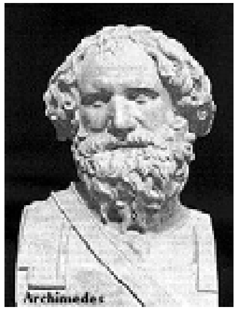
参考书

1. 吴子牛， 计算流体力学基本原理， 科学出版社，2002年

2. 任玉新，陈海昕，计算流体力学基础，清华大学出版社，2006年

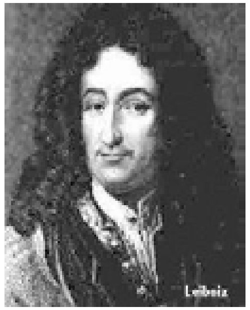
3. 张涵信 ，沈孟育，计算流体力学：差分方法的原理和应用， 国防工业出版社，2003年

Faces of Fluid Mechanics



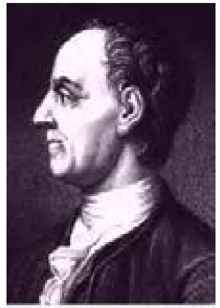
Archimedes
(C. 287-212 BC)

Newton
(1642-1727)

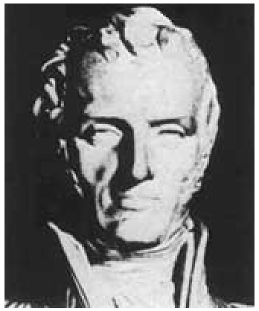


Leibniz
(1646-1716)

Bernoulli
(1667-1748)



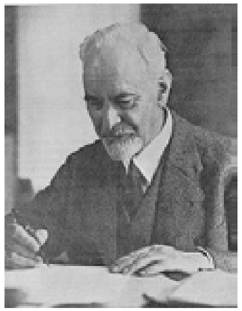
Euler
(1707-1783)



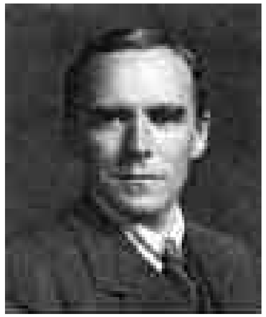
Navier
(1785-1836)

Stokes
(1819-1903)

Reynolds
(1842-1912)



Prandtl
(1875-1953)



Taylor
(1886-1975)

Kolmogorov
(1903-1987)

Conservation Laws

Physical principles

1. Mass is conserved
2. Newton's second law
3. Energy is conserved

Mathematical equations

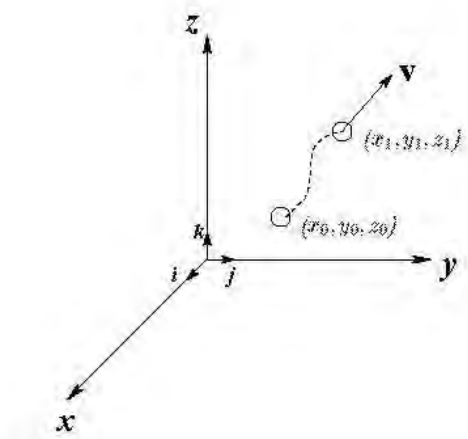
- continuity equation
- momentum equations
- energy equation

It is important to understand the meaning and significance of each equation in order to develop a good numerical method and properly interpret the results

Description of fluid motion

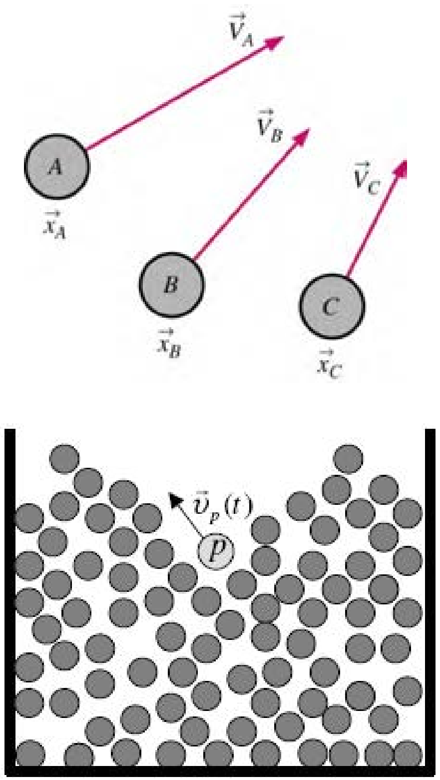
Eulerian monitor the flow characteristics in a fixed control volume

Lagrangian track individual fluid particles as they move through the flow field

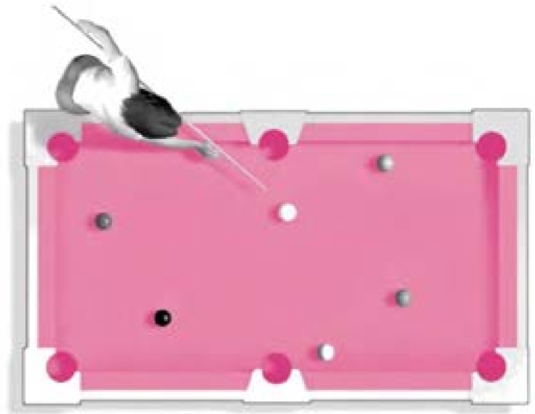


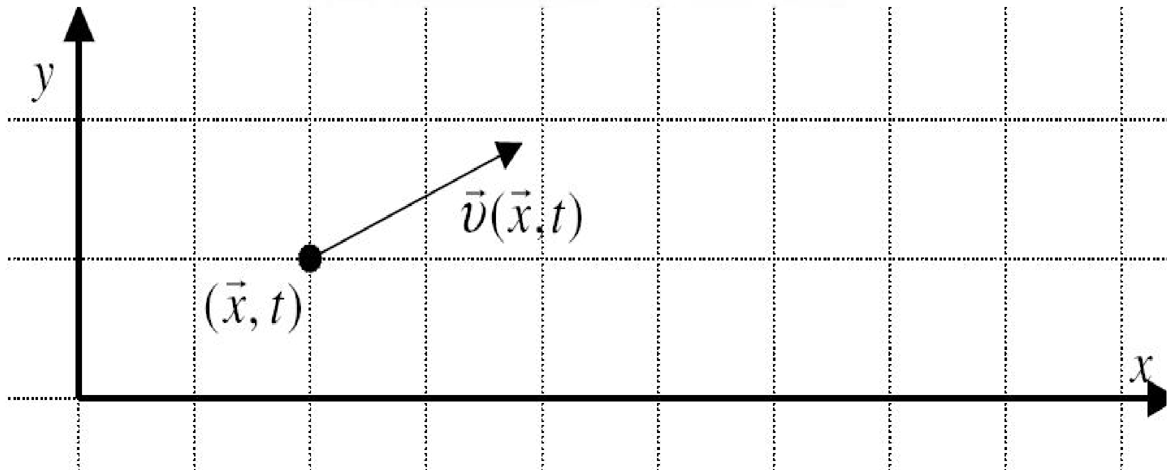
Two ways of describing a fluid flow:

Lagrangian description, Eulerian description



Lagrangian description; snapshot





Eulerian description; Cartesian grid

$$\underbrace{\frac{D}{Dt}}_{\text{Lagrangian}} \equiv \underbrace{\frac{\partial}{\partial t} + \overrightarrow{v_p} \cdot \nabla}_{\text{Eulerian}}$$

$$\underbrace{\frac{D\vec{G}}{Dt}}_{\substack{\text{Lagragian} \\ \text{rate of change}}} = \underbrace{\frac{\partial \vec{G}}{\partial t}}_{\substack{\text{Eulerian} \\ \text{rate of change}}} + \underbrace{\vec{v} \cdot \nabla \vec{G}}_{\substack{\text{Convective} \\ \text{rate of change}}}$$

$$\underbrace{\frac{D\vec{v}}{Dt}}_{\substack{\text{Lagragian} \\ \text{acceleration}}} = \underbrace{\frac{\partial \vec{v}}{\partial t}}_{\substack{\text{Eulerian} \\ \text{acceleration}}} + \underbrace{\vec{v} \cdot \nabla \vec{v}}_{\substack{\text{Convective} \\ \text{acceleration}}}$$

Summary of GE

1. Continuity equation / conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

2. Momentum equations / Newton's second law

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = -\nabla p + \nabla \cdot \tau + \rho \mathbf{g}$$

3. Energy equation / first law of thermodynamics

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho E \mathbf{v}) = \nabla \cdot (\kappa \nabla T) + \rho q - \nabla \cdot (p \mathbf{v}) + \mathbf{v} \cdot (\nabla \cdot \tau) + \nabla \mathbf{v} : \tau + \rho \mathbf{g} \cdot \mathbf{v}$$

$$E = e + \frac{|\mathbf{v}|^2}{2}, \qquad \frac{\partial (\rho e)}{\partial t} + \nabla \cdot (\rho e \mathbf{v}) = \nabla \cdot (\kappa \nabla T) + \rho q - p \nabla \cdot \mathbf{v} + \nabla \mathbf{v} : \tau$$

This PDE system is referred to as the *compressible Navier-Stokes equations*

Conservation form of GE

Generic conservation law for a scalar quantity

$$\frac{\partial u}{\partial t} + \nabla \cdot \mathbf{f} = q, \qquad \text{where} \quad \mathbf{f} = \mathbf{f}(u, \mathbf{x}, t) \quad \text{is the flux function}$$

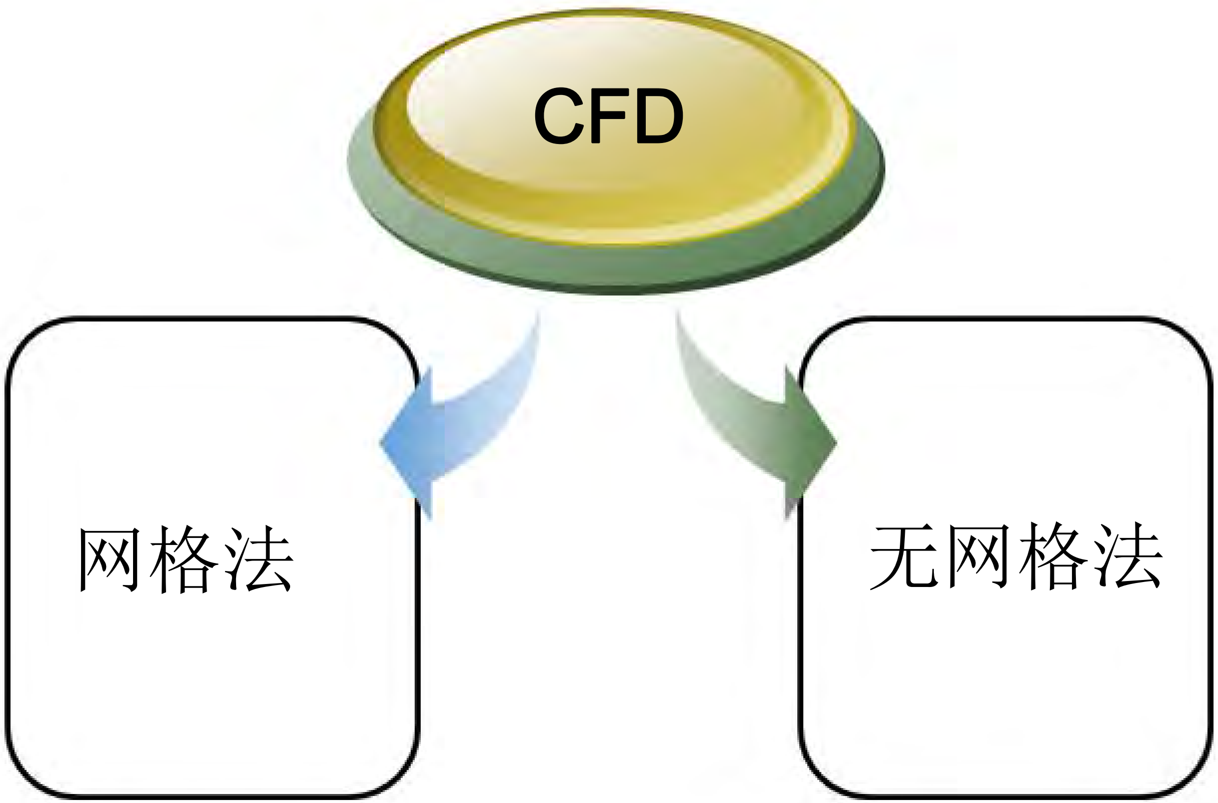
Conservative variables, fluxes and sources

$$U = \begin{bmatrix} \rho \\ \rho\mathbf{v} \\ \rho E \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} \rho\mathbf{v} \\ \rho\mathbf{v}\otimes\mathbf{v} + p\mathcal{I} - \tau \\ (\rho E + p)\mathbf{v} - \kappa\nabla T - \tau\cdot\mathbf{v} \end{bmatrix}, \quad Q = \begin{bmatrix} 0 \\ \rho\mathbf{g} \\ \rho(q + \mathbf{g}\cdot\mathbf{v}) \end{bmatrix}$$

Navier-Stokes equations in divergence form

$$\boxed{\frac{\partial U}{\partial t} + \nabla \cdot \mathbf{F} = Q} \qquad U \in \mathbb{R}^5, \quad \mathbf{F} \in \mathbb{R}^{3\times 5}, \quad Q \in \mathbb{R}^5$$

- representing all equations in the same generic form simplifies the programming
- it suffices to develop discretization techniques for the generic conservation law


CFD
网格法
无网格法

Based Lagrangian description:

Messless Particle method, SPH, MPS

Based Eulerian description:

FDM, FVM, FEM,…

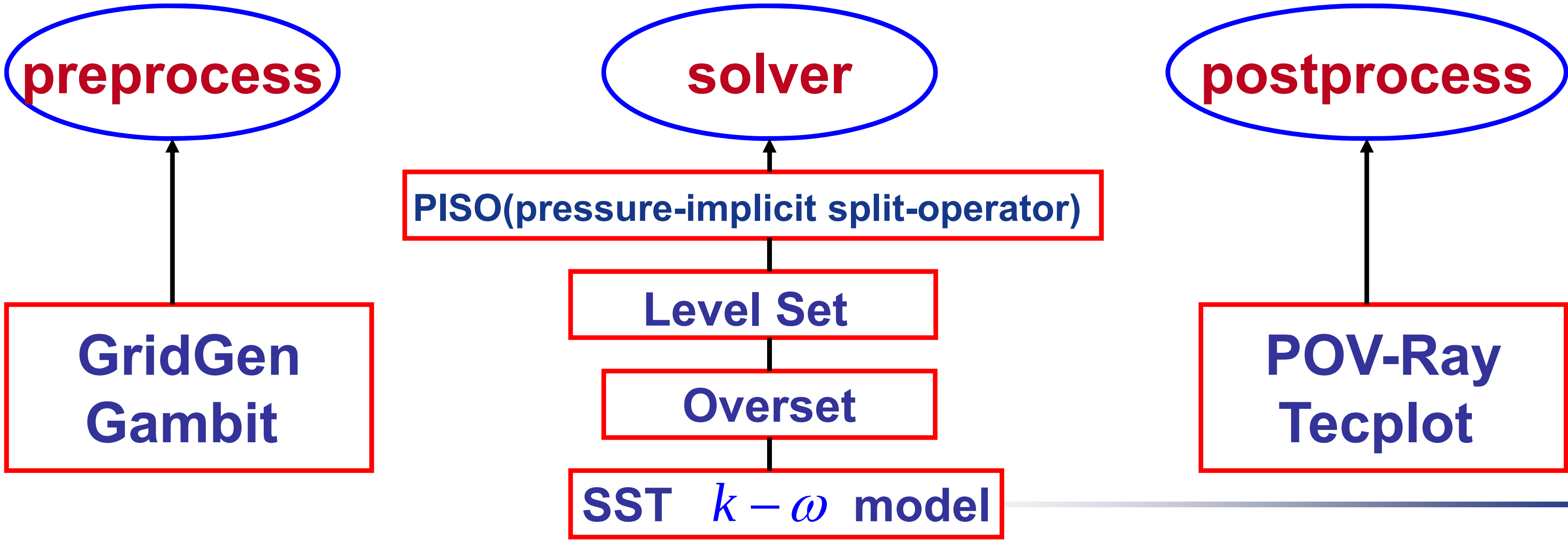
Introduction to

Solver Package naoe-FOAM-SJTU

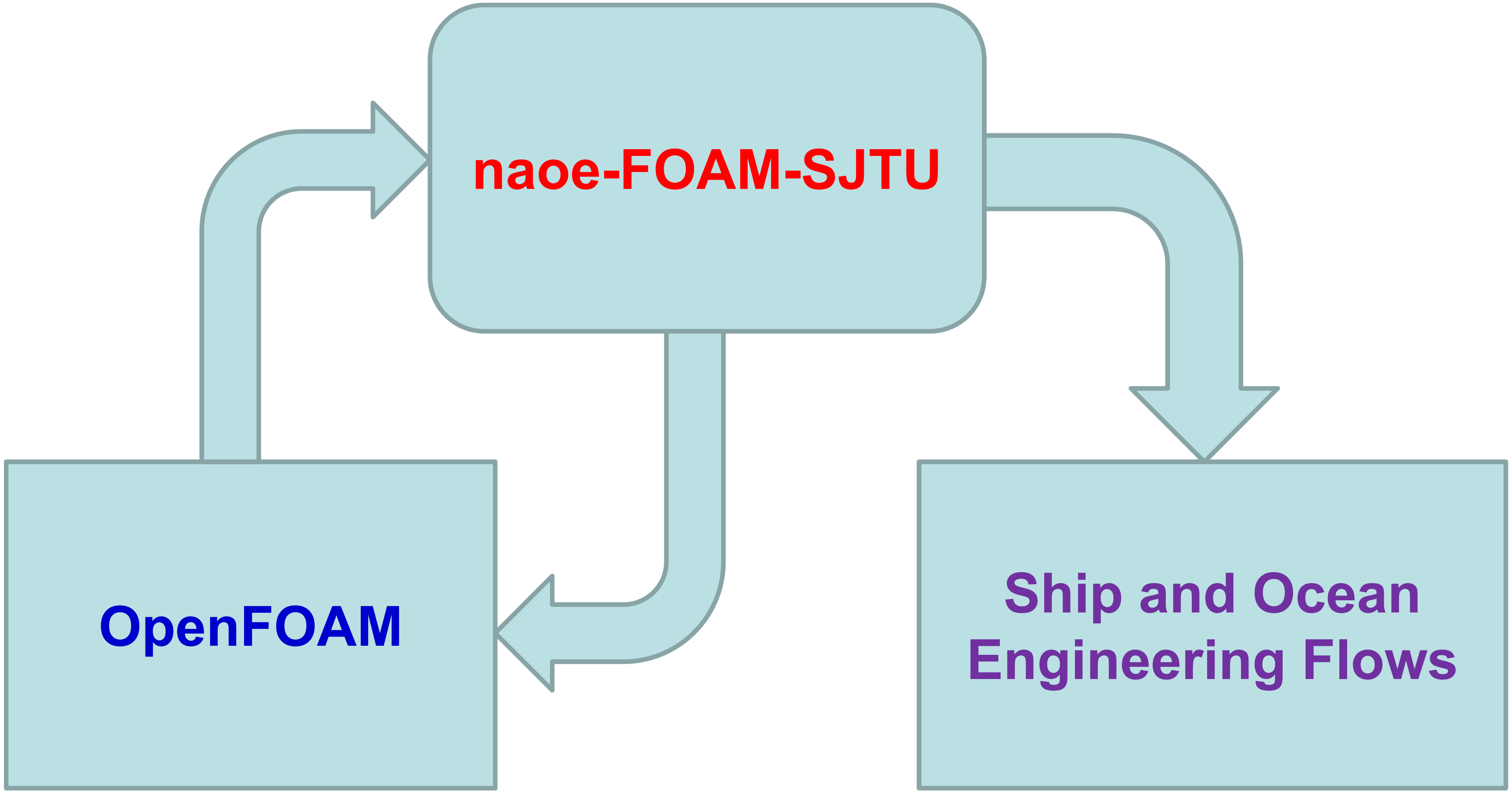
上海交通大學 Shanghai Jiao Tong University

CFD Package of naoe-FOAM-SJTU

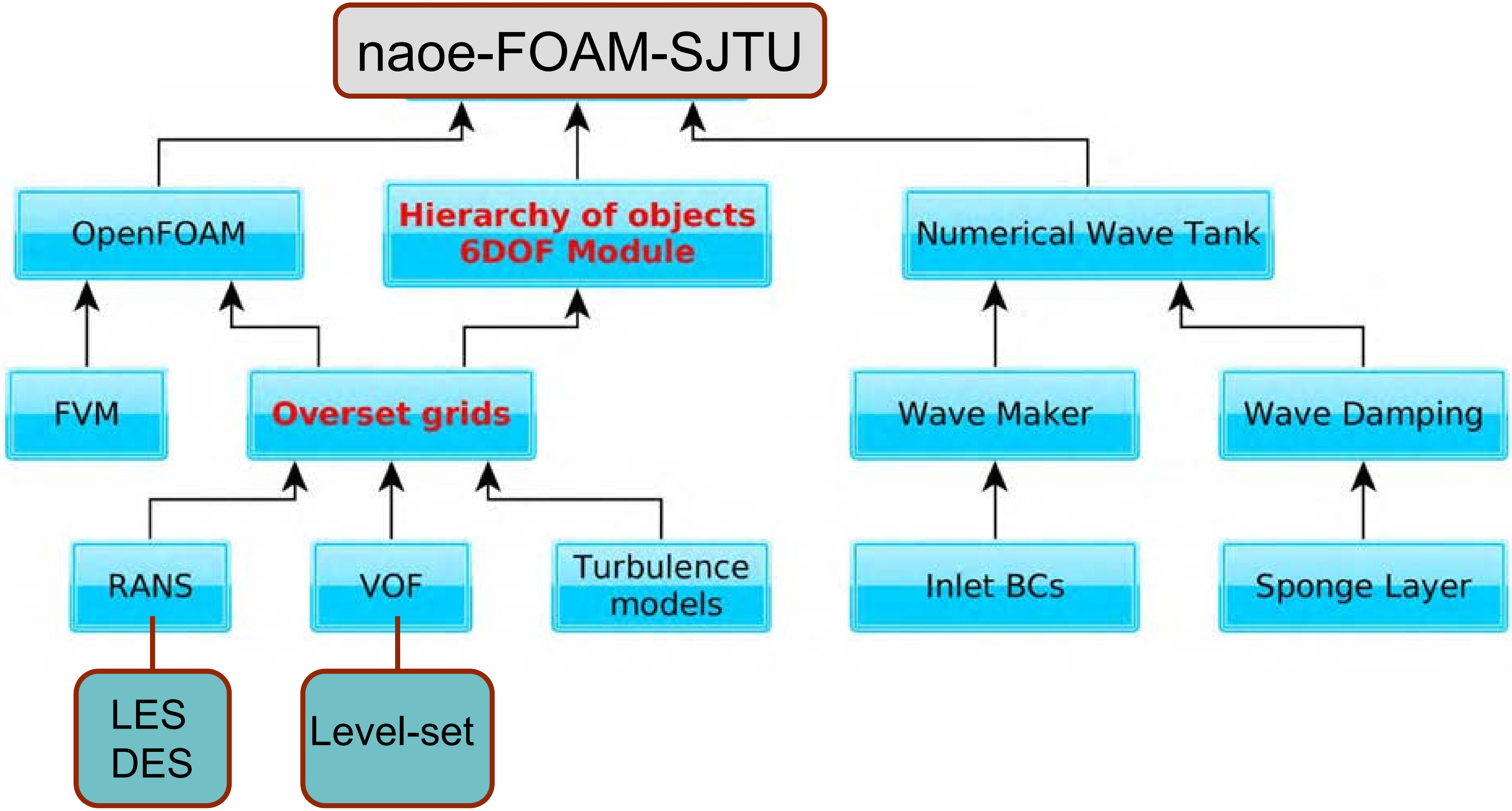
Develop a CFD solver (naoe-FOAM-SJTU 1.0) based on OpenFOAM to simulate ship motion flows and other related ocean engineering flows by the combination of dynamic overset, level set, PISO and RANS under the platform of OpenFOAM.



CFD Package of naoe-FOAM-SJTU

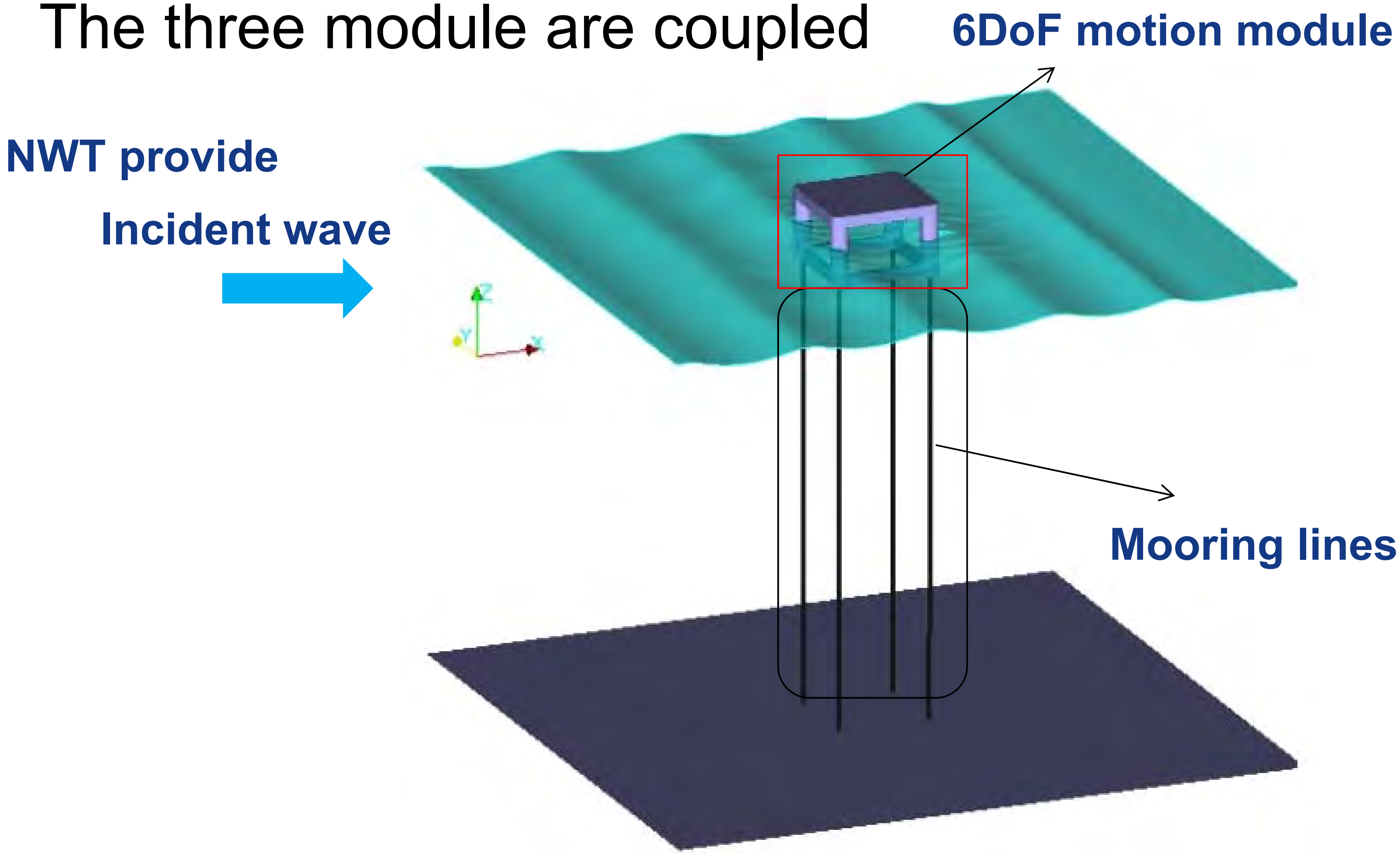


Main Structure of naoe-FOAM-SJTU



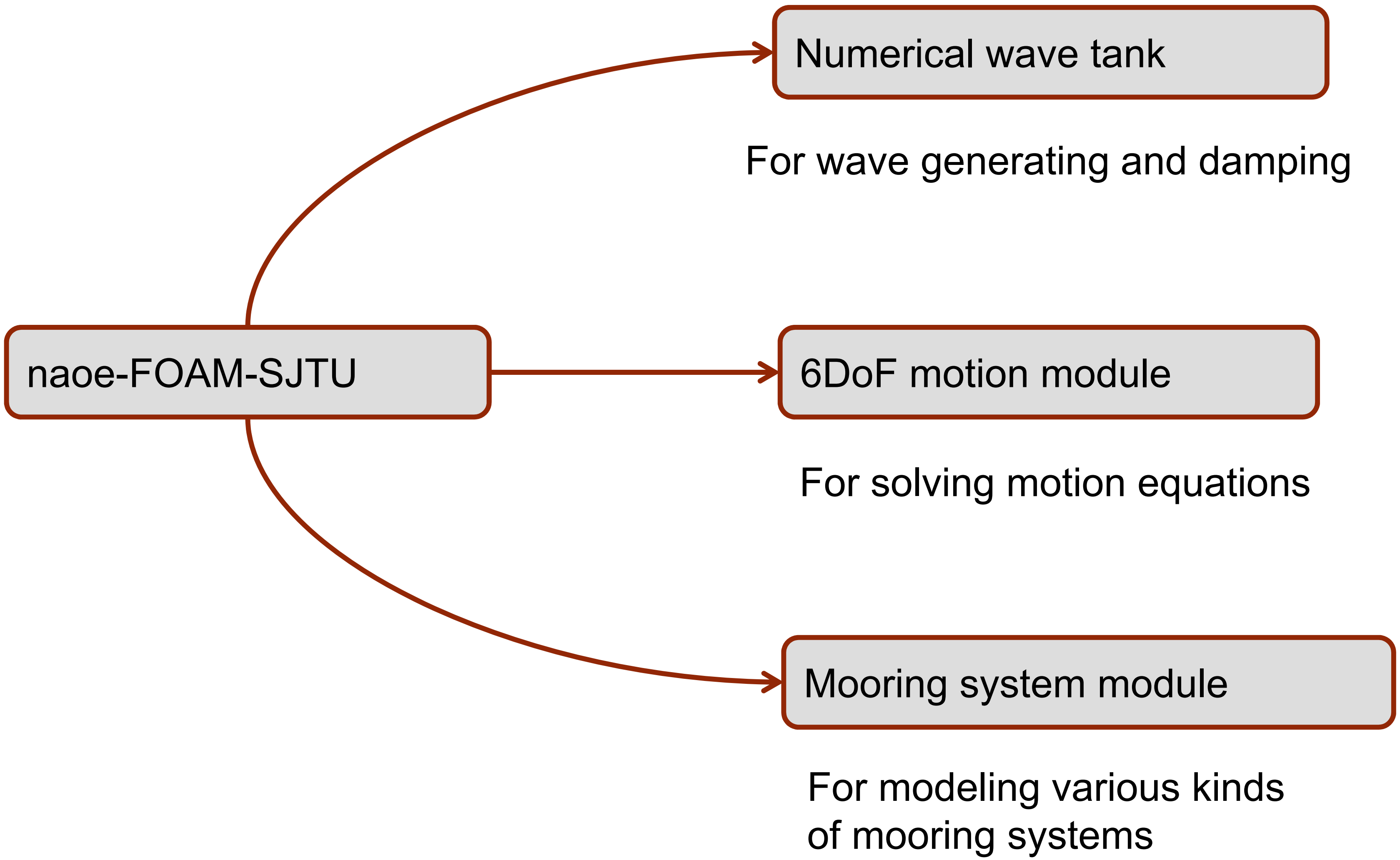
Introduction to naeo-FOAM-SJTU

- The three module are coupled



Shanghai Jiao Tong University

CFD Package of naoe-FOAM-SJTU



求解器基本框架搭建

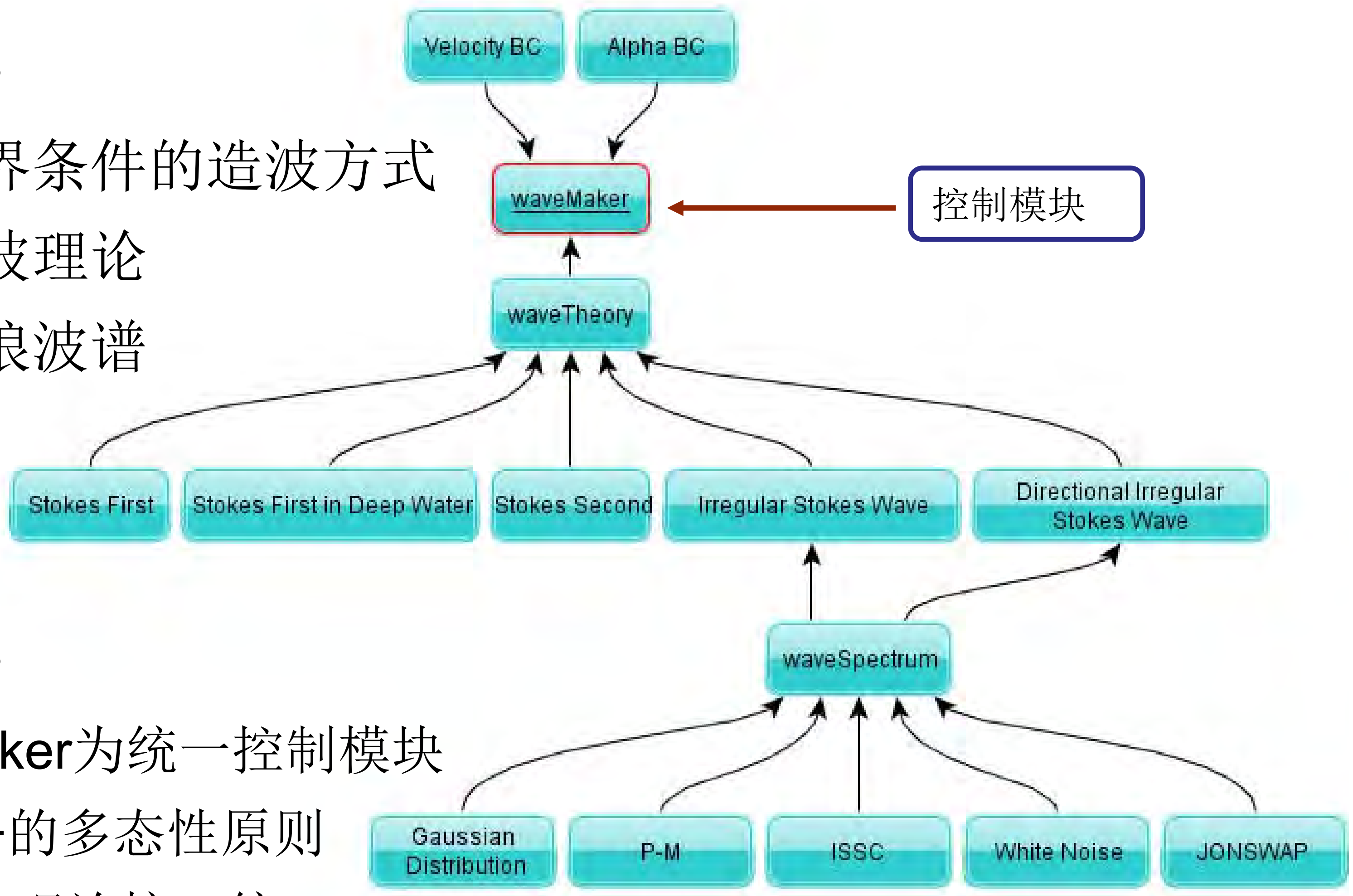
开发平台的选择：OpenFOAM

- 免费、源代码开放
- 有较高的开放性和自由性
- 可以在原有代码的基础上添加新的模块和功能
- 具有丰富的CFD方法和数据结构函数库
- 可以将原有的函数库和模块随意组合，形成完整的求解器

造波模块框架

造波模块：

- 采用边界条件的造波方式
- 多种造波理论
- 多种波浪波谱



设计思路：

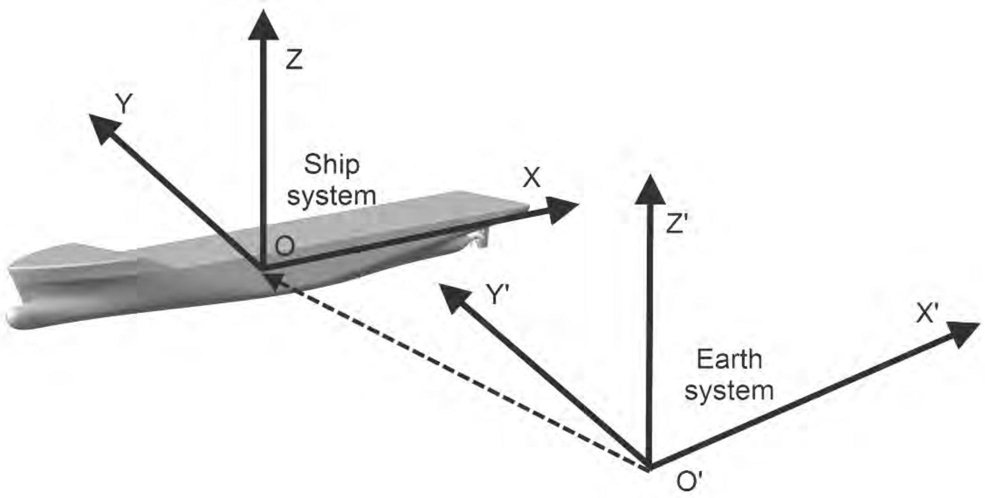
- waveMaker为统一控制模块
- 利用C++的多态性原则
- 所有造波理论接口统一
- 所有波浪波谱接口统一

六自由度运动模块

- 6DOF 模块– 采用两个坐标系（Euler角表示方式）
  - Earth-fixed system.
  - Body-fixed system.

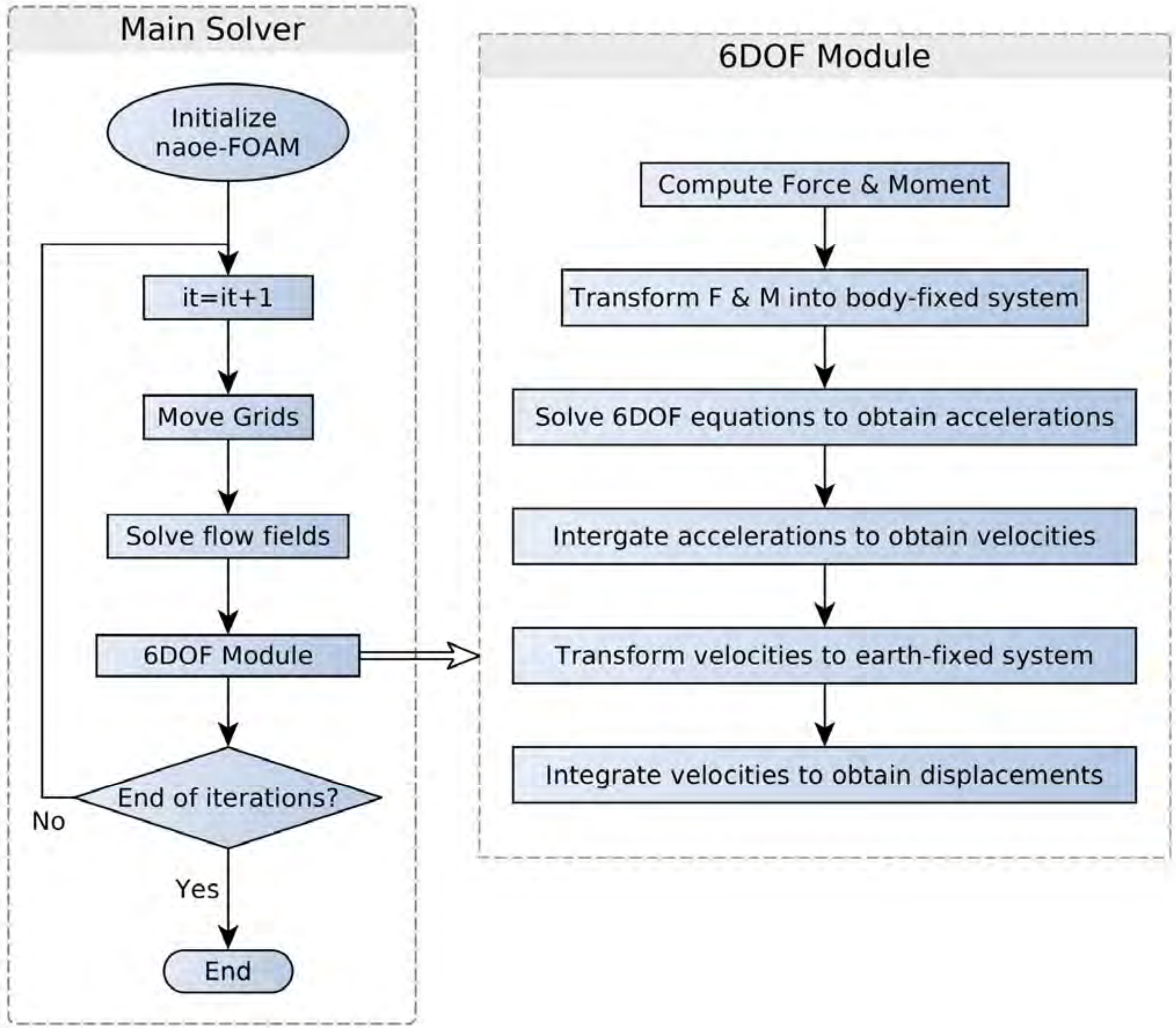
$$\dot{\mathbf{x}} = (\dot{\mathbf{x}}_1, \dot{\mathbf{x}}_2) = (\dot{x}, \dot{y}, \dot{z}, \dot{\phi}, \dot{\theta}, \dot{\psi})$$

$$\mathbf{v} = (\mathbf{v}_1, \mathbf{v}_2) = (u, v, w, p, q, r)$$

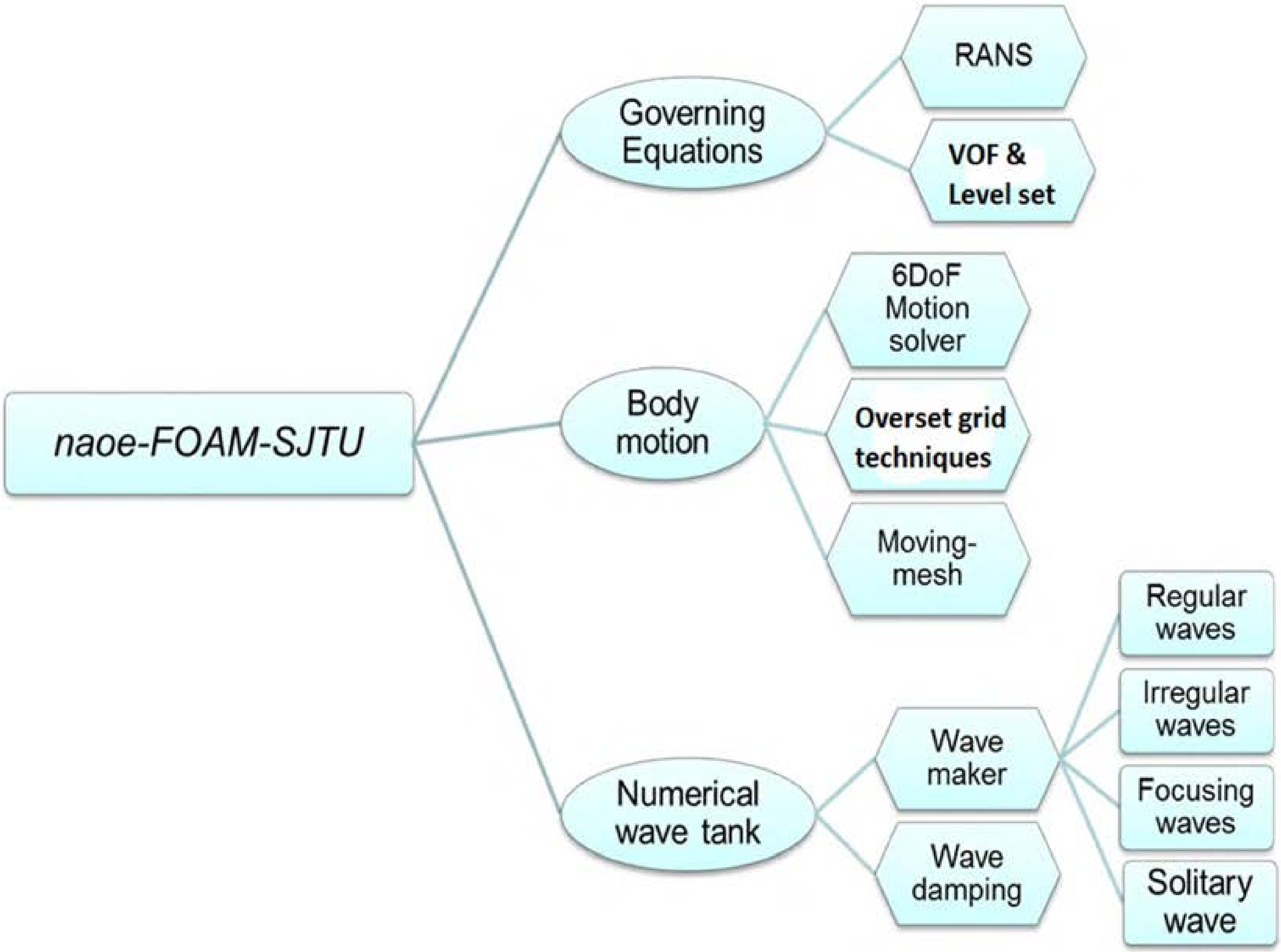


$$\begin{cases} \mathbf{v}_1 = \mathbf{J}_1^{-1} \cdot \dot{\eta}_1 \\ \mathbf{v}_2 = \mathbf{J}_2^{-1} \cdot \dot{\eta}_2 \\ \dot{\eta}_1 = \mathbf{J}_1 \cdot \mathbf{v}_1 \\ \dot{\eta}_2 = \mathbf{J}_2 \cdot \mathbf{v}_2 \end{cases}$$

六自由度运动模块


Main Solver
Initialize naoe-FOAM
it=it+1
Move Grids
Solve flow fields
6DOF Module
End of iterations?
No
Yes
End
6DOF Module
Compute Force & Moment
Transform F & M into body-fixed system
Solve 6DOF equations to obtain accelerations
Intergate accelerations to obtain velocities
Transform velocities to earth-fixed system
Integrate velocities to obtain displacements

naoe-FOAM-SJTU solver



CFD Package of naoe-FOAM-SJTU

naoe-FOAM-SJTU:

- An efficient 3D RANS solver (*naoe-FOAM-SJTU*) to treat hydrodynamic problems of naval architecture and ocean engineering.
- Based on open source package OpenFOAM
- Written in C++ → Object Oriented Programming (OOP) :

  Easy to：1) modify and extend current methods

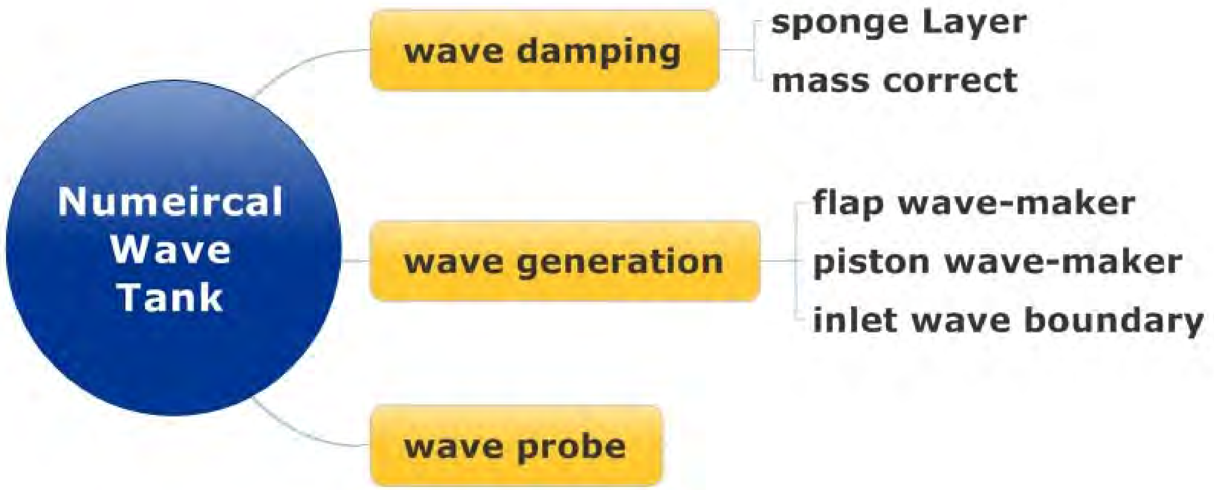
Capability of naoe-FOAM-SJTU:

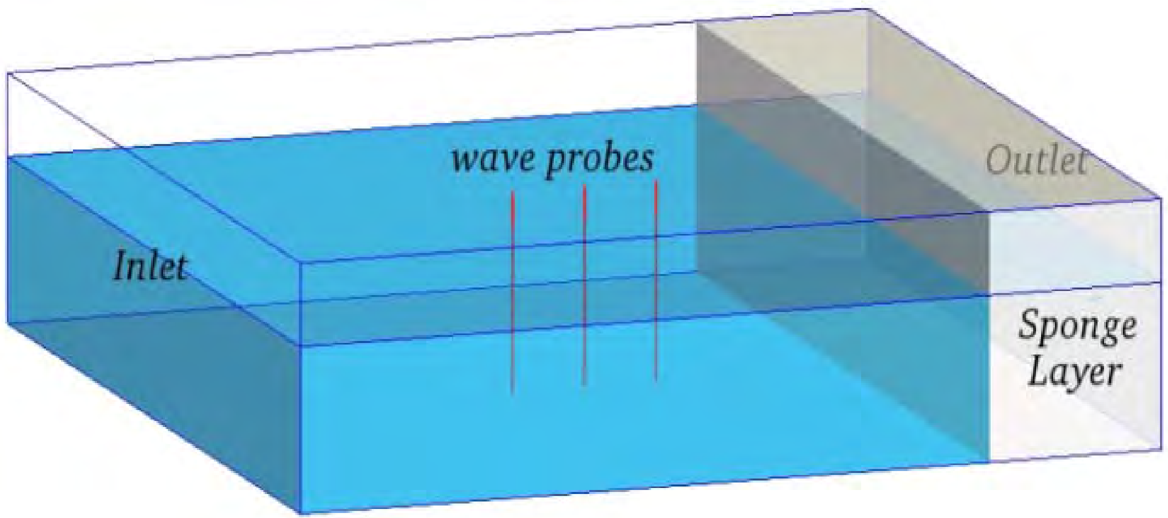
- Simulating the 6DoF motions of bodies
- Wave generation & Wave damping
- Mooring line system
- Capable of Multiple objects
- Treat interaction between nonlinear waves and structure.
- Predict wave impact forces of highly nonlinear fluid motions and nonlinear motions of structure due to *mono-chromatic incident waves* or other *violent incident waves*

