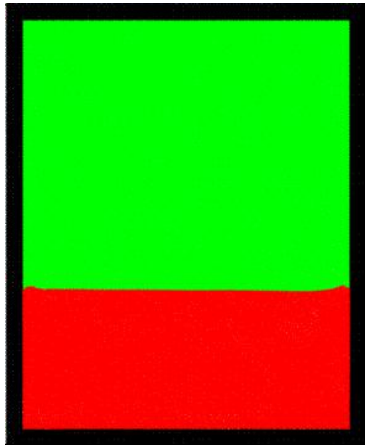
$\alpha=1e-3$



$\alpha=1e-2$



$\alpha=1e-1$



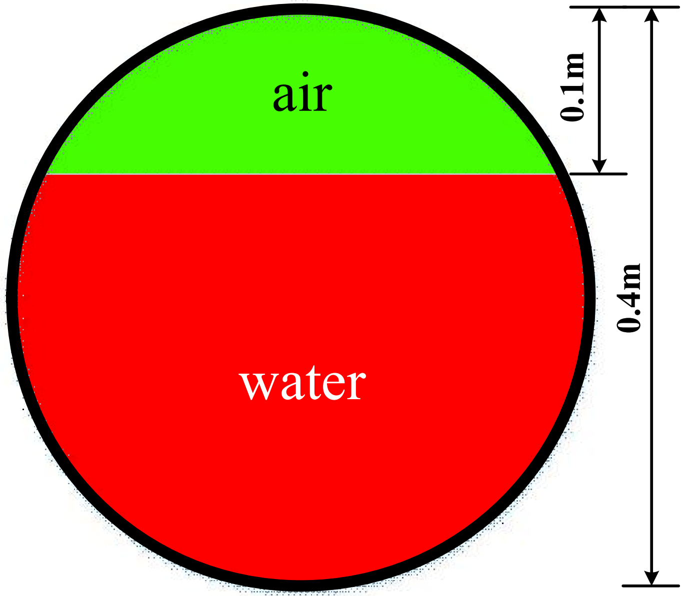
$\alpha=1$

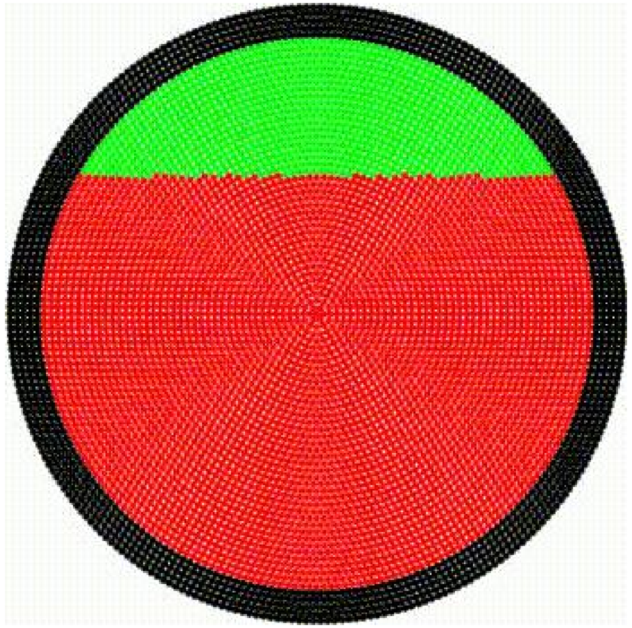
As g increases, the shape of the free surface of the water becomes more and more flat.

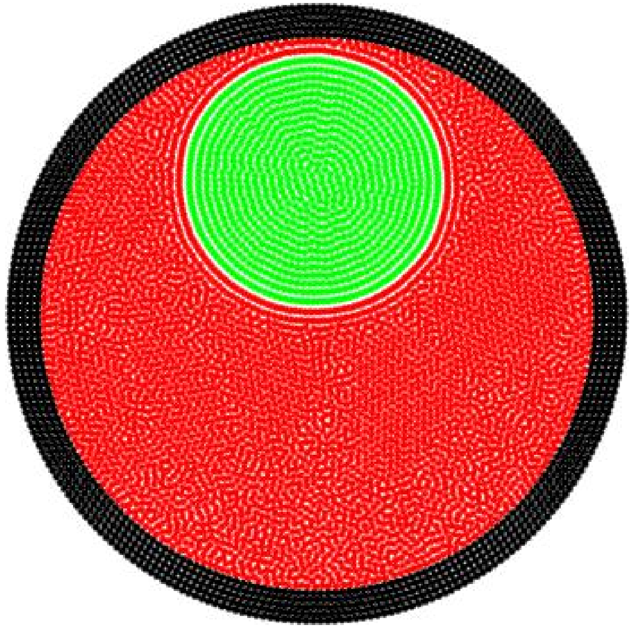
Cases

Case 2: 2D Cylindrical Tank

Yang A S. Investigation of liquid–gas interfacial shapes in reduced gravitational environments[J]. International Journal of Mechanical Sciences, 2008, 50(8):1304-1315.