Numerical Examples

Numerical Wave Tank

Numerical wave tank in naoe-FOAM-SJTU



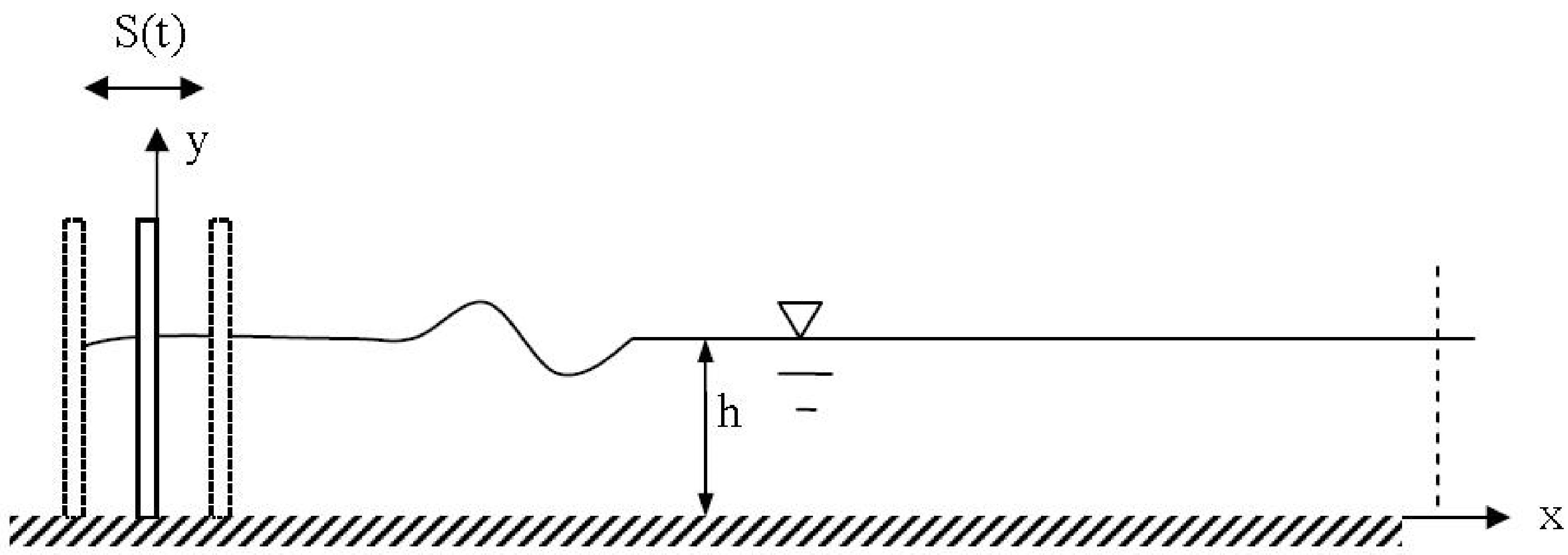


Numerical Wave Tank

- **Wave generation**
  - Piston wave maker
  - Flap wave maker
  - Wave making boundary
  - Spinning dipole

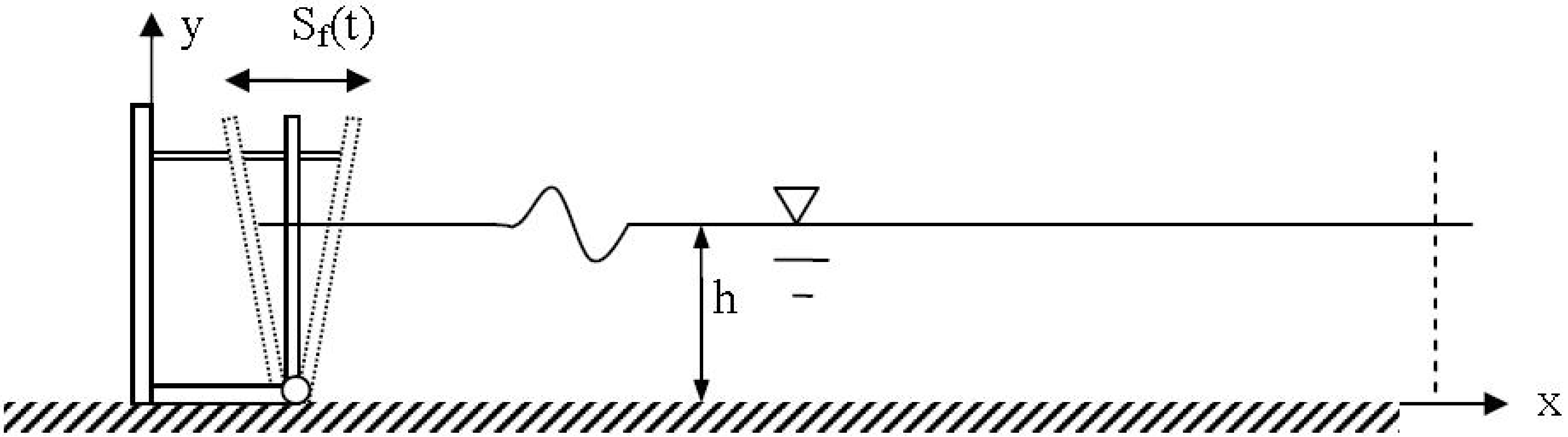
Numerical Wave Tank

- **Piston wave maker**



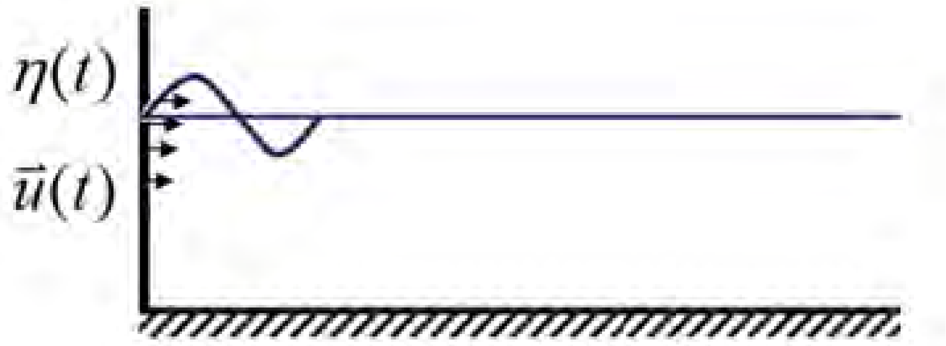
Numerical Wave Tank

- **Flap wave maker**

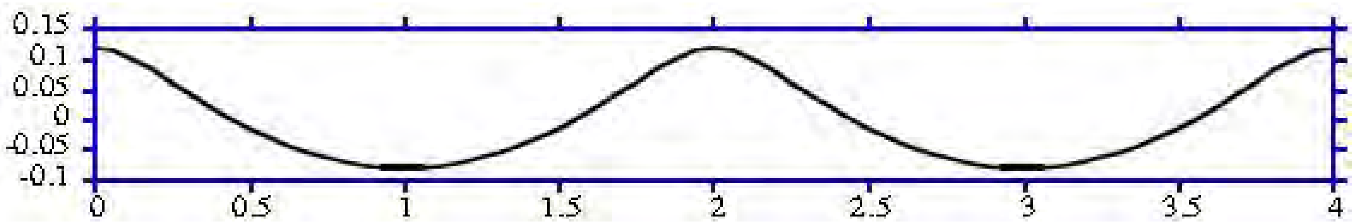


Numerical Wave Tank

- **Wave making boundary**



$$\psi(x, z) = B_o z + \sum_{j=1}^{N} B_j \frac{\sinh jkz}{\cosh jkD} \cos jkx$$



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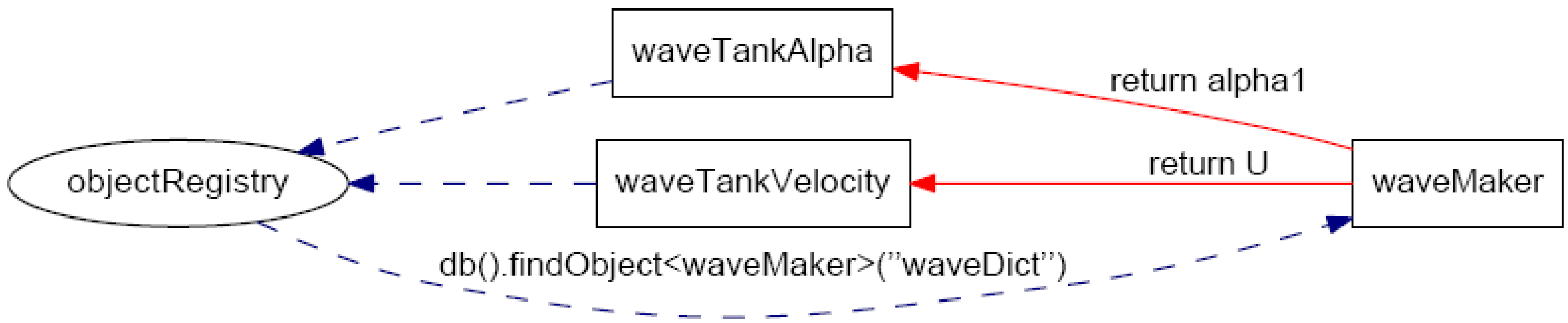
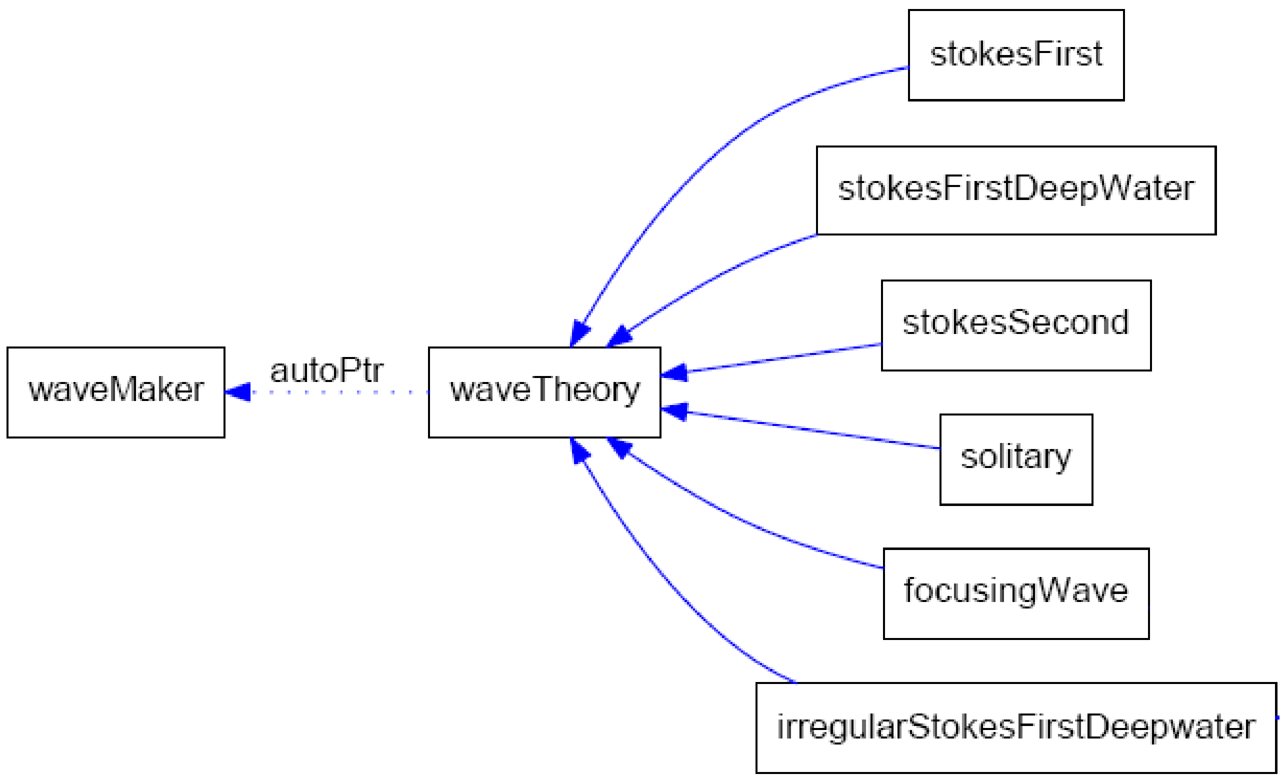
Numerical Wave Tank

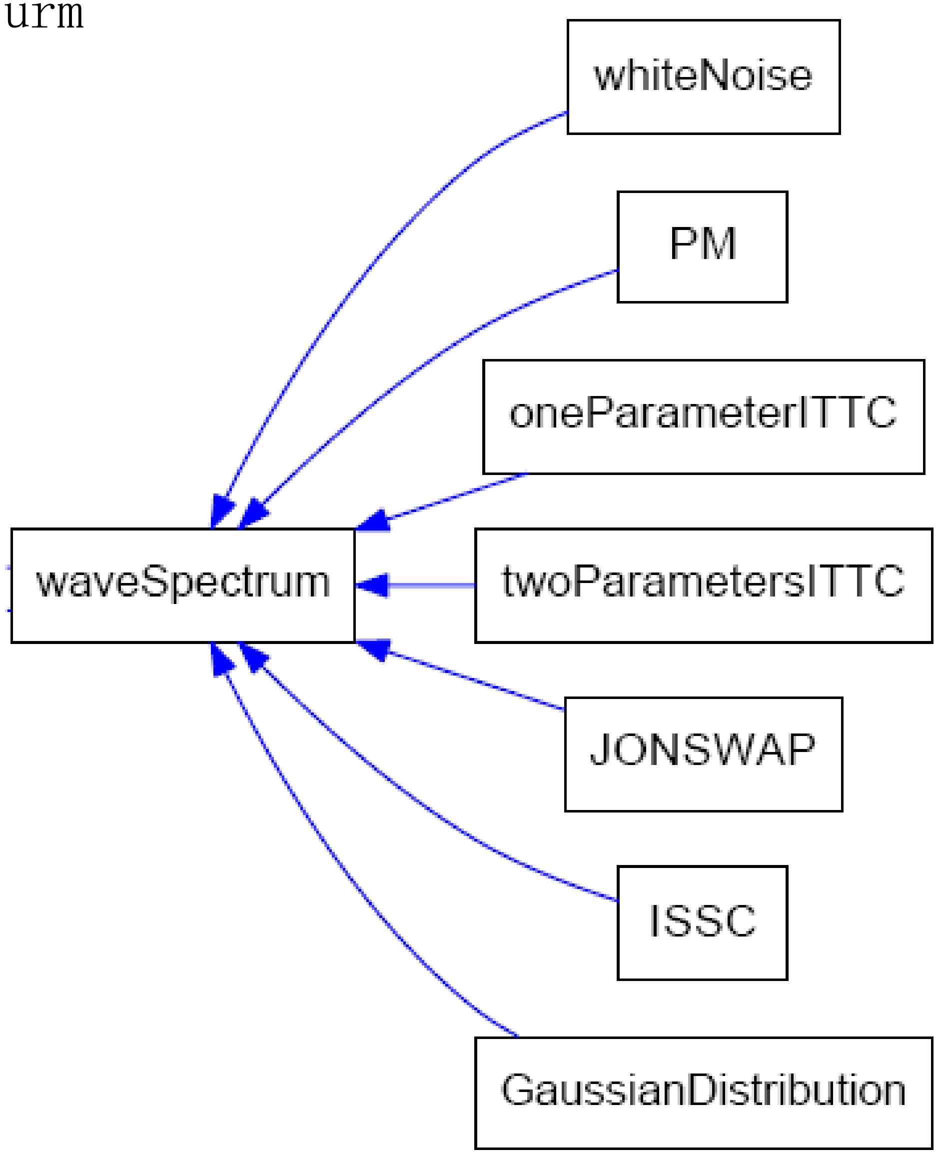
- waveTheory





Numerical Wave Tank

- Wave specturm



Numerical Wave Tank

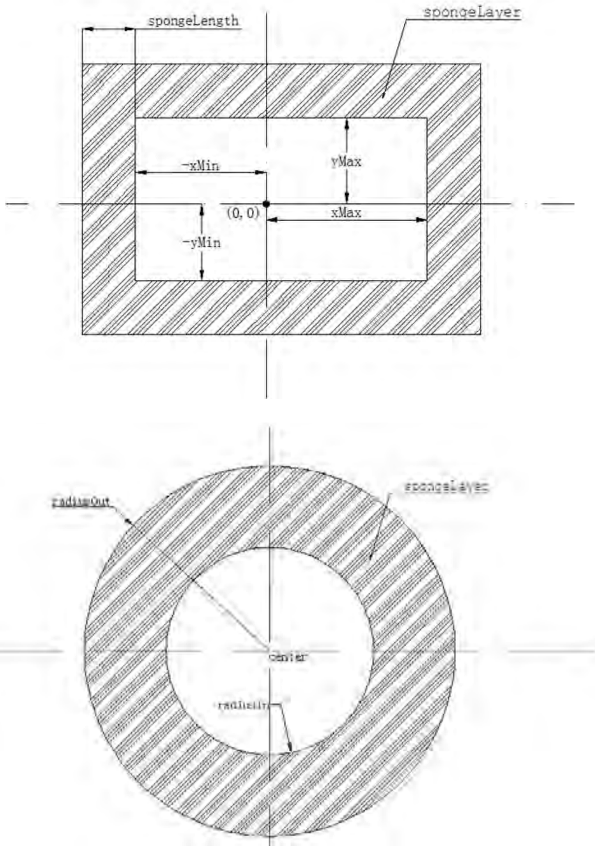
Wave Damping (sponge layer)

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho(\mathbf{U} - \mathbf{U}_g)\mathbf{U}) = -\nabla p_d - \mathbf{g} \cdot \mathbf{x} \nabla \rho + \nabla \cdot (\mu_{\text{eff}} \nabla \mathbf{U}) + (\nabla \mathbf{U}) \cdot \nabla \mu_{\text{eff}} + f_\sigma + \boxed{f_s}$$

Source Term: $f_s(x) = \begin{cases} -\rho \alpha_s \left(\frac{x - x_s}{L_s}\right)^2 (\mathbf{U} - \mathbf{U}_{ref}) & \text{inside sponge layer} \\ 0 & \text{outside sponge layer} \end{cases}$

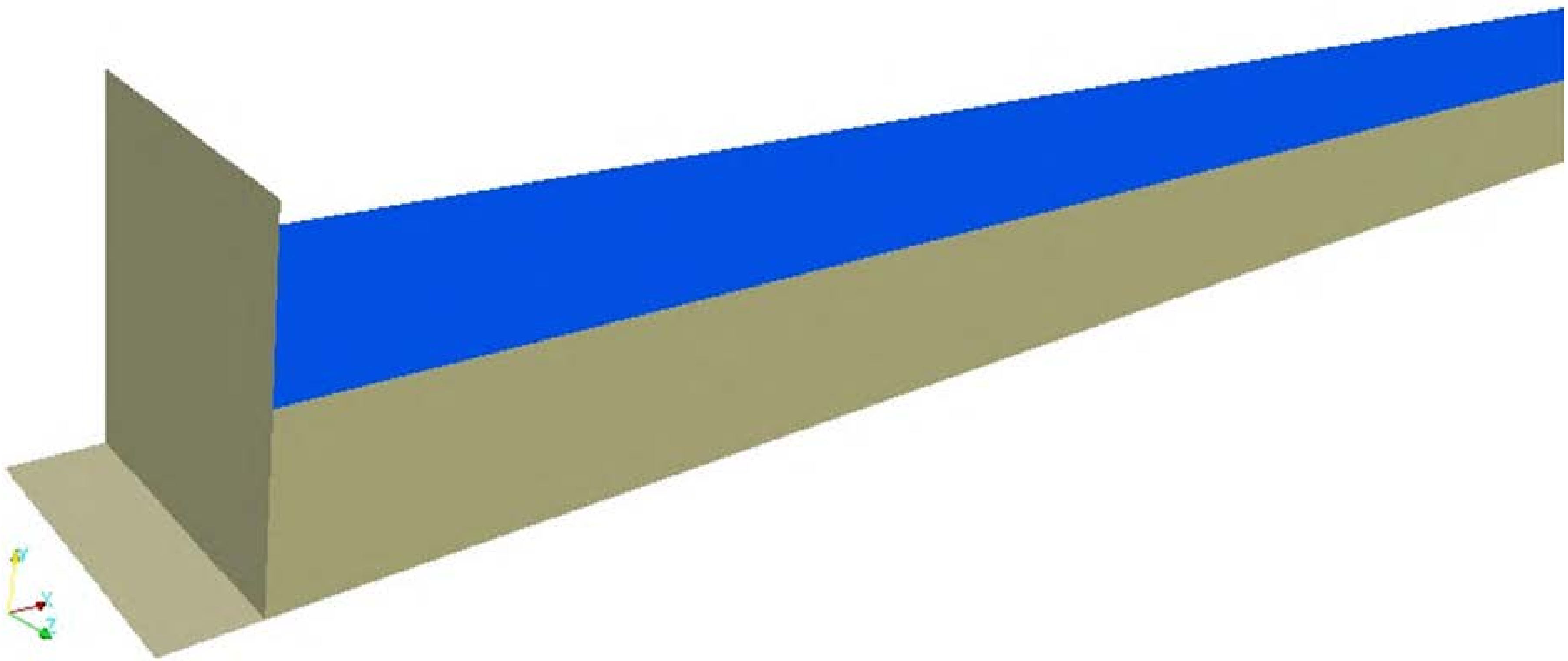
X_s start position of sponge layer
L_s the length of sponge layer
α_s maximum strength of sponge layer

Sponge layer shapes

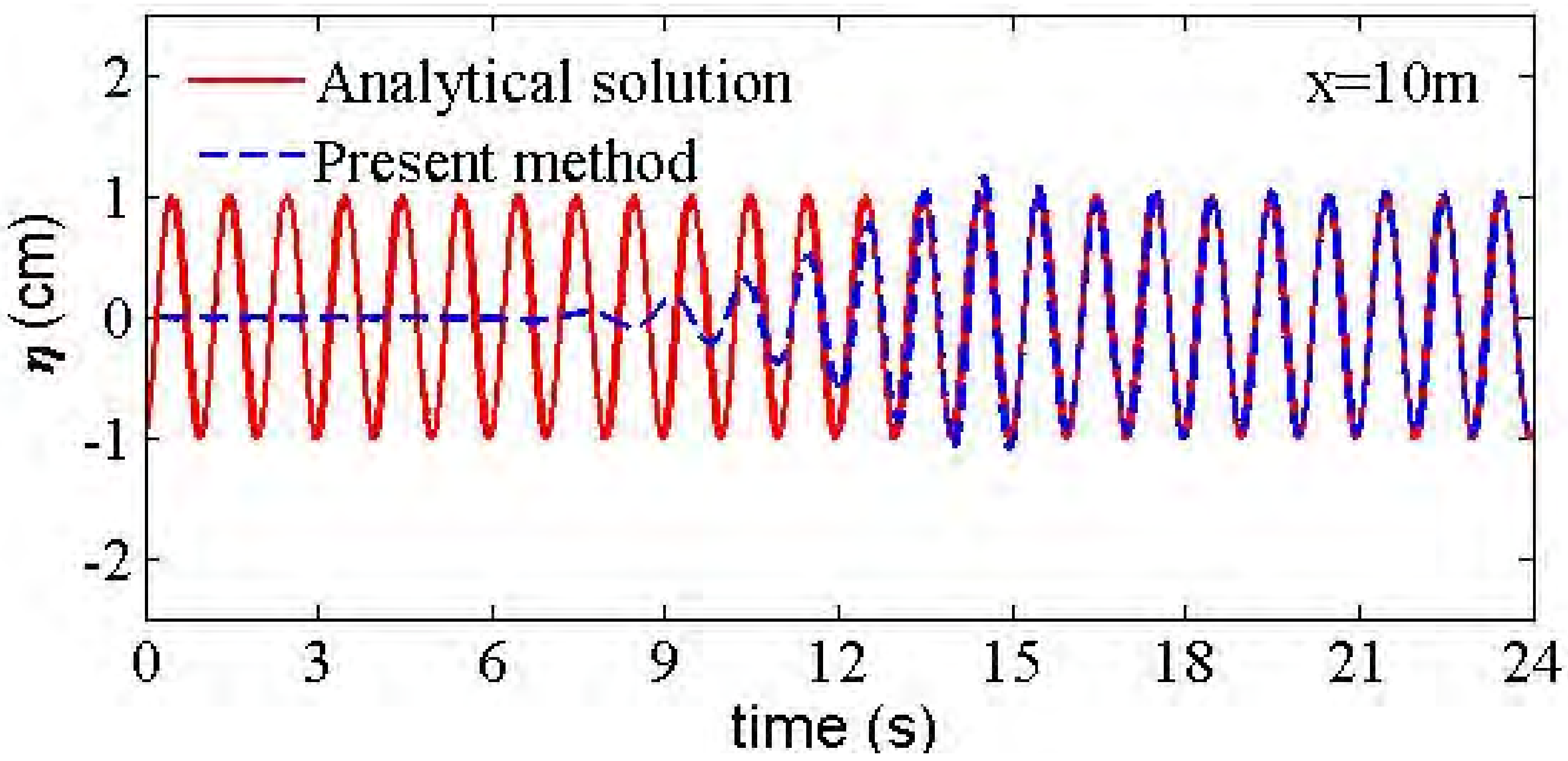


Linear periodic waves

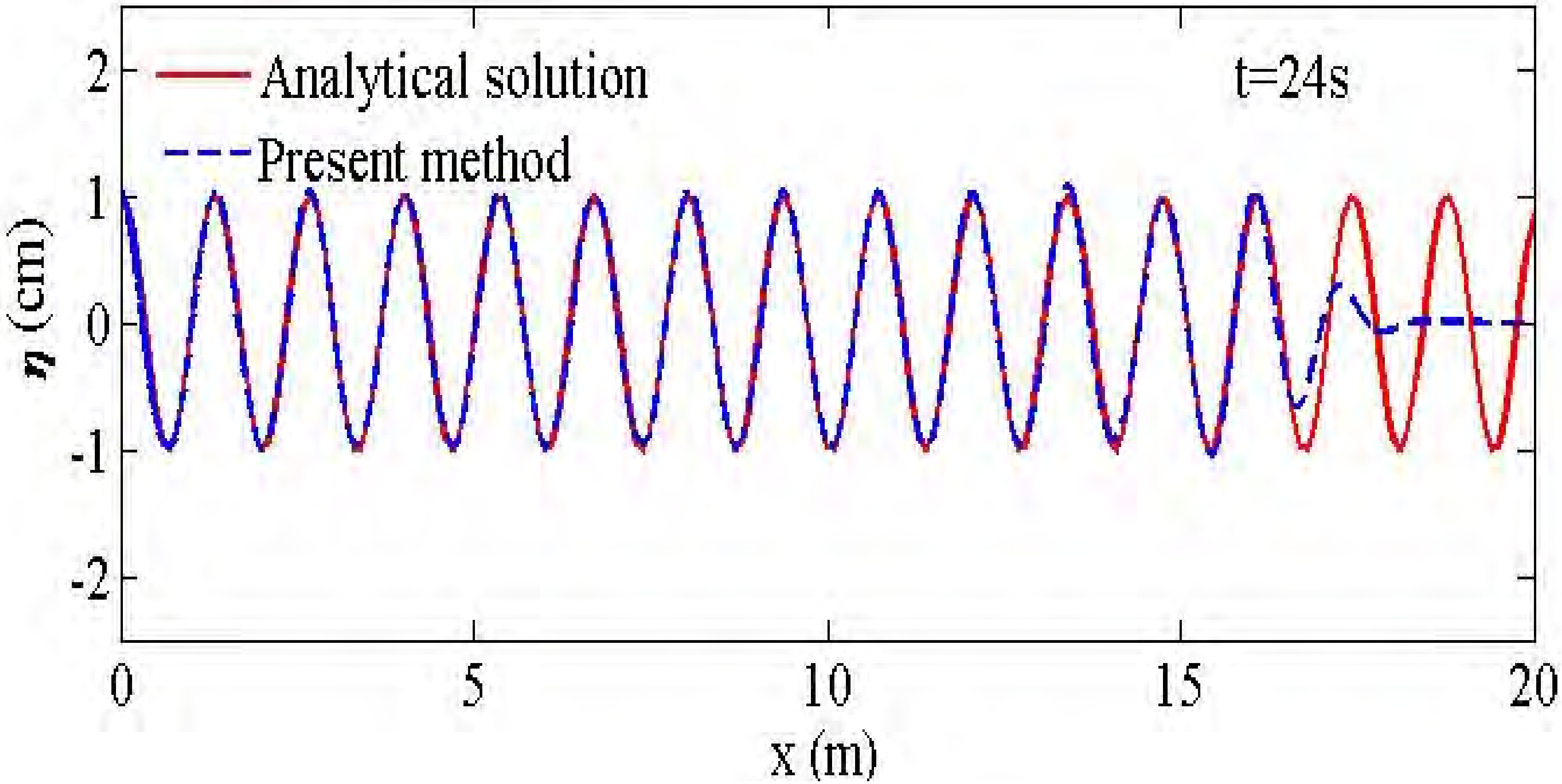
linear wave (piston)



Linear periodic waves

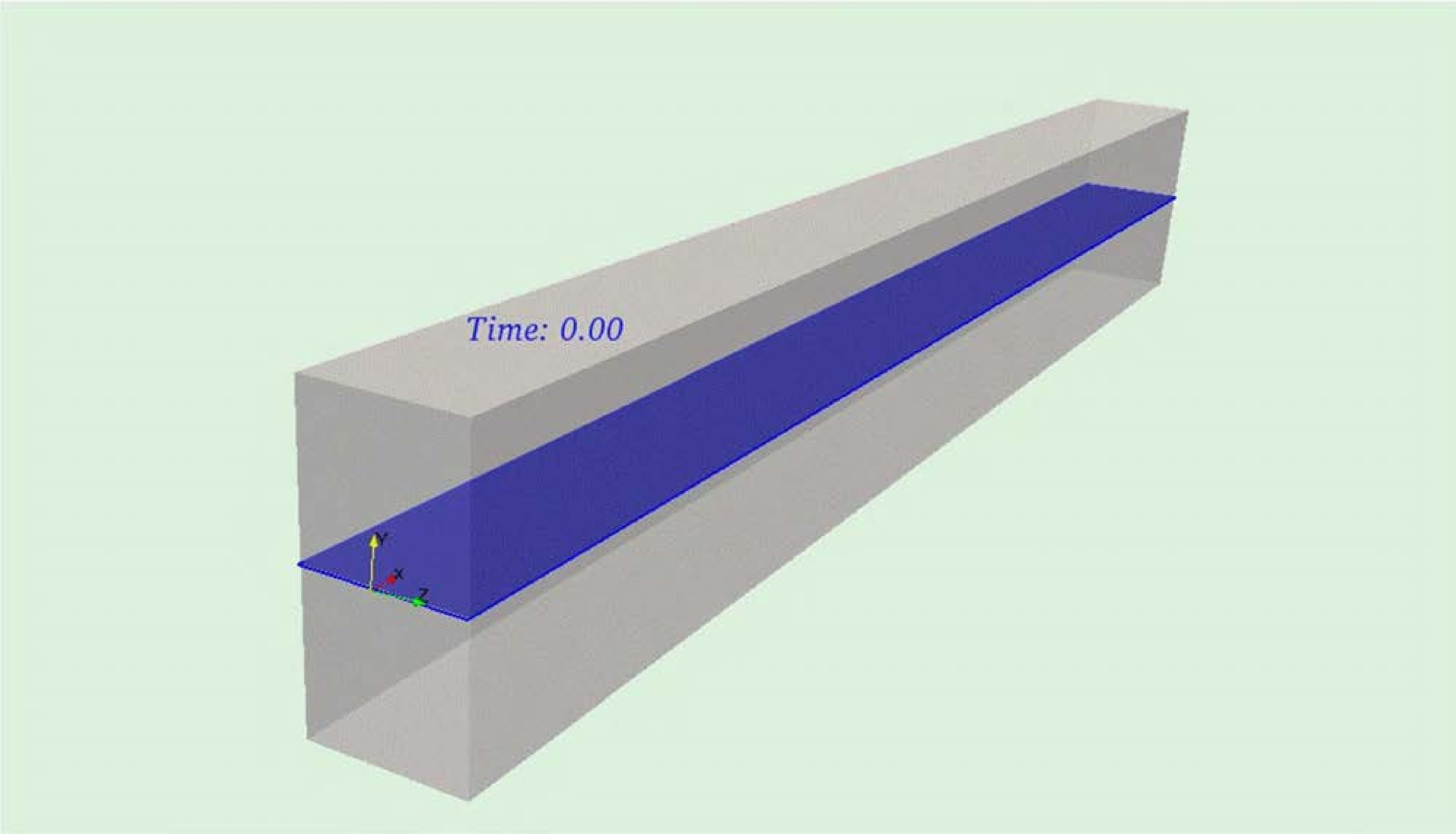


Linear periodic waves

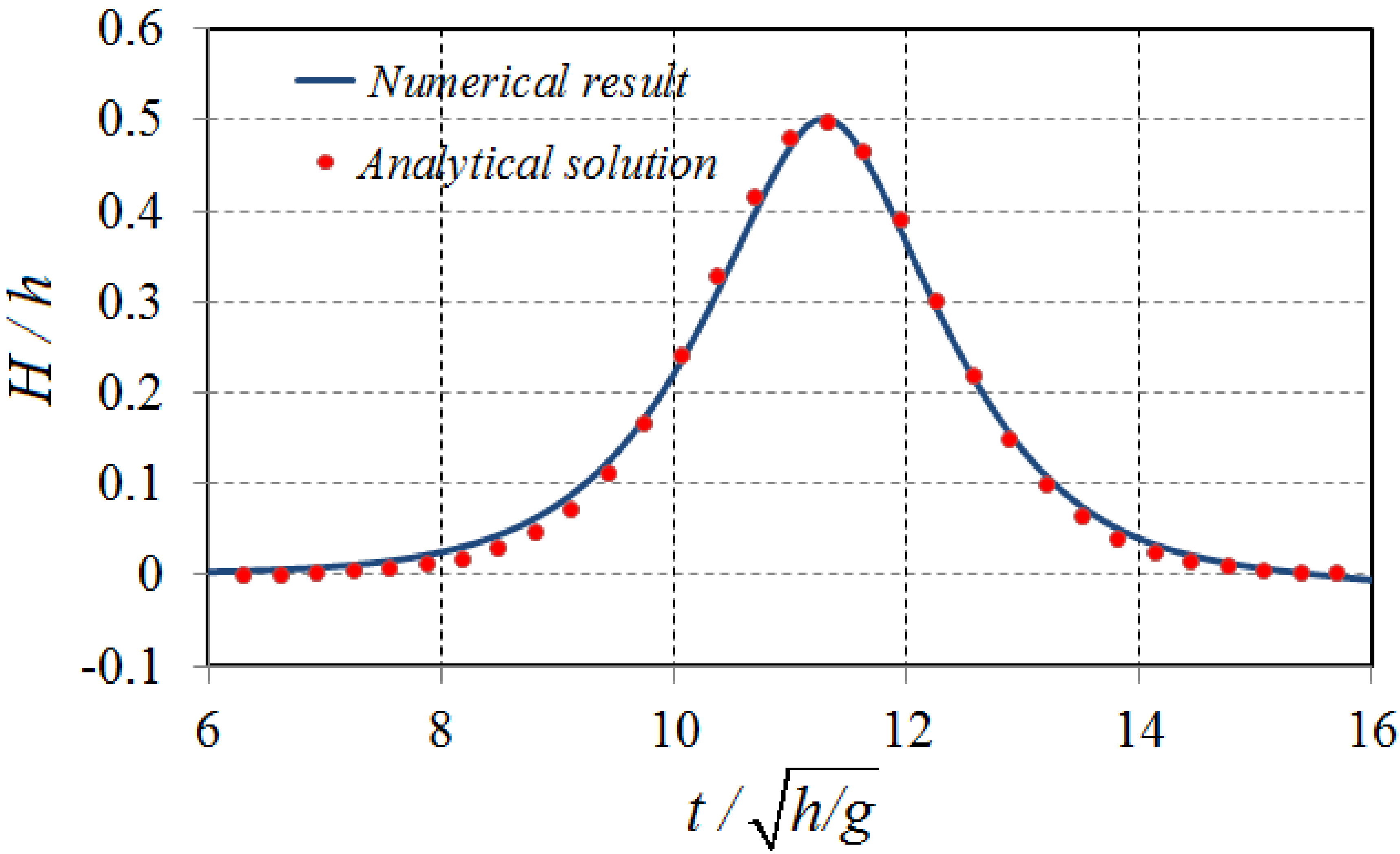


Solitary wave

- Solitary wave generated by piston-type wave-maker

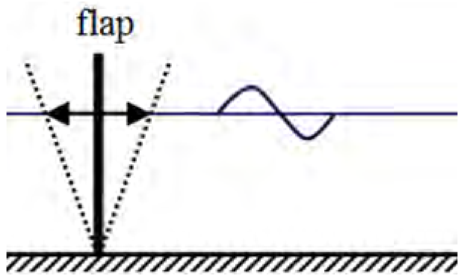


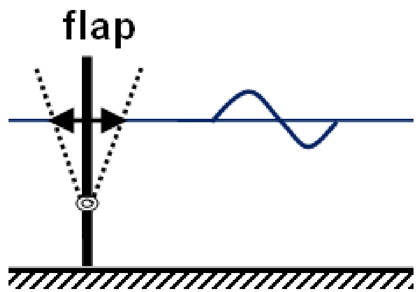
Solitary wave

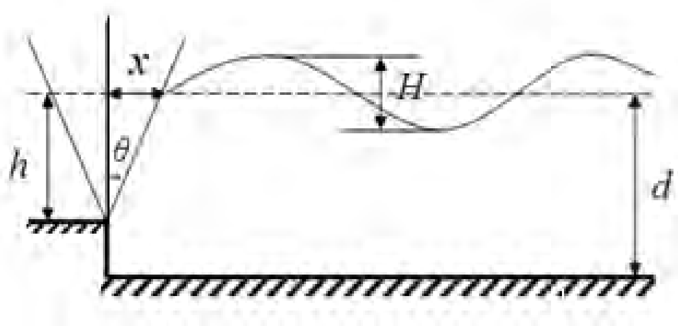


Numerical Wave Tank

- Flap-type







$$S = H\frac{kh[kd + \sinh(kd)\cosh(kd)]}{2\sinh(kd)[kh\sinh(kd) - \cosh(kd) + \cosh(k(d-h))]}$$

- This method is effective when generating waves in deep water

Freak Waves

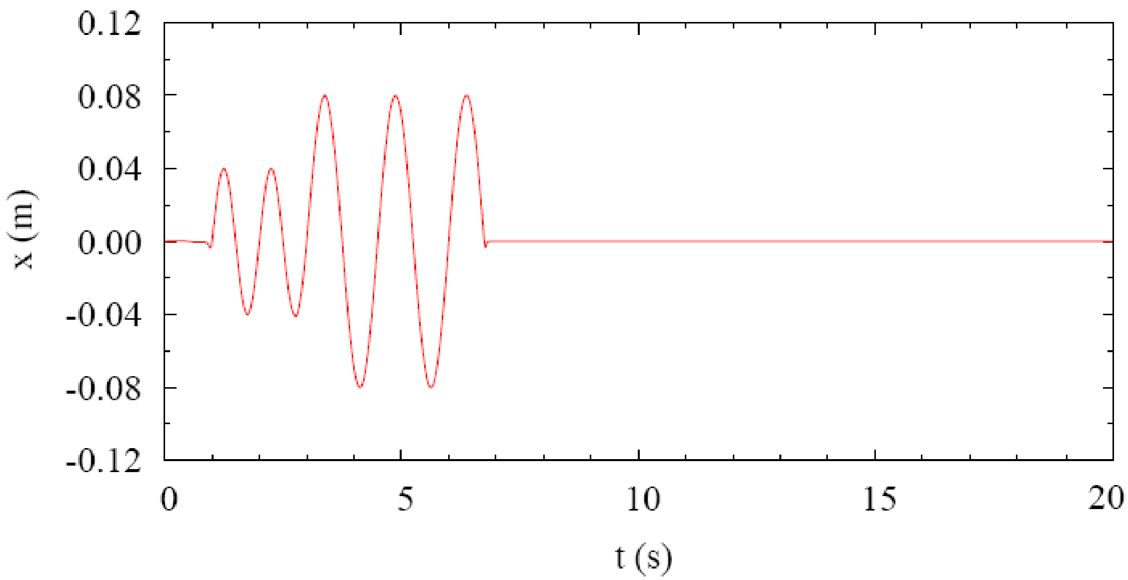
Freak wave generated in experiment of Cox & Ortega (2002)

- Displacement of the wave-maker

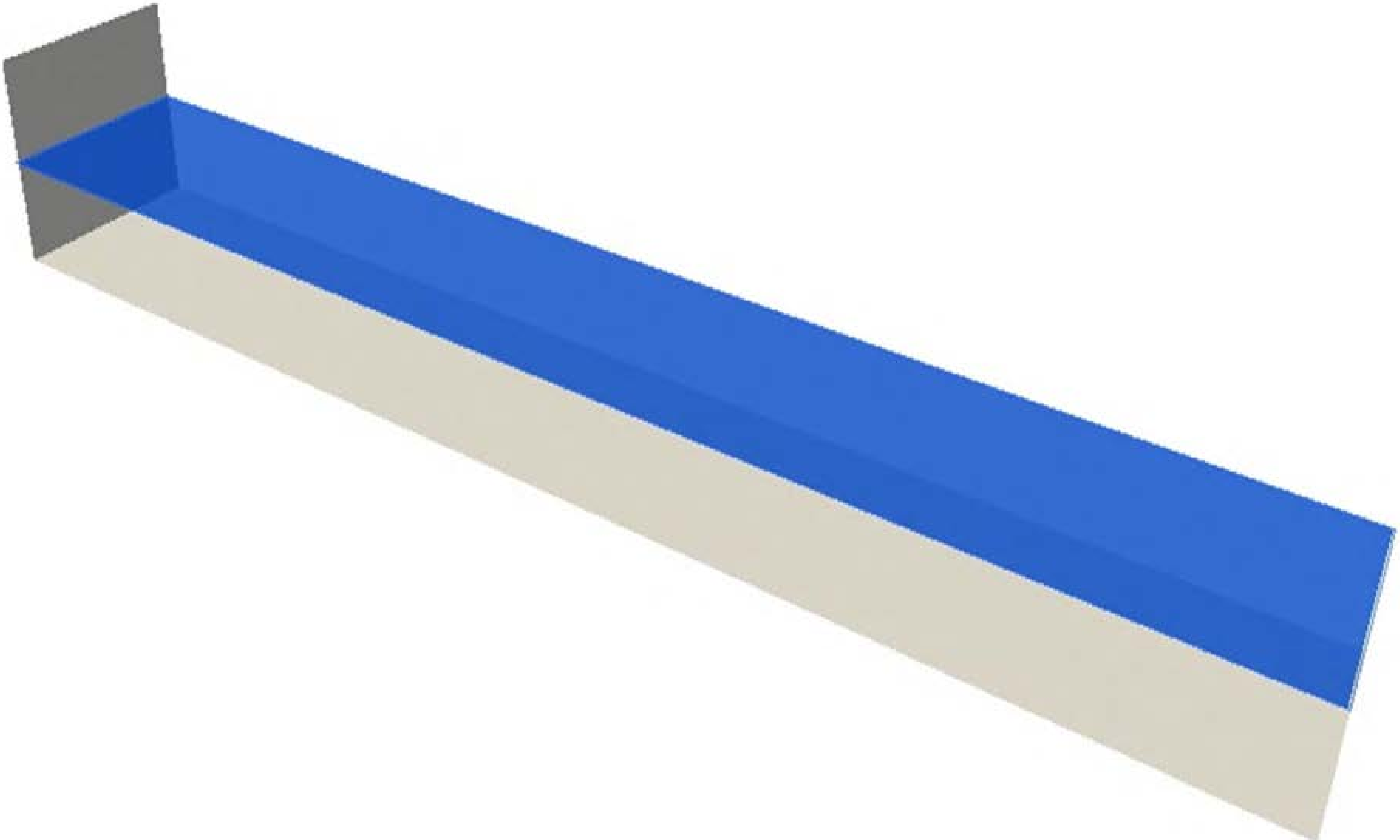
$$x=\begin{cases} A_1 \sin(\omega_1(t-1)) & 1 < t < 1+2T_1 \\ A_2 \sin(\omega_2(t-1-2T_1)) & 1+2T_1 < t < 1+2T_1+2.5T_2 \\ 0 & otherwise \end{cases}$$

$A_1=0.04m \quad T_1=1.0s \quad \omega_1=\frac{2\pi}{T_1}$

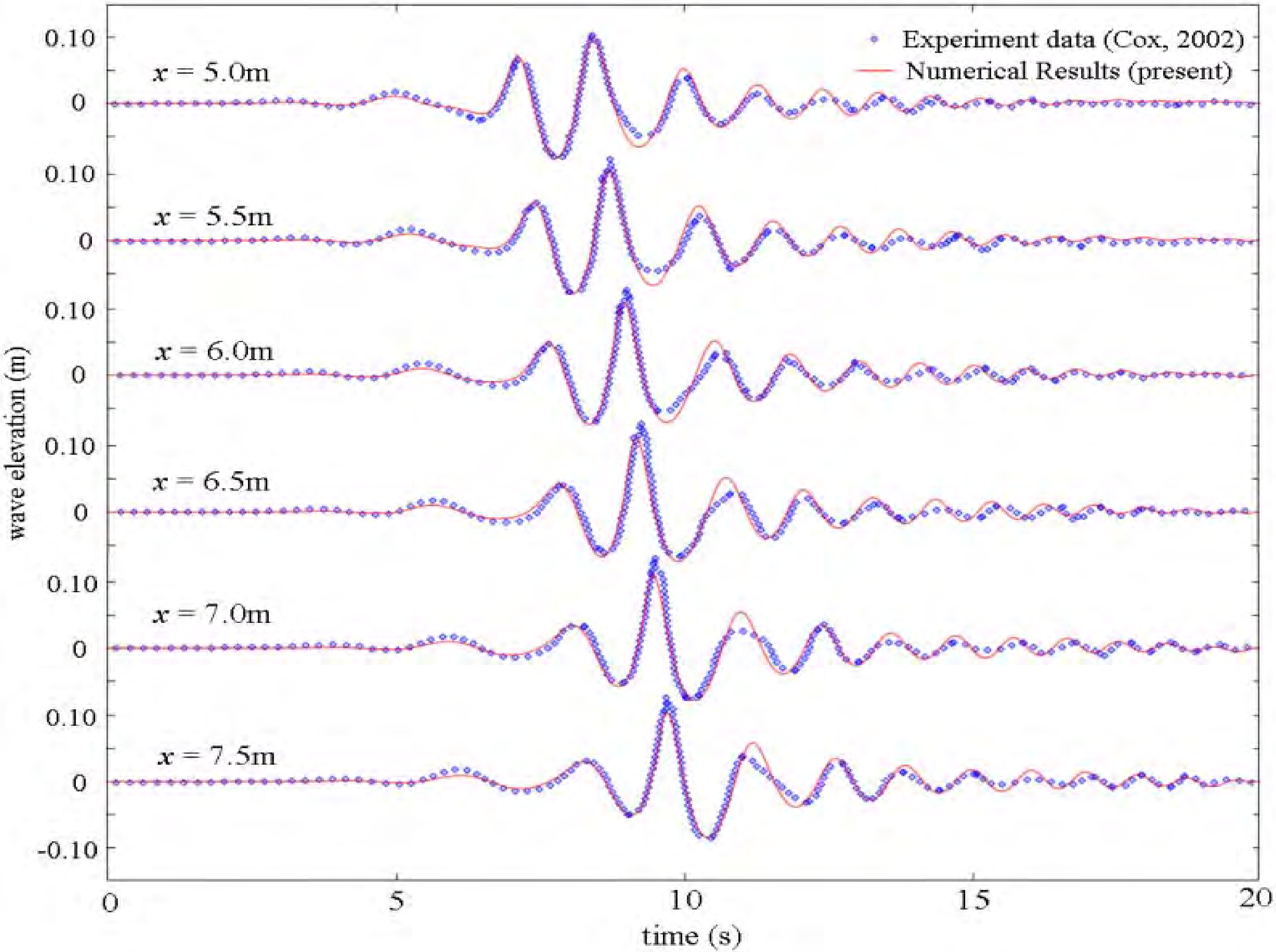
$A_2=0.08m \quad T_2=1.5s \quad \omega_2=\frac{2\pi}{T_2}$



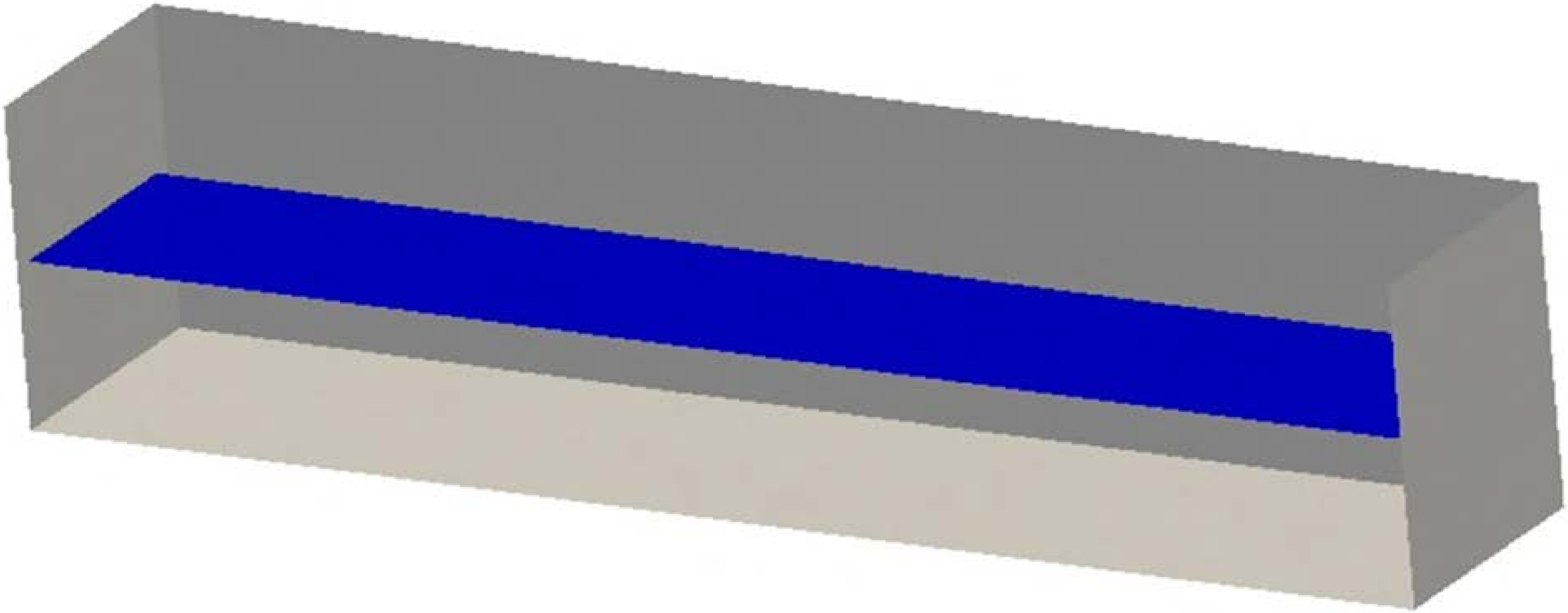
Freak Waves



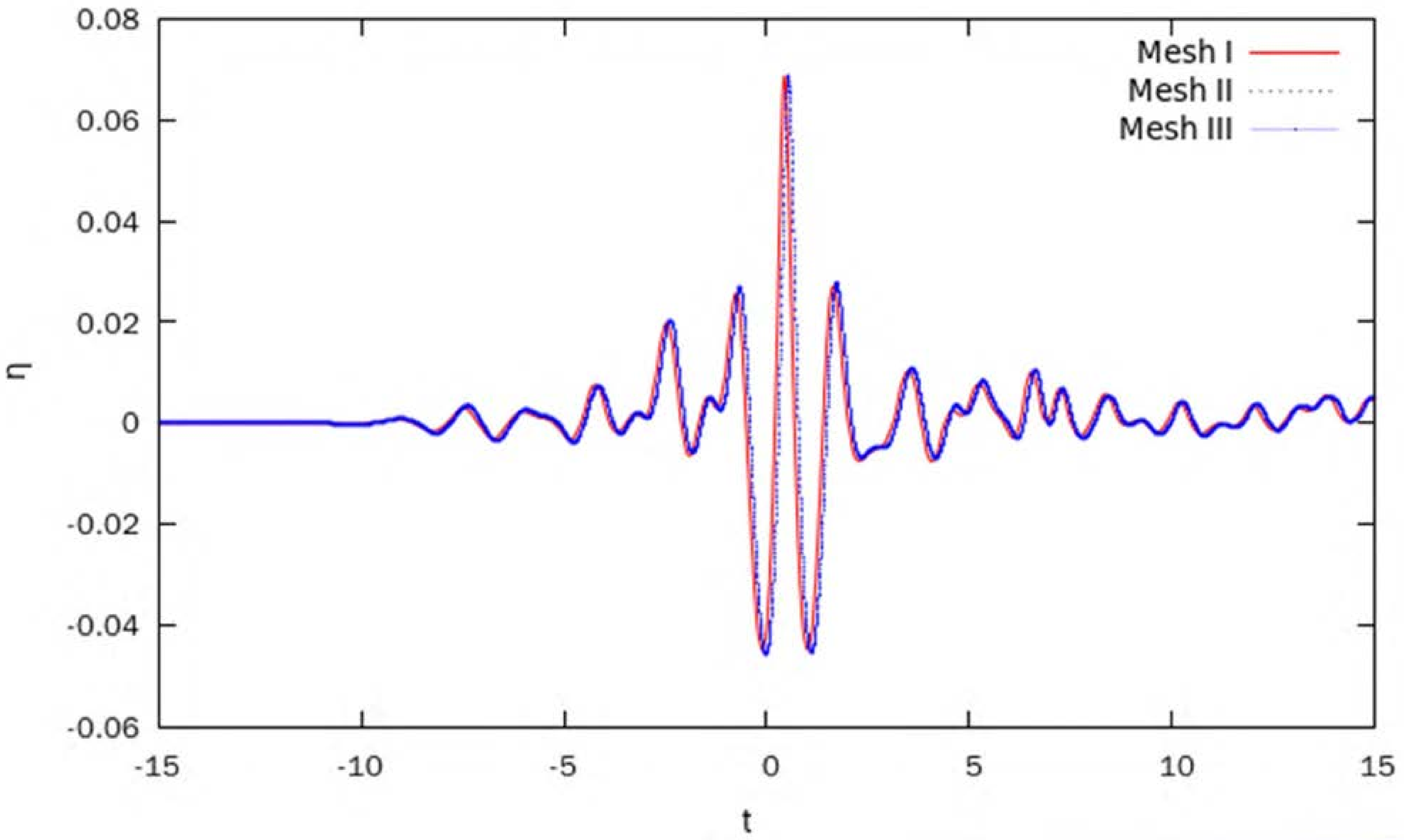
Freak Waves


Experiment data (Cox, 2002)
Numerical Results (present)
x = 5.0m
x = 5.5m
x = 6.0m
x = 6.5m
x = 7.0m
x = 7.5m
0.10
0
-0.10
wave elevation (m)
0
5
10
15
20
time (s)

Focused Waves

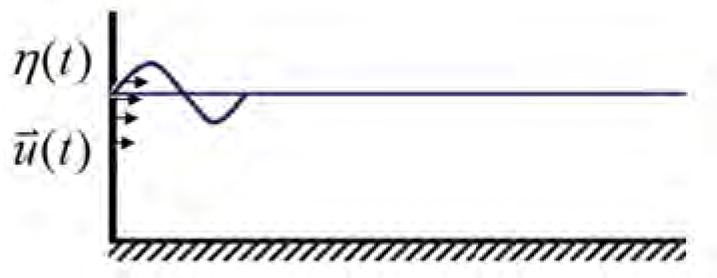


Freak Waves


0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
η
-15
-10
-5
0
5
10
15
t
Mesh I
Mesh II
Mesh III

Numerical Wave Tank

- Inlet wave boundary



Specify wave profile and water velocity at the fixed inlet boundary

Linear wave

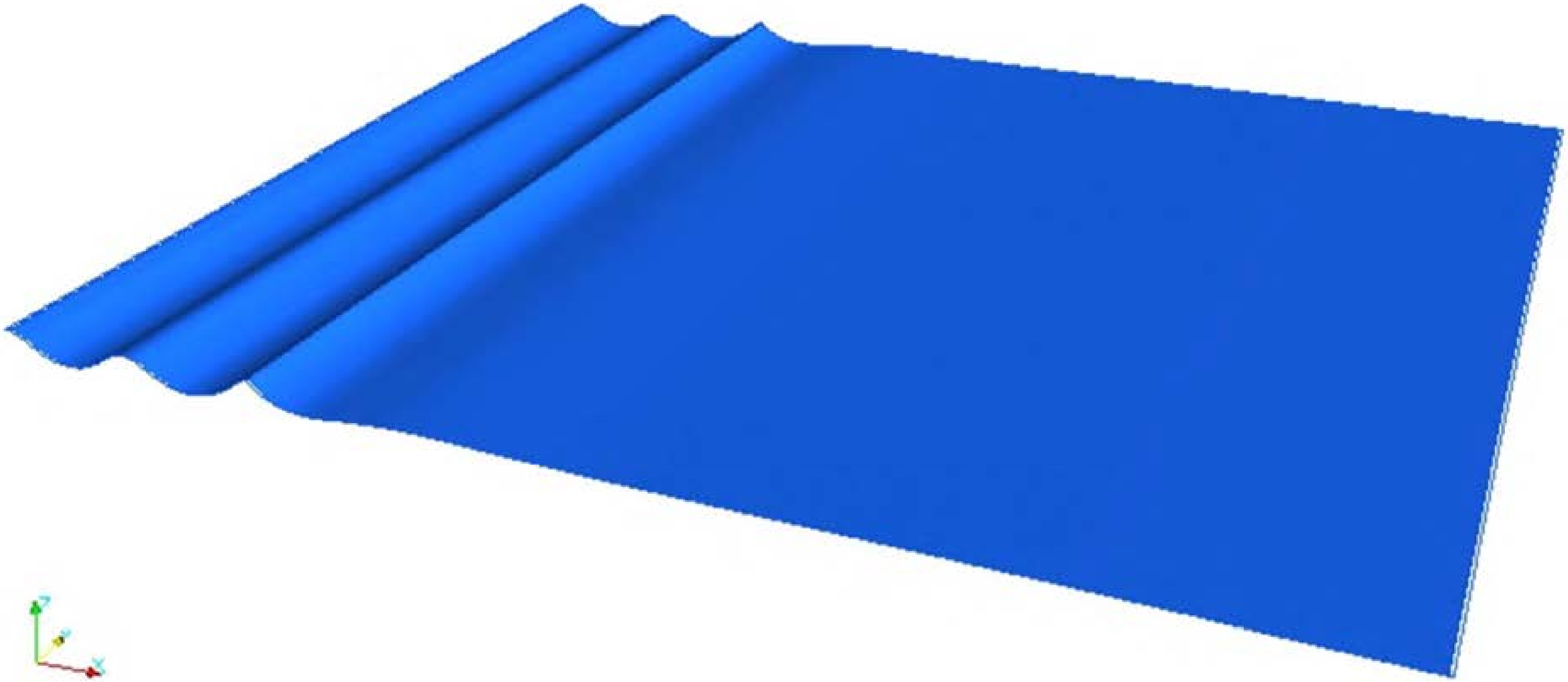
$$\eta = a\cos(\mathbf{k}\cdot\mathbf{x} - \omega_e t + \delta)$$
$$u = U_0 + a\omega e^{kz}\cos(\mathbf{k}\cdot\mathbf{x} - \omega_e t + \delta)$$
$$v = a\omega e^{kz}\cos\beta\cos(\mathbf{k}\cdot\mathbf{x} - \omega_e t + \delta)$$
$$w = a\omega e^{kz}\sin\beta\sin(\mathbf{k}\cdot\mathbf{x} - \omega_e t + \delta)$$
$$\omega_e = \omega + U_0 k\cos\beta$$

Stokes 2nd-order wave

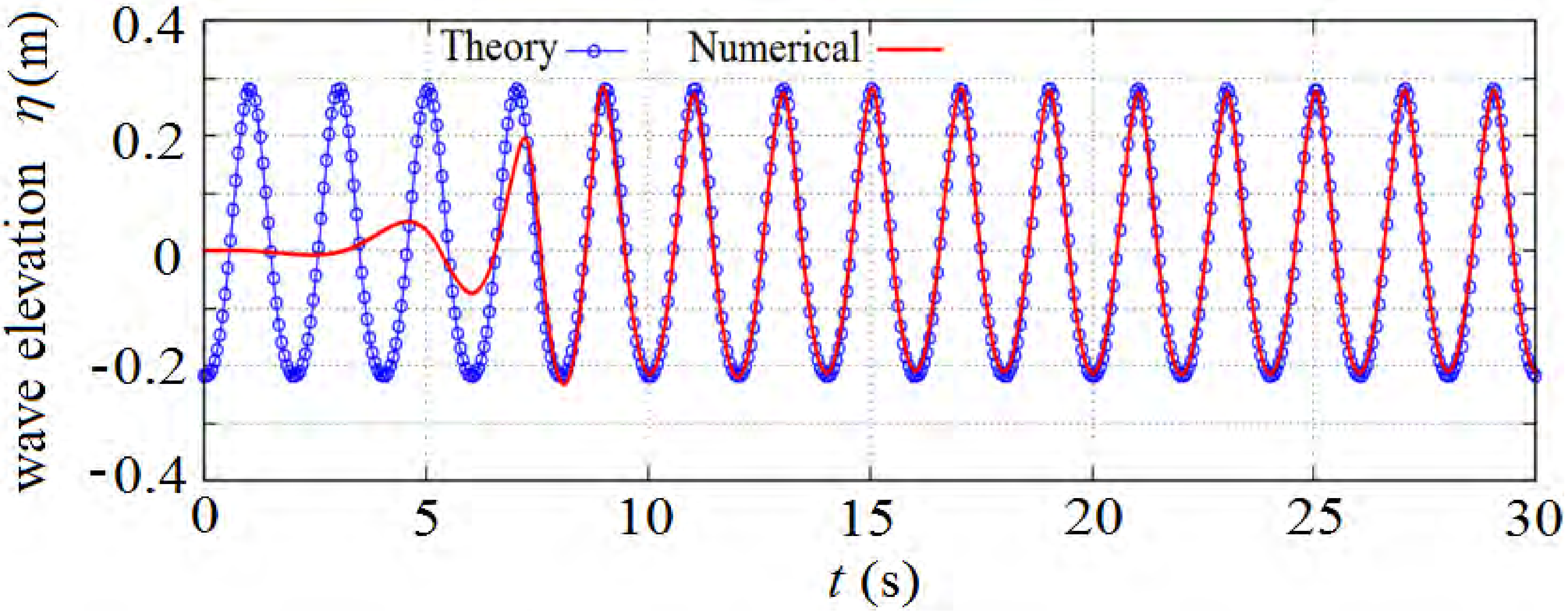
$$\eta = \frac{H}{2}\cos(kx - \omega t) + \frac{H}{8}\left(\frac{\pi H}{L}\right)\frac{\cosh kd}{\sinh^3 kd}(\cosh 2kd + 2)\cos 2(kx - \omega t)$$

2^{nd} order Stokes wave

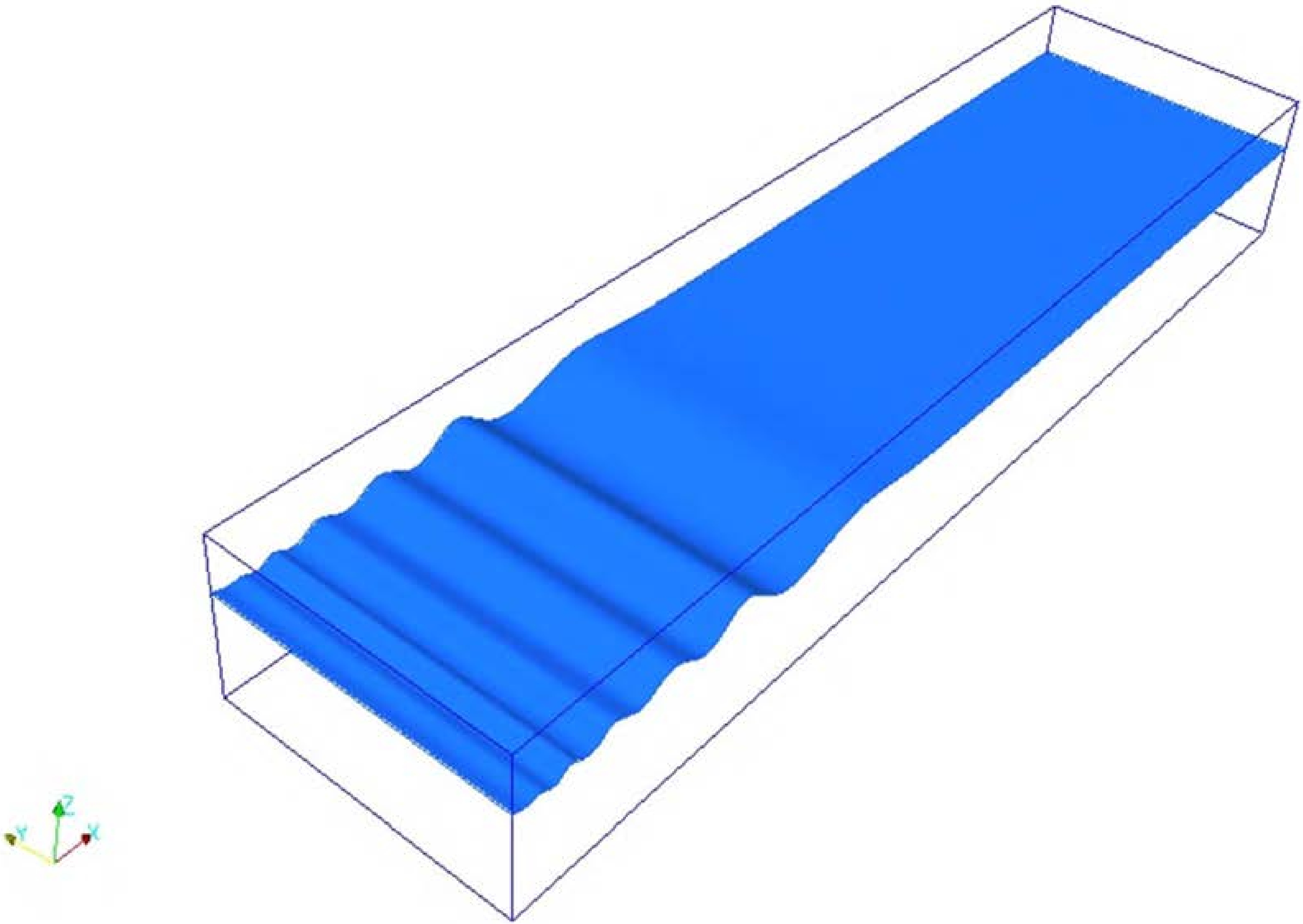
Stokes 2nd-order wave



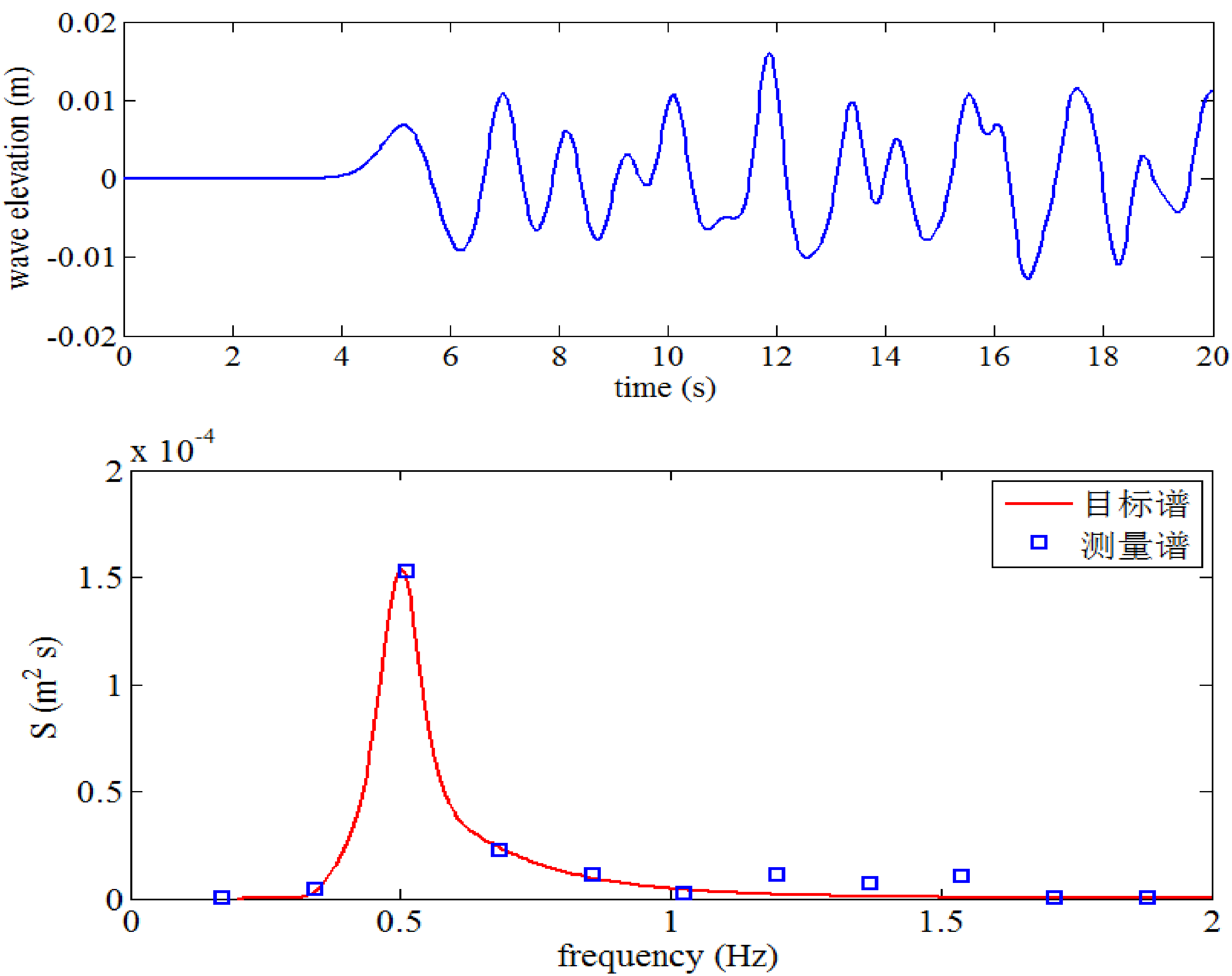
2nd order Stokes wave



Irregular waves



Irregular waves



Multidirectional waves

3D irregular wave (short crest waves)

$$\eta(x,y,t)=\sum_{i=1}^{N_f}\sum_{j=1}^{M_\theta}a_{ij}\cos\left(k_i x\cos\theta_j+k_i y\sin\theta_j-\omega_i t+\phi_{ij}\right)$$

$$a_{ij}=S(f_i)D(\theta_j)$$

Wave spectrum

P-M
ITTC
JONSWAP
……

Directional spreading function

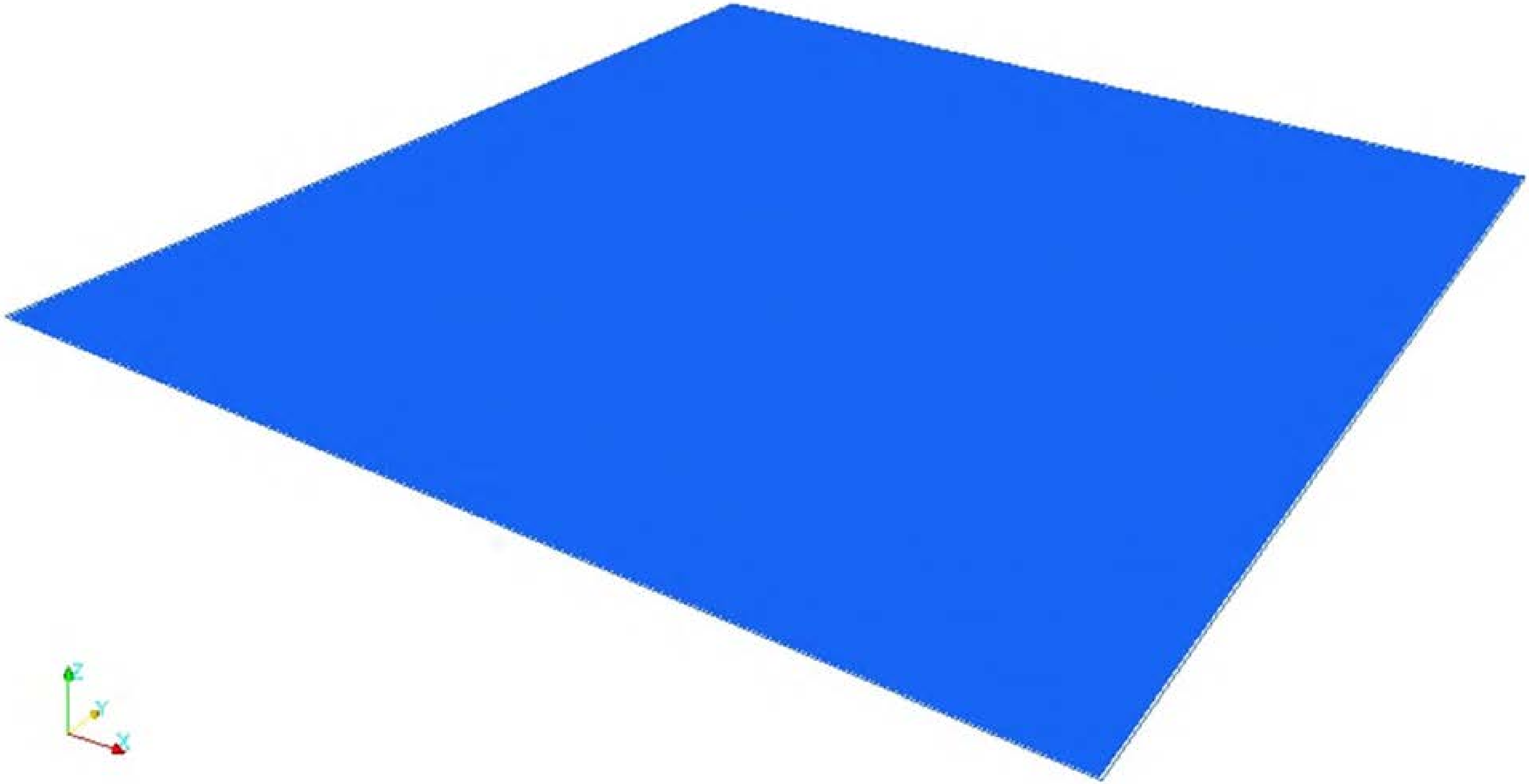
$$D(\theta_j)=k_n\cos^n(\theta_j)\qquad \left|\theta_j\right|\le\frac{\pi}{2}$$

$$n=2\quad k_n=\frac{2}{\pi}$$

- Here JONSWAP spectrum is used .
- N_f number of the wave frequencies,
- M_θ number of the wave direction.

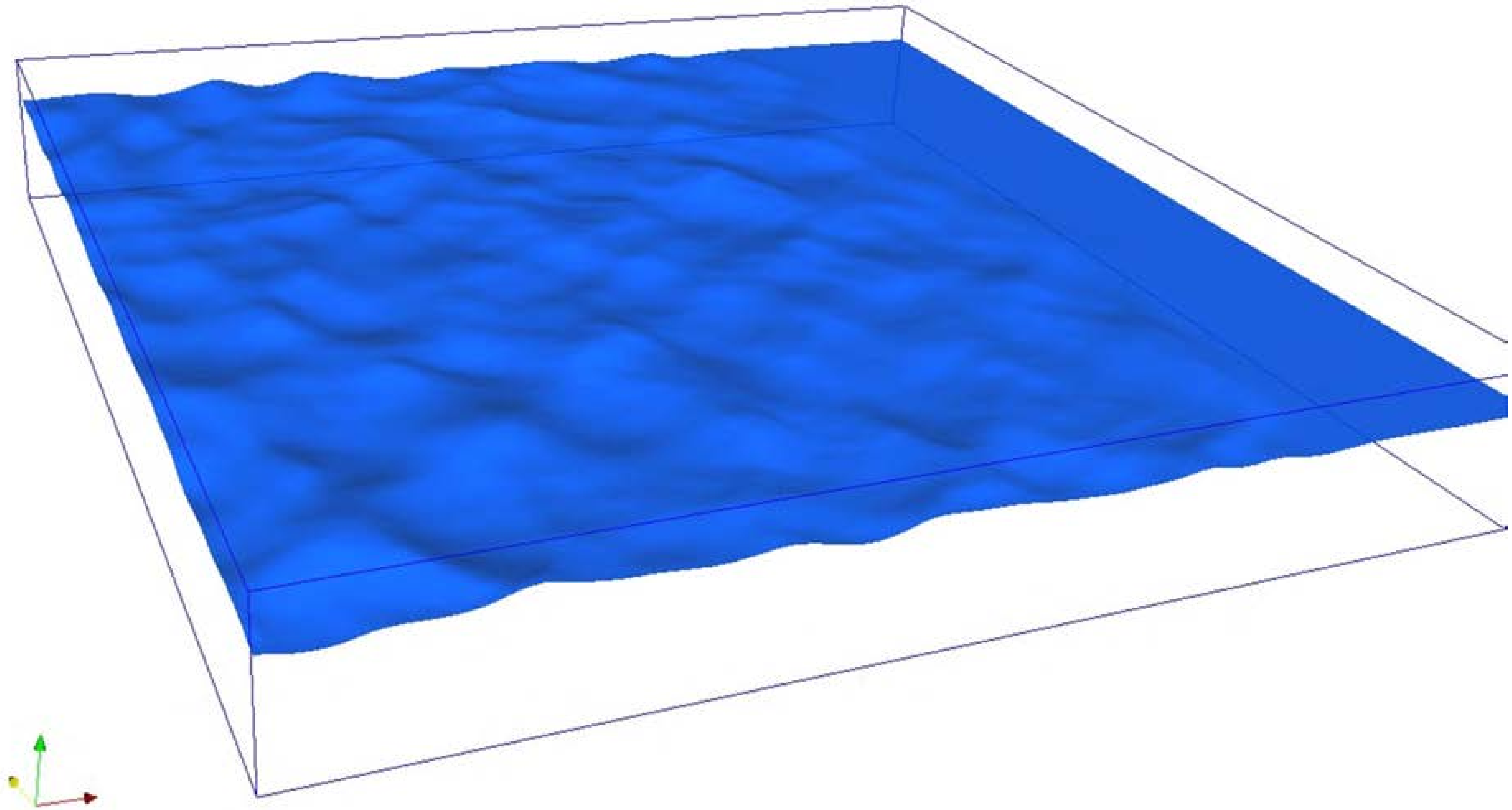
Multidirectional waves

Multidirectional irregular wave



H_s =0.1m, T_p =1.2s, N_f =21, M_θ =31

Multidirectional waves



$$H_s = 0.6\,\mathrm{m}, \quad T_p = 1.1\,\mathrm{s}, \quad N_f = 22, \quad M_\theta = 30$$

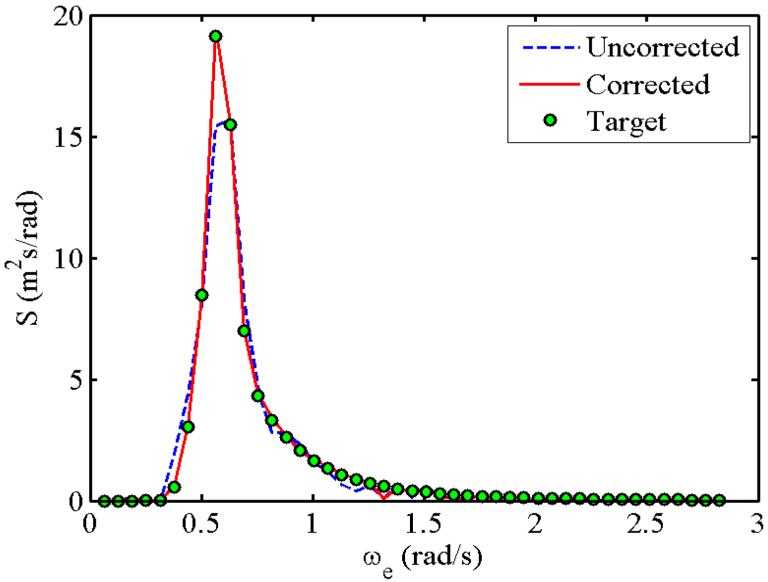
Wave spectrum Correction

- Uncorrected Input wave spectrum S_{I1}
- Target wave Spectrum S_T
- Measured wave Spectrum S_M

  Obtained with a wave probe at specified location.
- Corrected Input wave spectrum S_{I2}

$$S_{I2}(\omega_i) = \frac{S_{I1}(\omega_i) S_T(\omega_i)}{S_M(\omega_i)}$$

By the wave spectrum correction , the obtained wave spectrum is in accord with the target spectrum finally, as shown in the figure.



3D Focused Waves

3D focusing wave

$$\eta(x,y,t)=\sum_{i=1}^{N_f}\sum_{j=1}^{M_\theta}a_{ij}\cos\left(k_i(x-\boxed{x_f})\cos\theta_j+k_i(y-\boxed{y_f})\sin\theta_j-\omega_i(t-\boxed{t_f})\right)$$

- Focusing point $(x_f\ ,y_f\ )$
- Focusing time t_f.

3D Focused Waves

focusing wave

H_s=0.06m, T_p=1.2s, N_f=21, M_θ=31

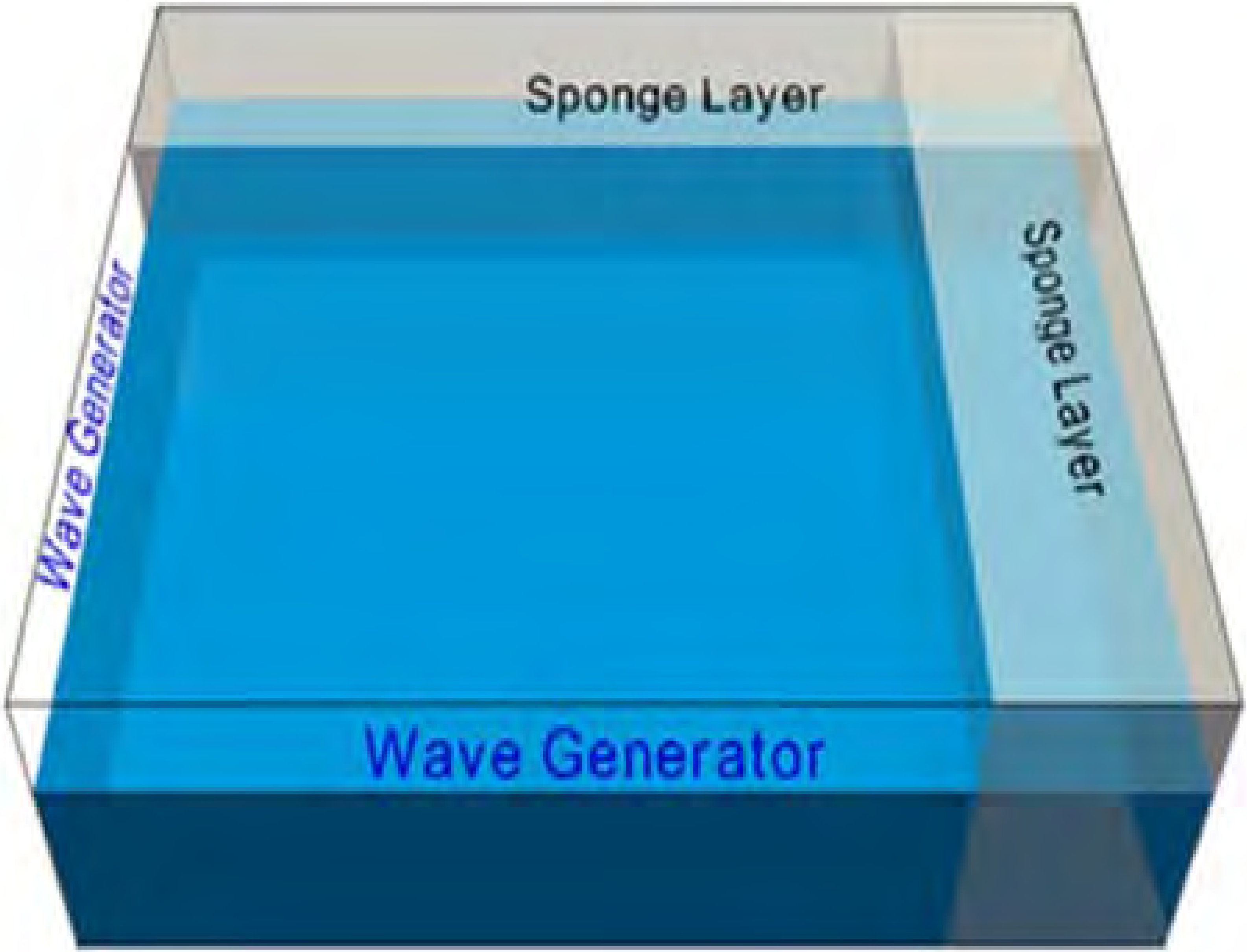
f_{max}=0.83, f_{min}=1.25

Assumed focusing point (7, 0)

Assumed focusing time t=8s

Using the JONSWAP spectrum

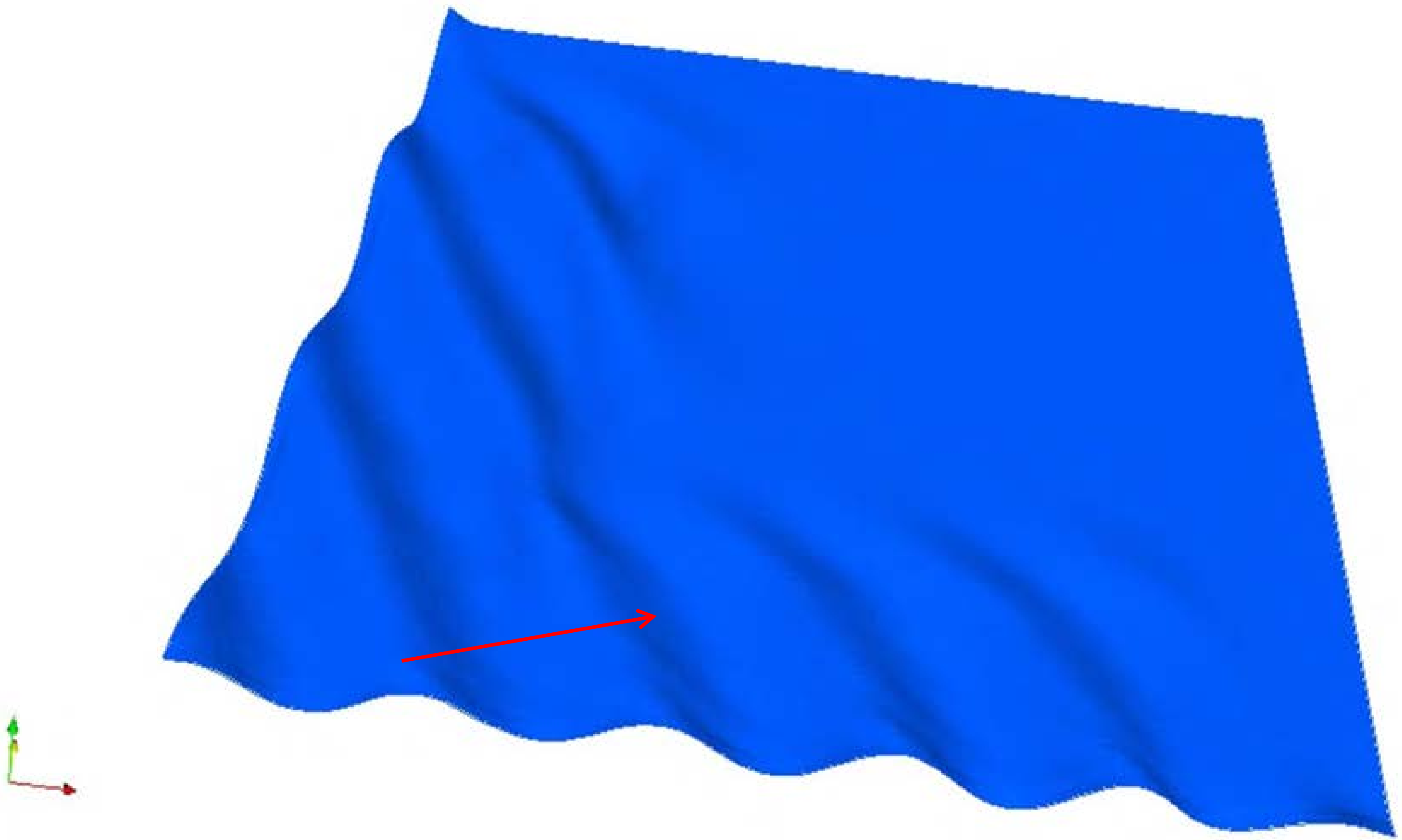
Oblique Wave Tank



X

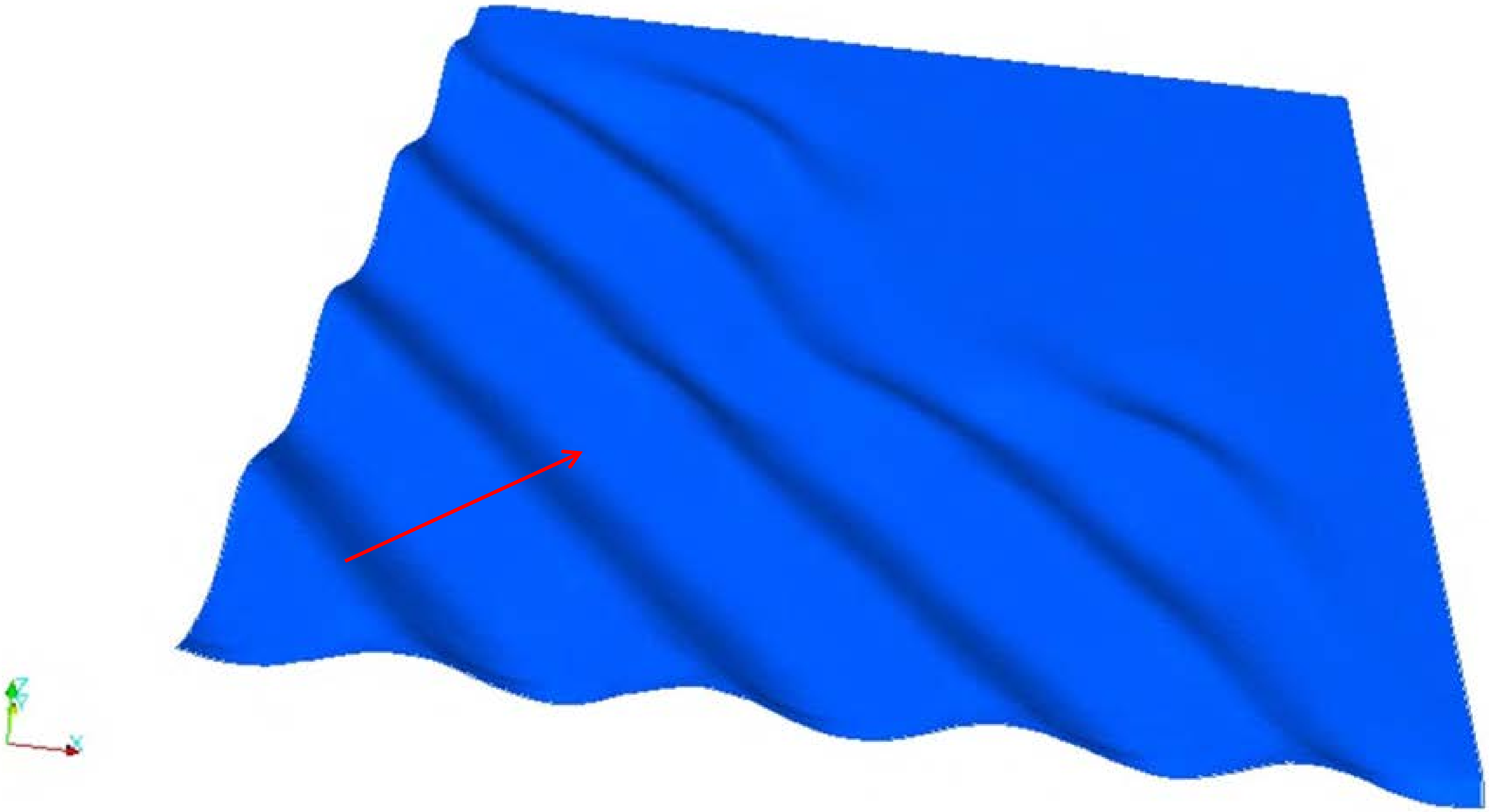
Oblique Wave Tank

Oblique wave (30 degree)



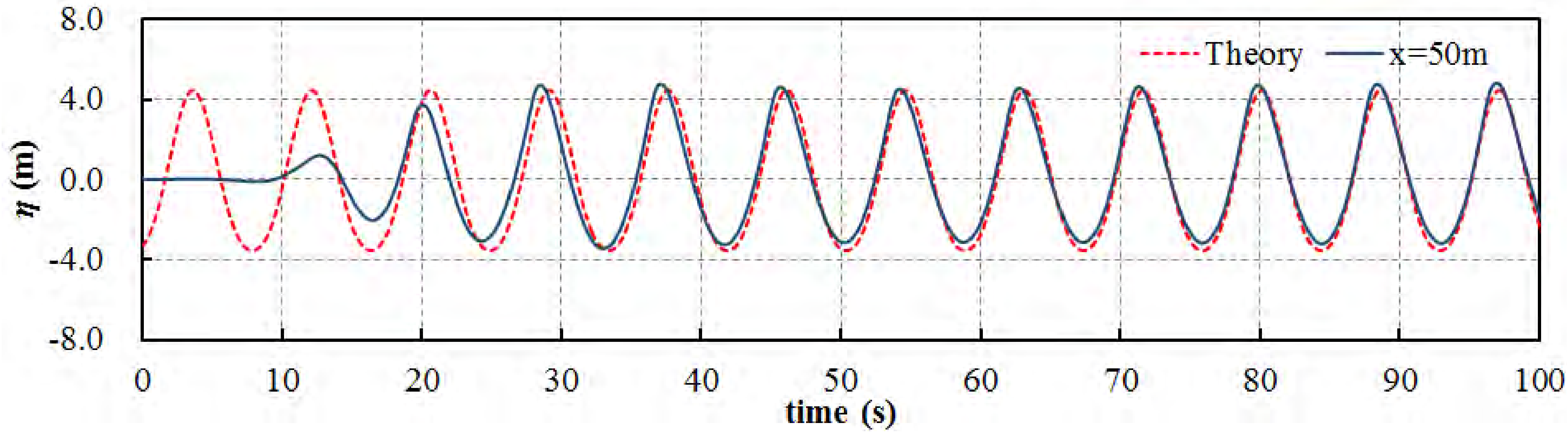
Oblique Wave Tank

Oblique wave (45 degree)