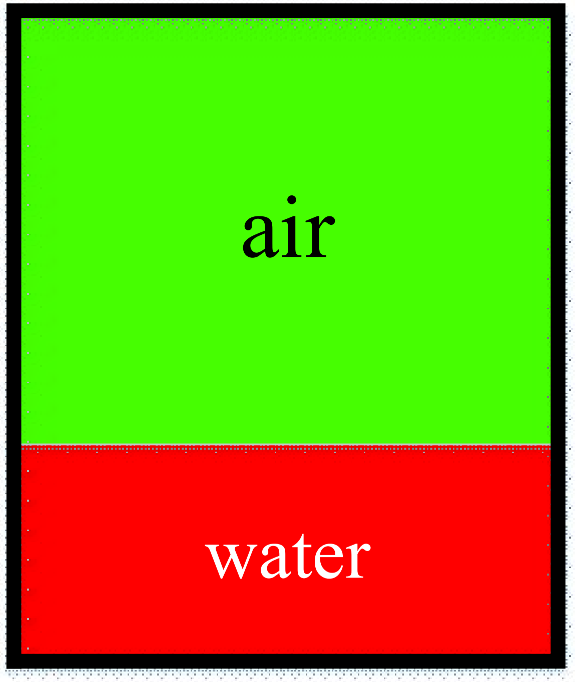
water	1000kg/m³ / 1.002e-3
air	1.293kg/m³ / 1.709e-5
Surface tension coefficient	0.0727
Contact angle	0°
Initial spacing	0.005m
Gravity acceleration	0

Water particles	3961
Air particles	12000
Boundary particles	1290
Time step(s)	1e-5

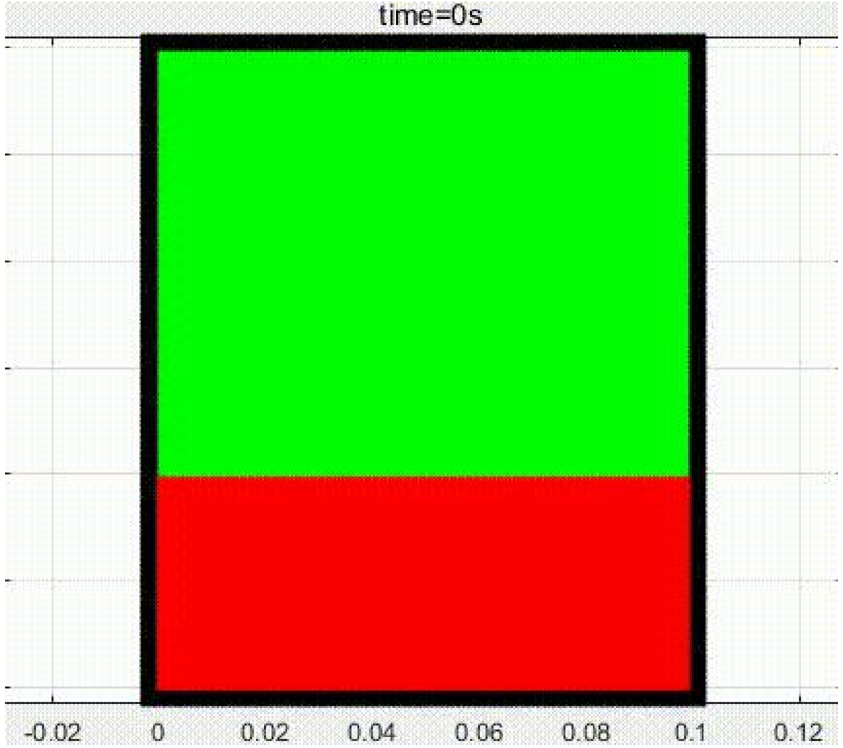
The bubble is circular。

Cases

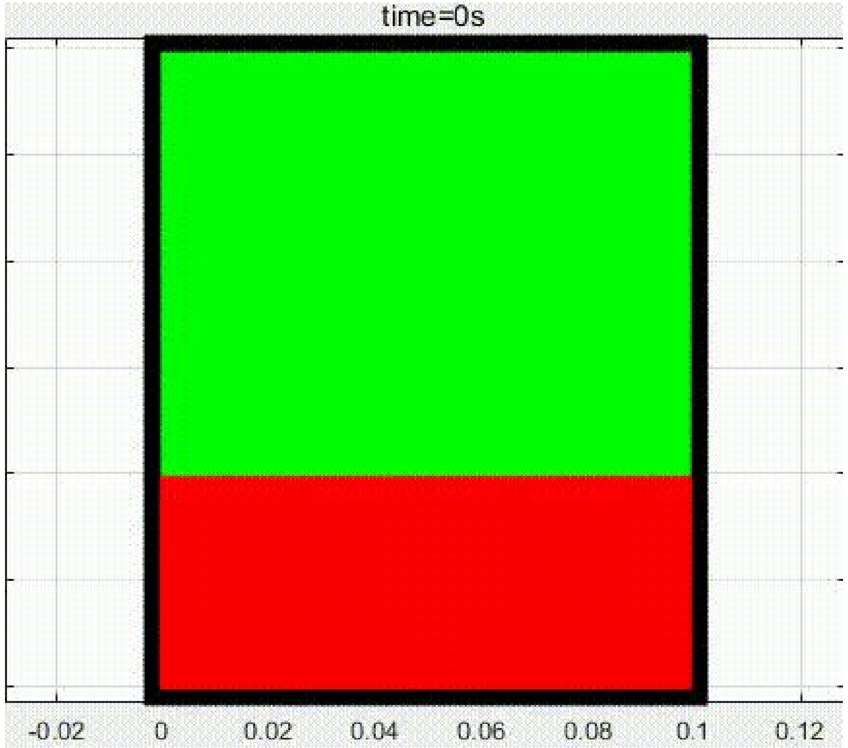
case 3: water-filled container subject to translational motion