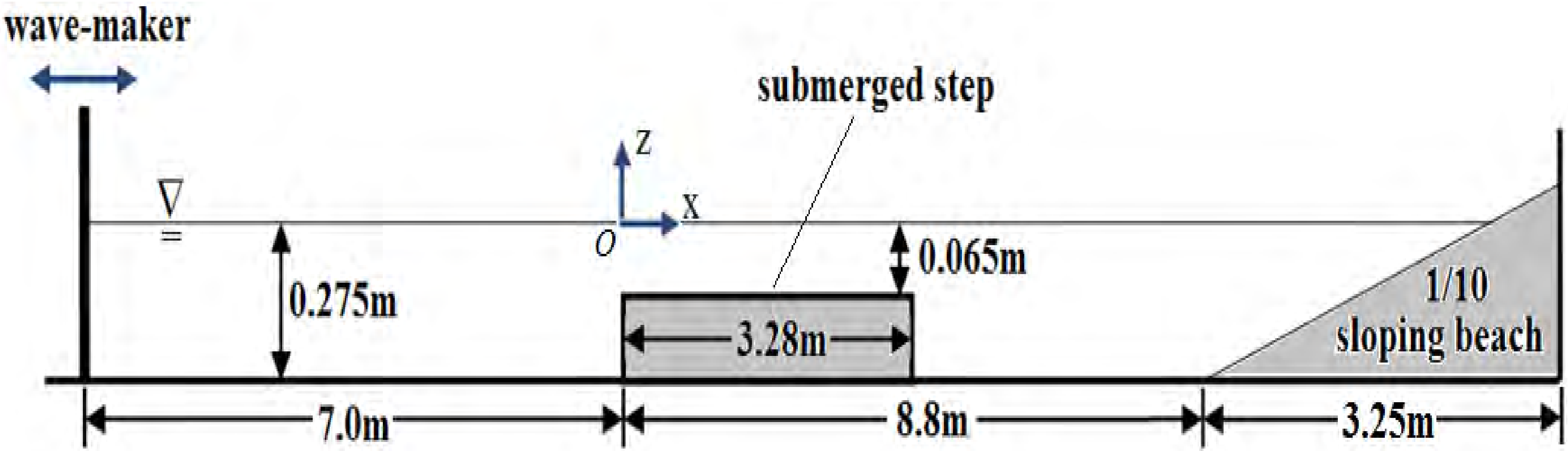


Oblique Wave Tank

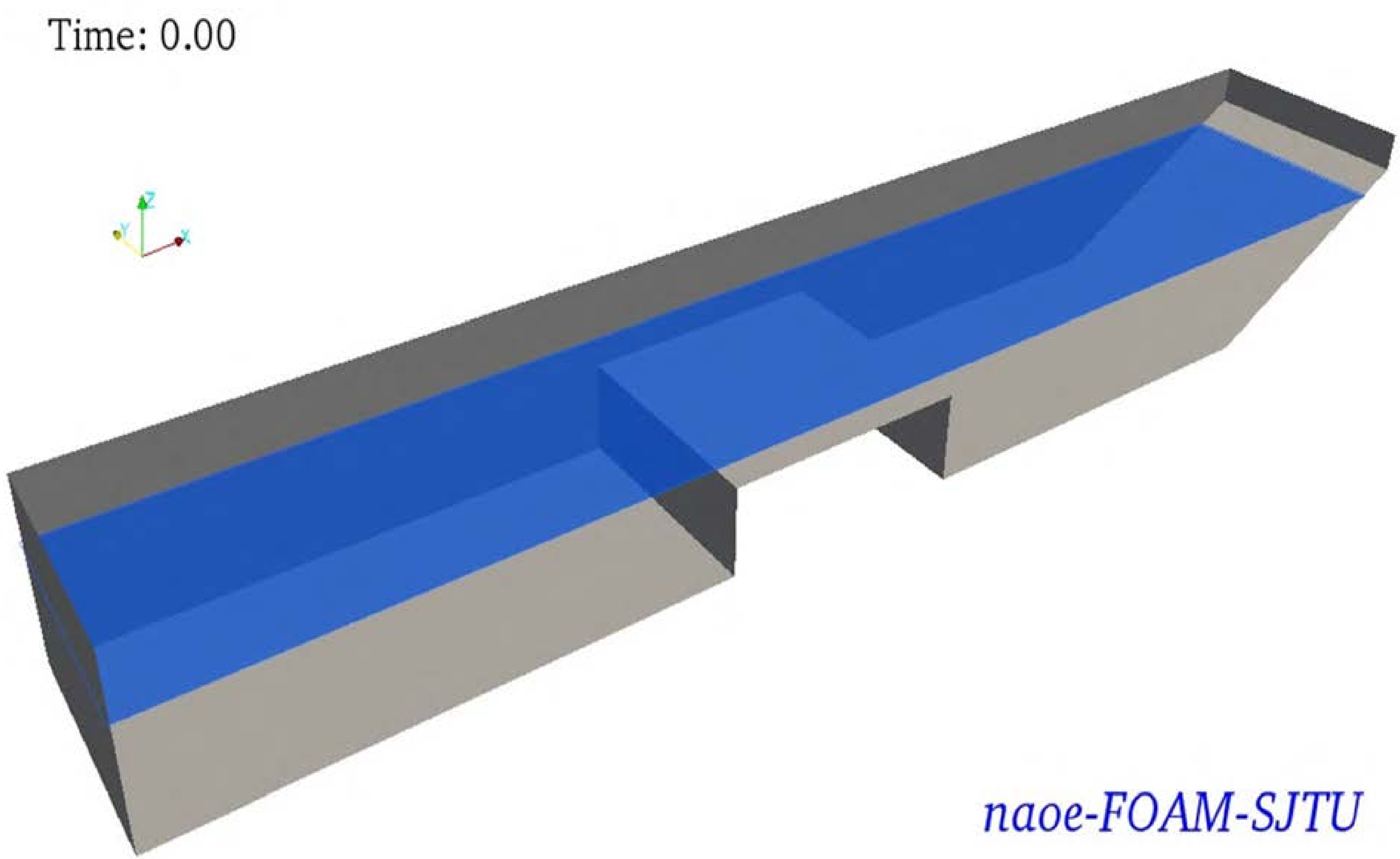
H=8.0m, T=8.5s

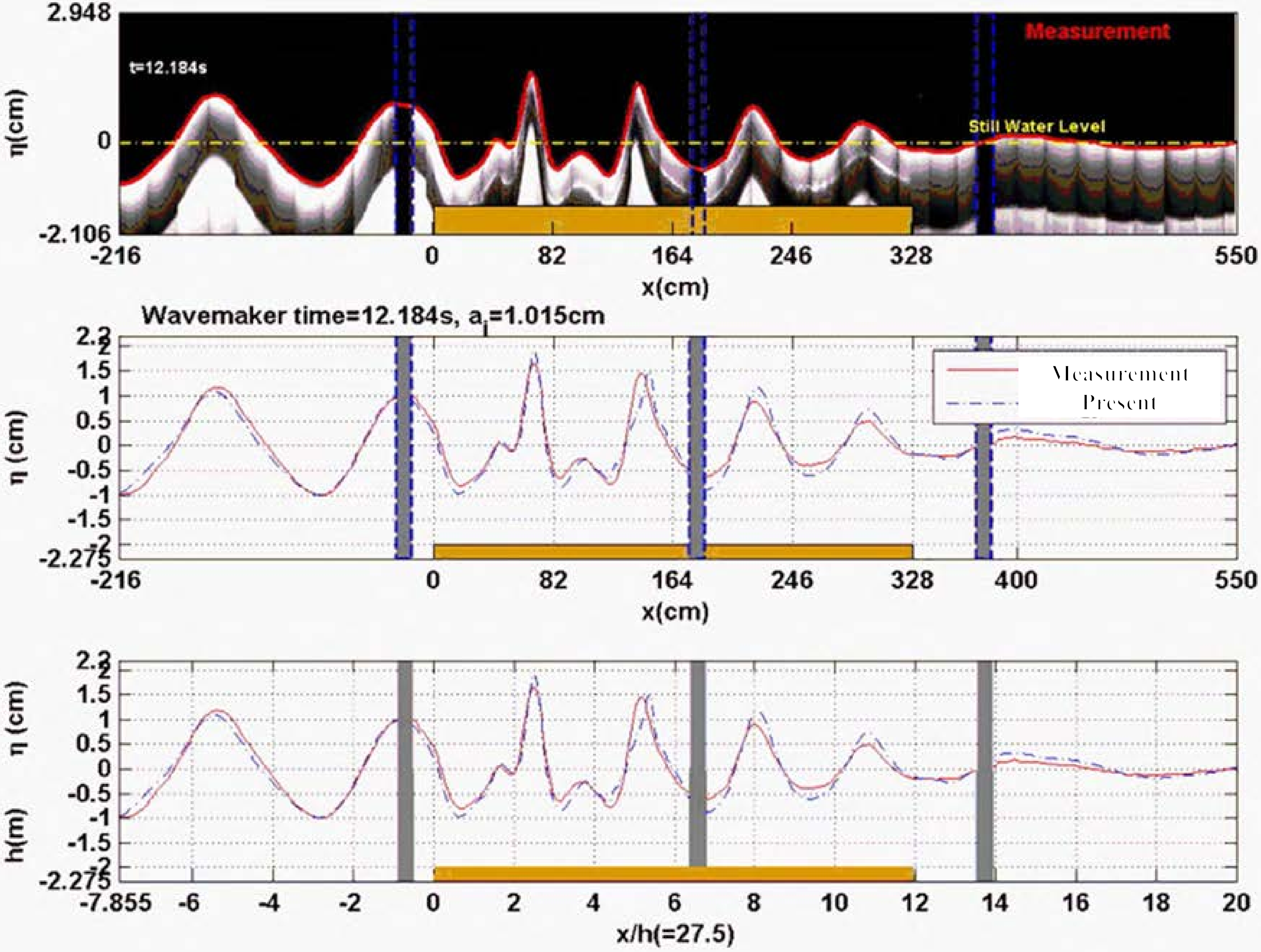


Regular Wave propagation on Step

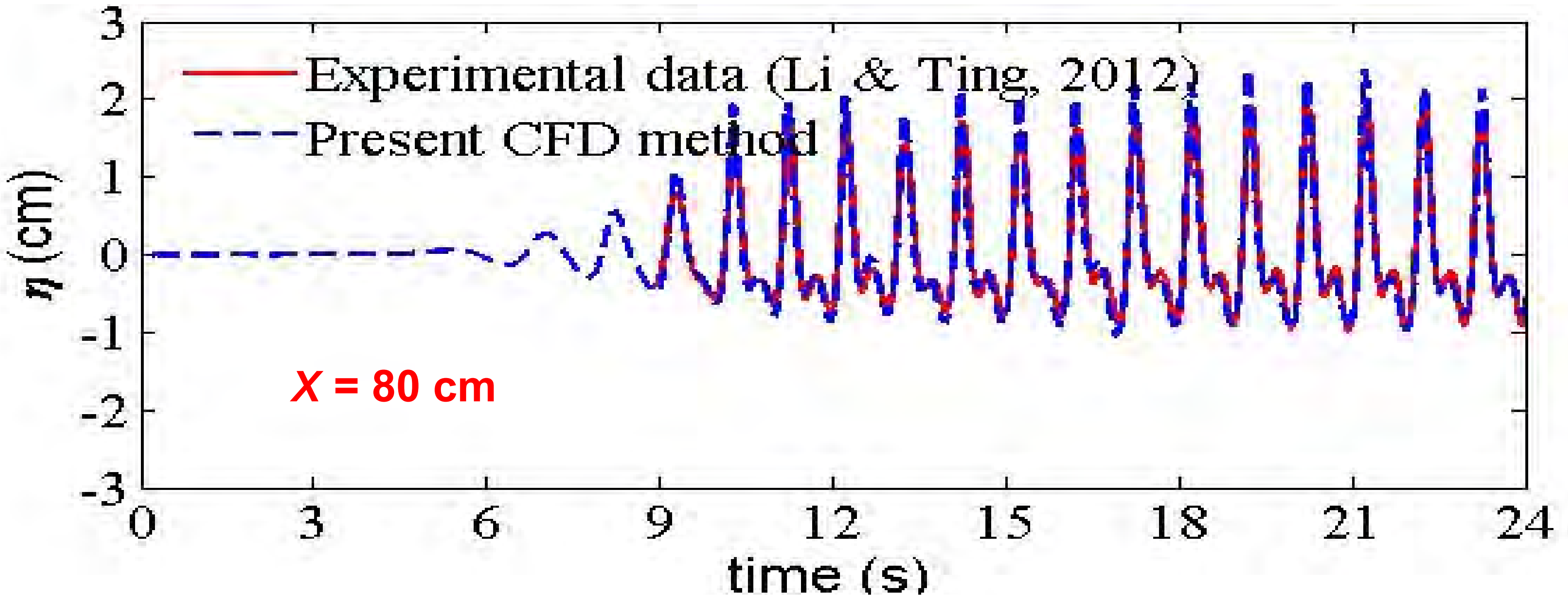


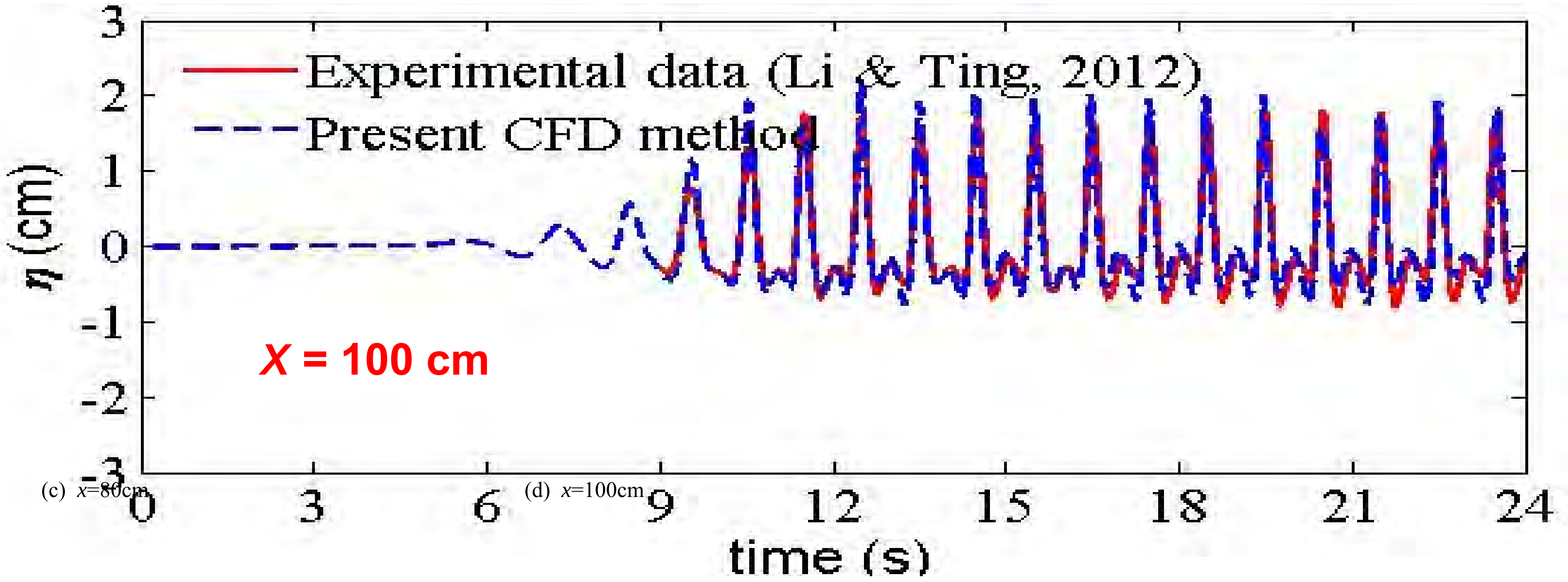
Regular Wave propagation on Step



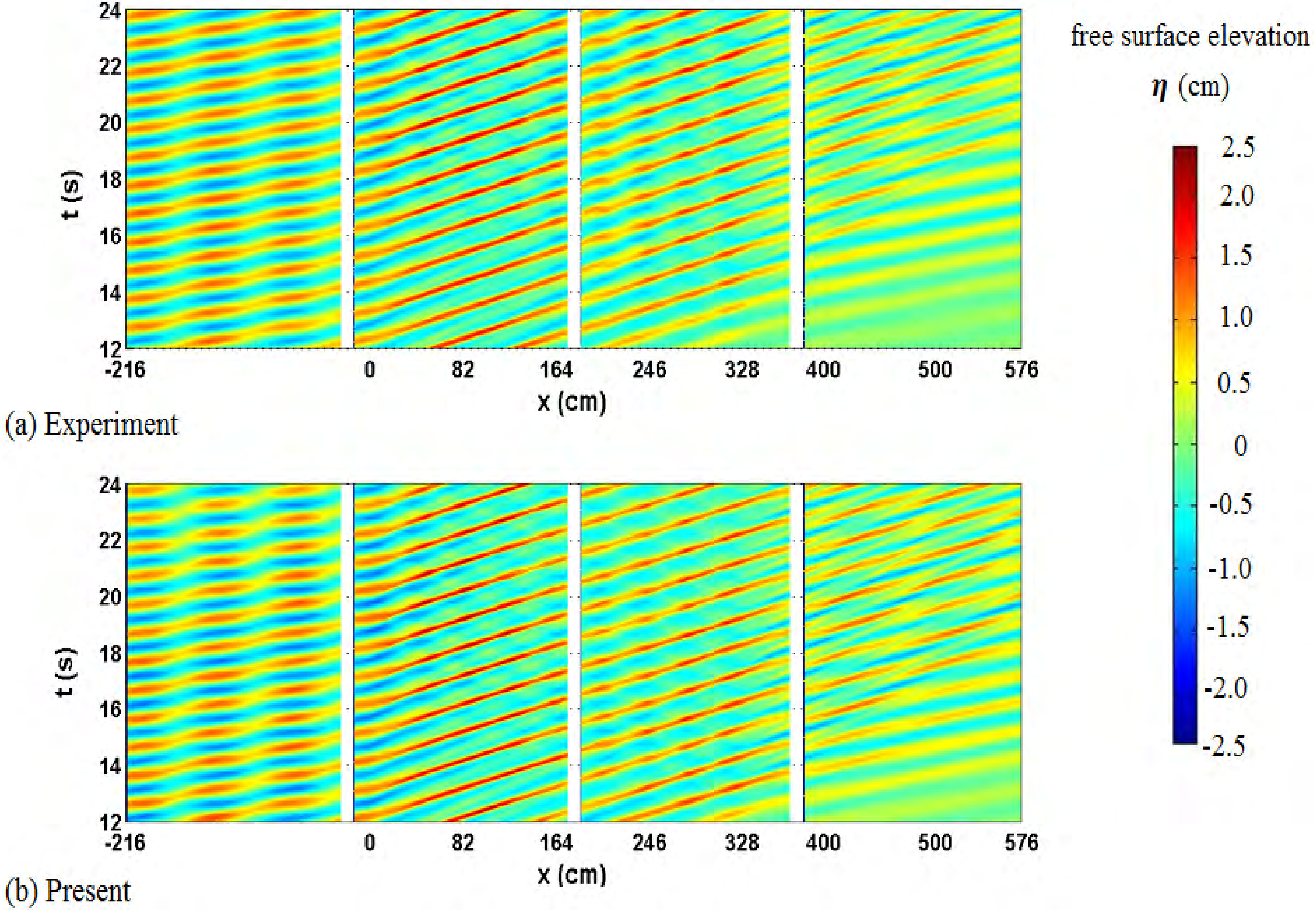


Measurement
t=12.184s
Still Water Level
η(cm)
2.948
0
-2.106
-216
0
82
164
246
328
550
x(cm)
Wavemaker time=12.184s, a_i=1.015cm
Measurement
Present
η (cm)
400
x(cm)
h(m)
x/h(=27.5)

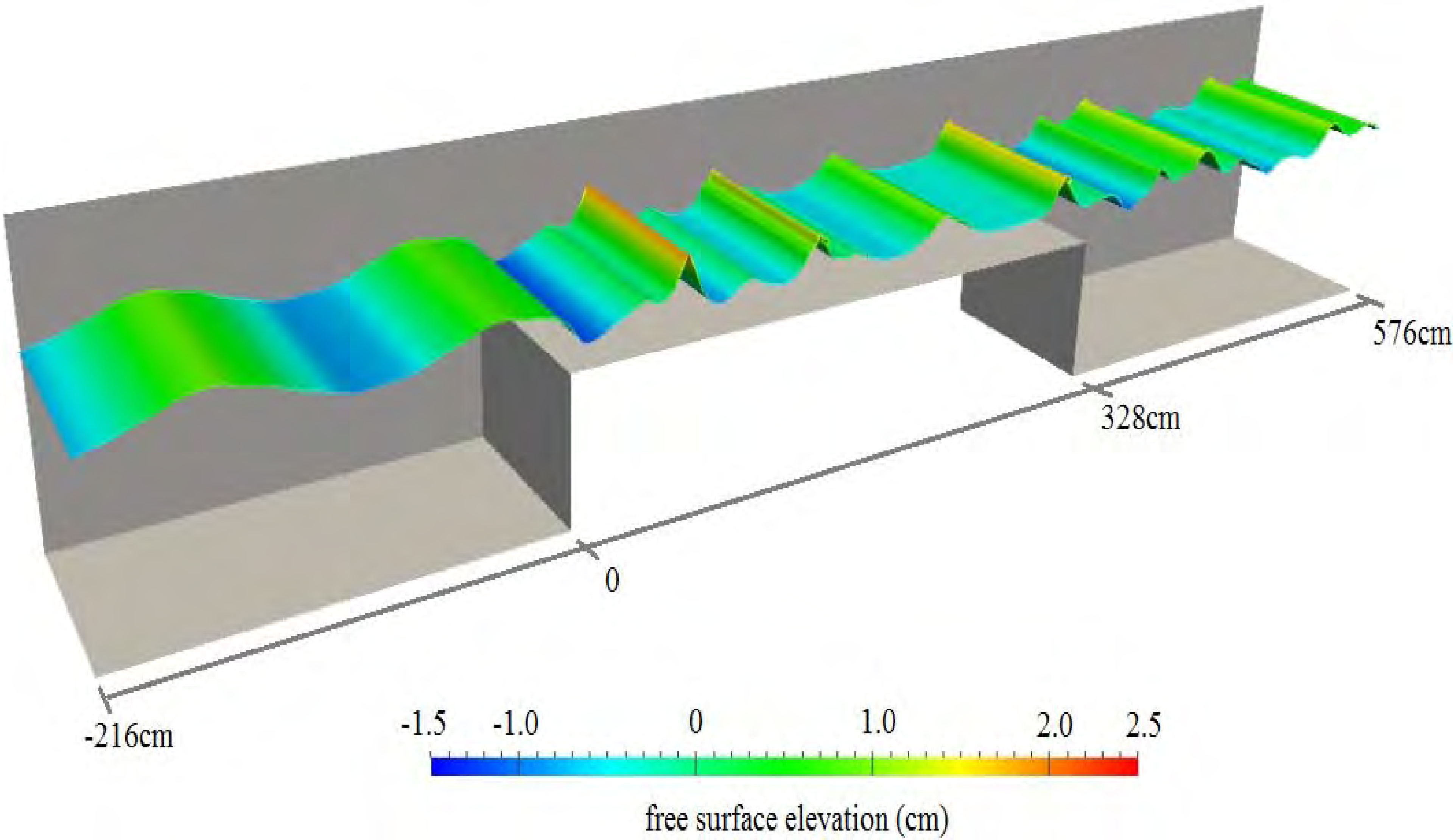


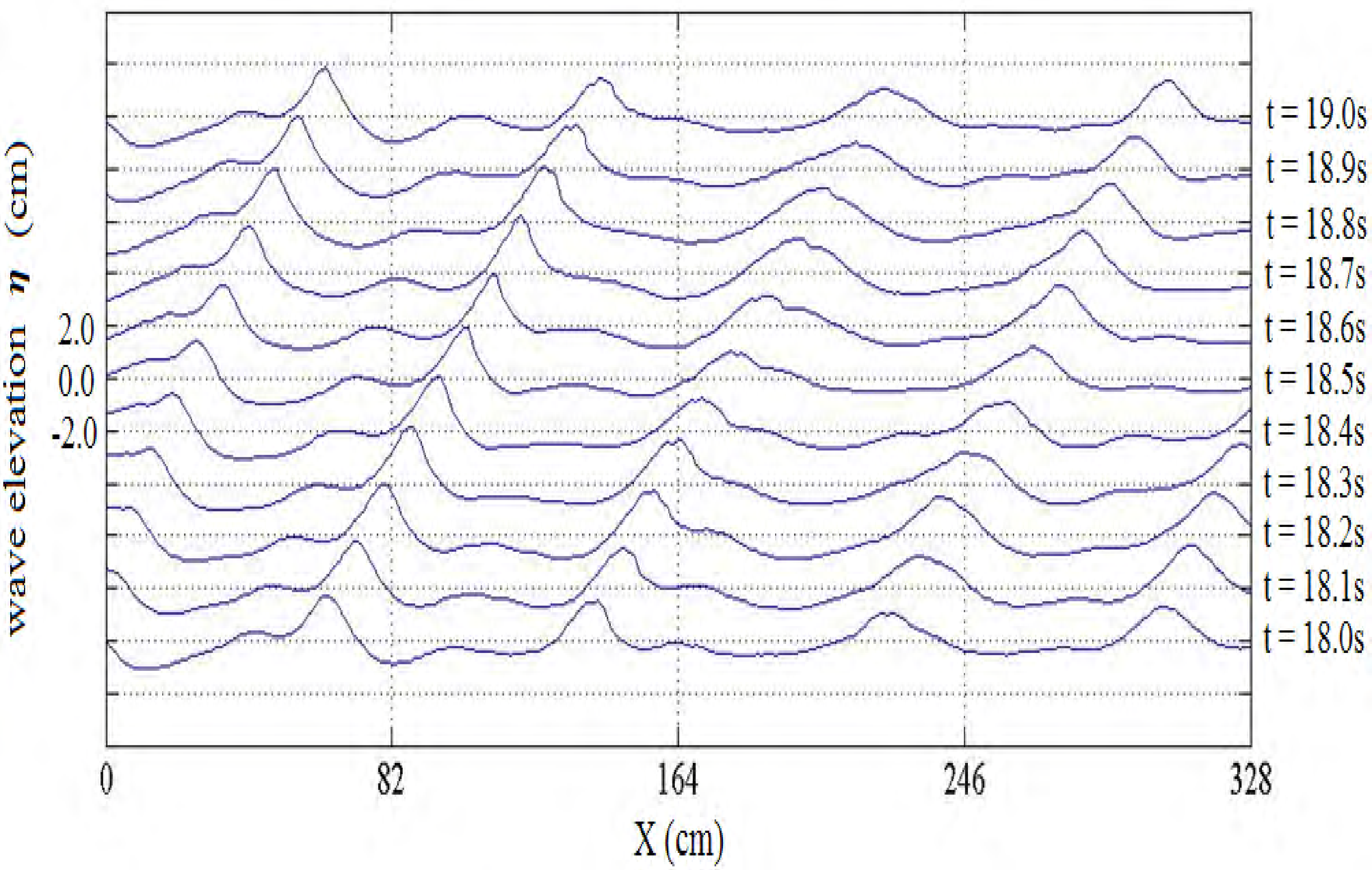


(c) *x*=80cm (d) *x*=100cm

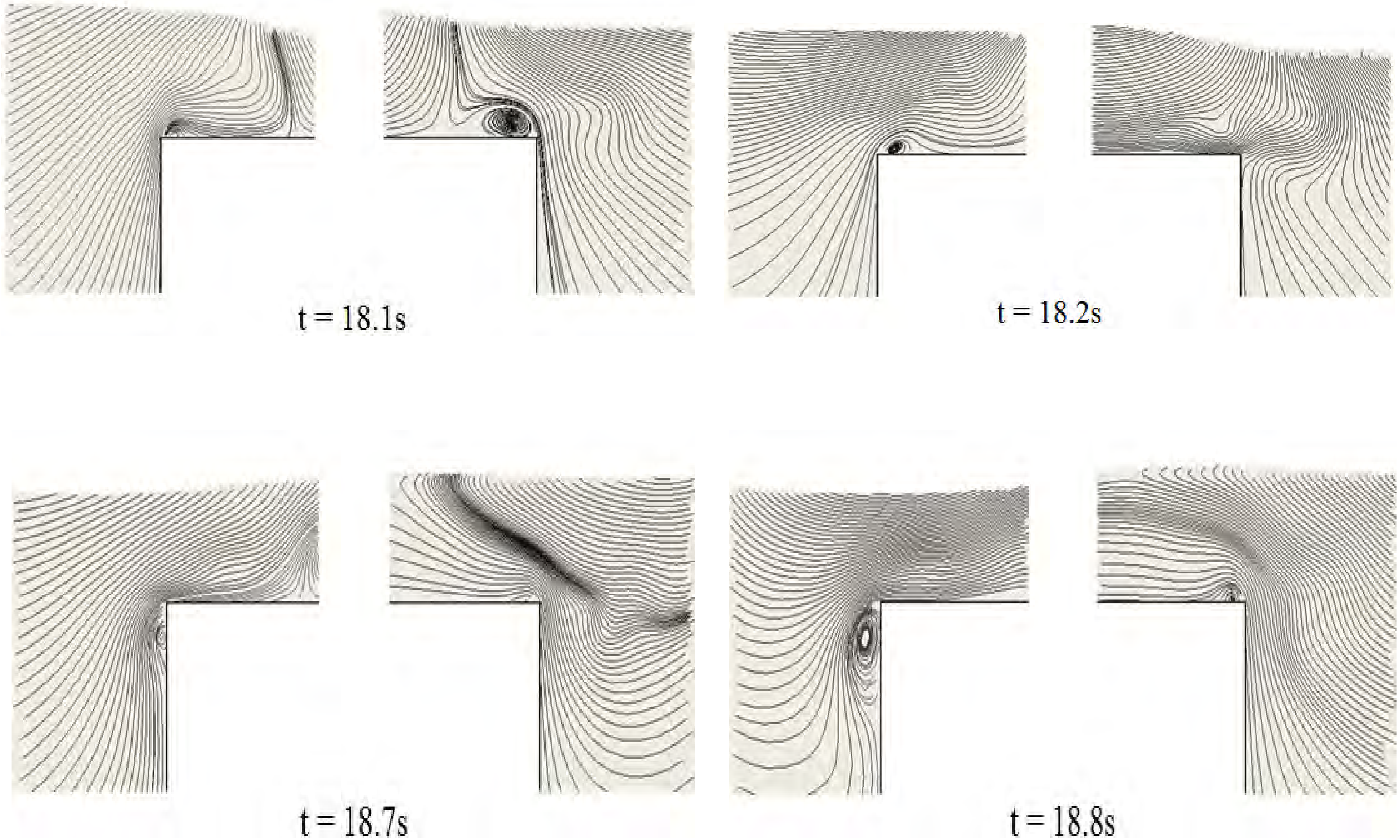


The stack image of the wave profile evolution


576cm
328cm
0
-216cm
-1.5
-1.0
0
1.0
2.0
2.5
free surface elevation (cm)


wave elevation η (cm)
2.0
0.0
-2.0
0
82
164
246
328
X (cm)
t = 19.0s
t = 18.9s
t = 18.8s
t = 18.7s
t = 18.6s
t = 18.5s
t = 18.4s
t = 18.3s
t = 18.2s
t = 18.1s
t = 18.0s

(j)

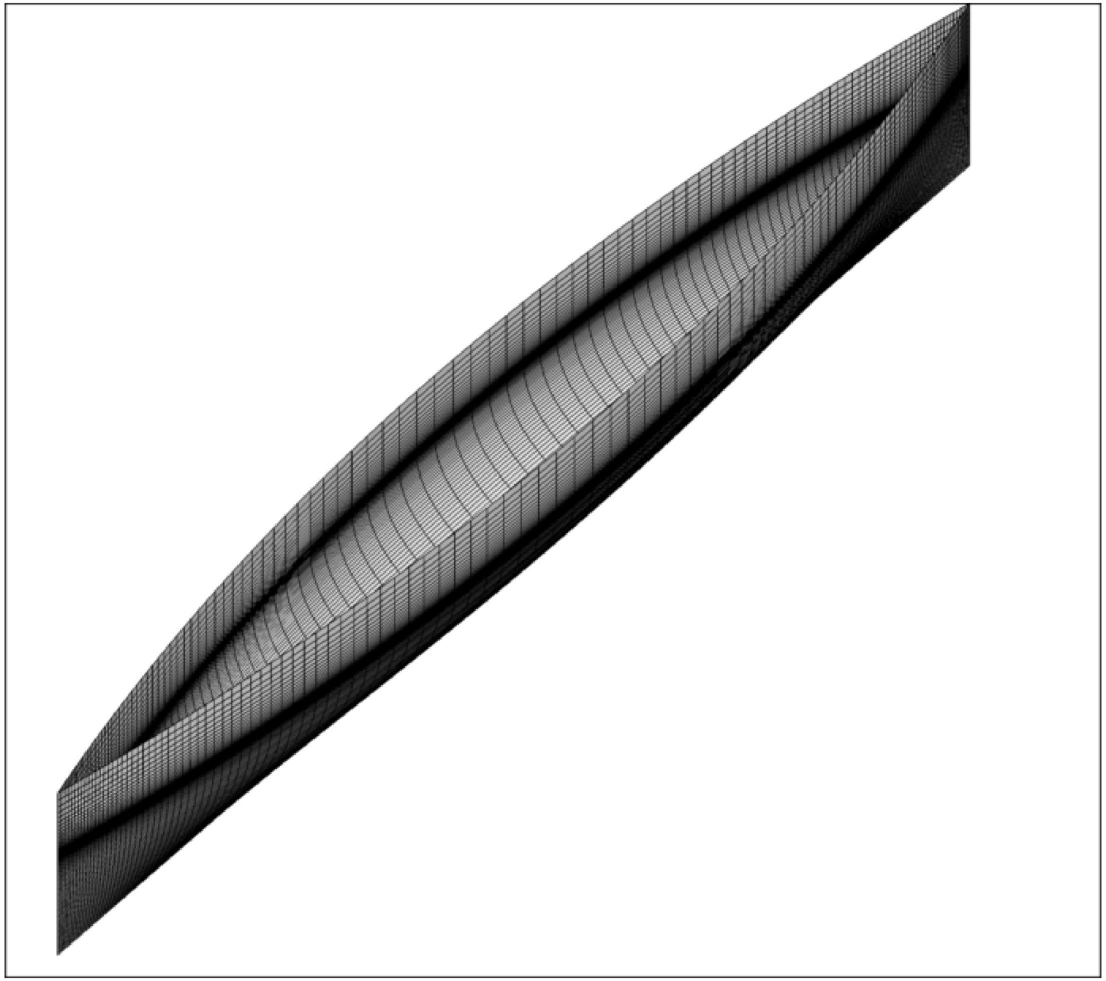


Ship wave-making and Resistance in still water

Wigley Ship Motion in Still Water

Single Wigley motion in still water

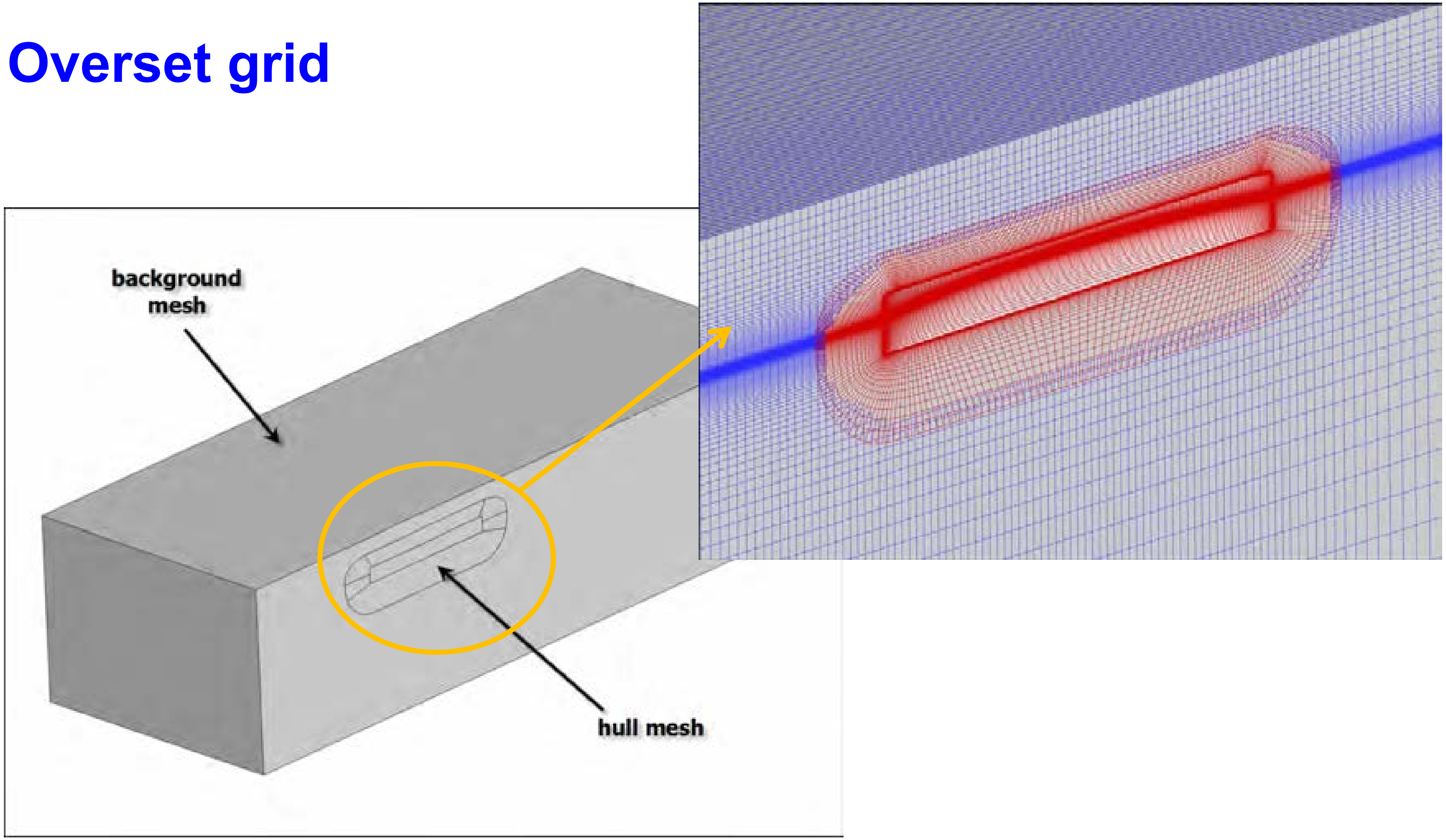
$$y=\frac{B}{2}[\frac{4x}{L}(1-\frac{x}{L})][1-(\frac{z}{H})^2]$$



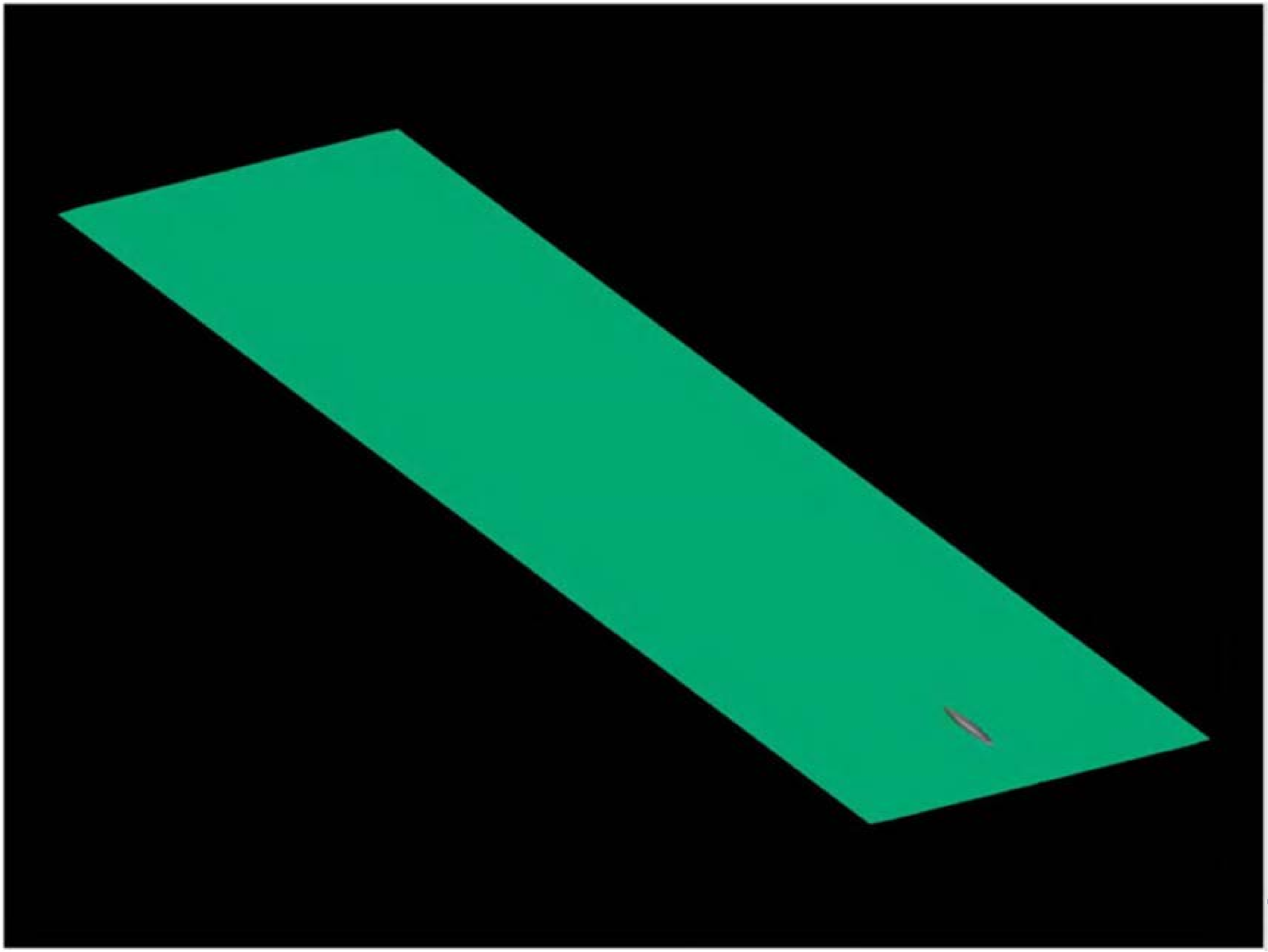
Wigley hull Grid

Single Wigley motion in still water

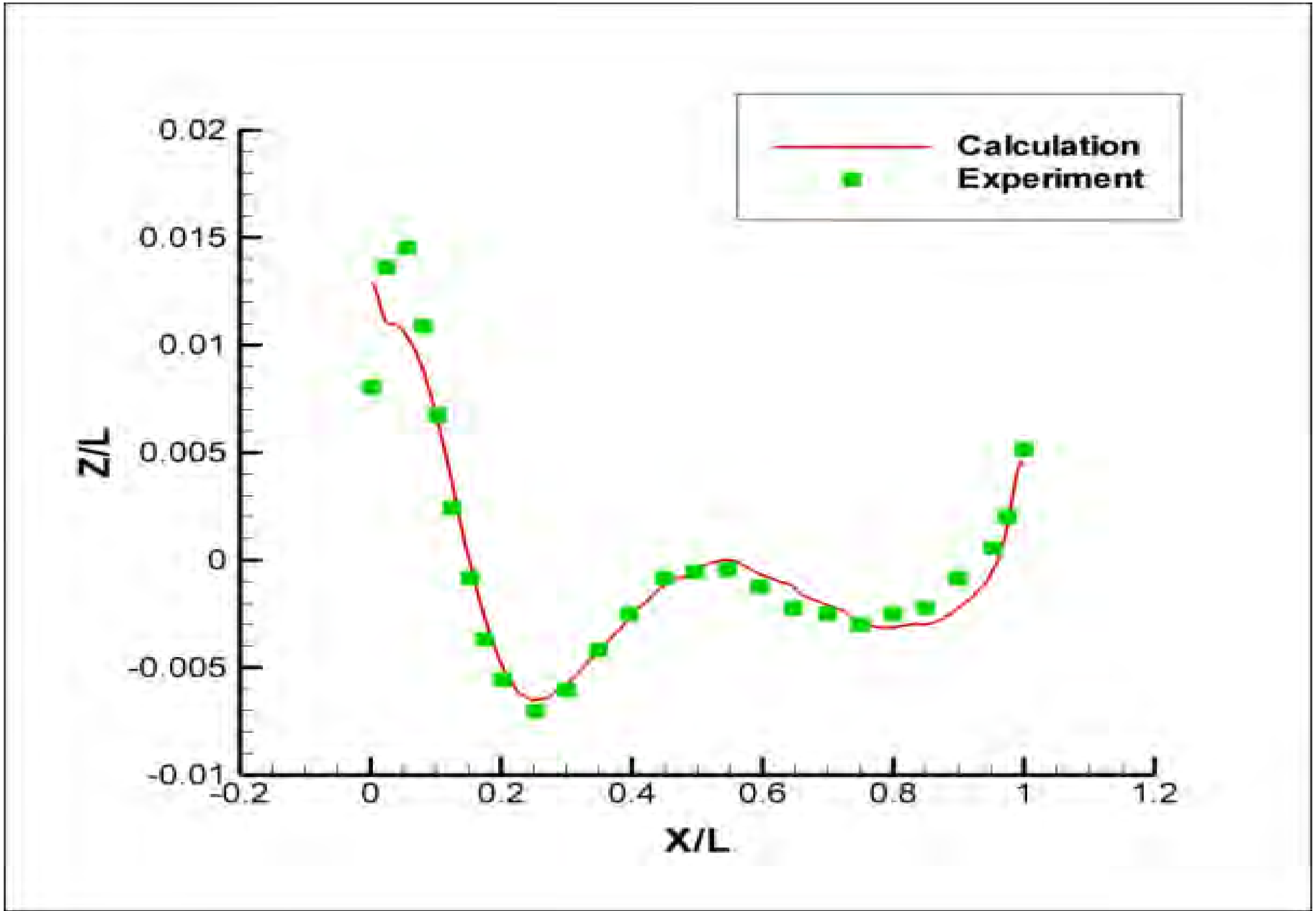
Overset grid



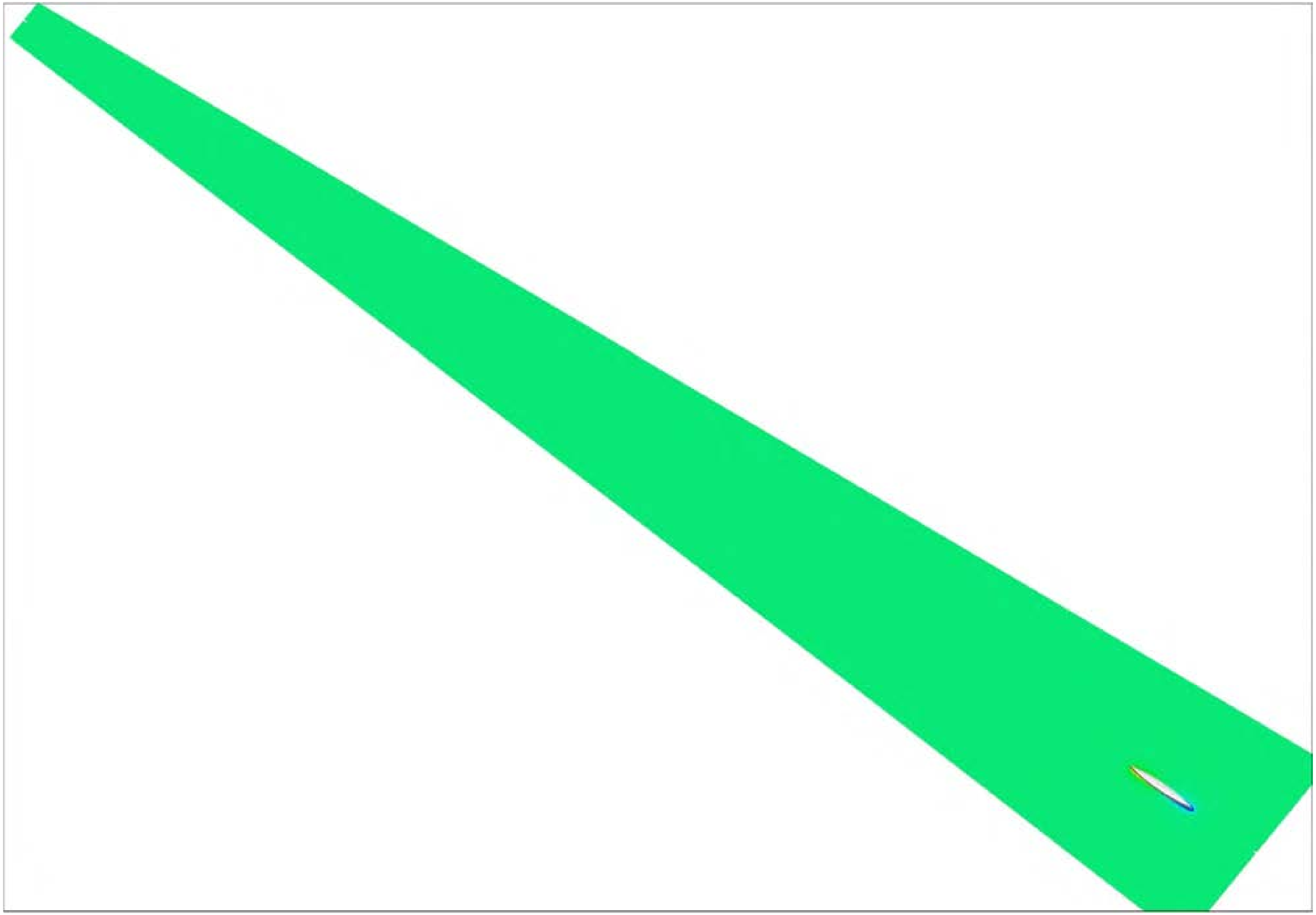
Single Wigley motion in still water

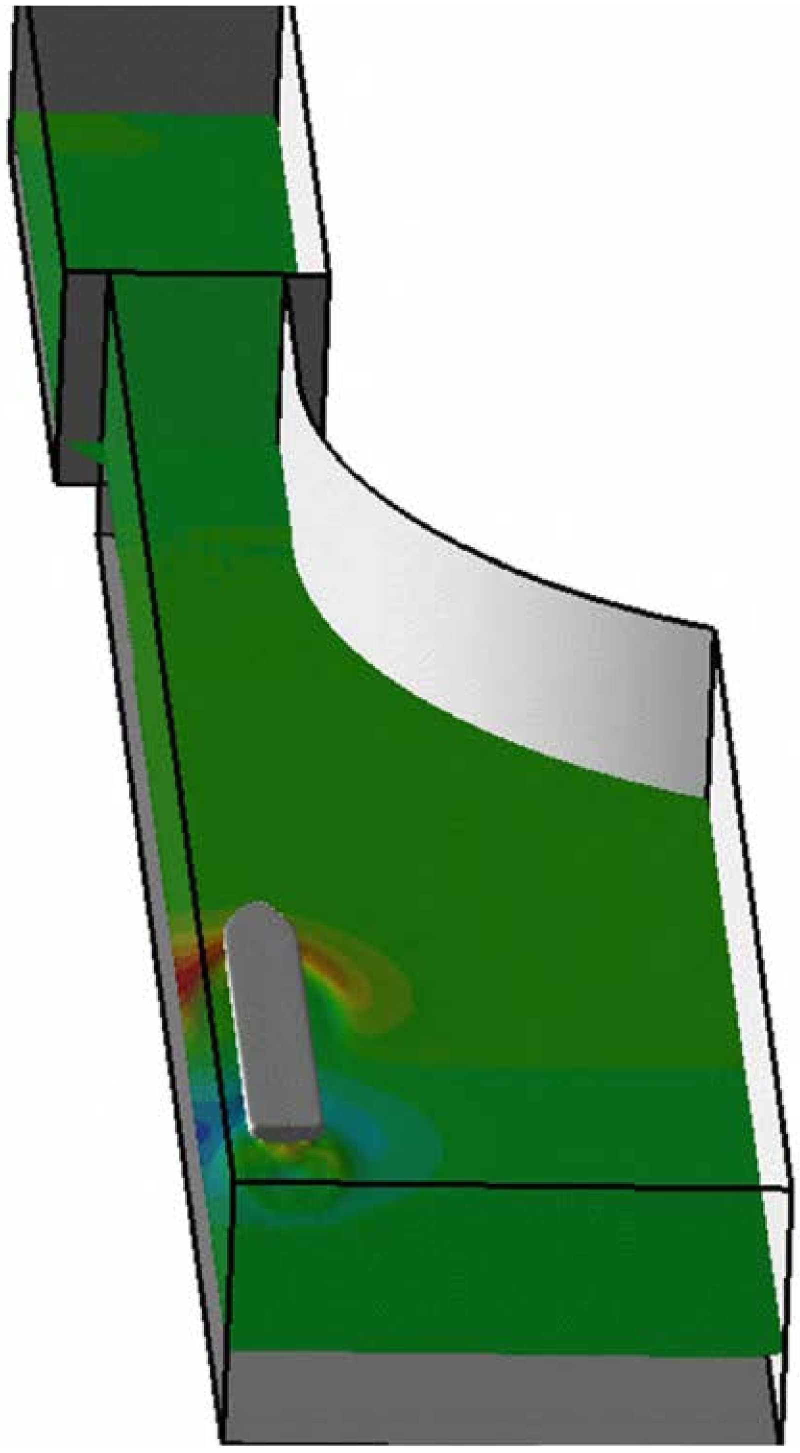


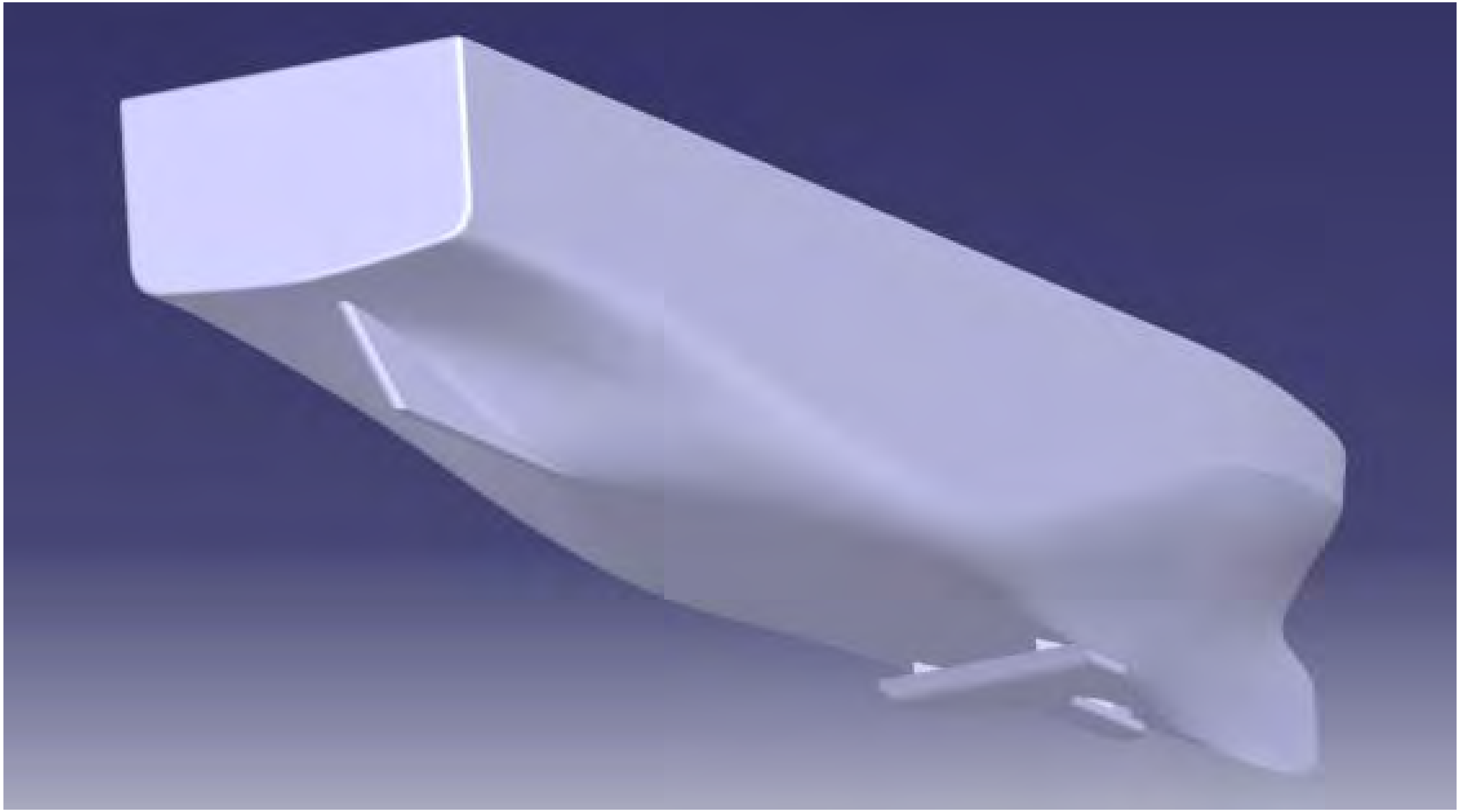
Single Wigley motion in still water

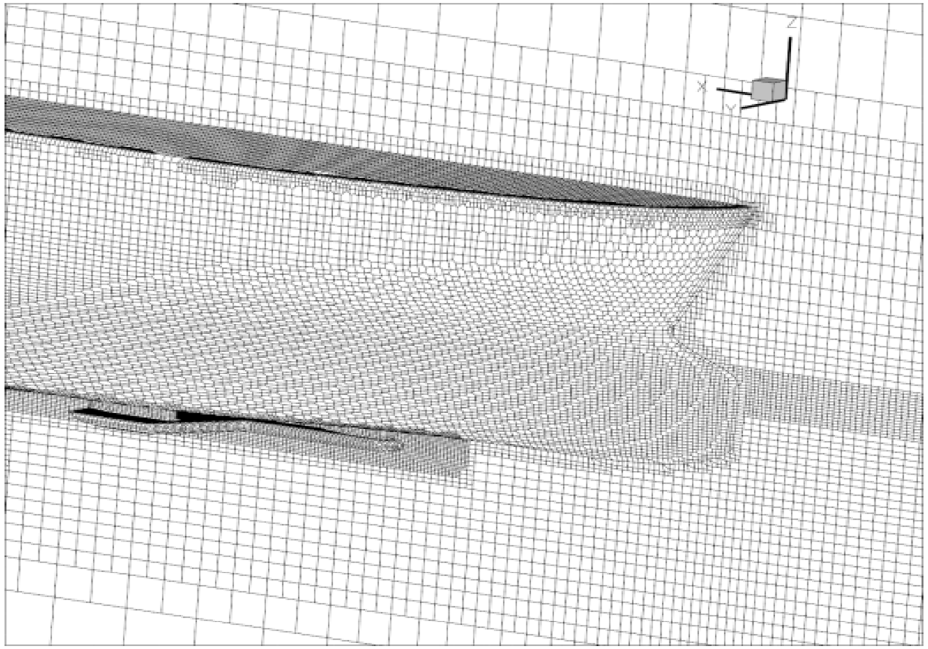


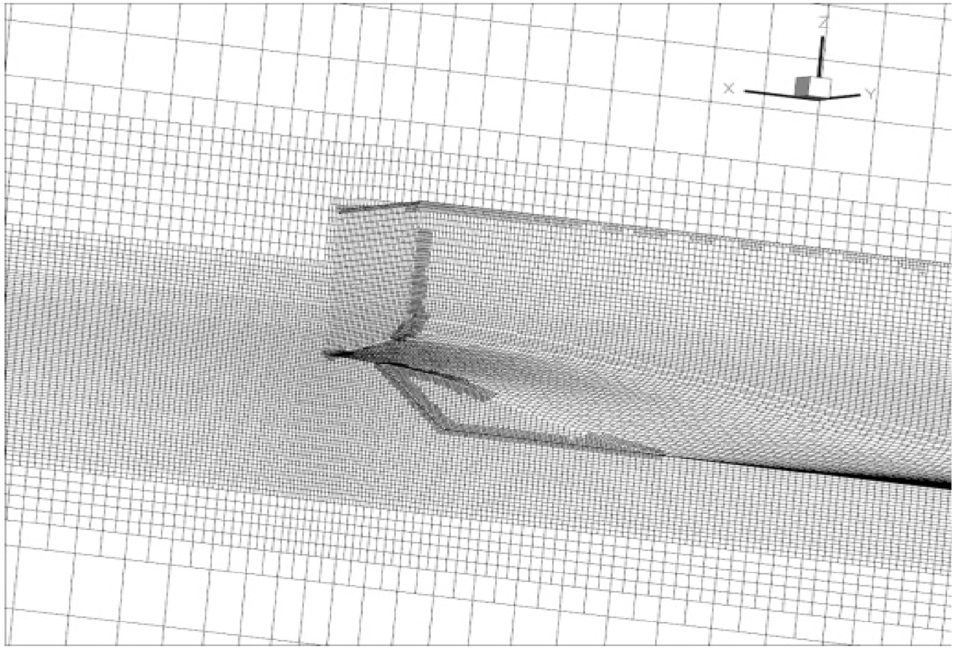
Wave profile on hull surface at Fn=0.289

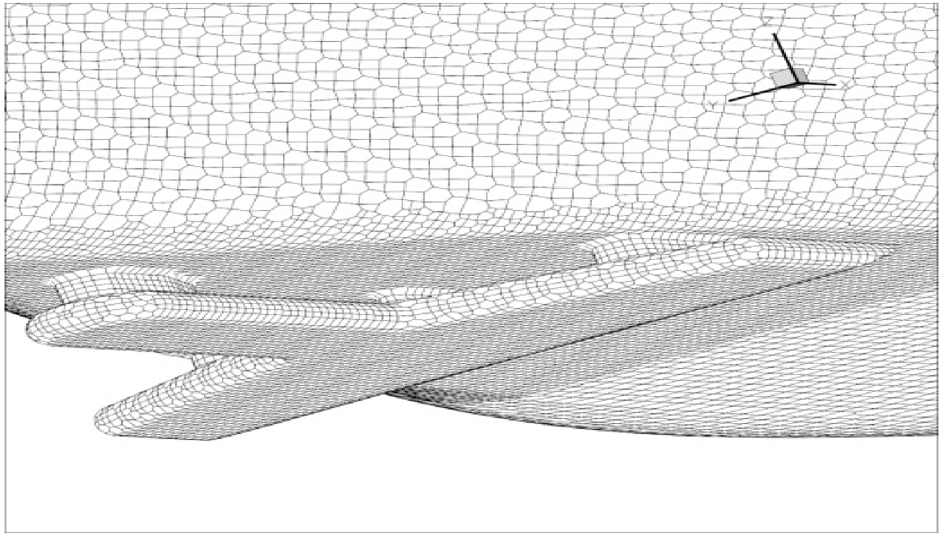


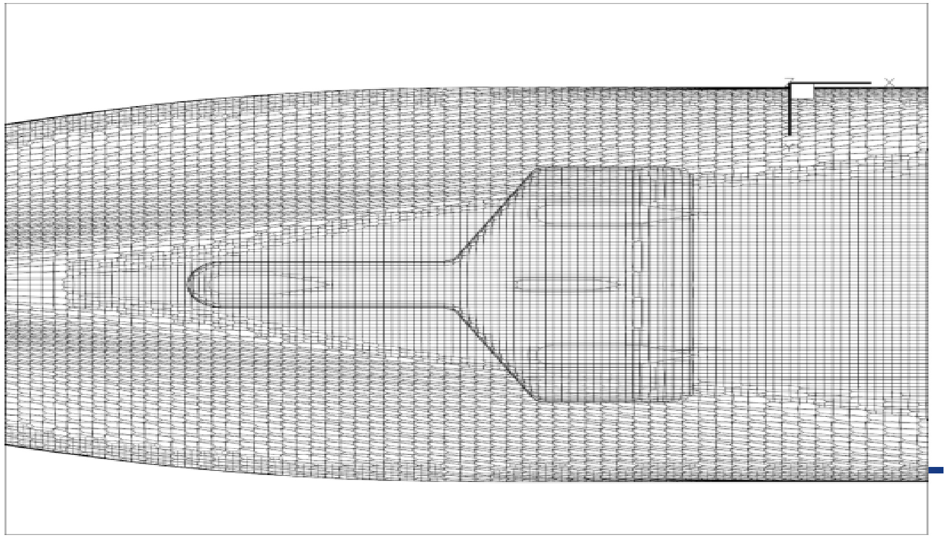


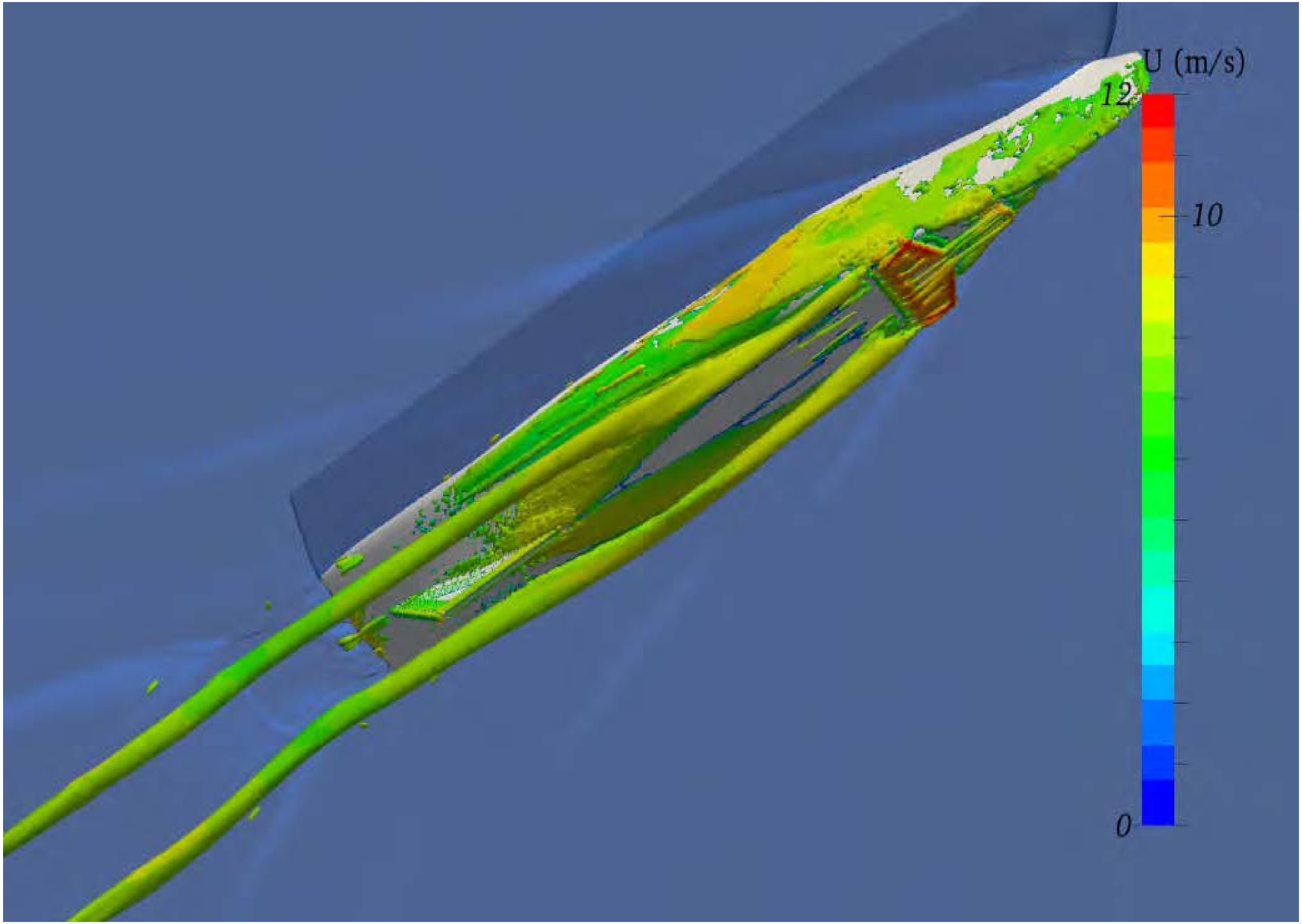


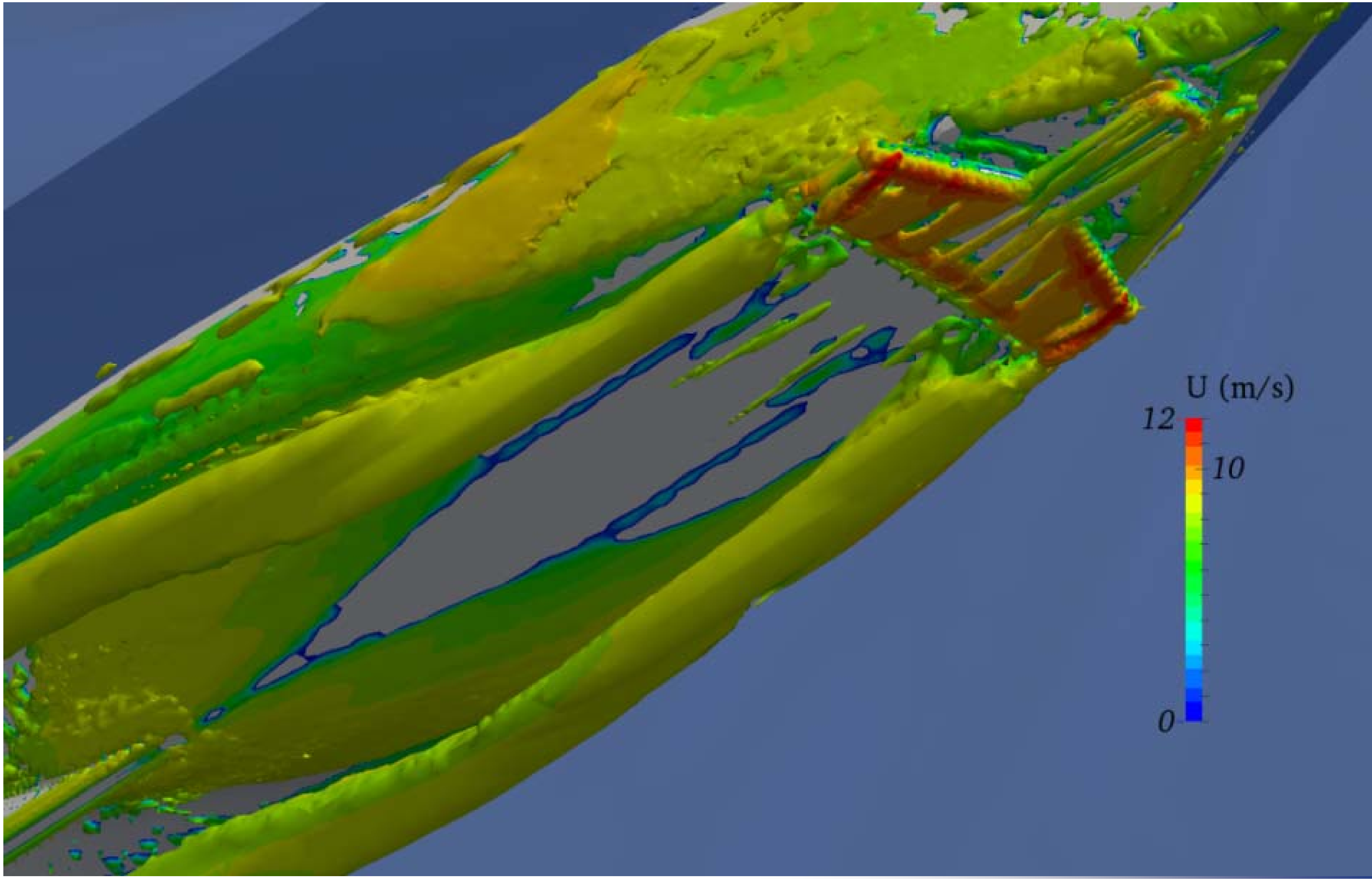


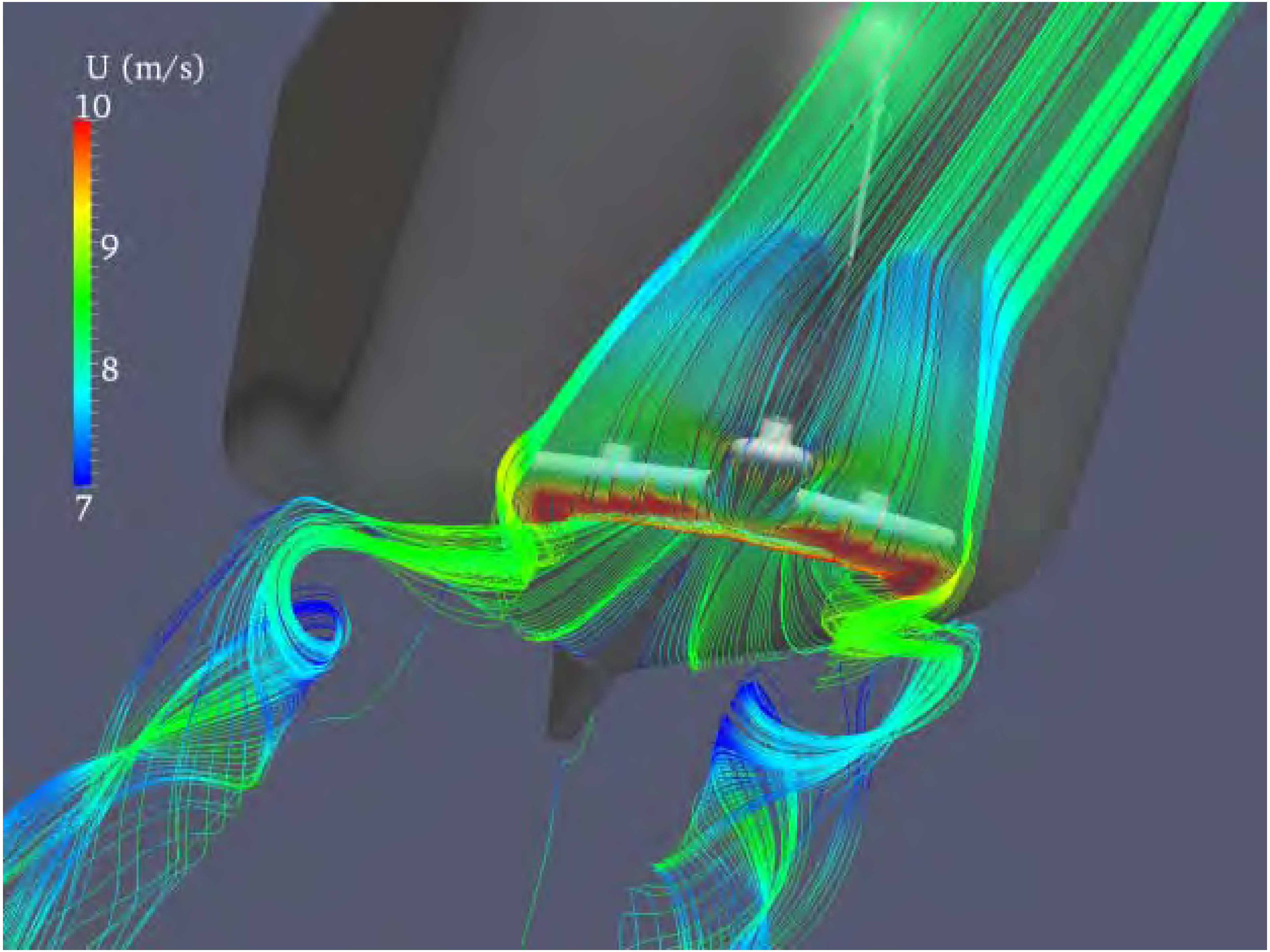


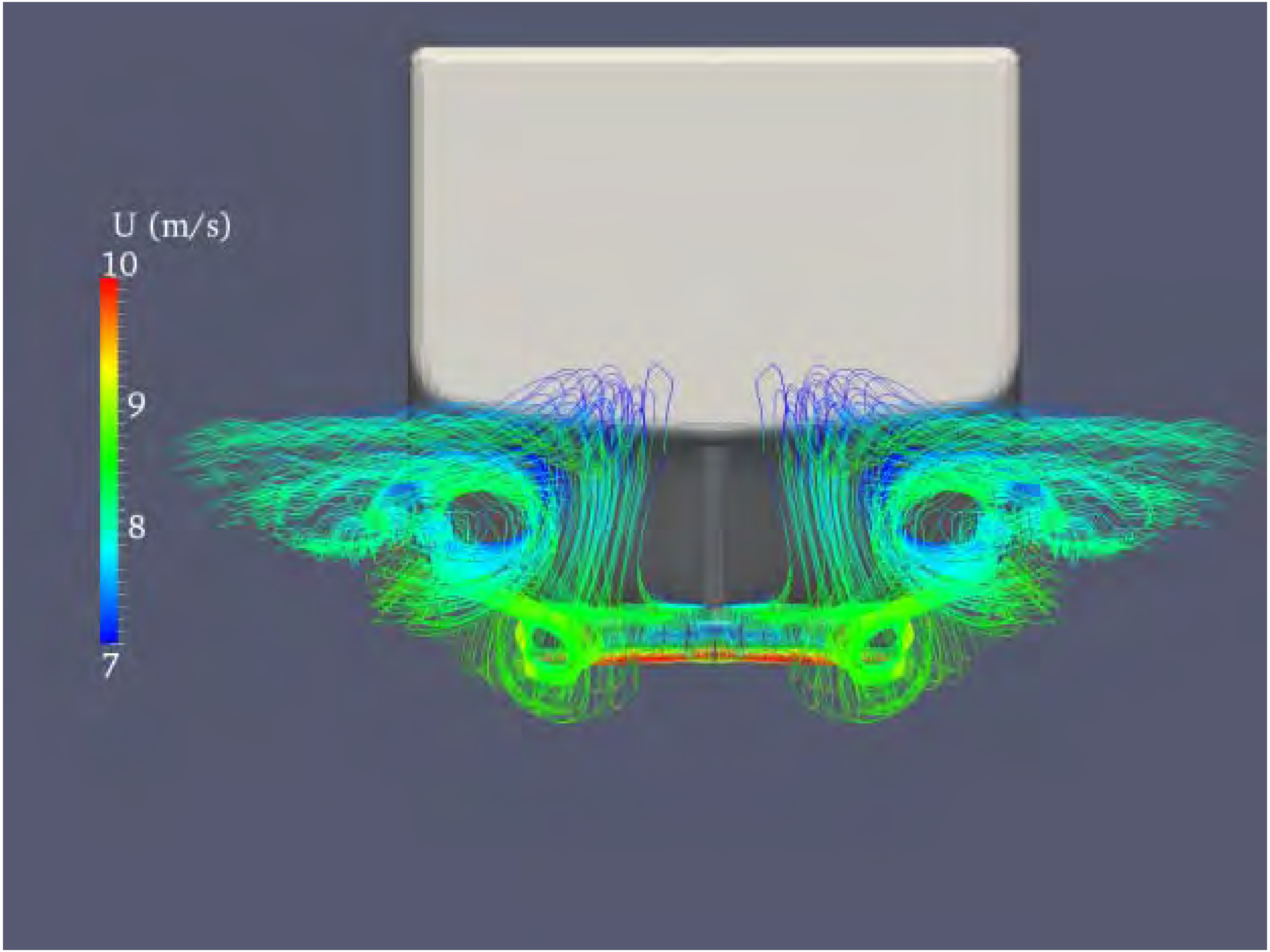




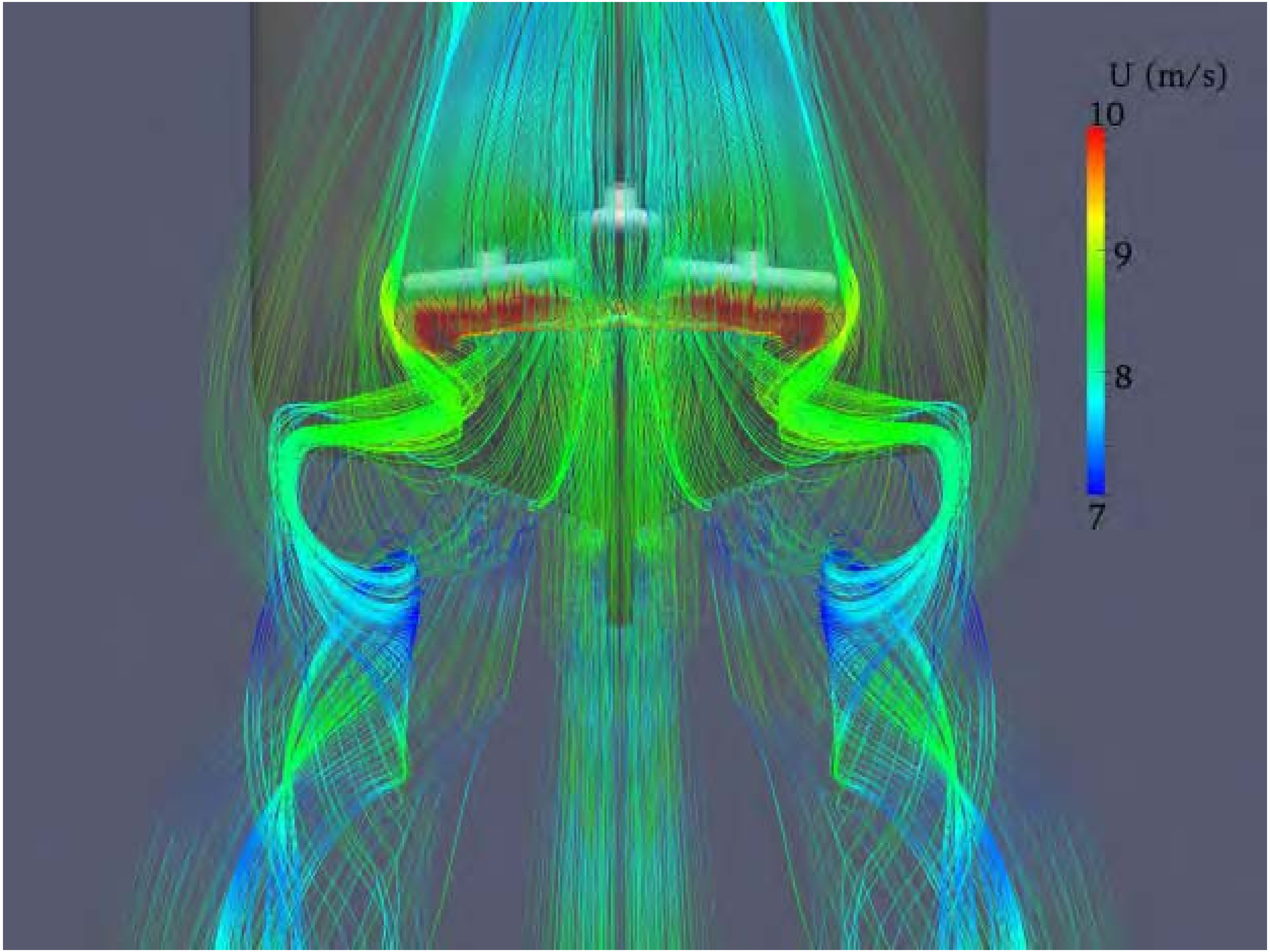

U (m/s)
12
10
0

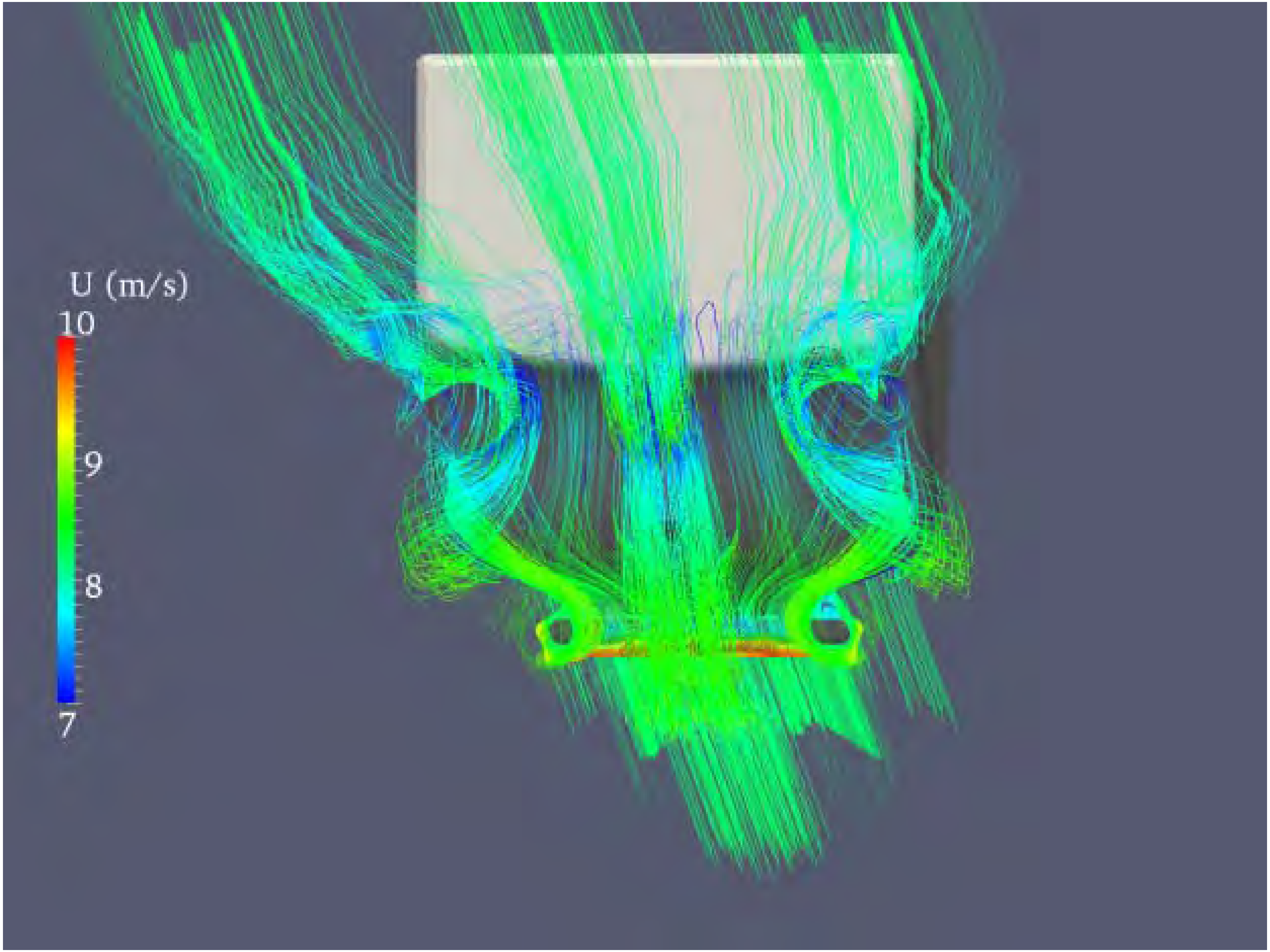

U (m/s)
12
10
0


U (m/s)
10
9
8
7



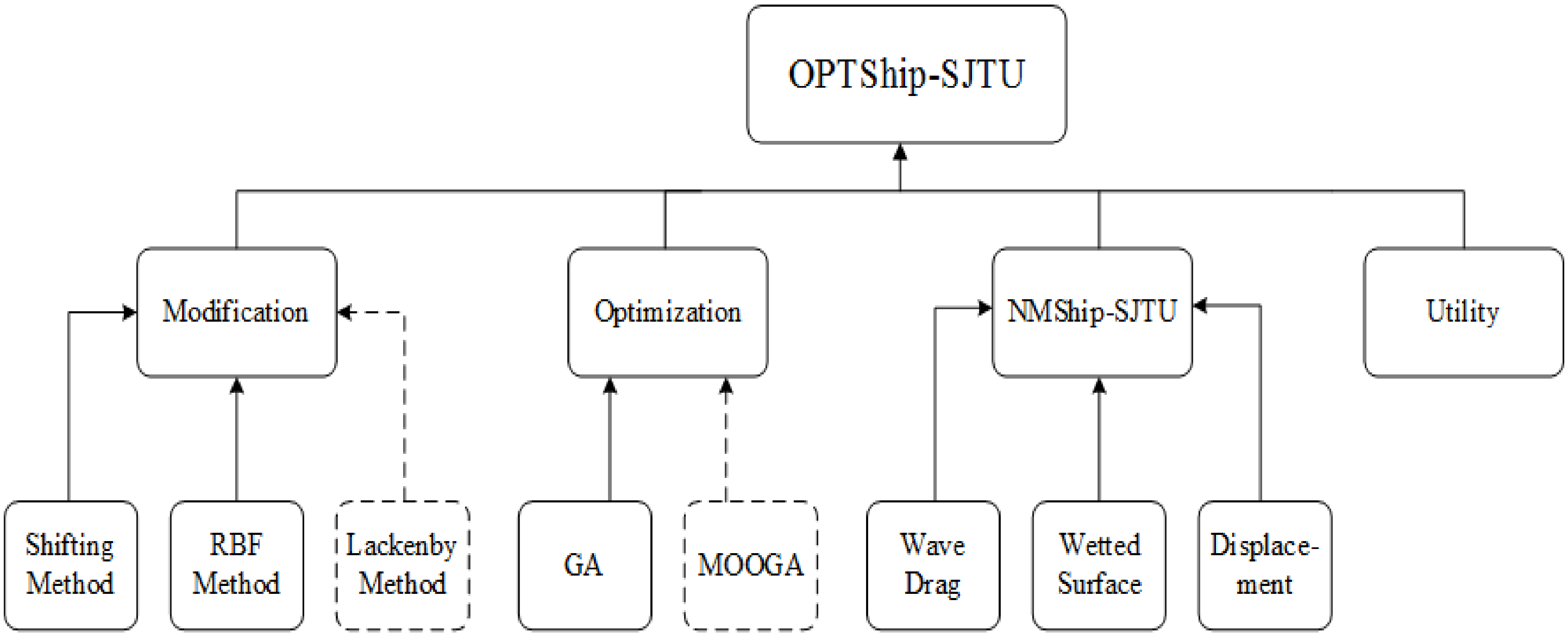
U (m/s)
10
9
8
7


U (m/s)
10
9
8
7

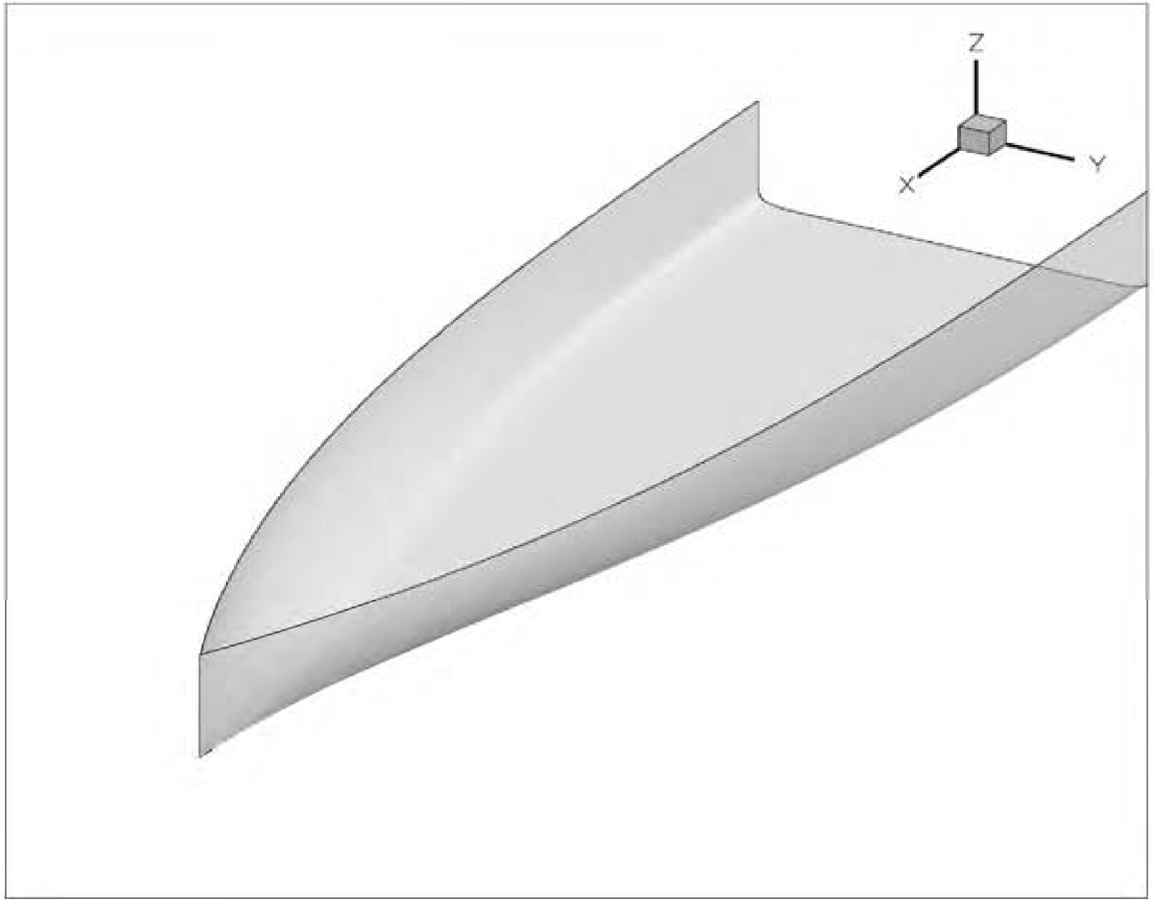

U (m/s)
10
9
8
7

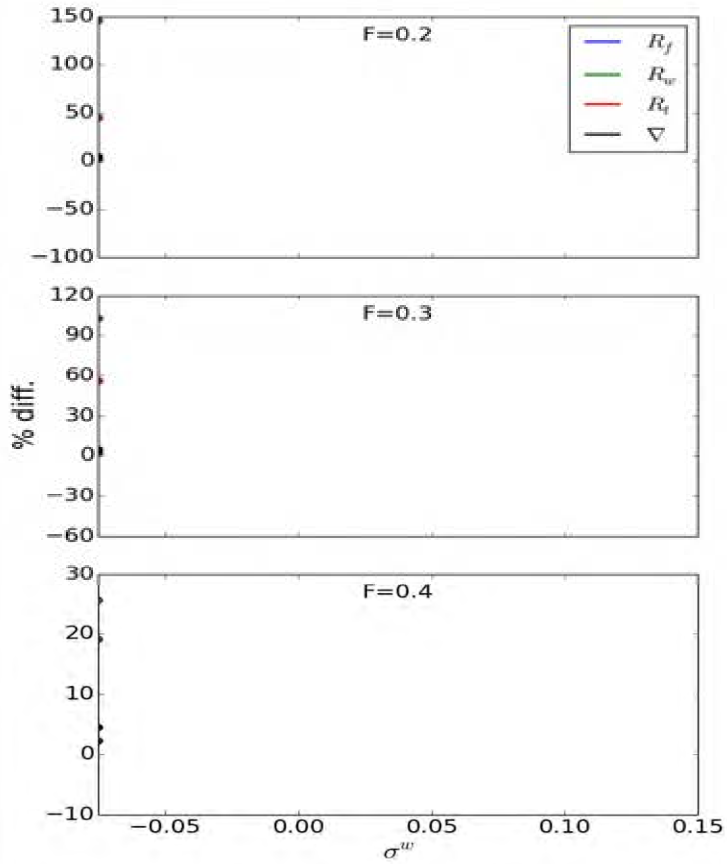
Ship hull optimization

Main structure of OPTShip-SJTU



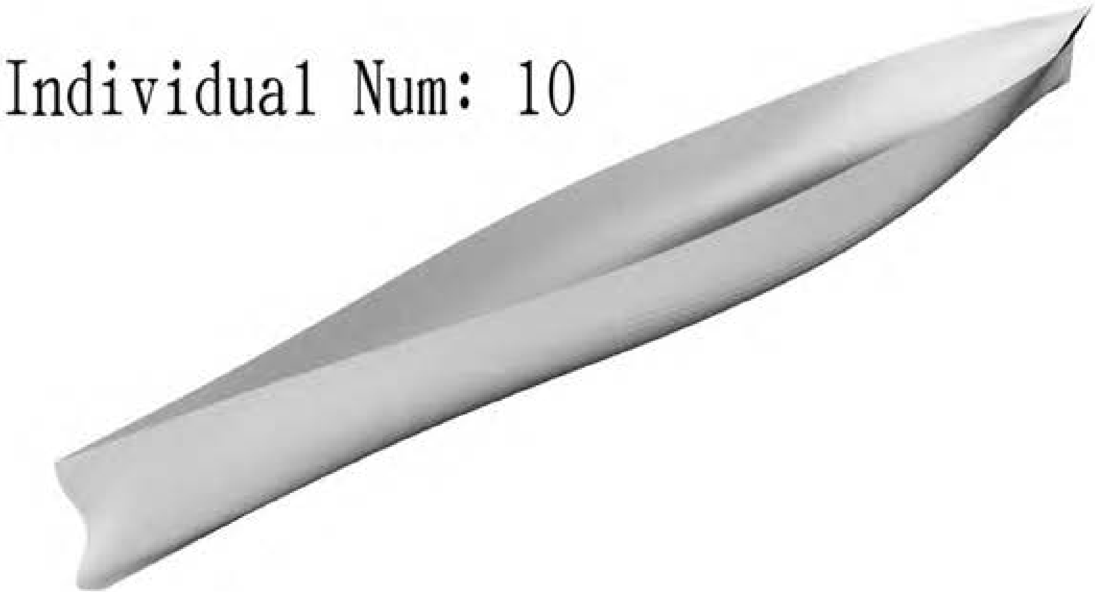
OPTShip-SJTU for ship hull optimization

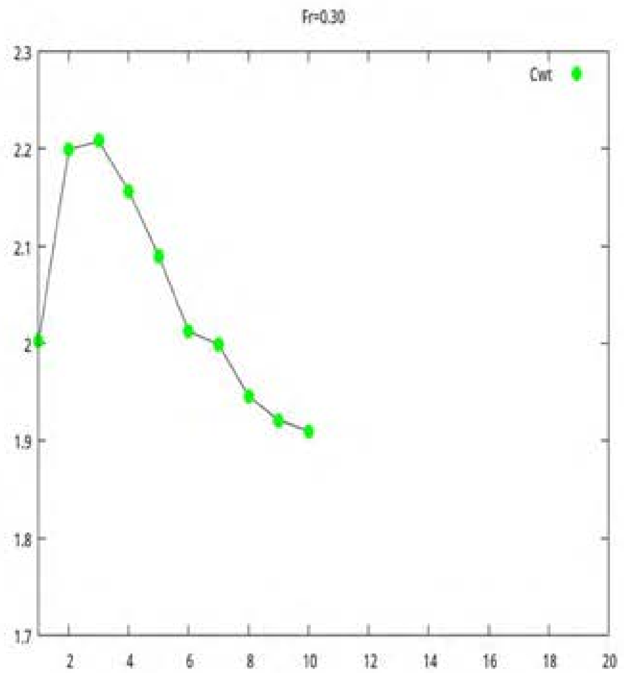




上海交通大學
Shanghai Jiao Tong University

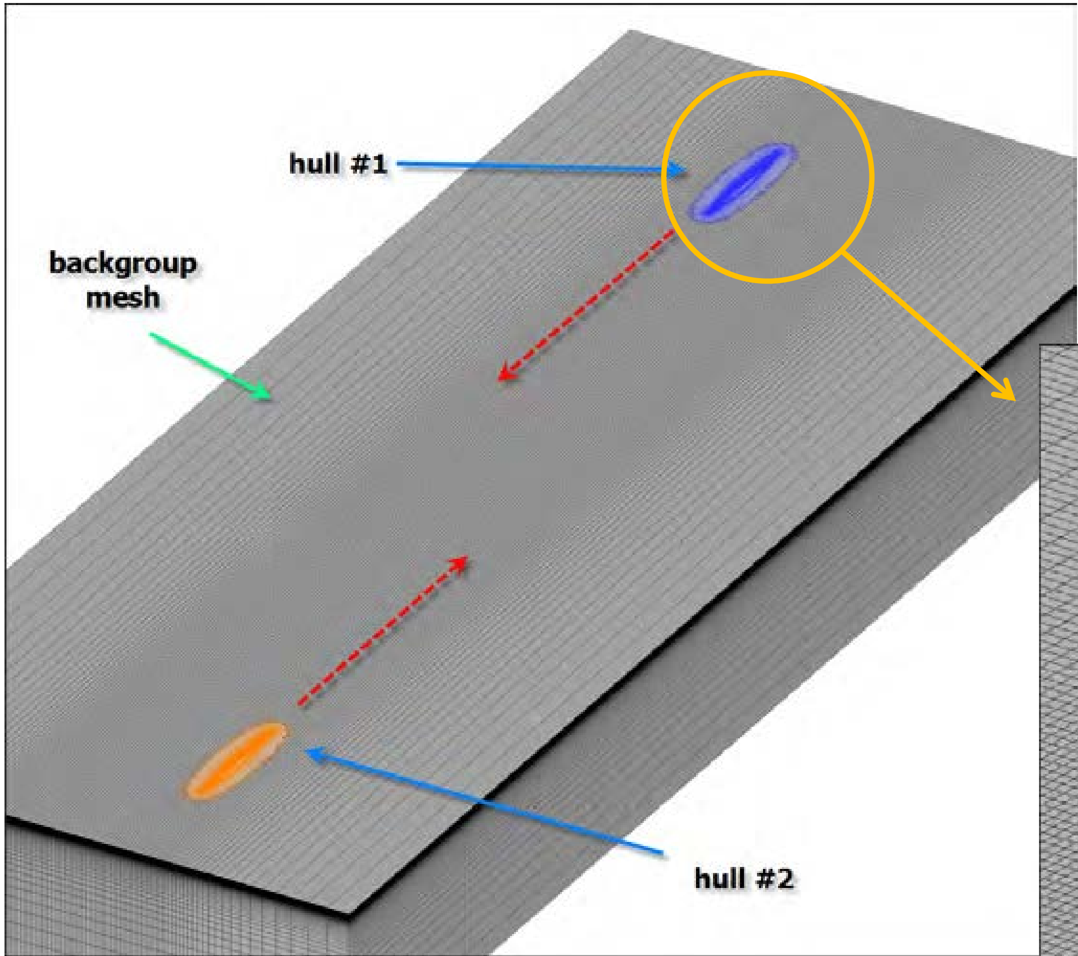
OPTShip-SJTU for ship hull optimization



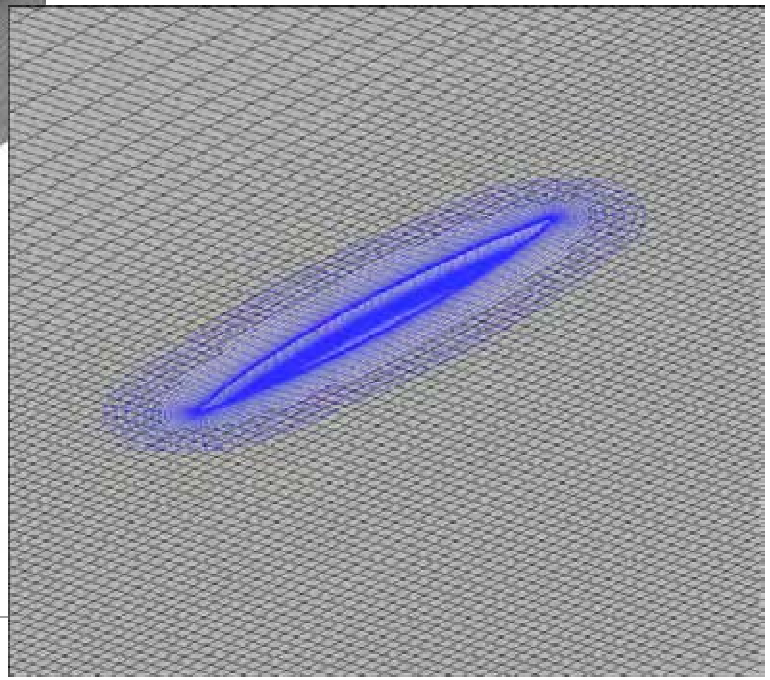


Two Wigley Ships Passing Each Other

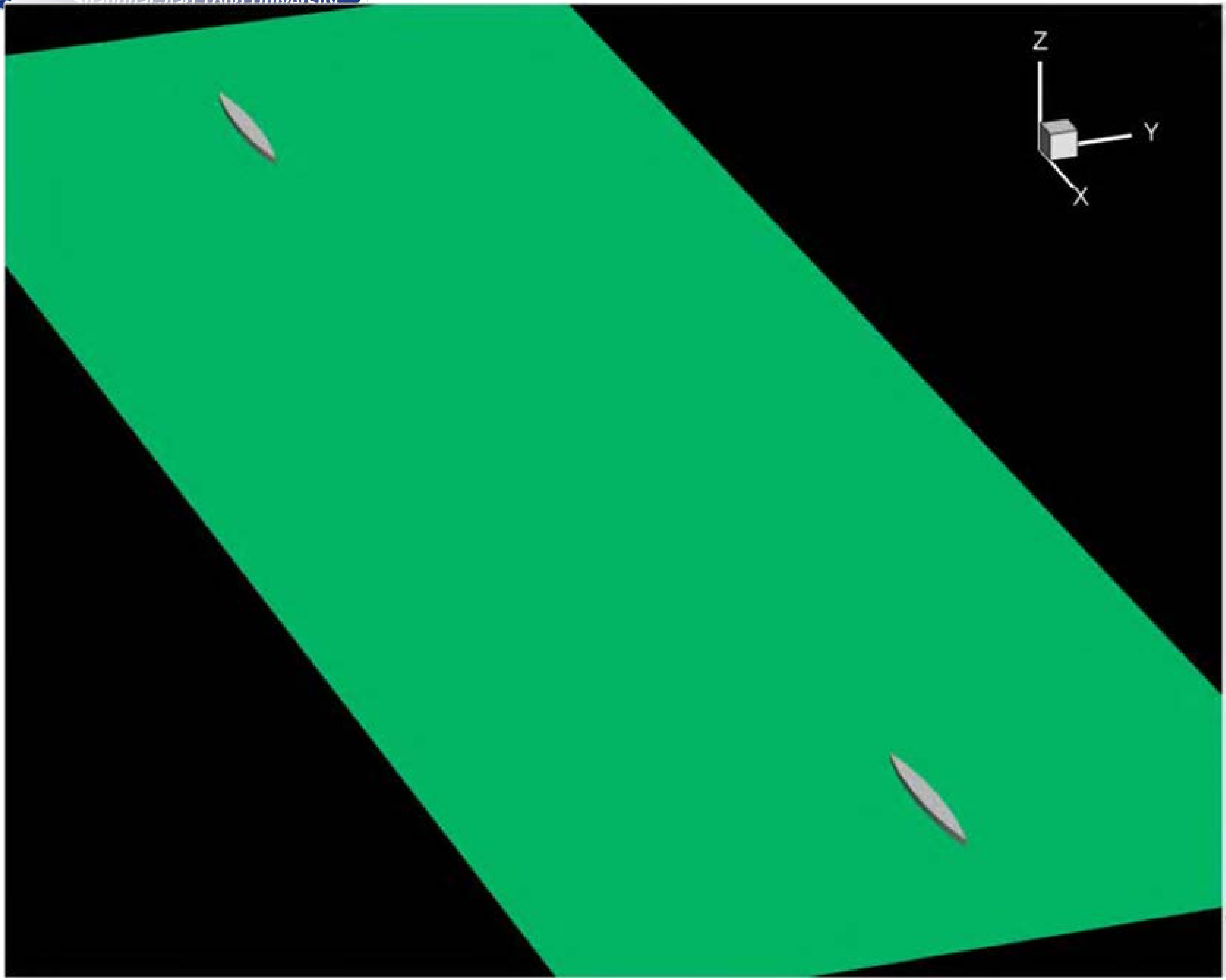
Two Wigleys Passing Each Other



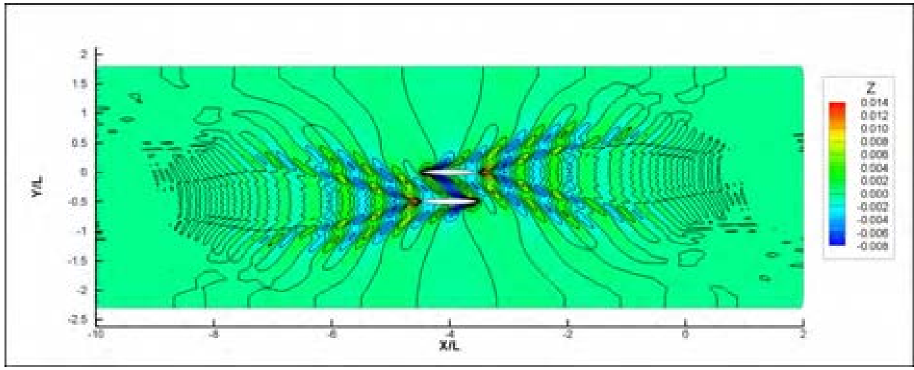
Overset grid



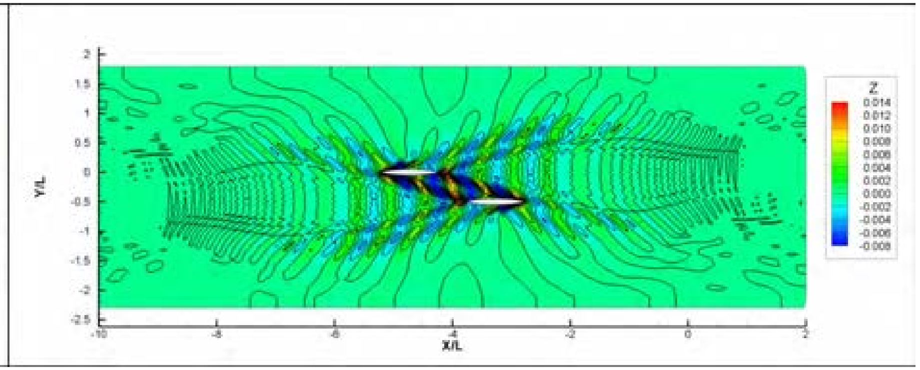
Two Wigleys Passing Each Other



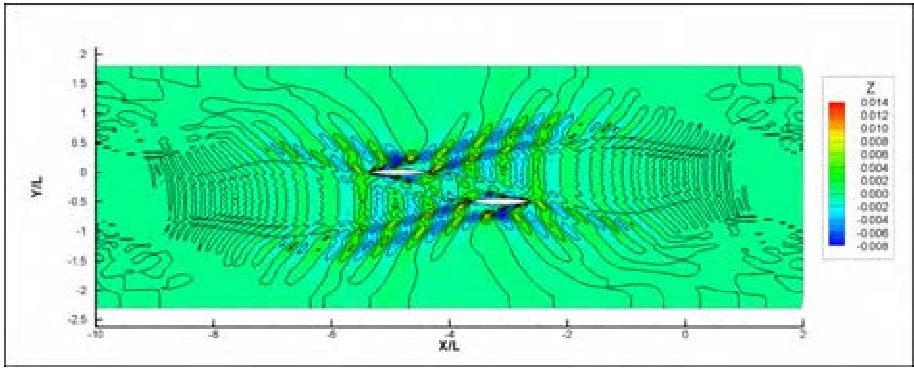
Two Wigleys Passing Each Other



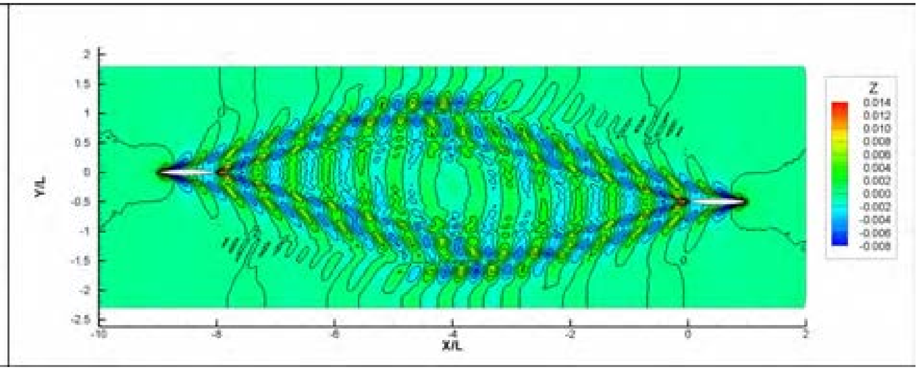
(1) t=5.50



(2) t=6.23(波峰)