$x = A\sin(\omega t)$



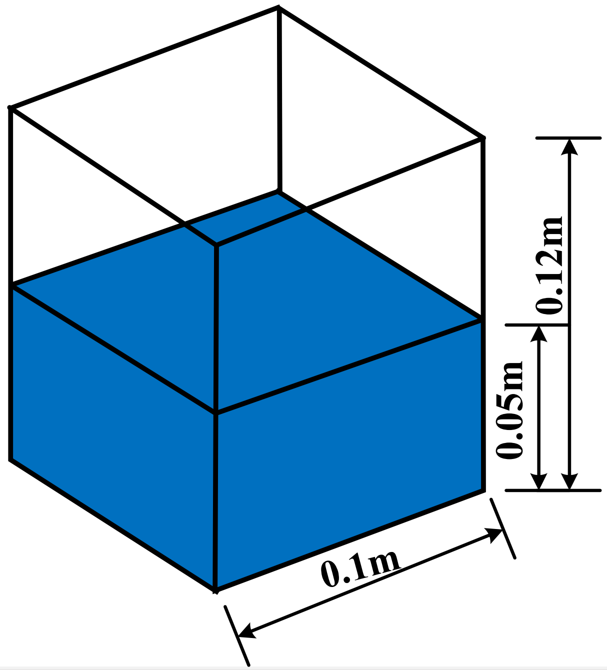
$x = 0.01\sin(\pi t)$

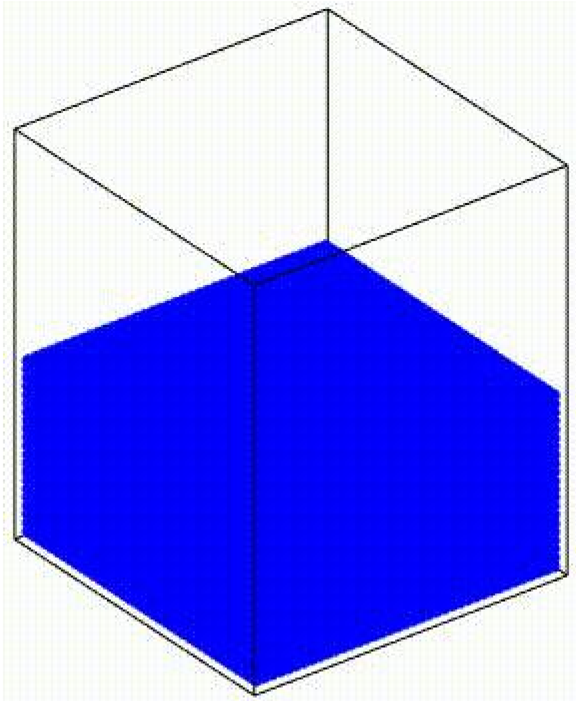


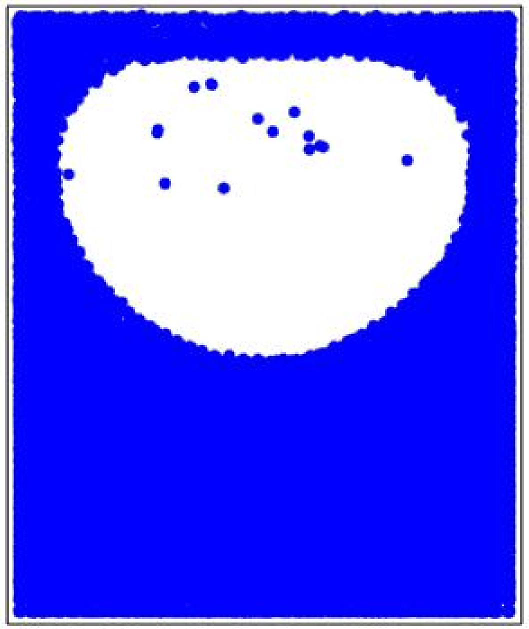
$x = 0.02\sin(\pi t)$

Cases

case 4: 3D Flow induced by wall adhesion







water	1000kg/m³ / 1.002e-3
air	1.293kg/m³ / 1.709e-5
Surface tension coefficient	0.0727
Contact angle	5°
Initial spacing	0.0025m
Gravity acceleration	0

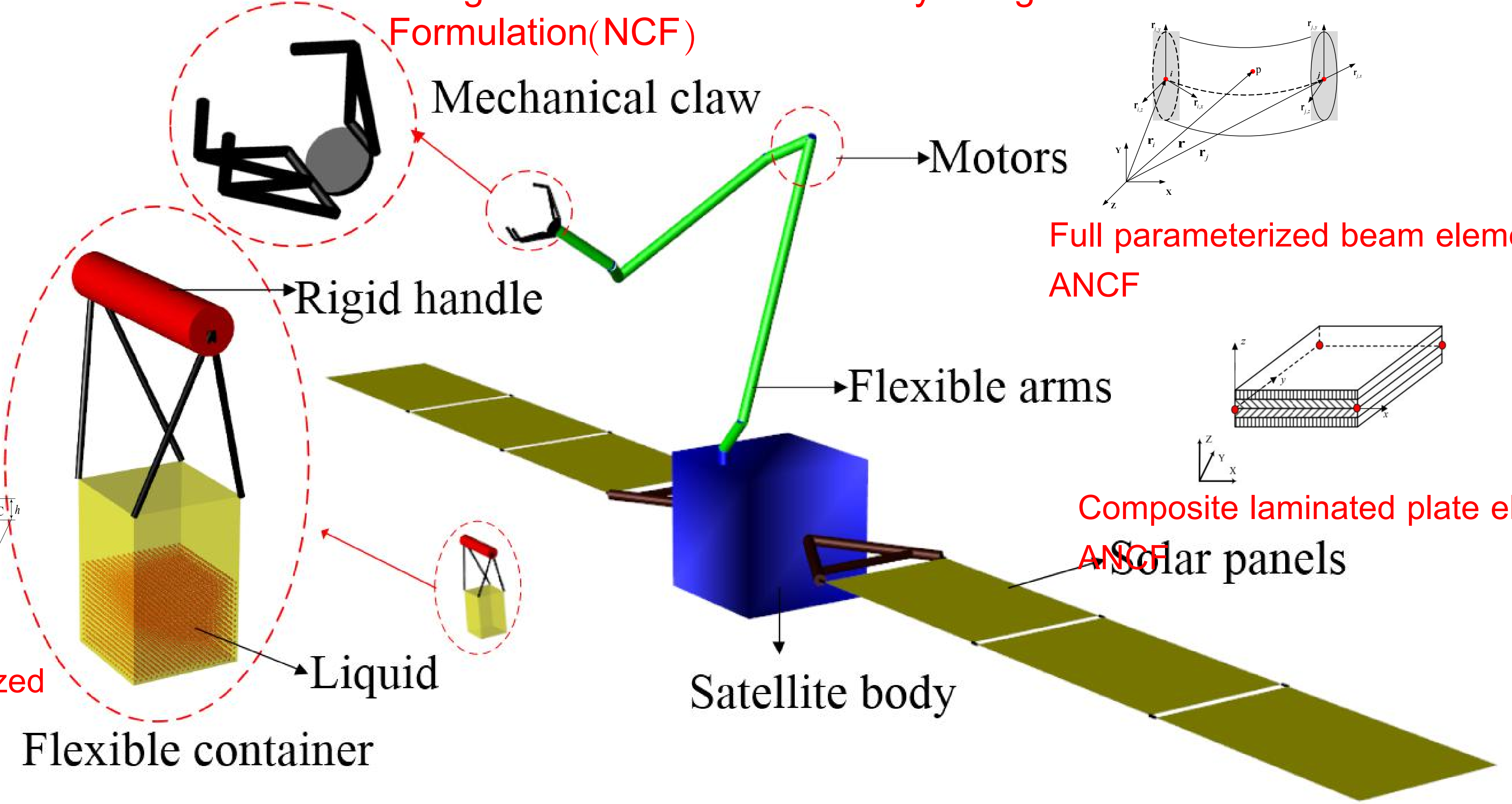
Water particles	31941
Air particles	39546
Boundary particles	22812
Time step(s)	1e-5