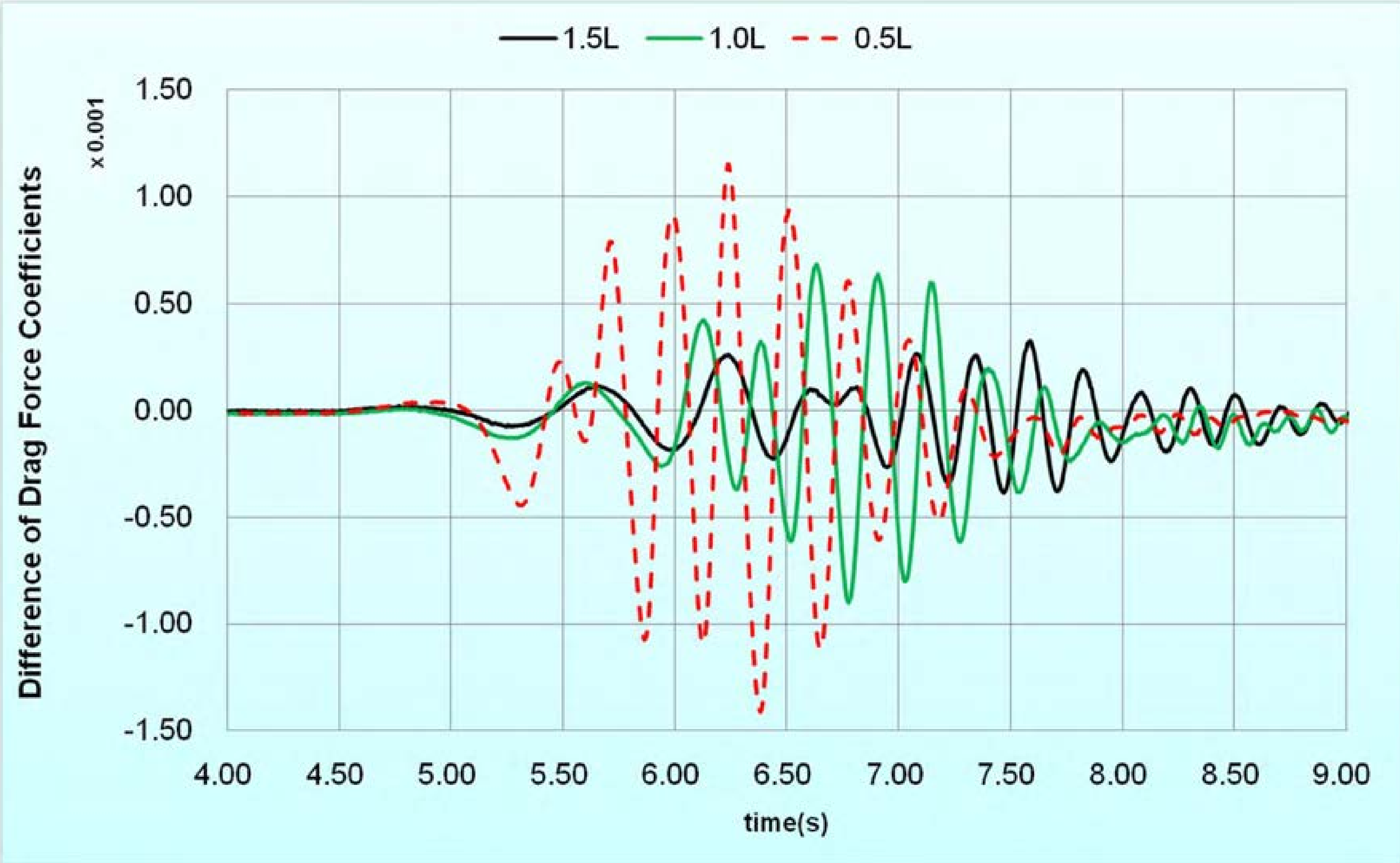
(3) t=6.37（波谷）



(4) t=10.00

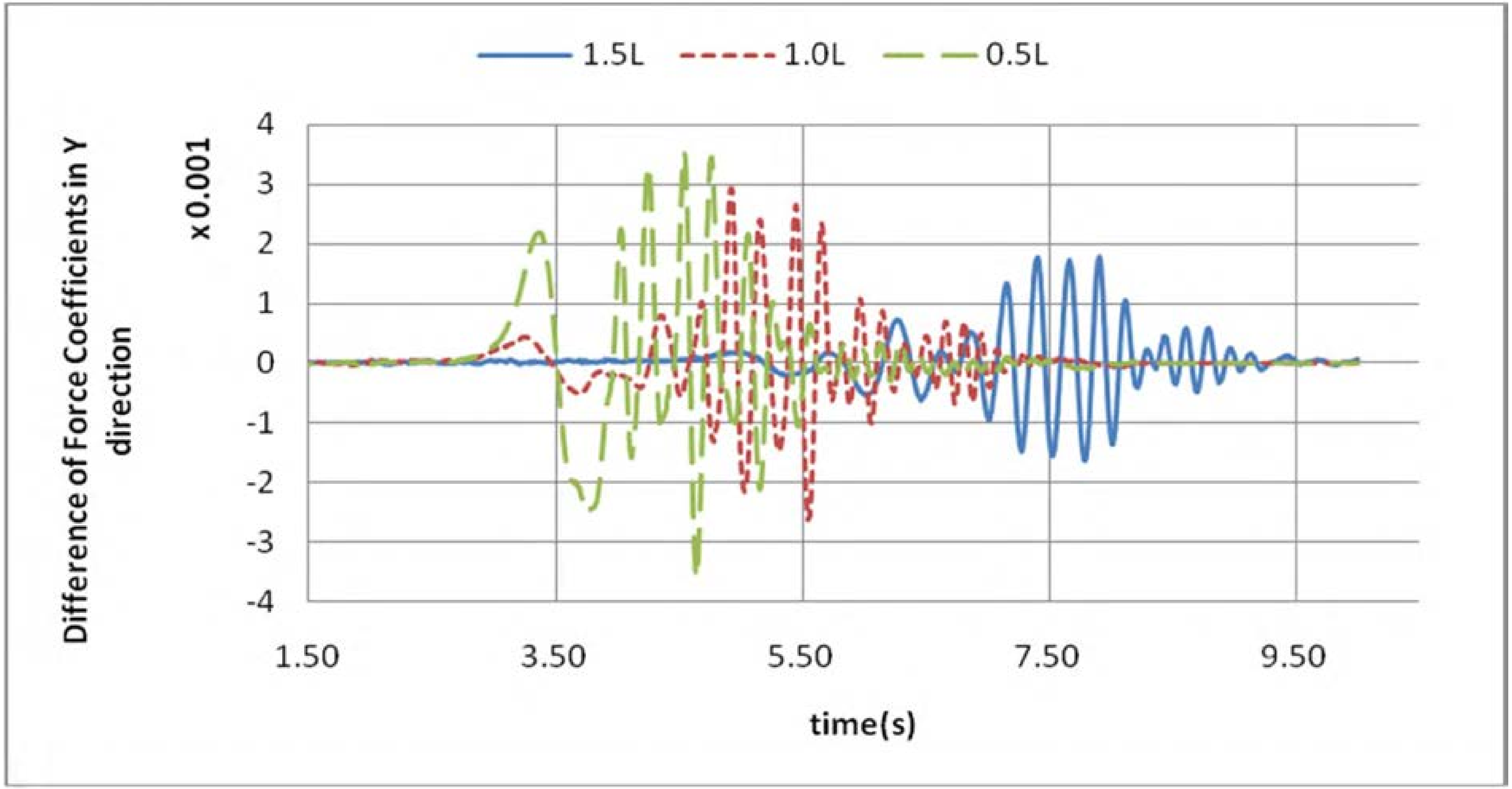
Fres suface at Fn=0.30, D=0.5L

Two Wigleys Passing Each Other



Force in X Direction

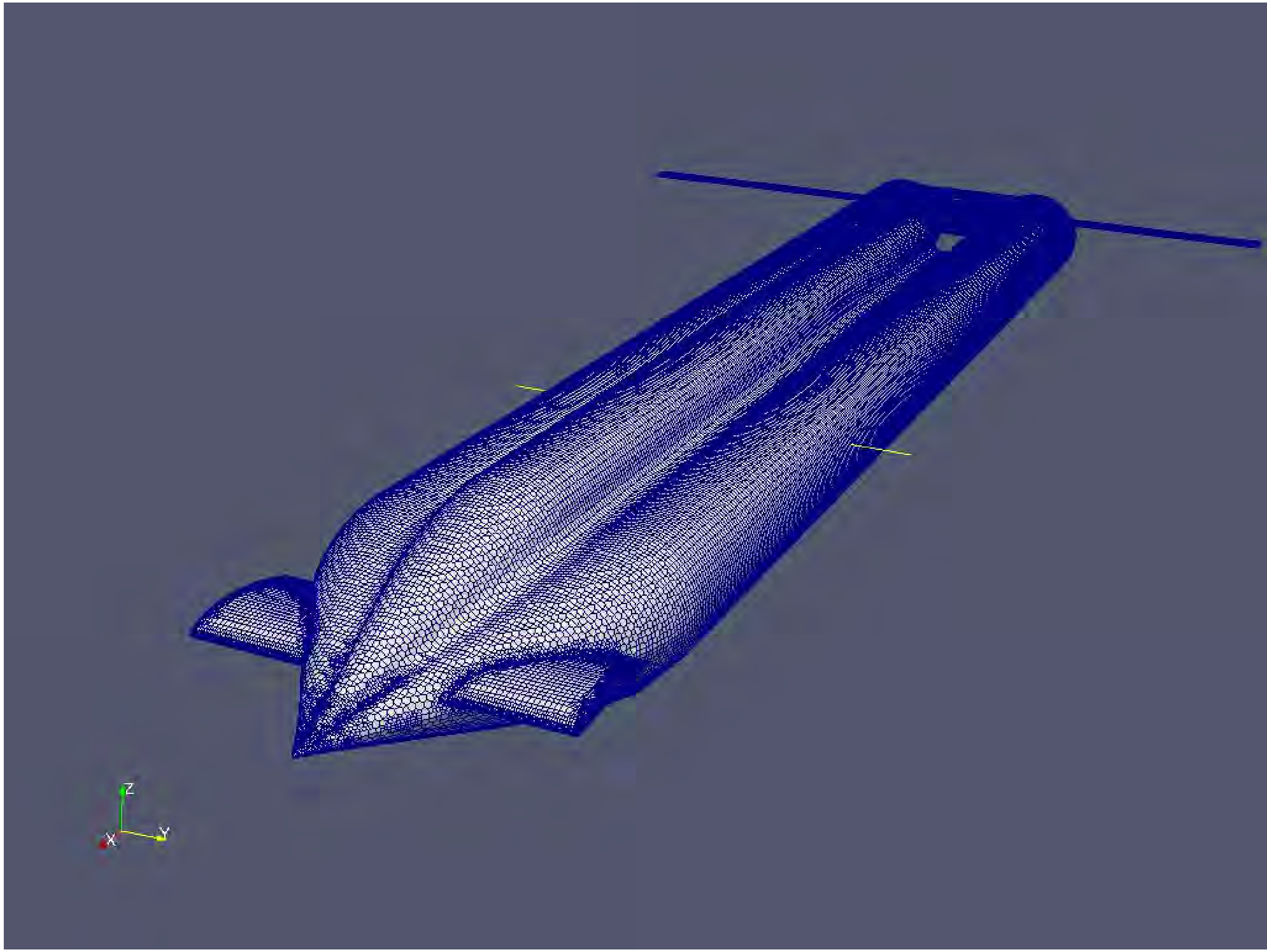
Two Wigleys Passing Each Other



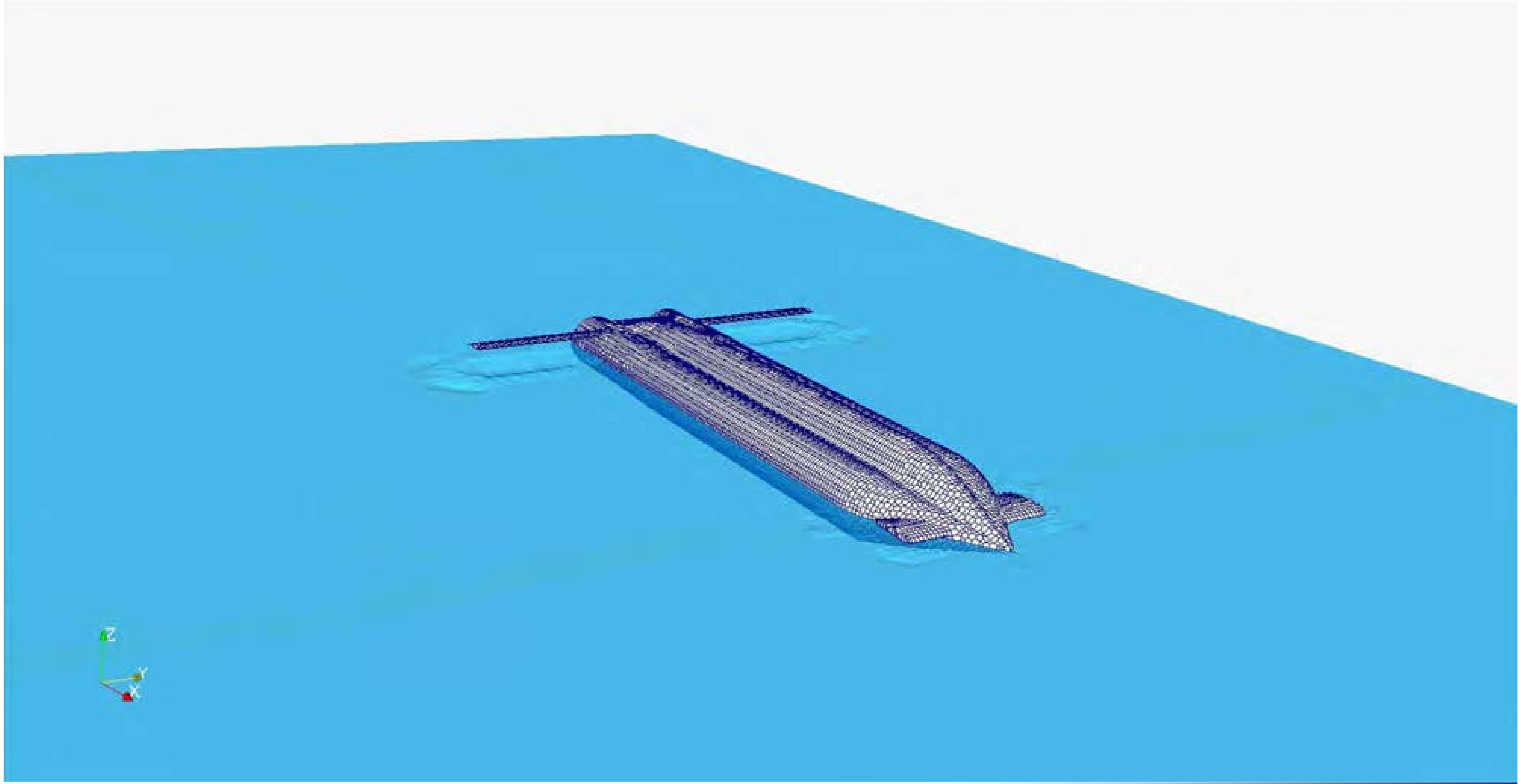
Force in Y Direction

High Speed Boat in Still Water

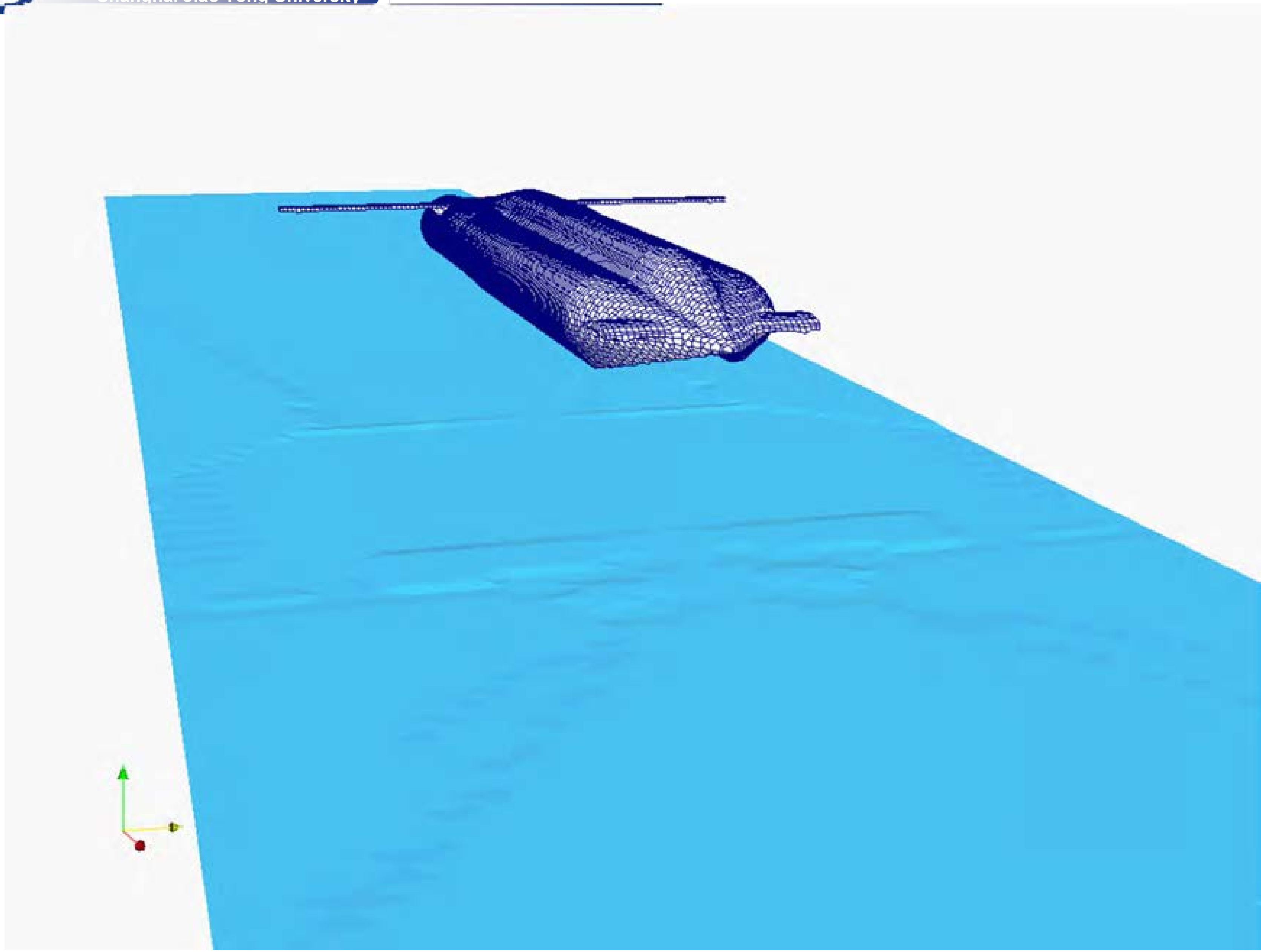
High Speed Surface Boat



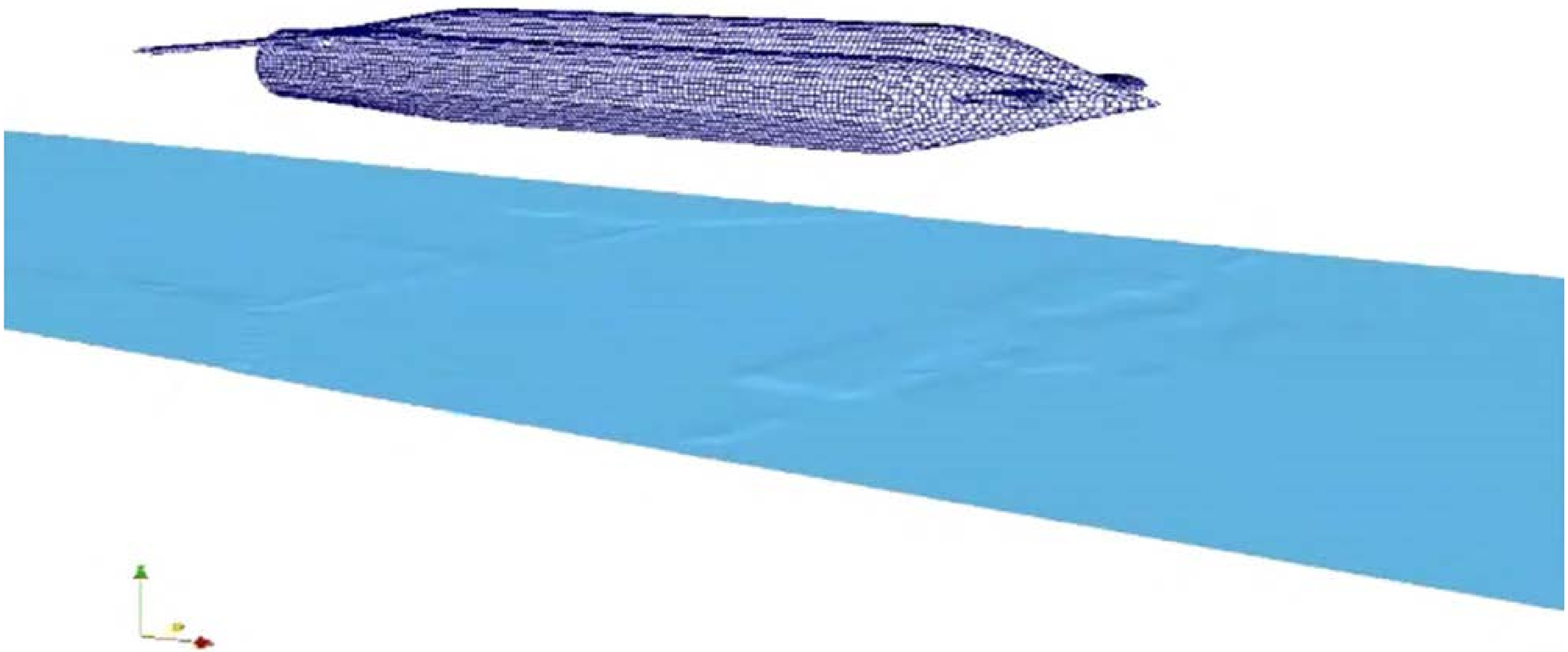
High Speed Surface Boat



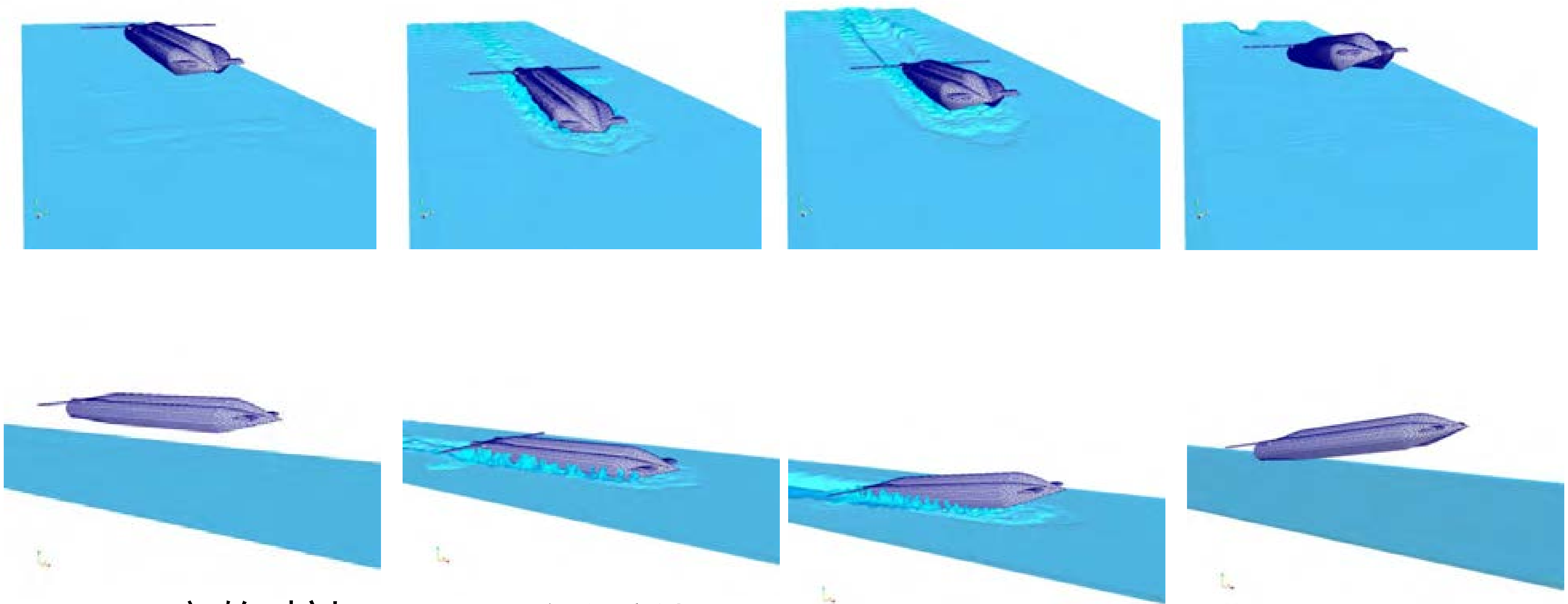
High Speed Surface Boat



High Speed Surface Boat



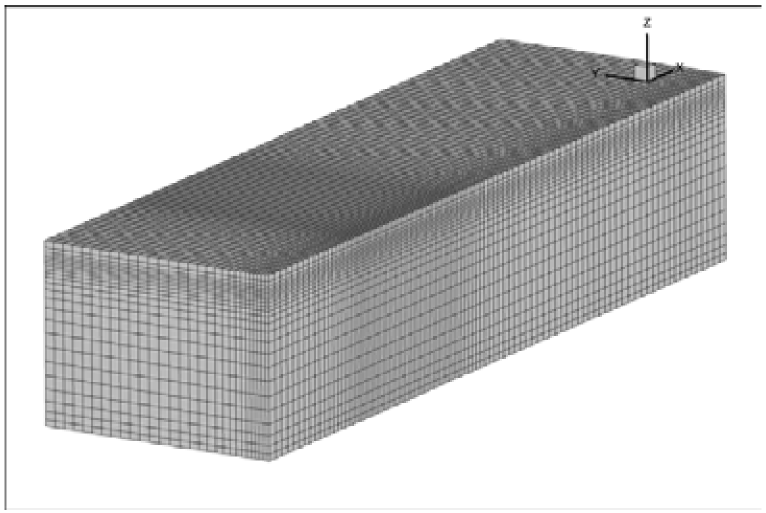
High Speed Surface Boat

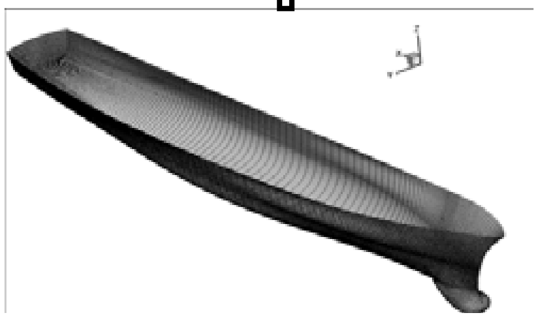


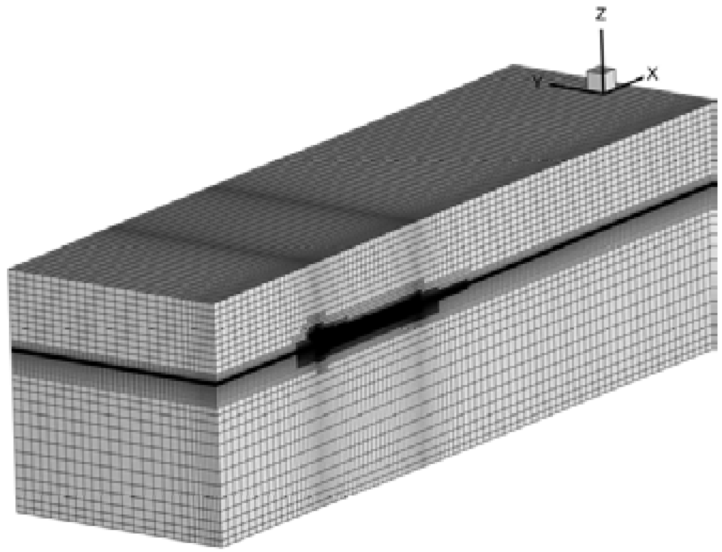
t=0 初始时刻　t=0.38完全接触水面　t=0.38开始反弹　t=0.50 反弹途中

Ship Motion in Waves

DTMB 5415 Ship Motion in Waves

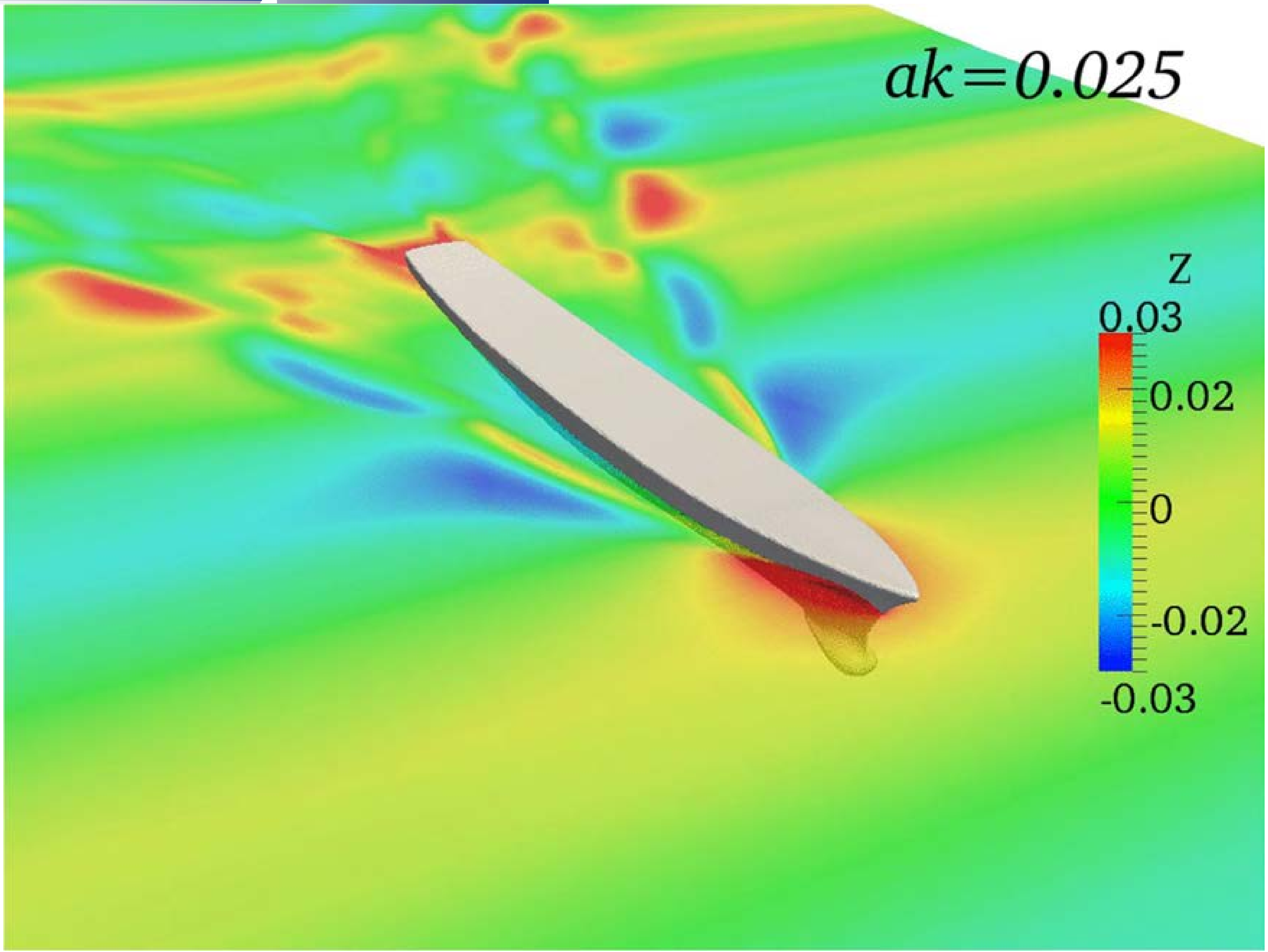


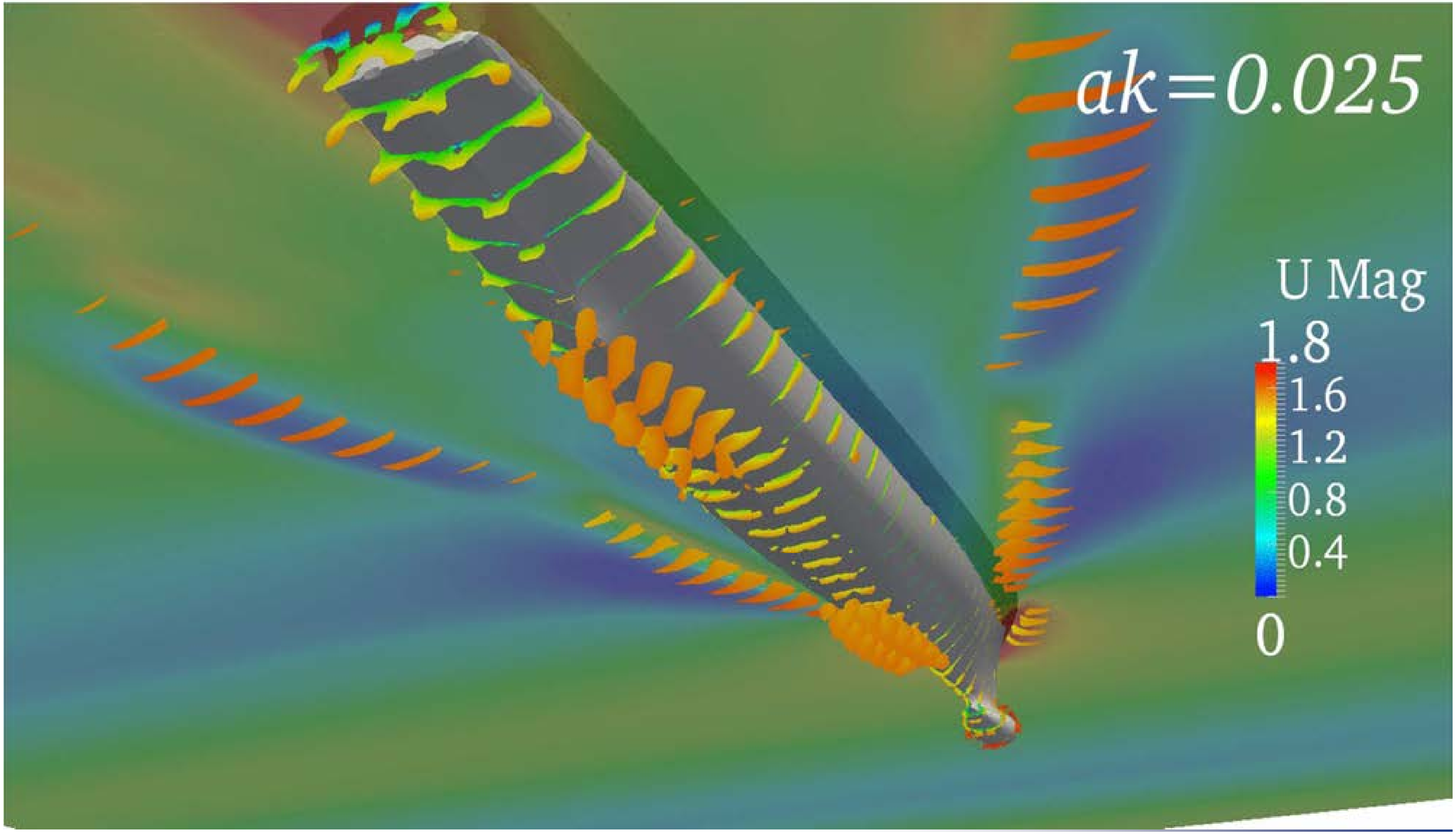


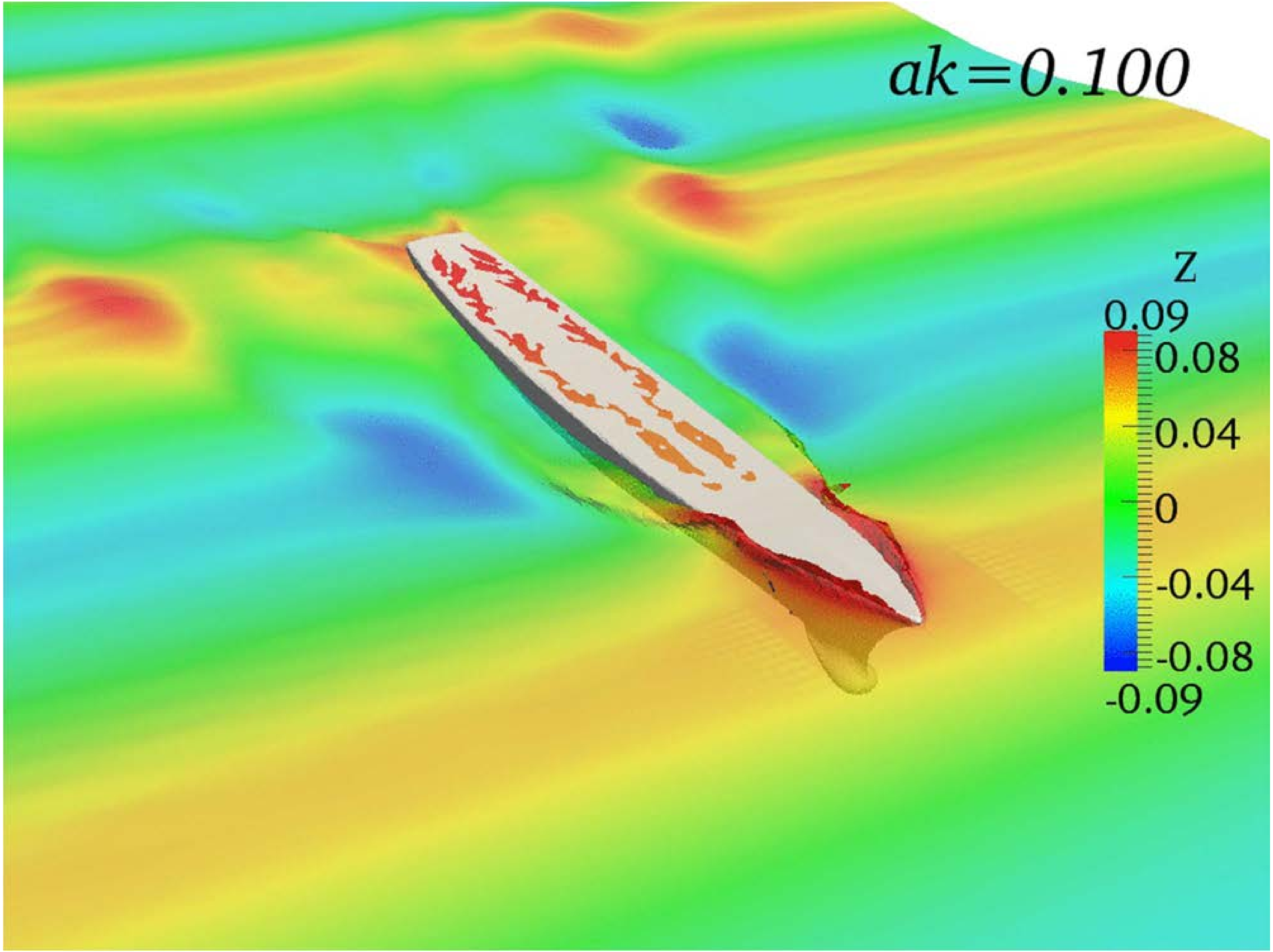


DTMB 5415 Ship Motion in Waves

Ship is induced to move under coming waves.

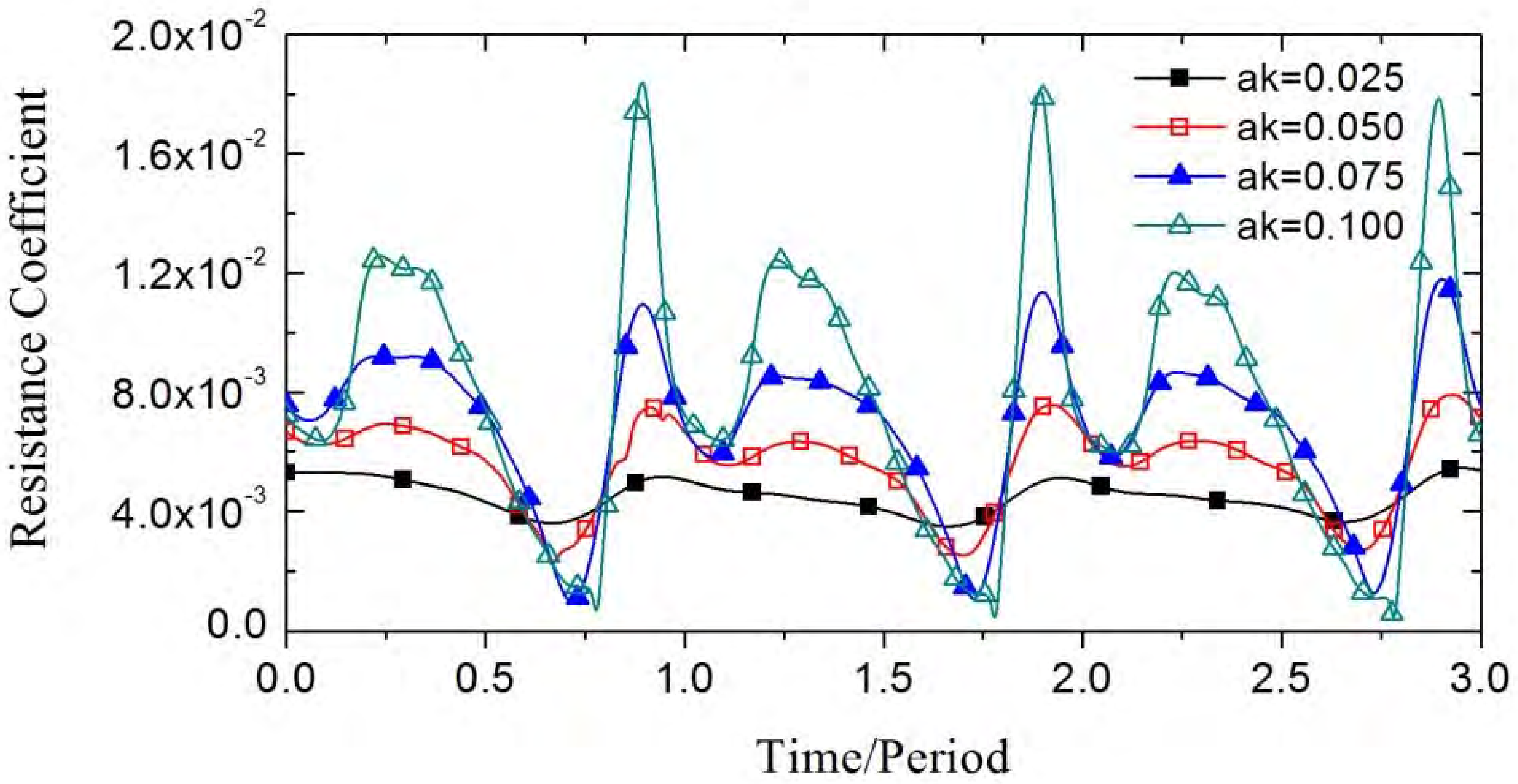


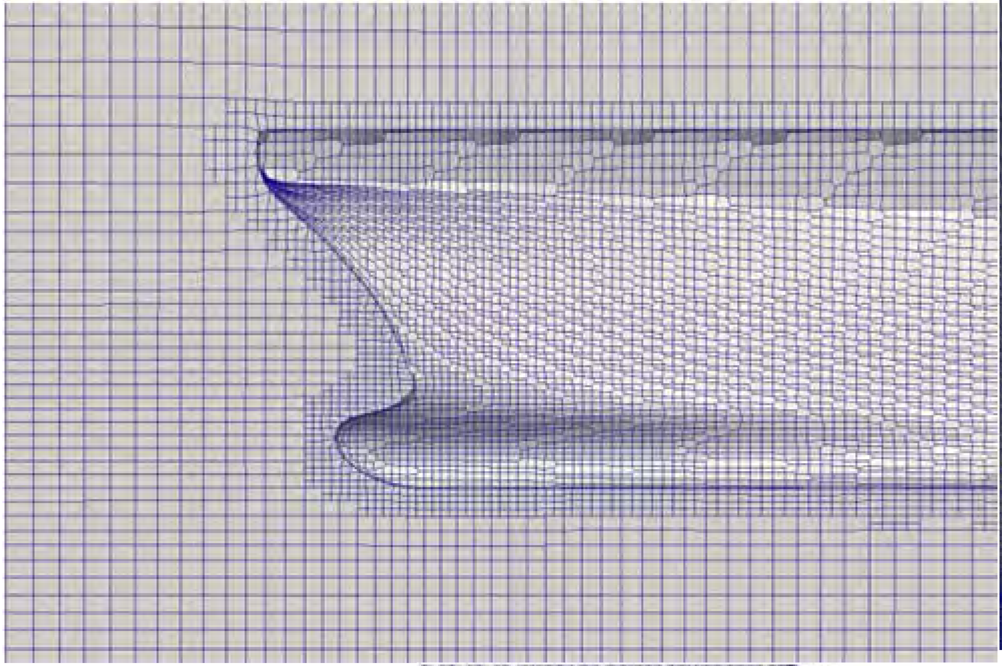

ak=0.025
U Mag
1.8
1.6
1.2
0.8
0.4
0

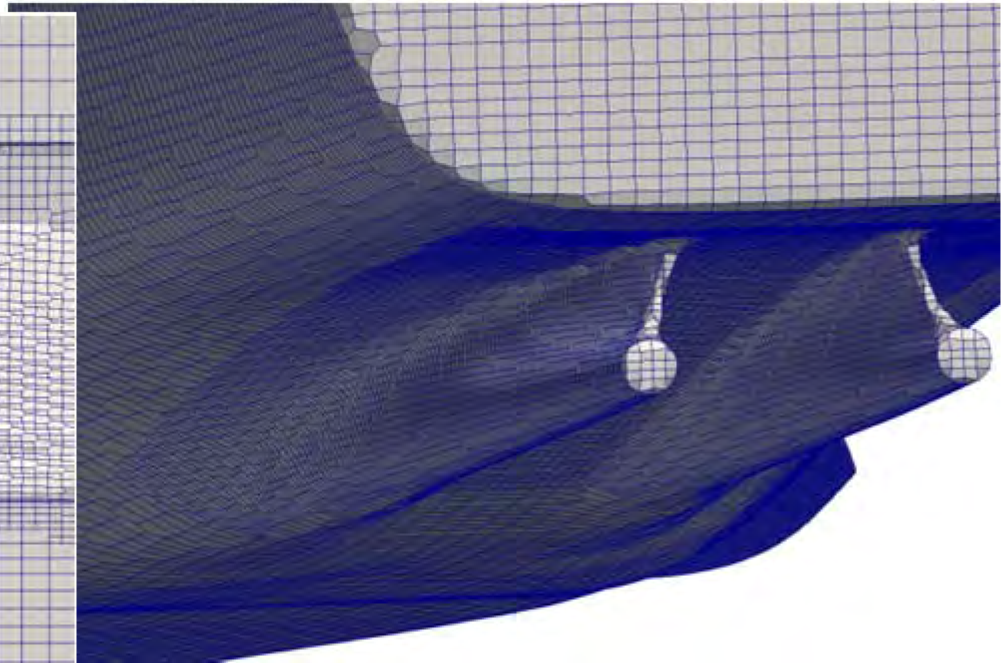


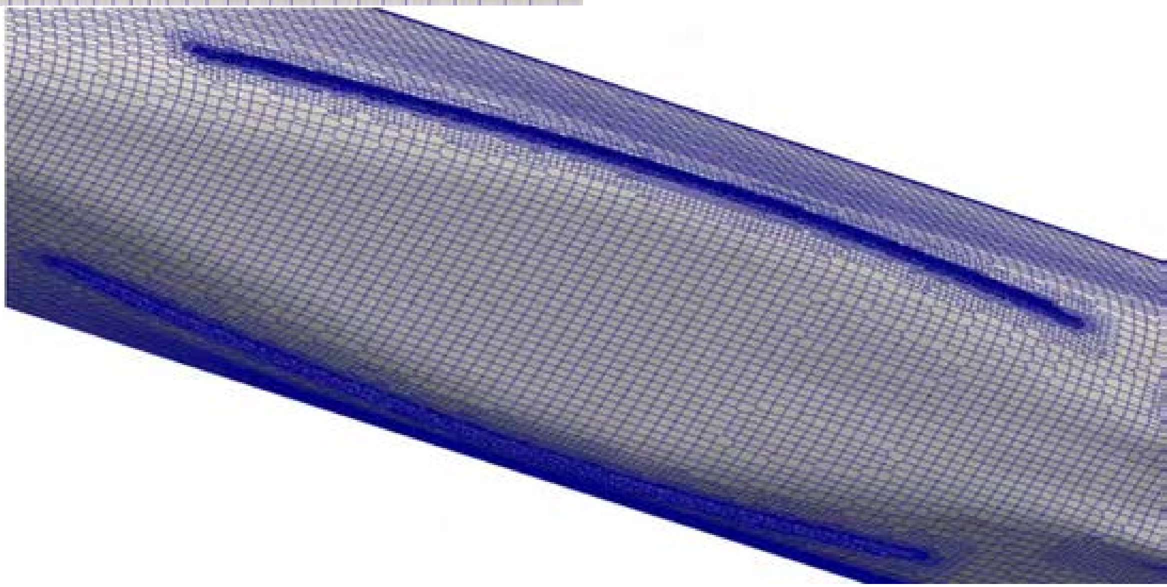
ak=0.100
Z
0.09
0.08
0.04
0
-0.04
-0.08
-0.09

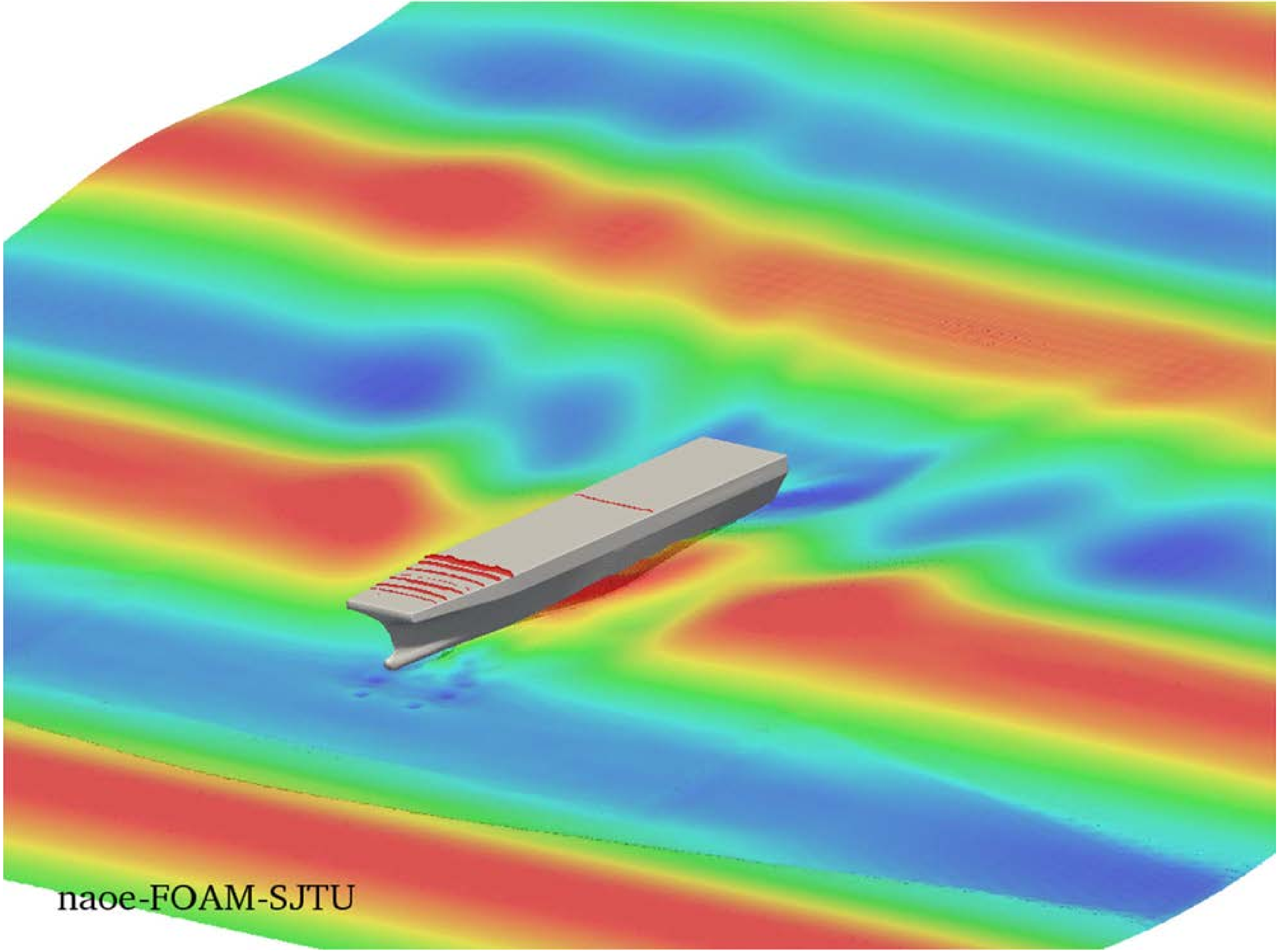
Green Water for DTMB 5415 Ship

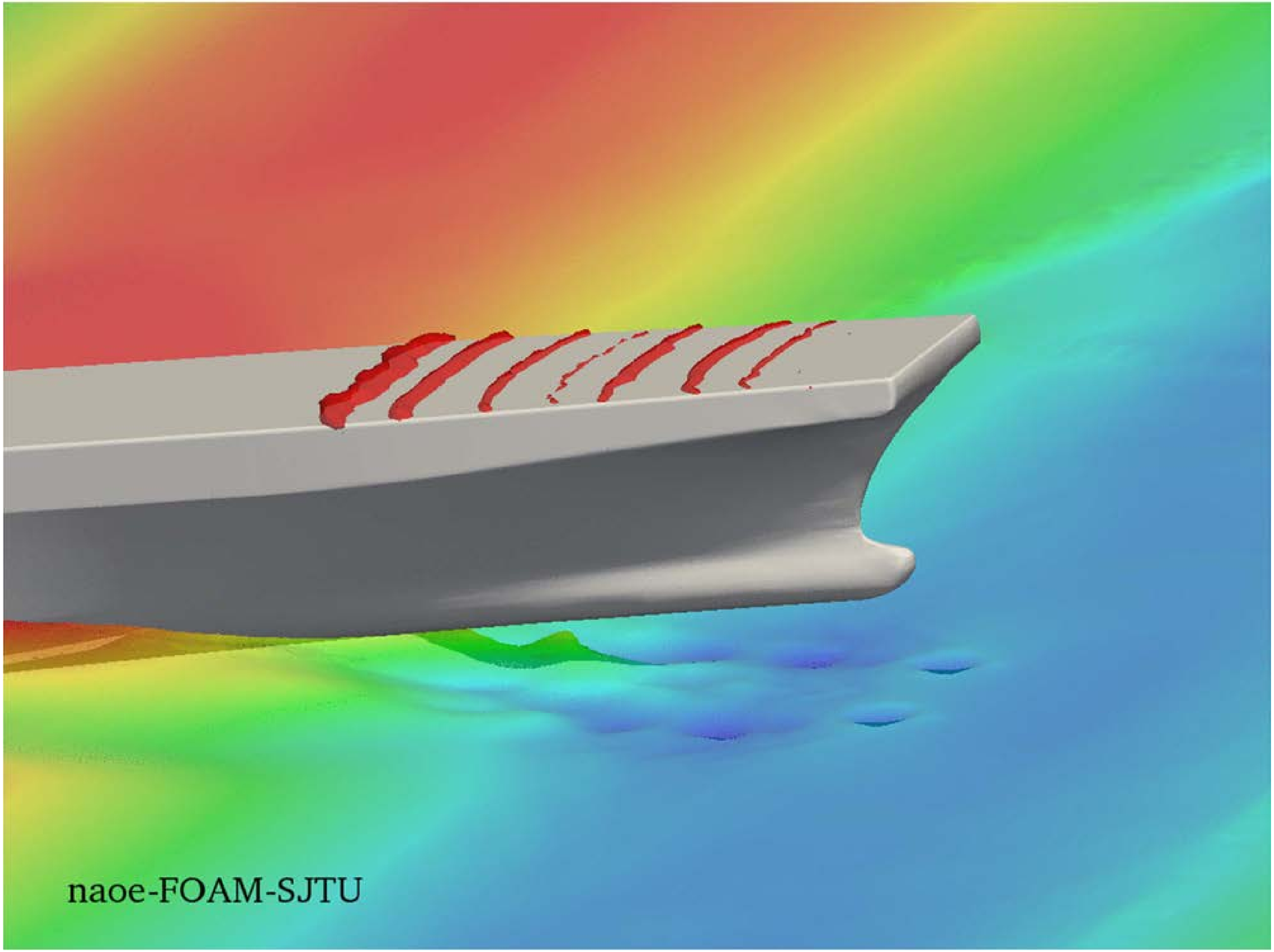









naoe-FOAM-SJTU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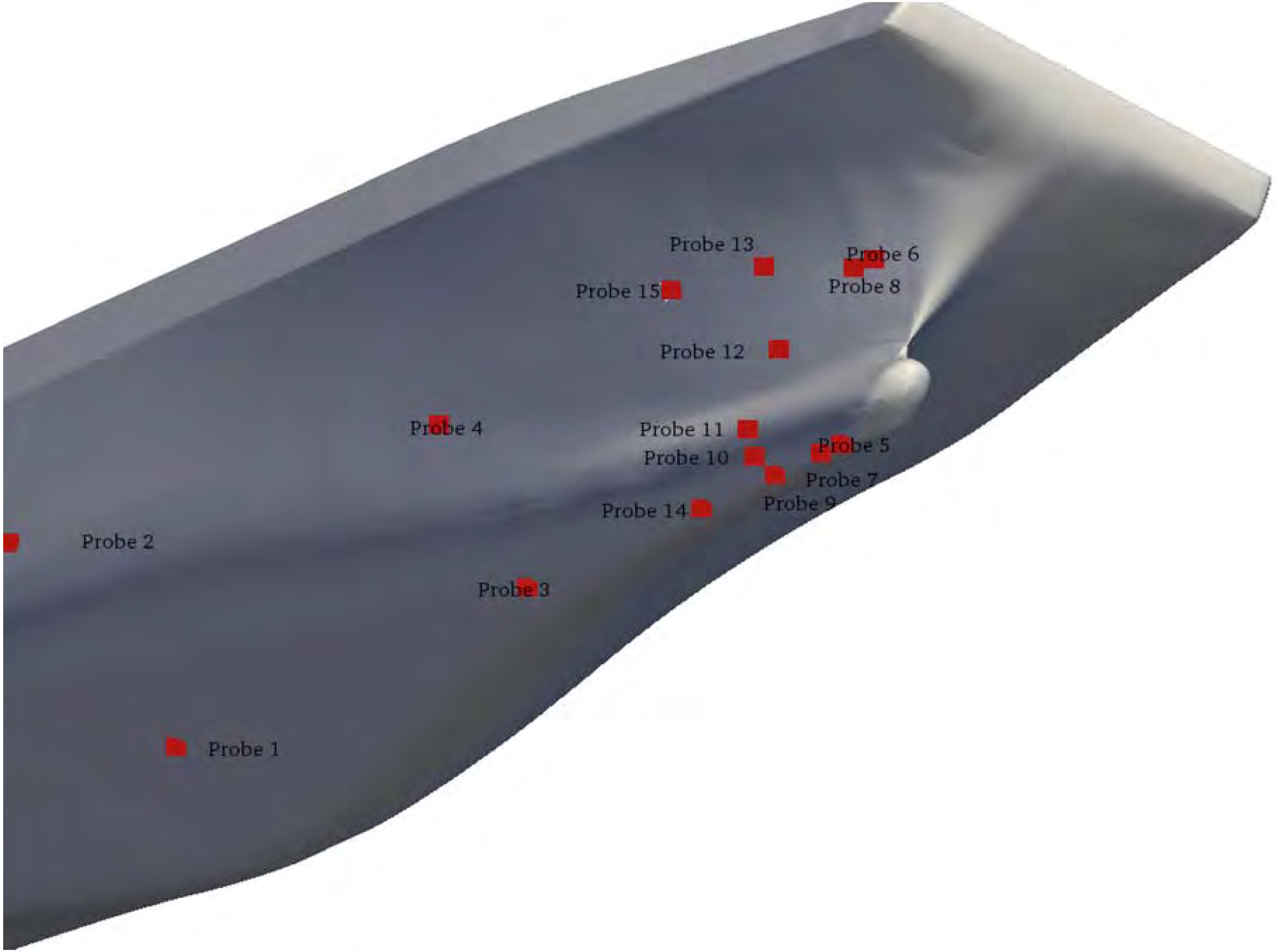
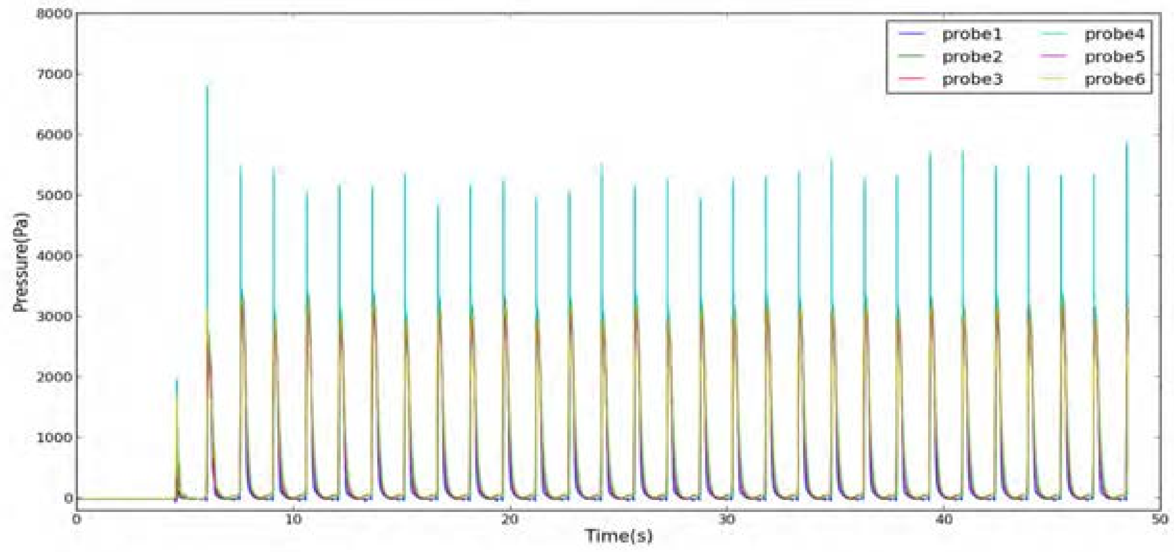
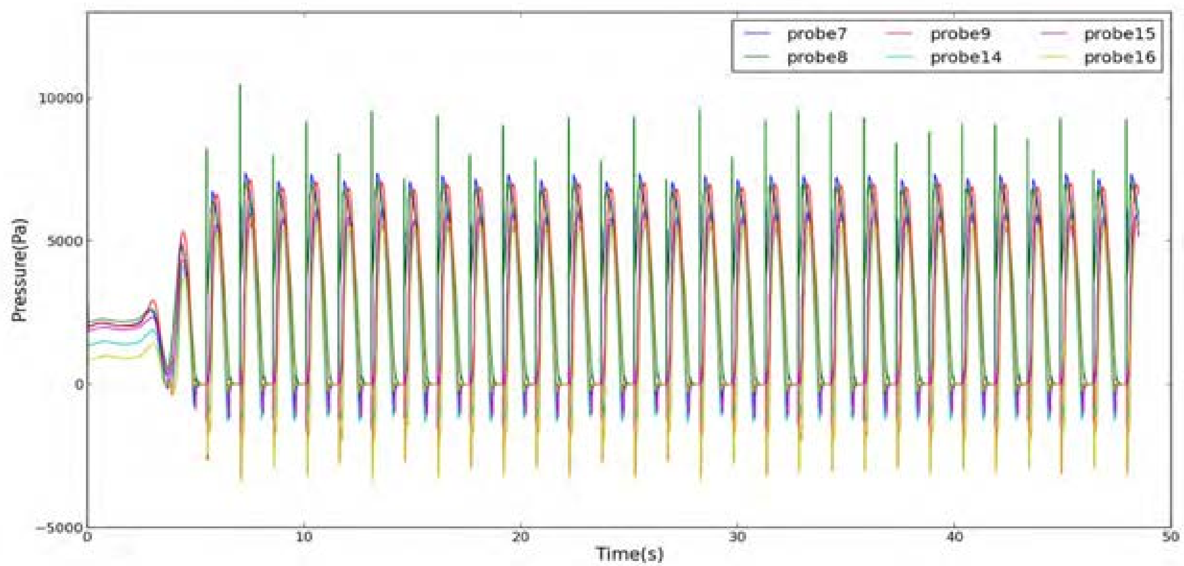
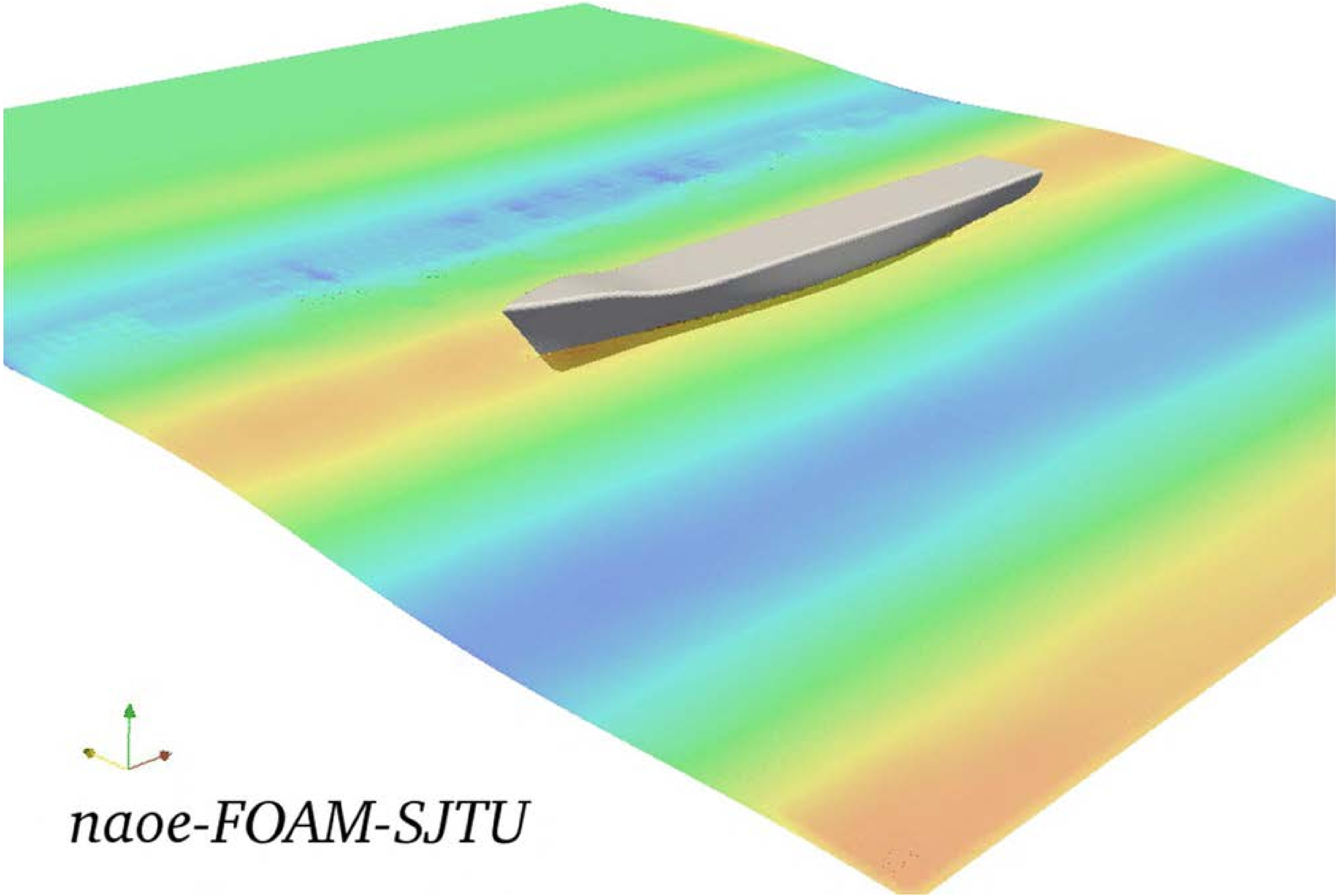

Probe 13
Probe 6
Probe 15
Probe 8
Probe 12
Probe 4
Probe 11
Probe 5
Probe 10
Probe 7
Probe 14
Probe 9
Probe 2
Probe 3
Probe 1

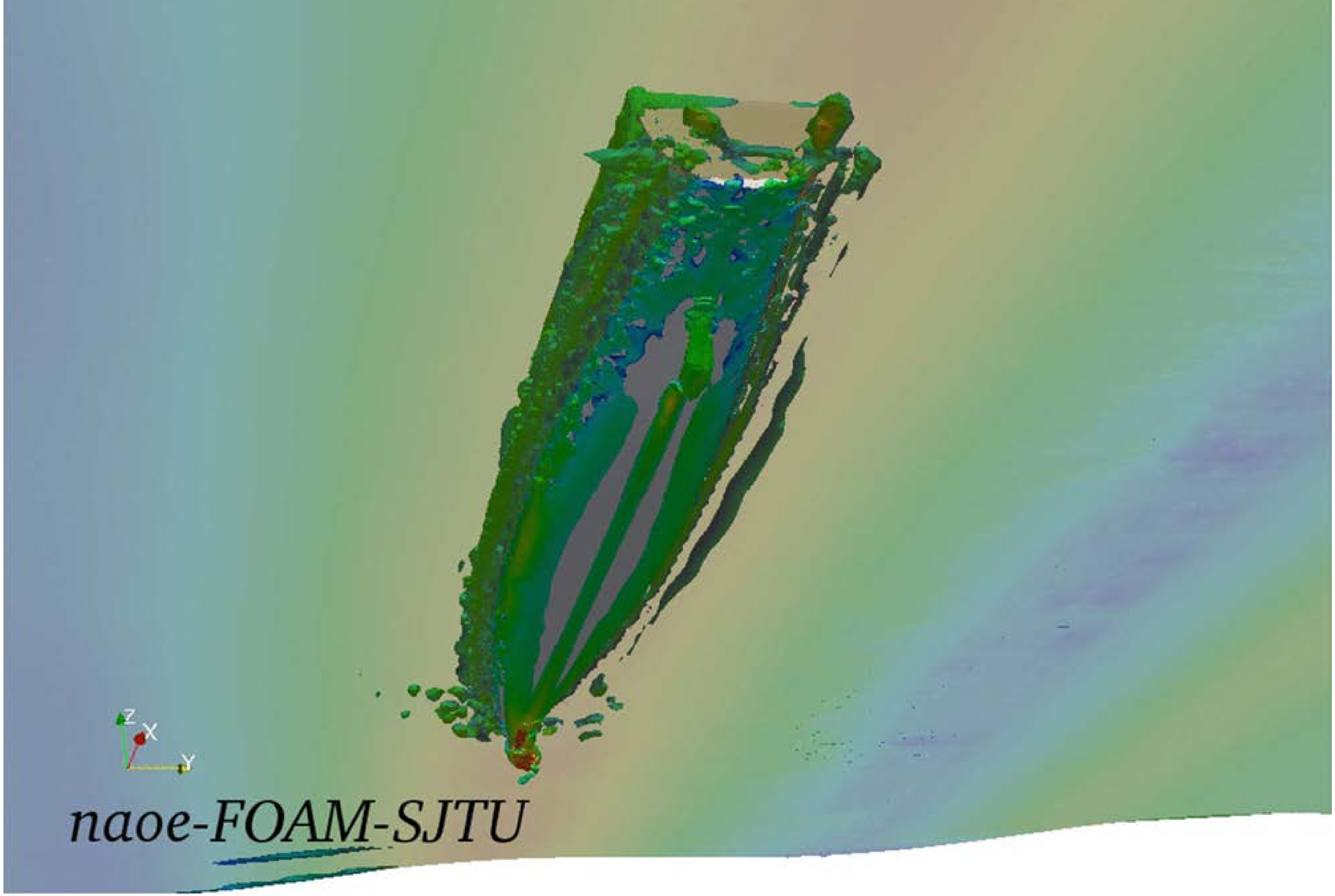
Impact point pressure histories

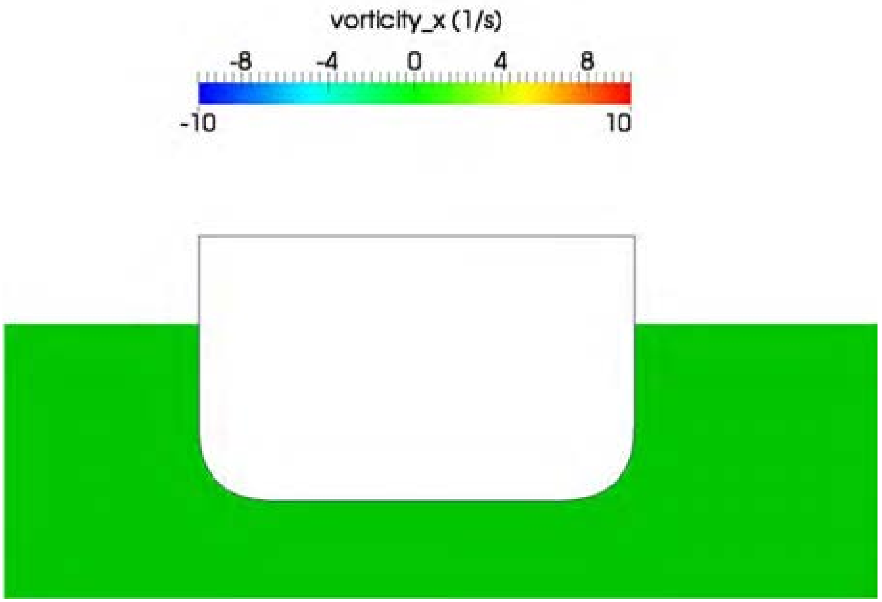




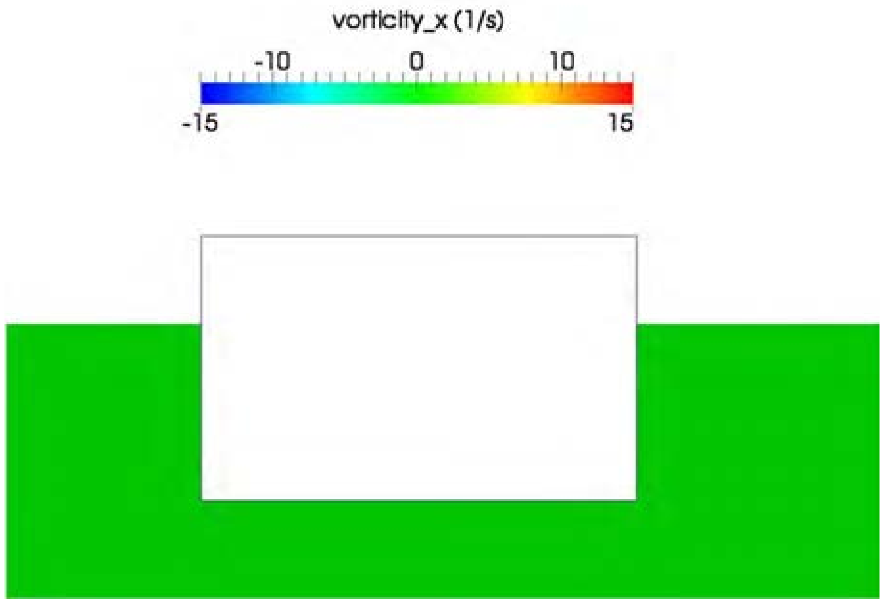

naoe-FOAM-SJTU

四级横浪-0航速-粘性涡流场



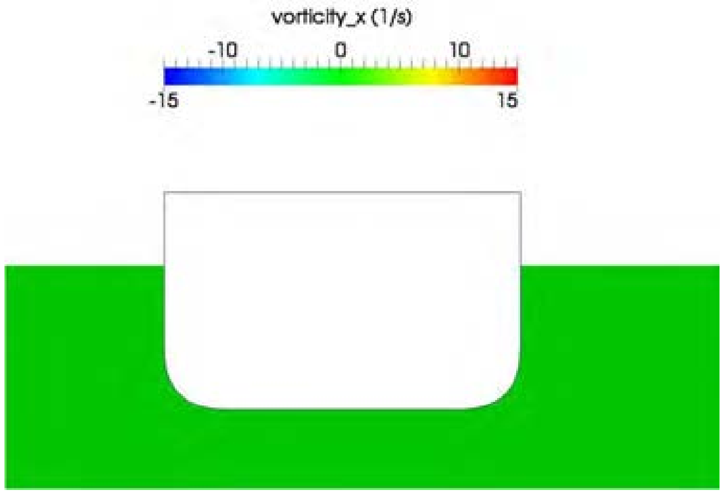


圆弧舭部 Circle bilge

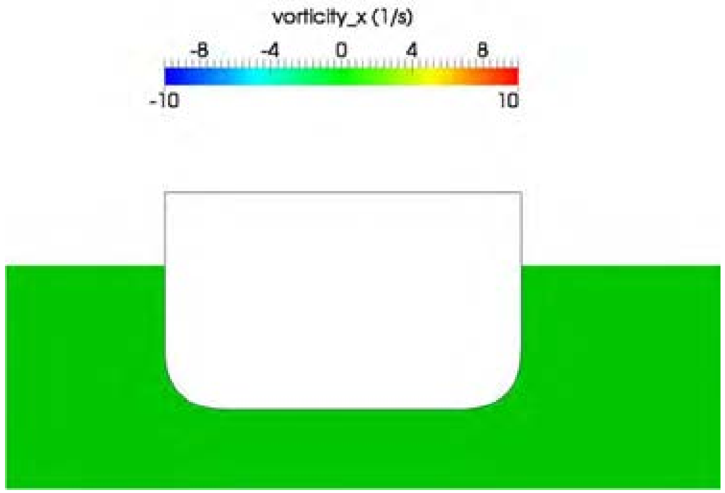


直角舭部 Right bilge

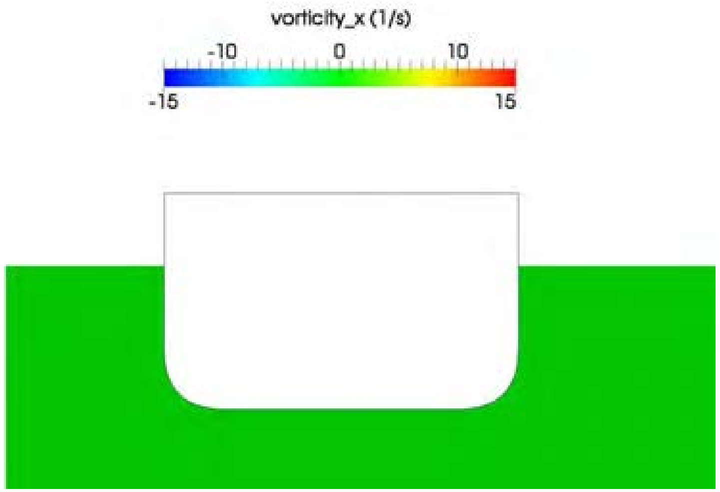
Roll motion



W=5.2745rad/s

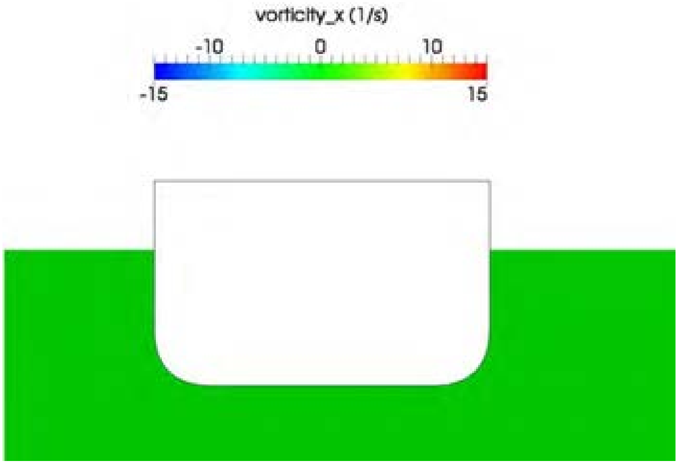


W=10rad/s

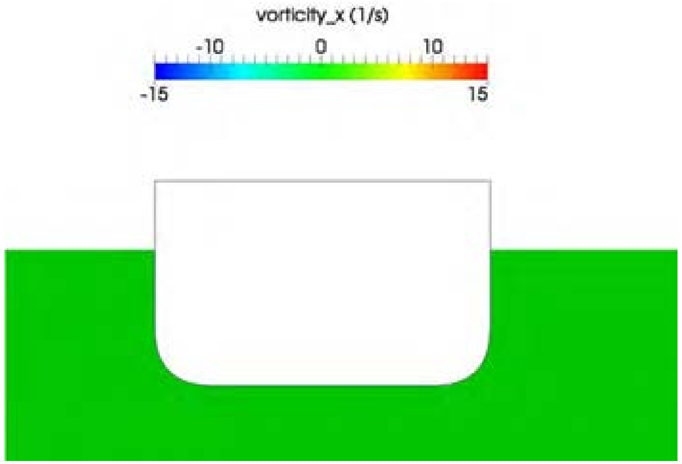


W=15rad/s

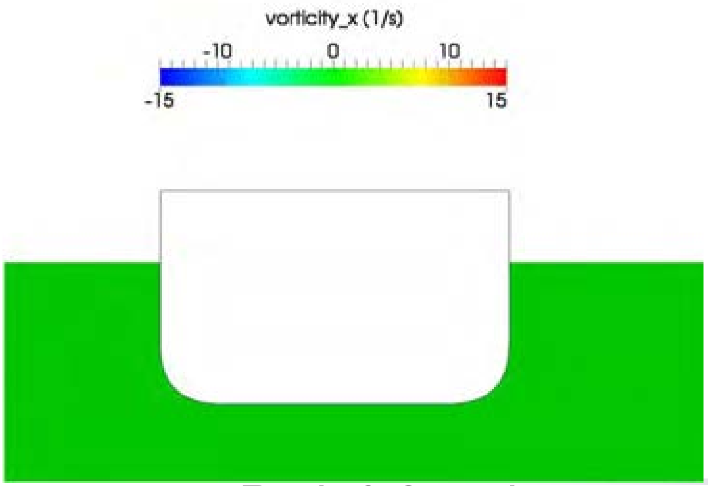
Roll motion



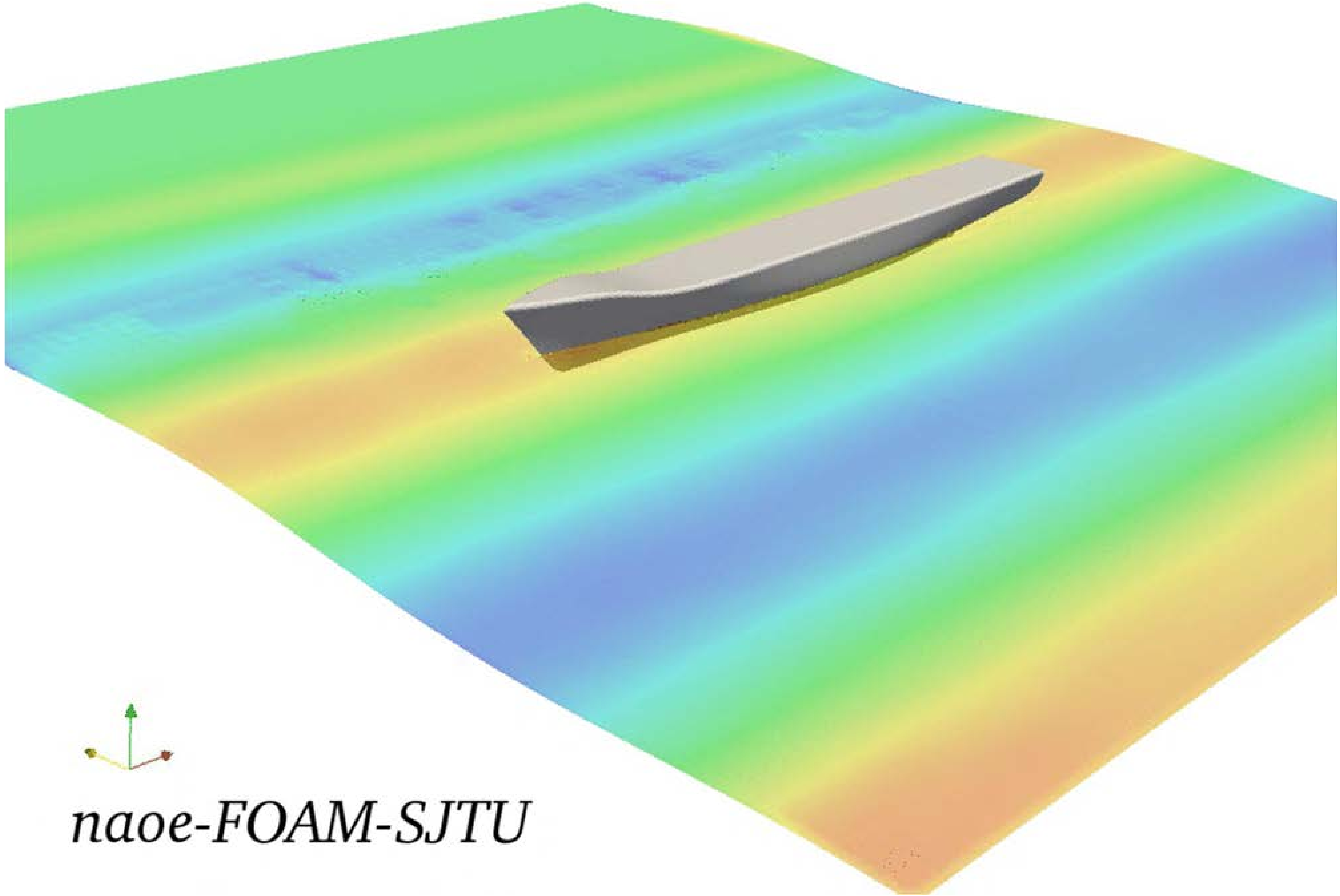
Rad=0.15rad

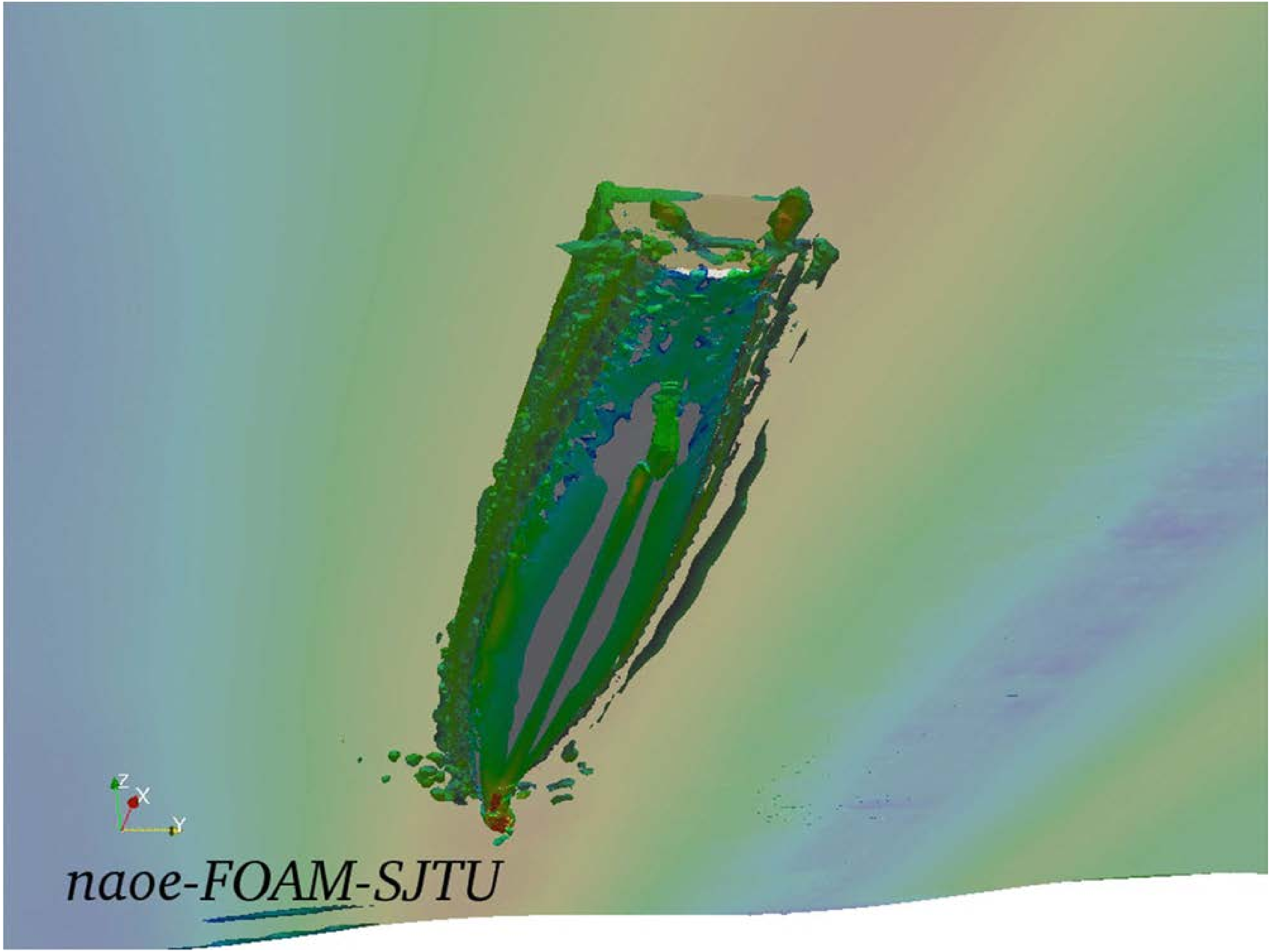


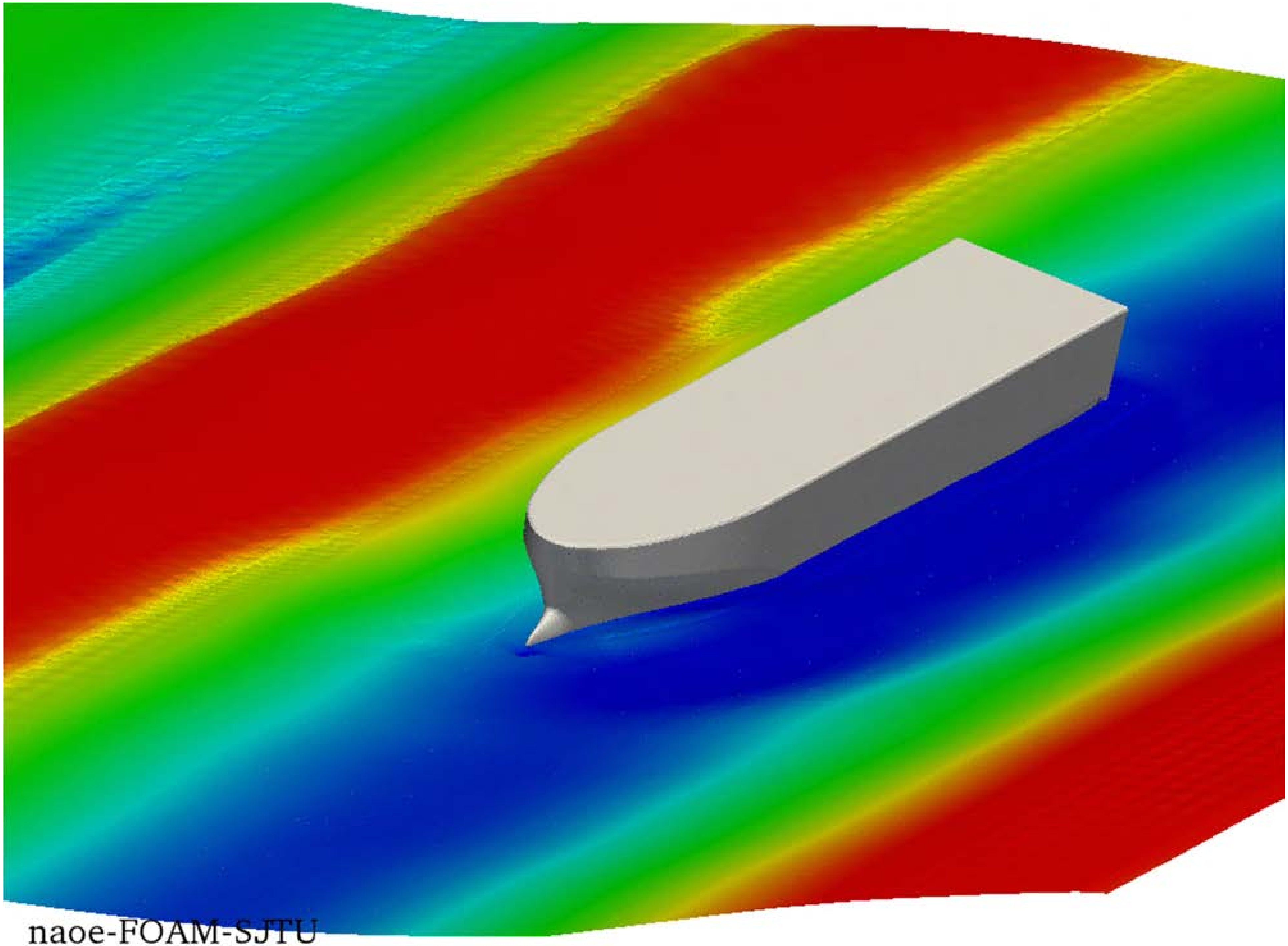
Rad=0.2rad



Rad=0.25rad


naoe-FOAM-SJTU


naoe-FOAM-SJTU
Z
X
Y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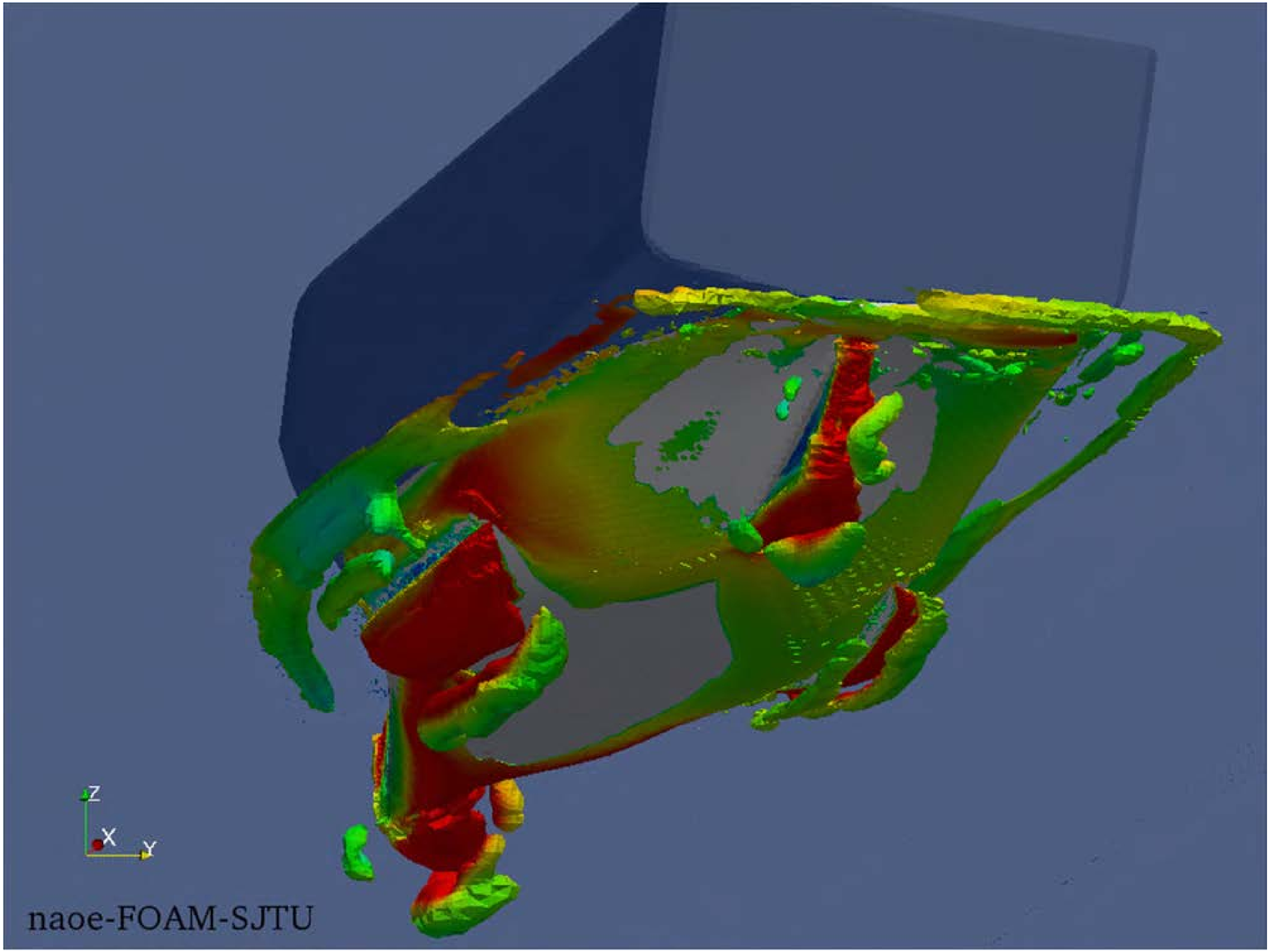
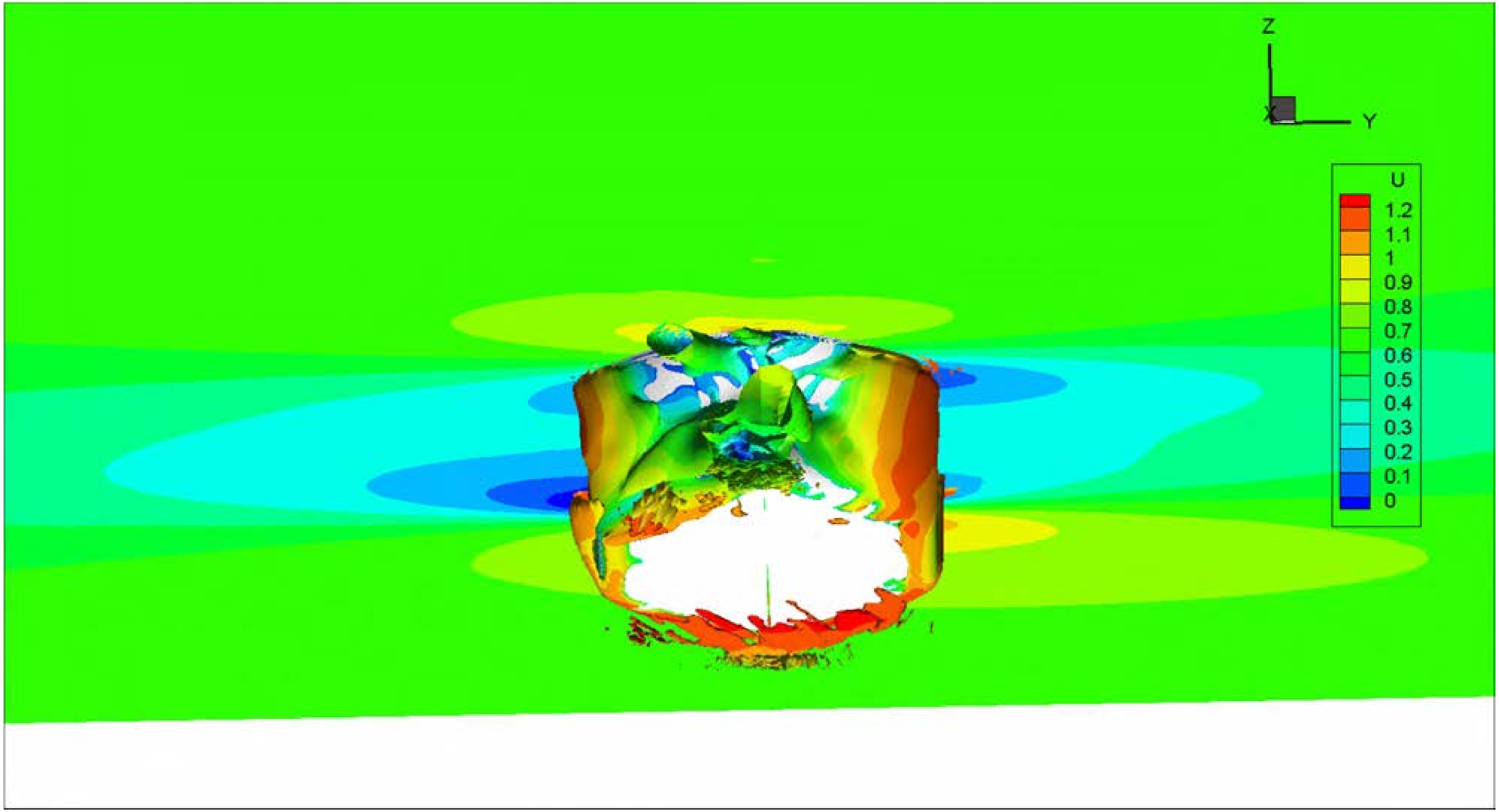
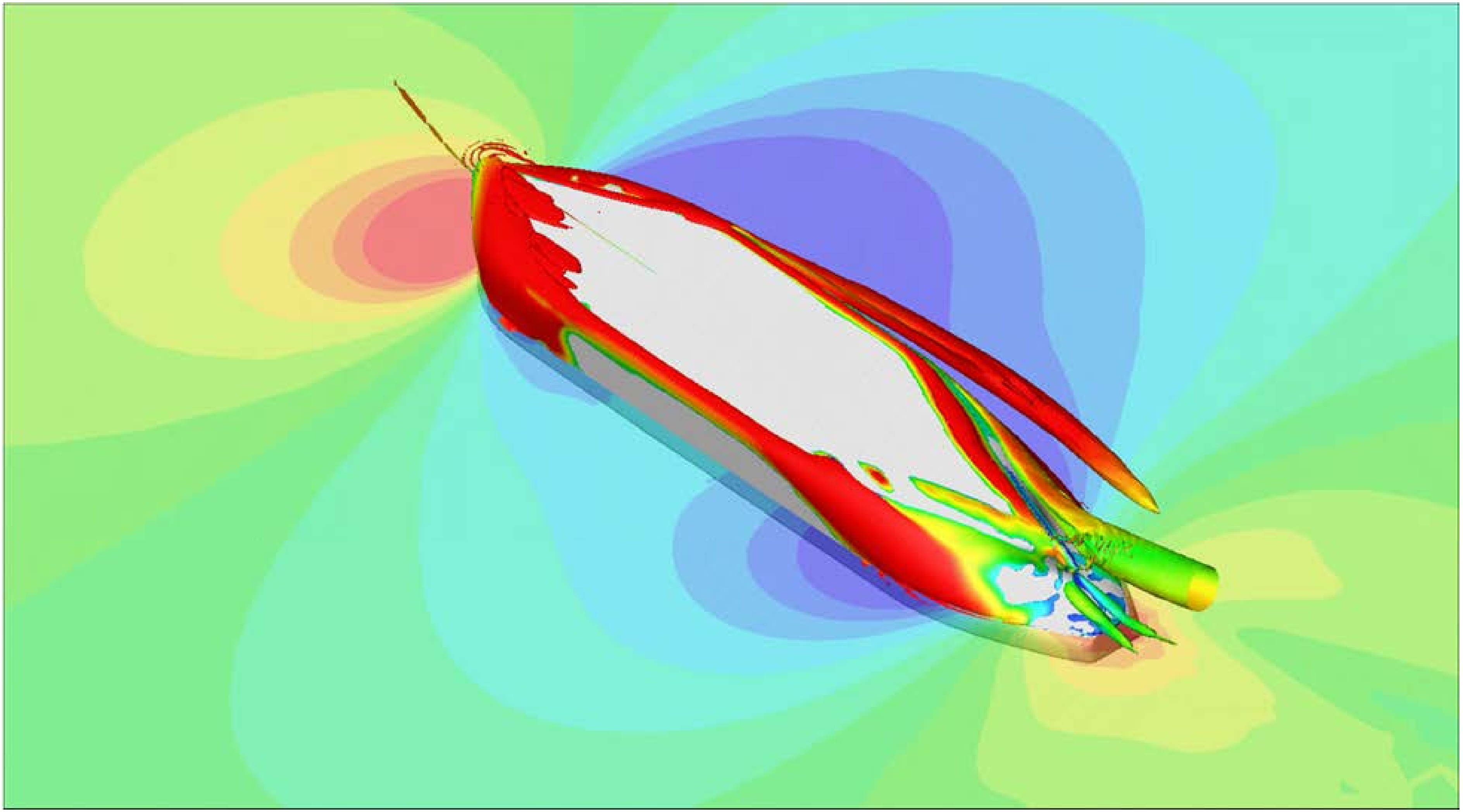
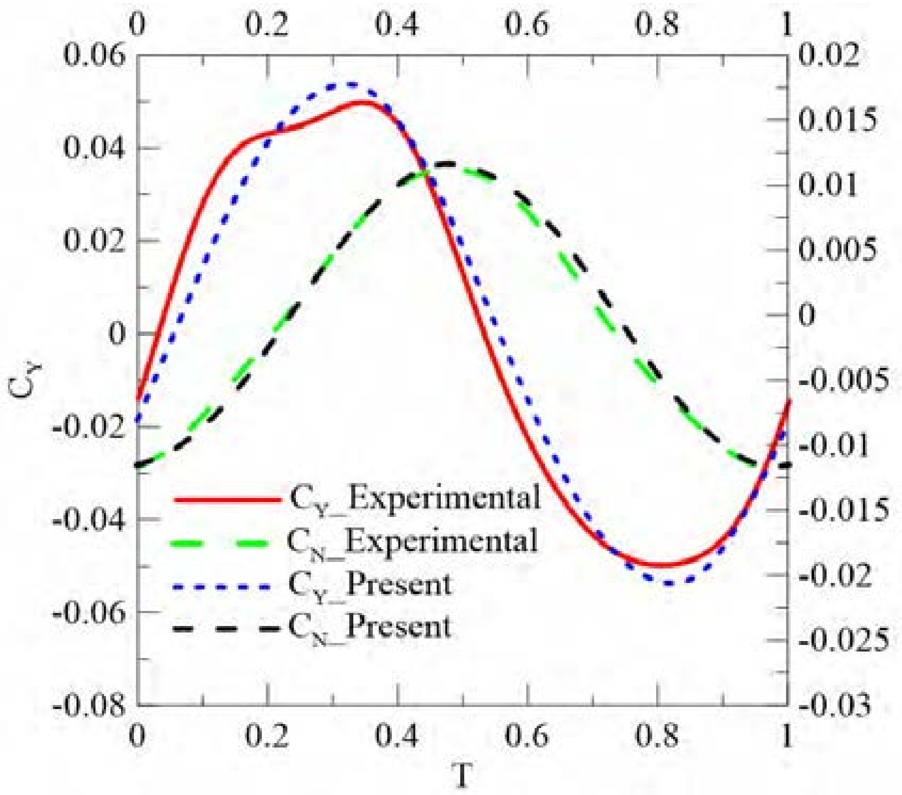