weizhen_kong@aliyun.com

Cases

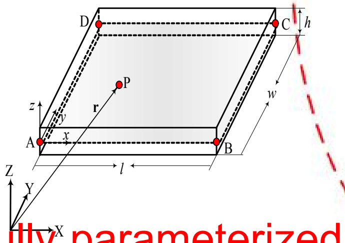
Case 5: rigid-liquid-flexible coupled spacecraft system

All rigid bodies are described by using Natural Coordinates Formulation(NCF)



Full parameterized beam element of ANCF

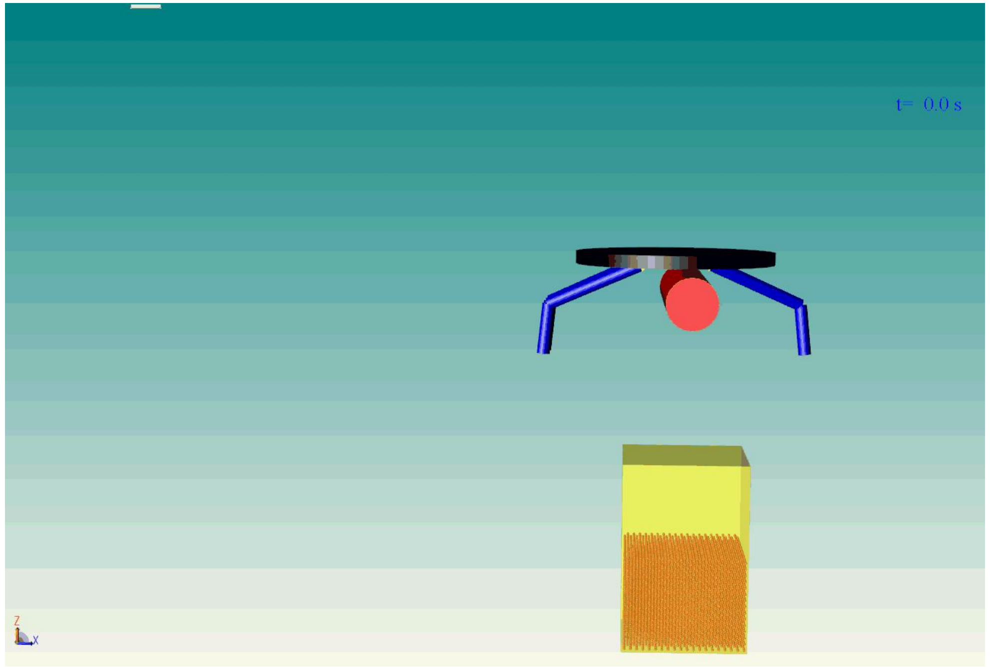
Composite laminated plate element of ANCF

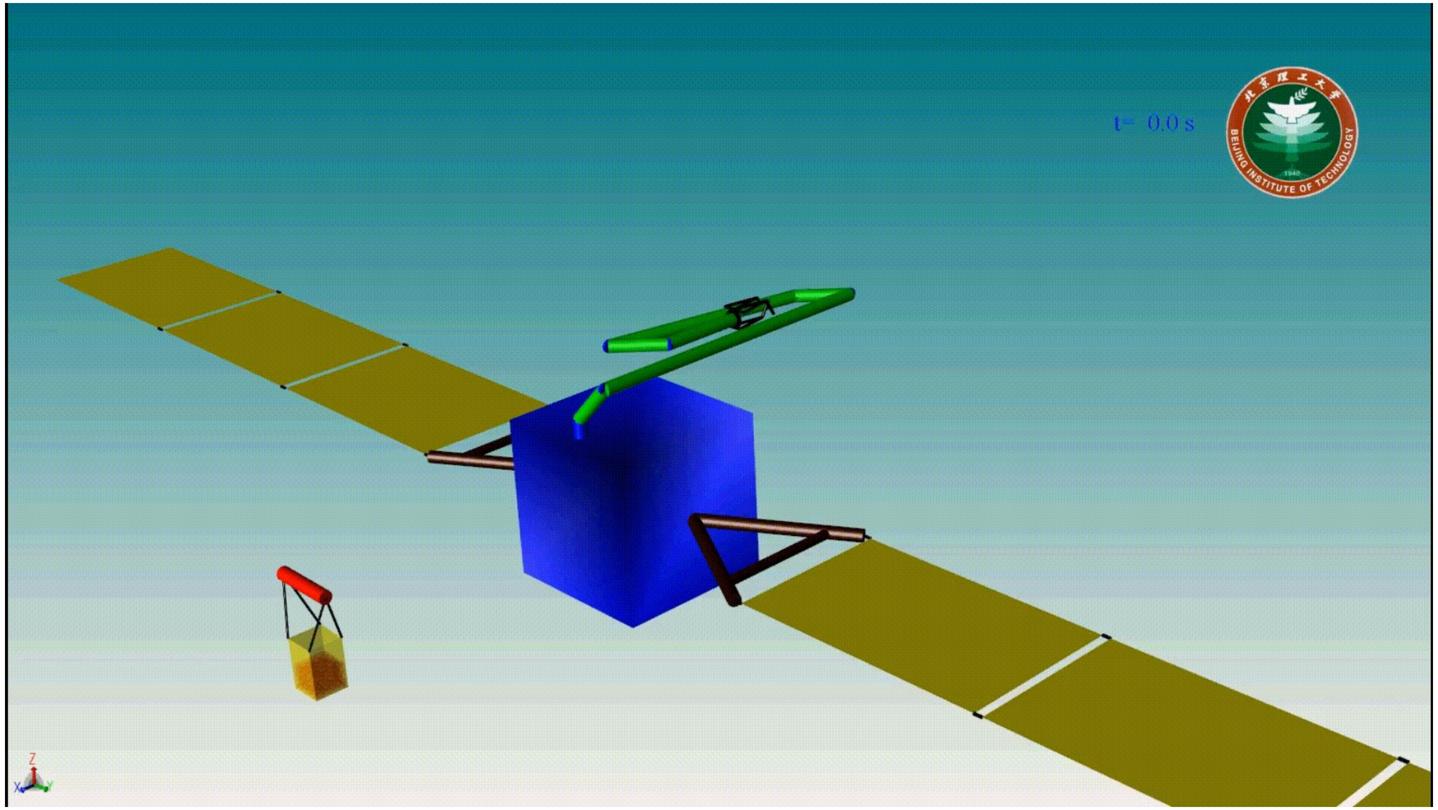


Fully parameterized shell element of ANCF

Cases

Case 5: rigid-liquid-flexible coupled spacecraft system





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Conclusions

1, Try to validate the efficiency and accuracy of using surface tension and contact angle in liquid sloshing problem;
2, Use SPH and ANCF to describe a complex rigid-liquid-flexible coupled spacecraft system and make it easier to study the influence of liquid sloshing to flexible multibody system.

Thanks for your attention

Weizhen Kong Qiang Tian

School of Aerospace Engineering
Beijing Institute of Technology

Email: weizhen_kong@aliyun.com

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