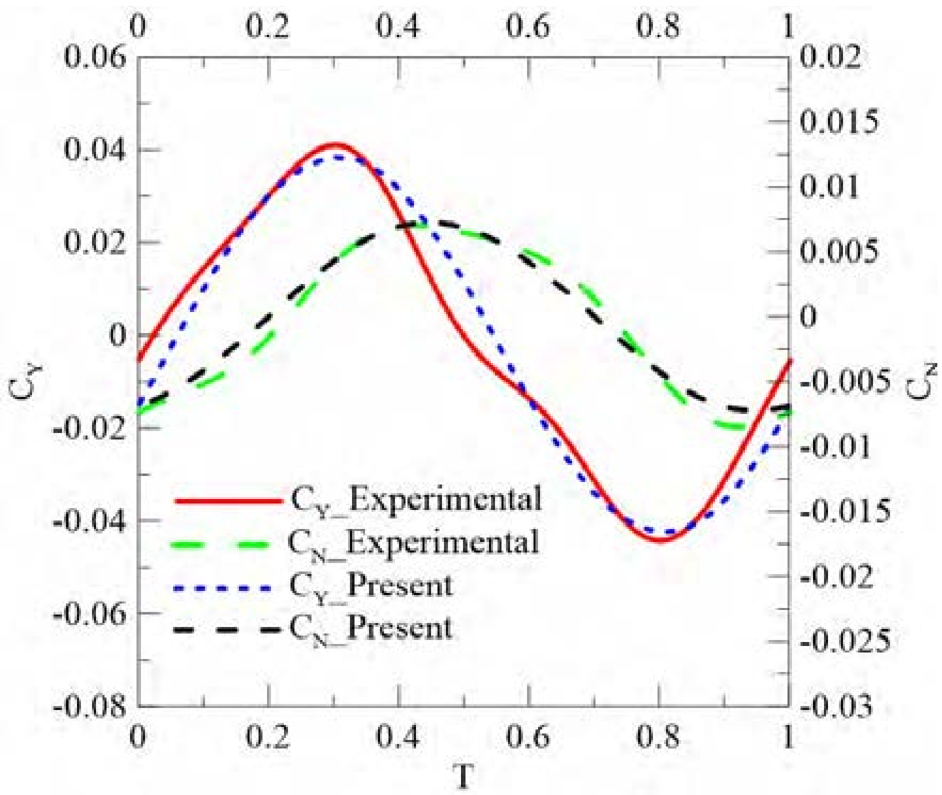
Z
X
Y
naoe-FOAM-SJTU


Z
X
Y
U
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

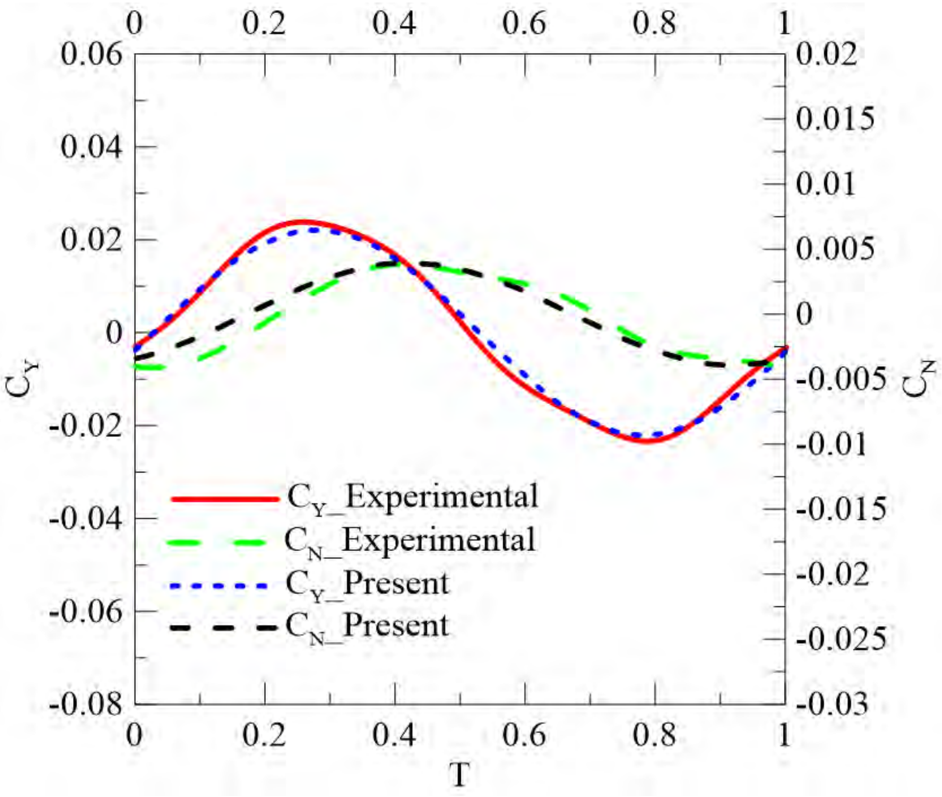




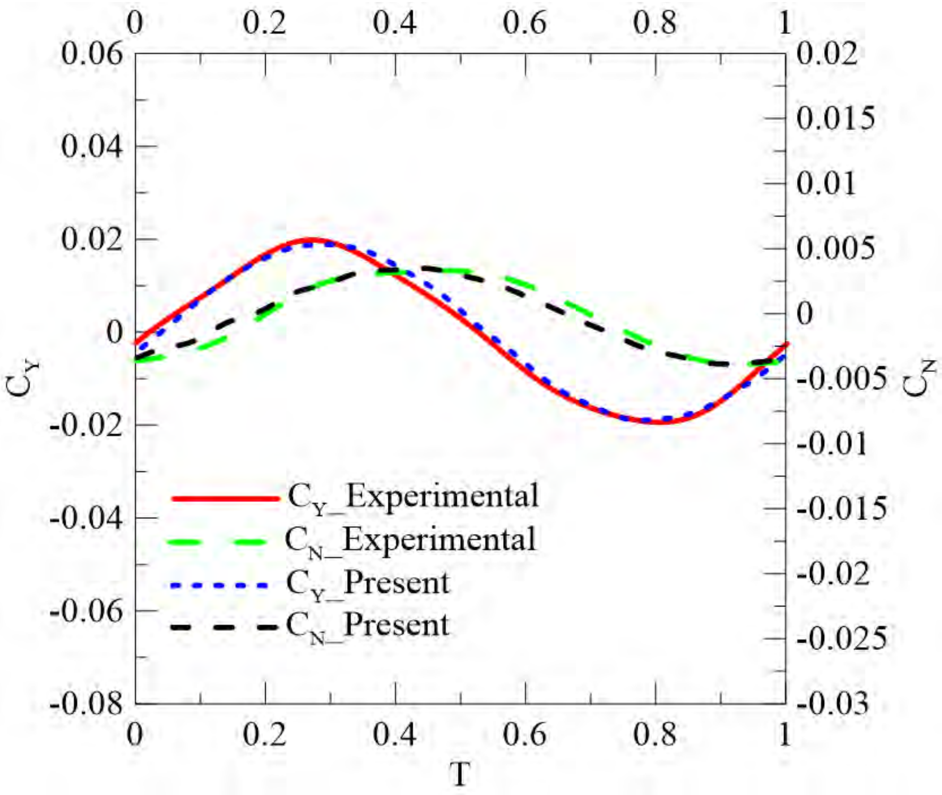
深吃水比**h/T=1.2**时水动力计算结果



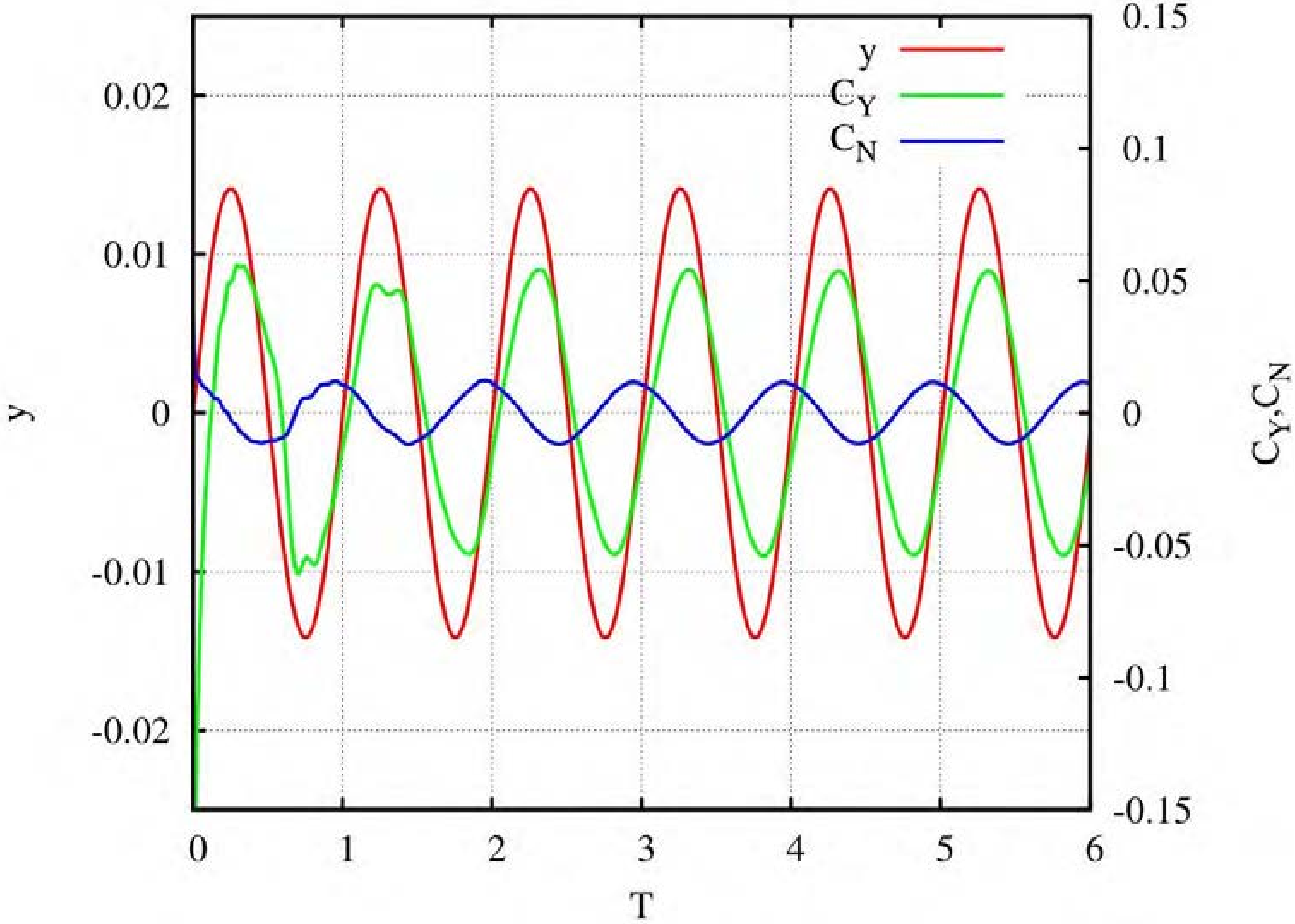
水深吃水比**h/T=1.5**时水动力计算结果



水深吃水比**h/T=3.0**时水动力计算结果



水深吃水比**h/T=8.3**时水动力计算结果

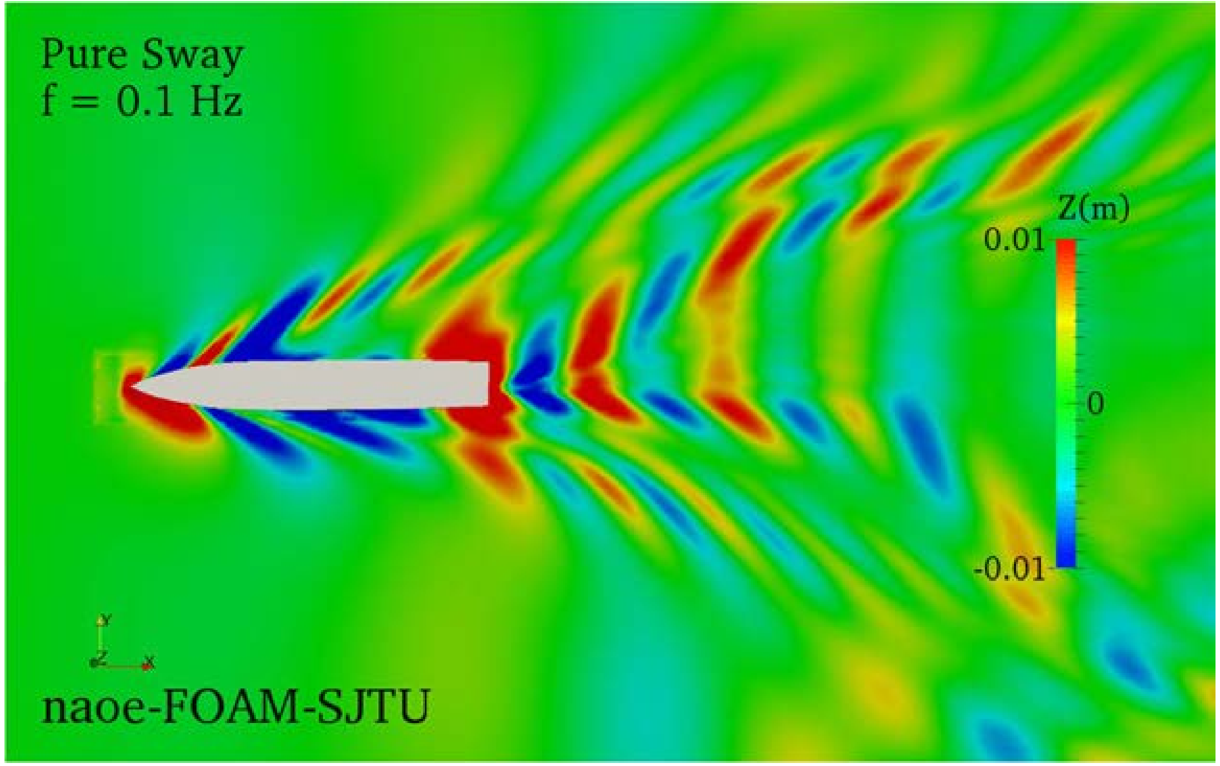


横向运动与侧向力及转艏力矩的相位关系

Calculation of derivative hydrodynamic coeff

h/T	8.3	3.0	1.5	1.2
v'	0.04	0.04	0.04	0.04
$\tilde{\varphi}_y$	0.1412	0.1267	0.2260	0.3517
$\tilde{\varphi}_n$	0.8800	0.8486	1.1473	1.1627
Y_0(N)	35.034	40.768	78.463	99.206
N_0(N·m)	50.121	51.415	93.344	150.431
$Y_{\dot{v}}'$	-0.01438	-0.01677	-0.03170	-0.03861
Y_v'	-0.01012	-0.01058	-0.03608	-0.07014
$N_{\dot{v}}'$	-0.001891	-0.002013	-0.002272	-0.003535
N_v'	-0.01133	-0.01131	-0.02495	-0.04049

DTMB pure sway



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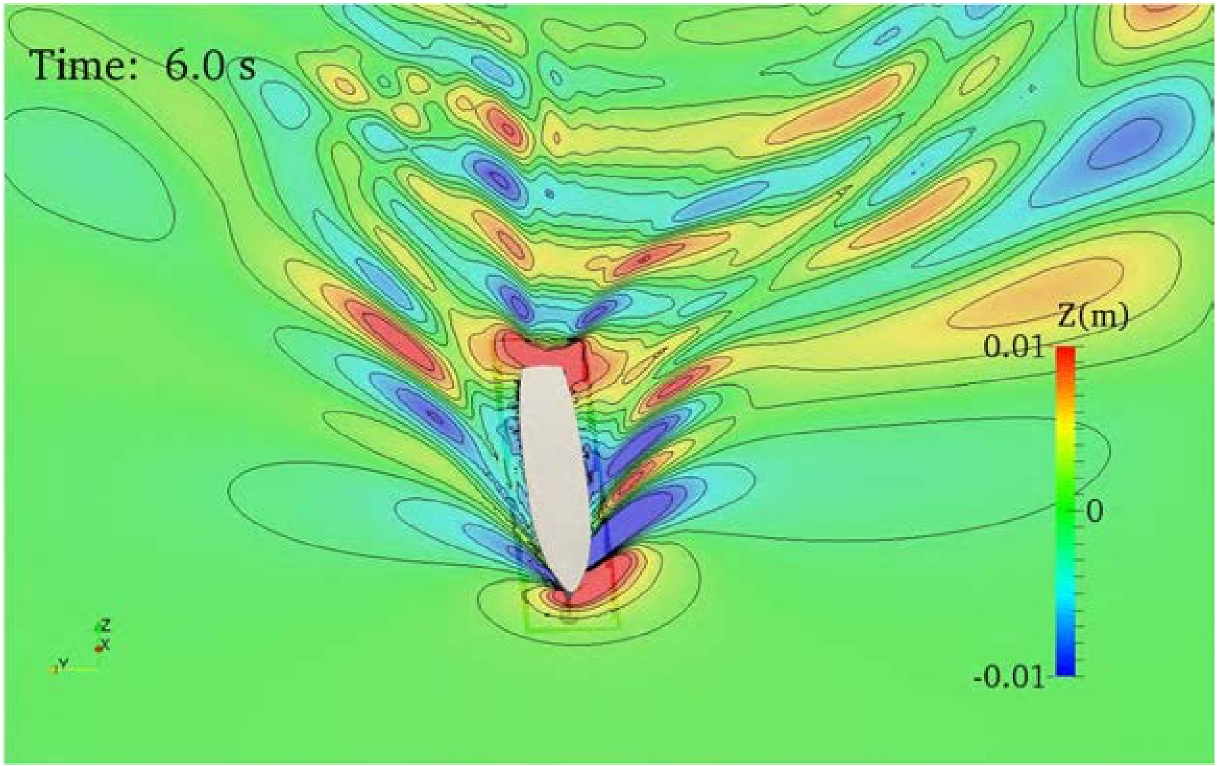
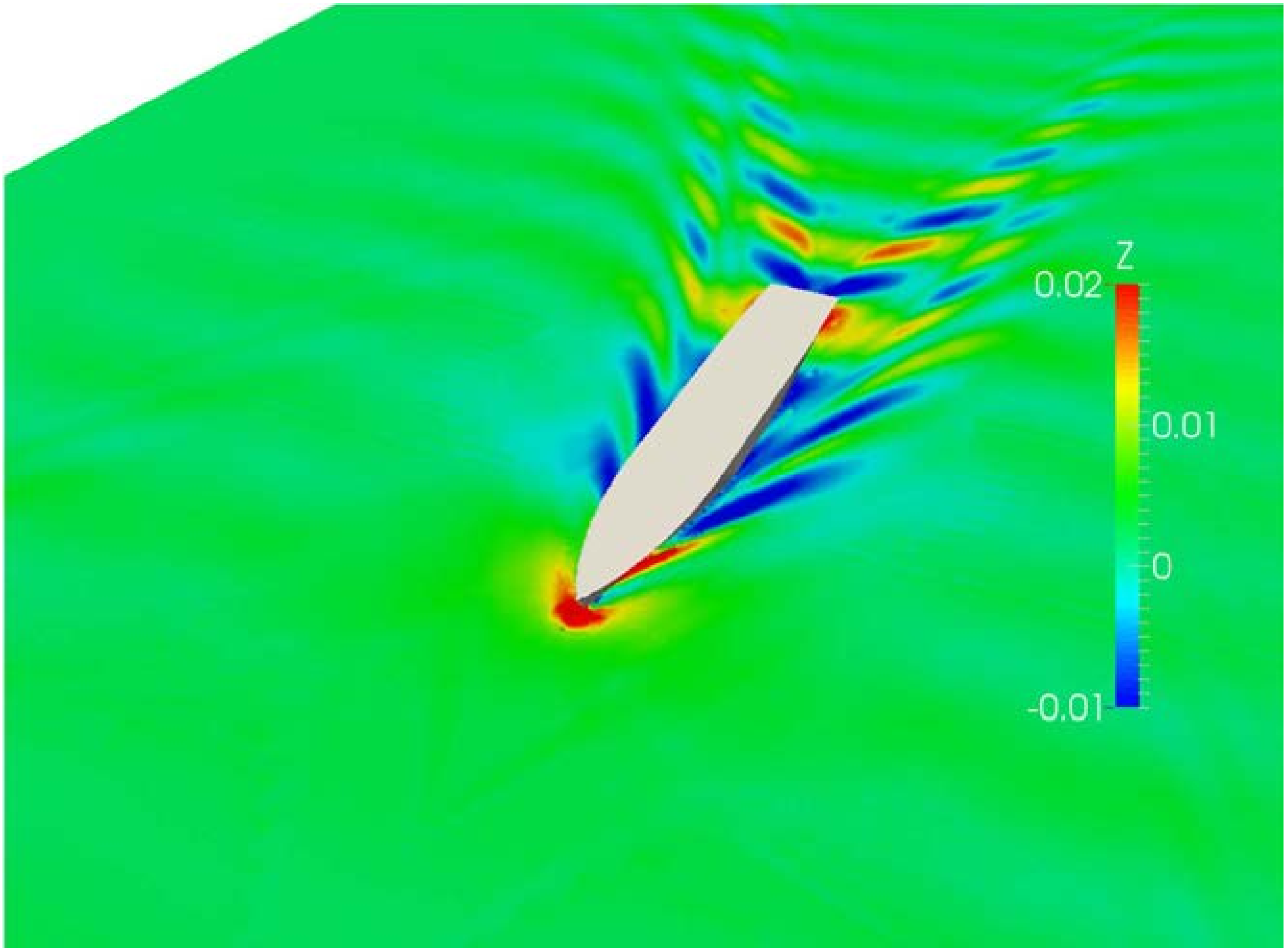
DTMB 5415 pure yaw



Pure Yaw Motion

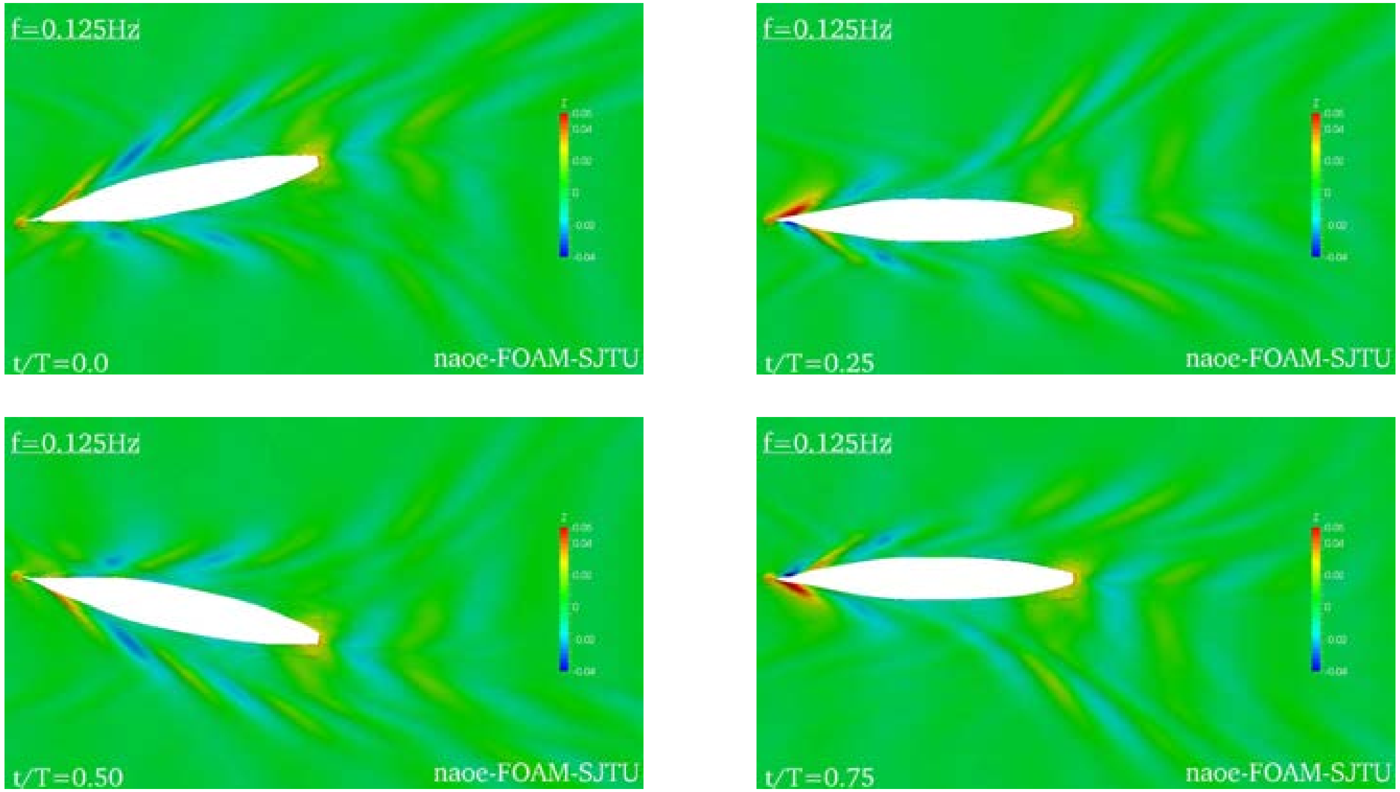
1



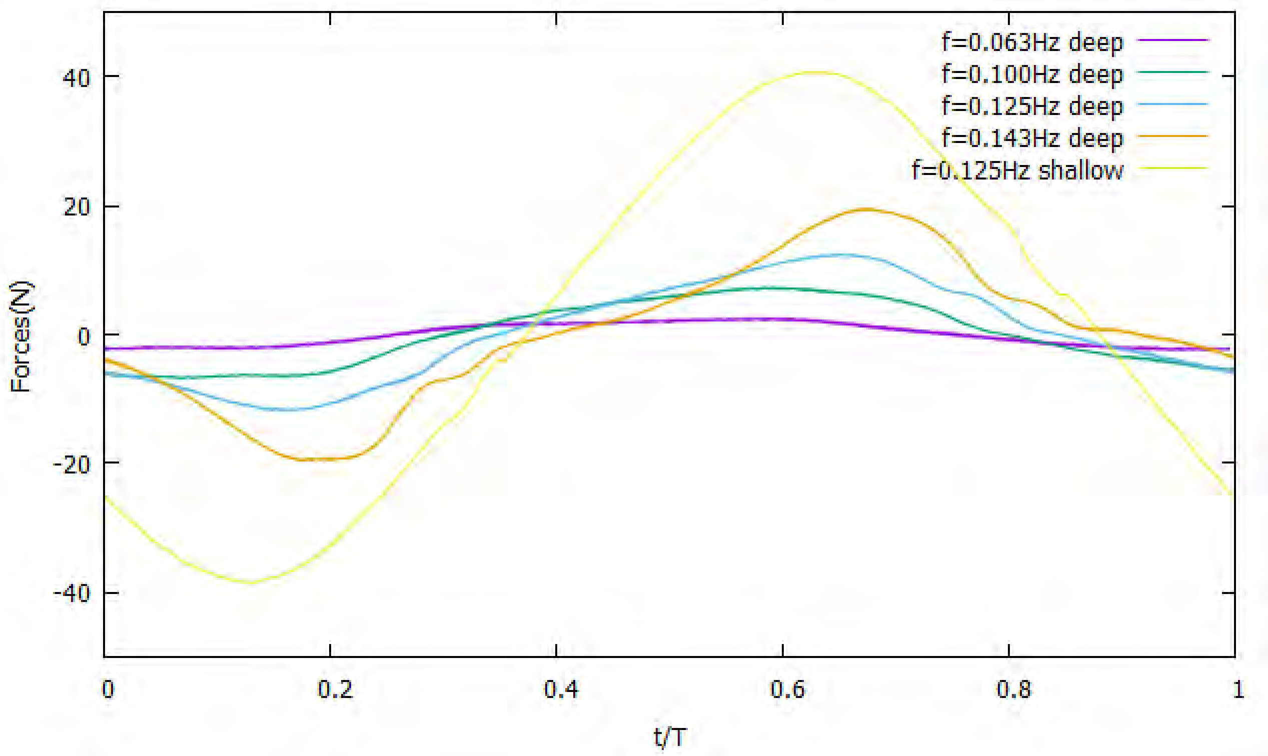
Flow field information

Wave pattern

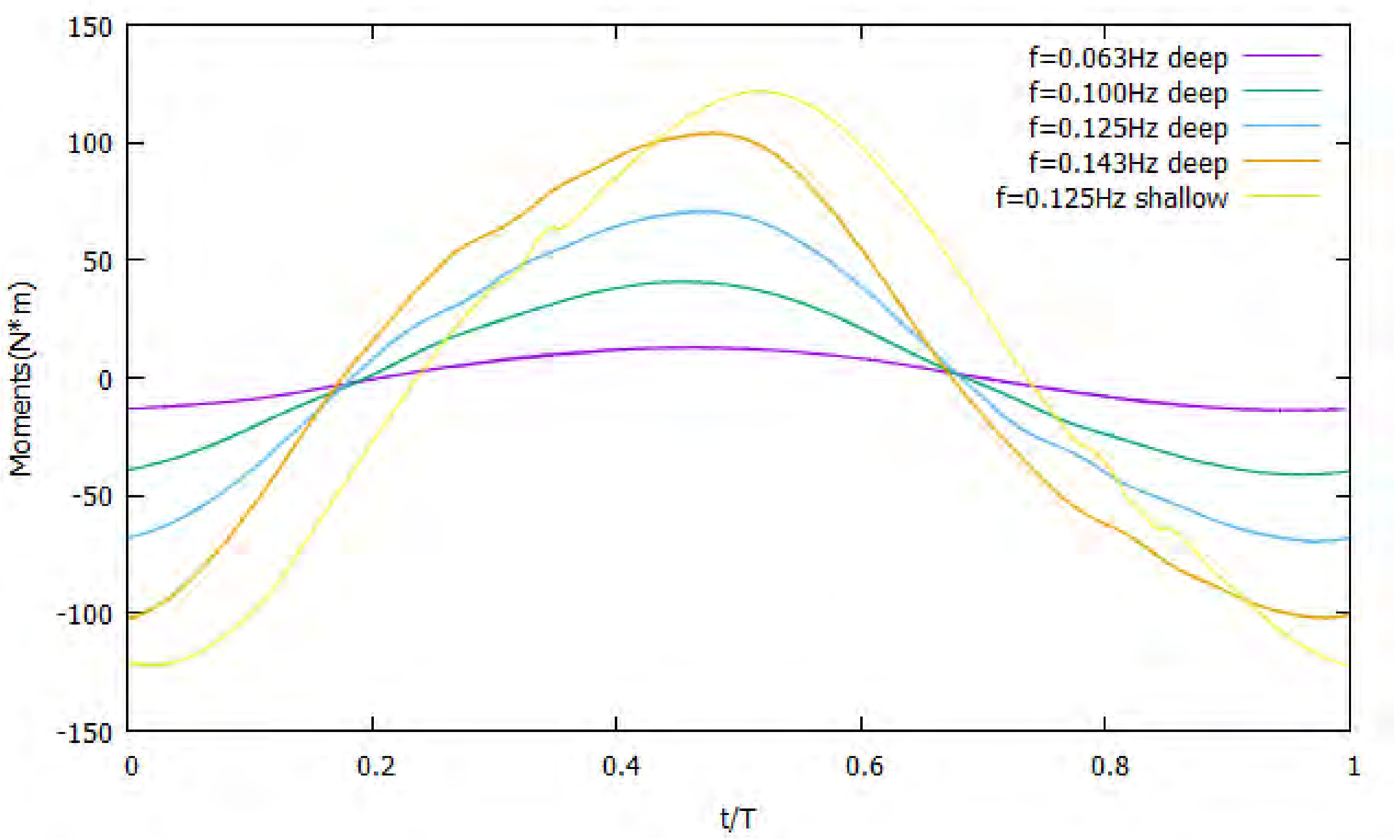
Free surface of ω=0.76 for pure yaw in deep water at sequential motion phases

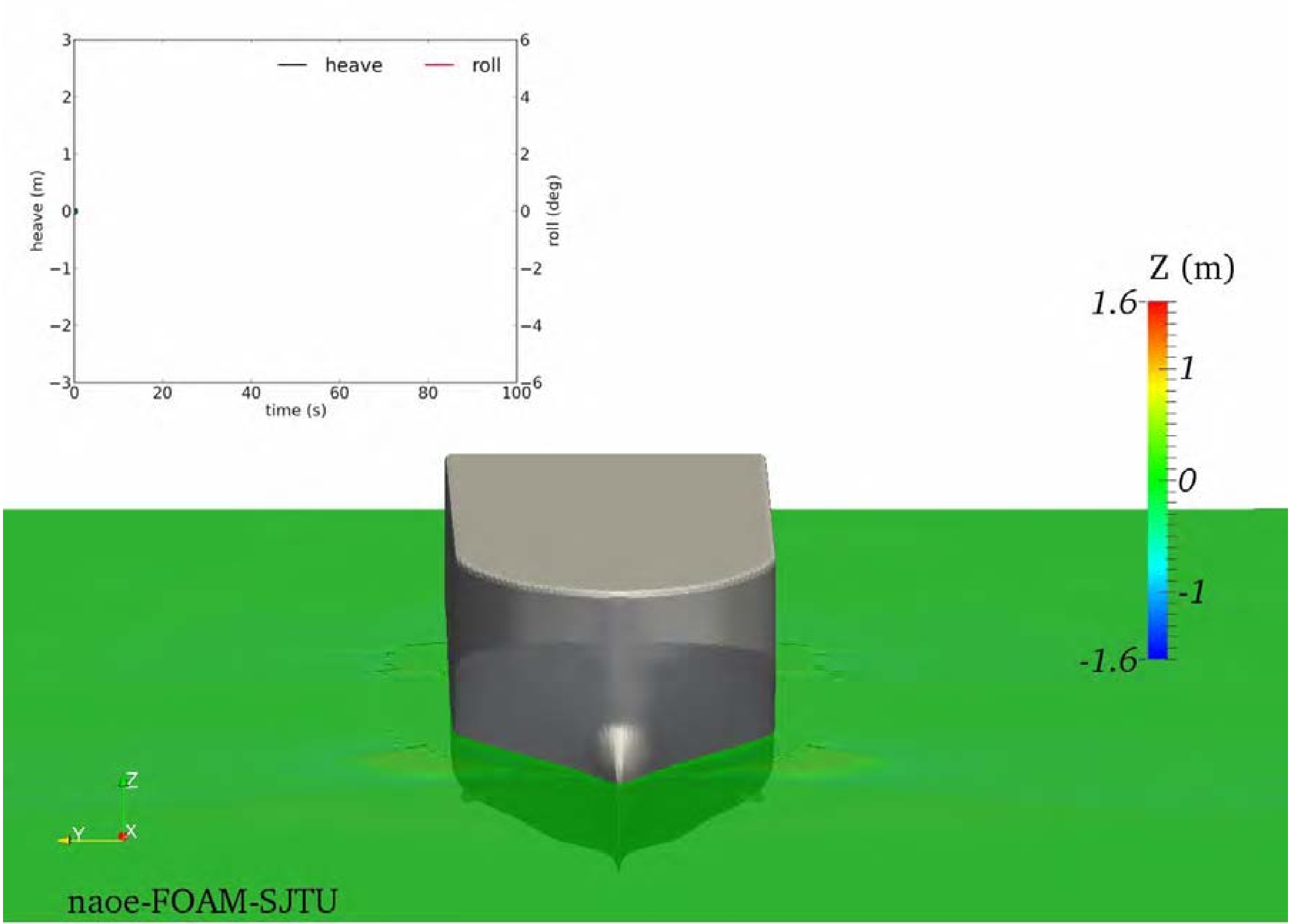


Lateral forces during one period for pure yaw at different frequencies in deep and shallow water

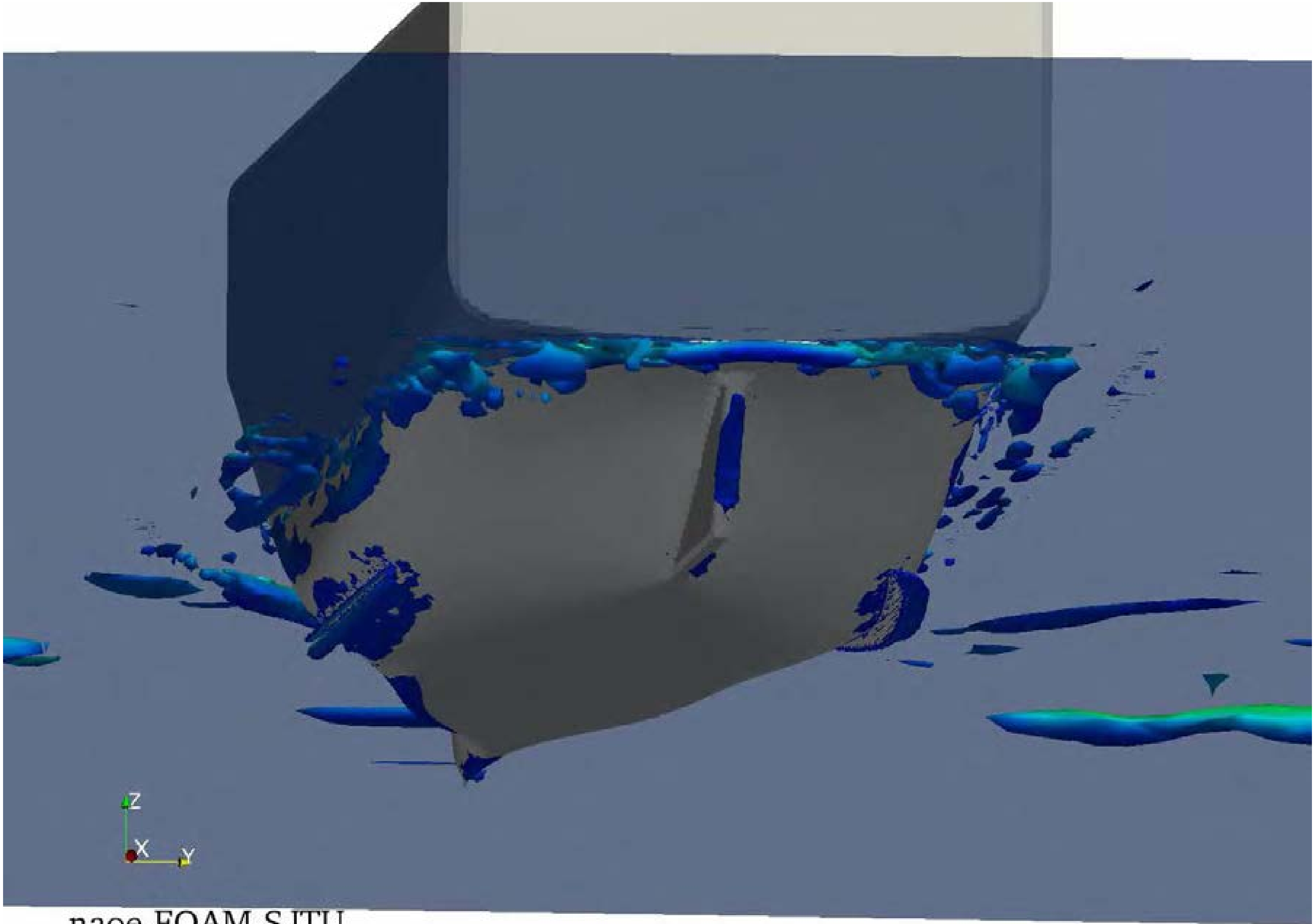


Turn moments during one period for pure yaw at different frequencies in deep and shallow water





heave
roll
heave (m)
roll (deg)
time (s)
0
20
40
60
80
100
3
2
1
0
−1
−2
−3
6
4
2
0
−2
−4
−6
Z (m)
1.6
1
0
-1
-1.6
Z
Y
X
naoe-FOAM-SJTU



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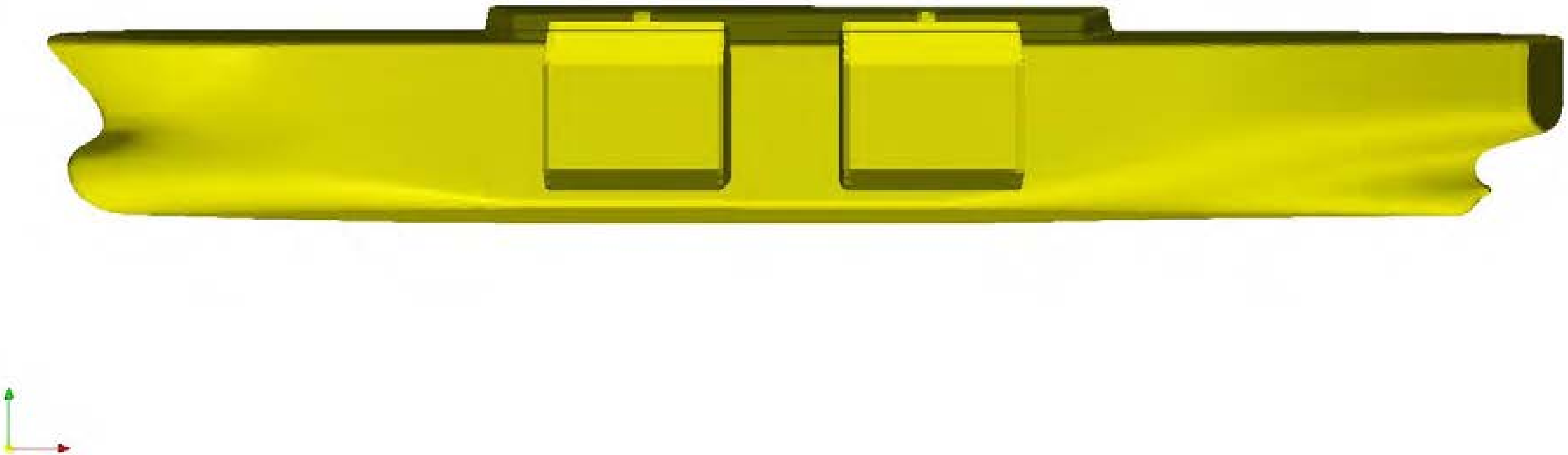
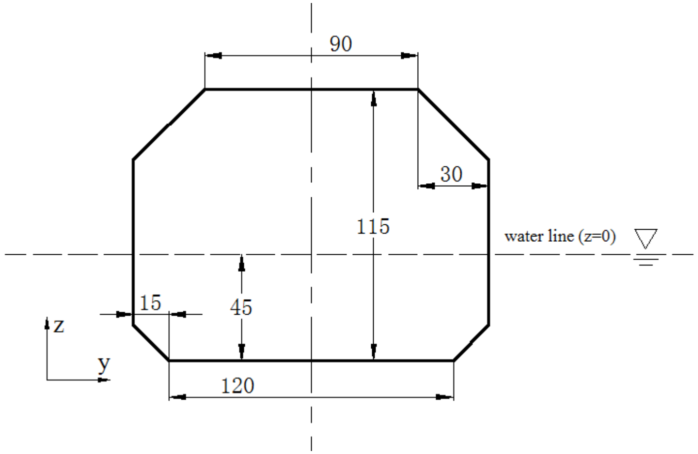
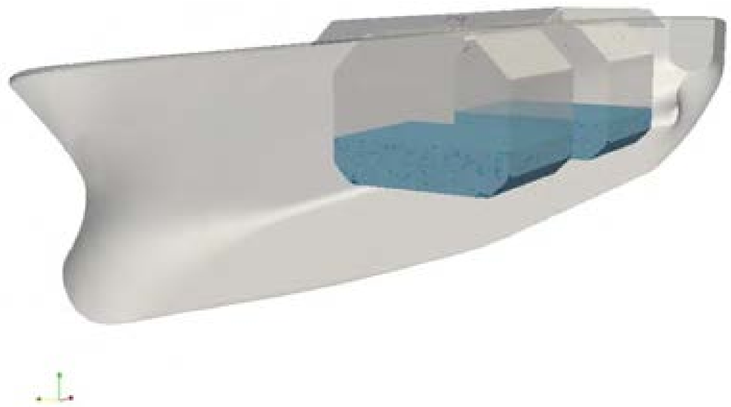
LNG Tank Sloshing

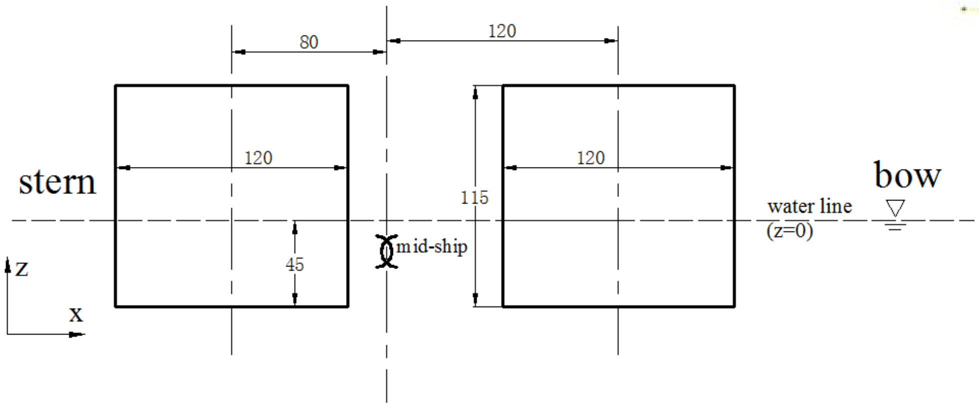


Geometry of LNG tanks



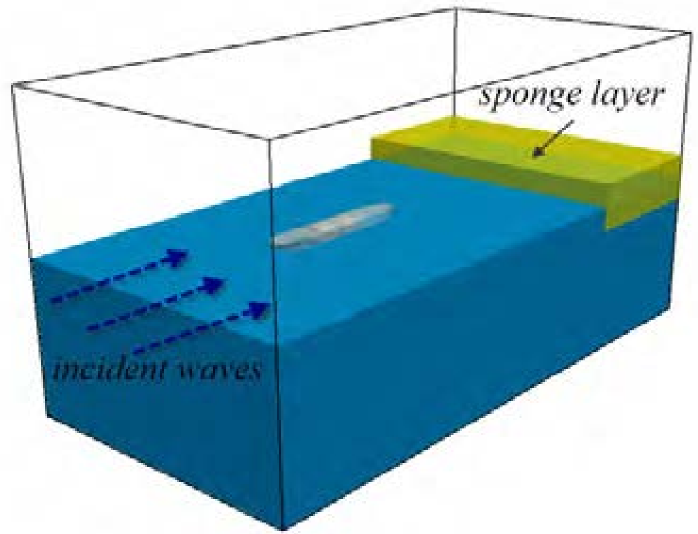
Font View



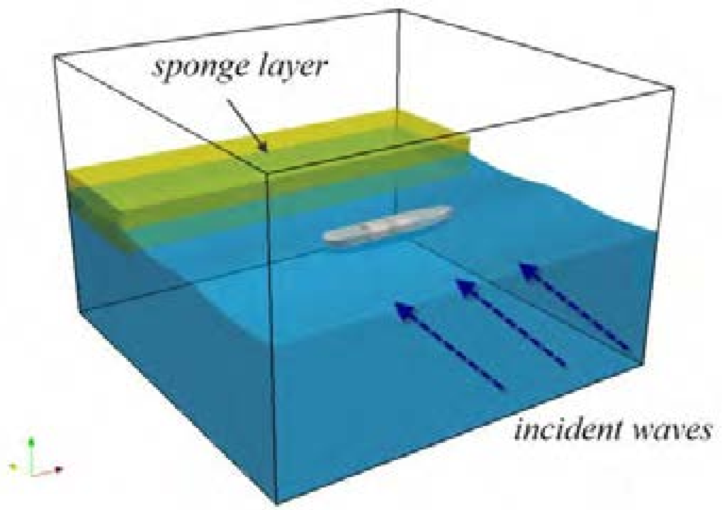


Side View

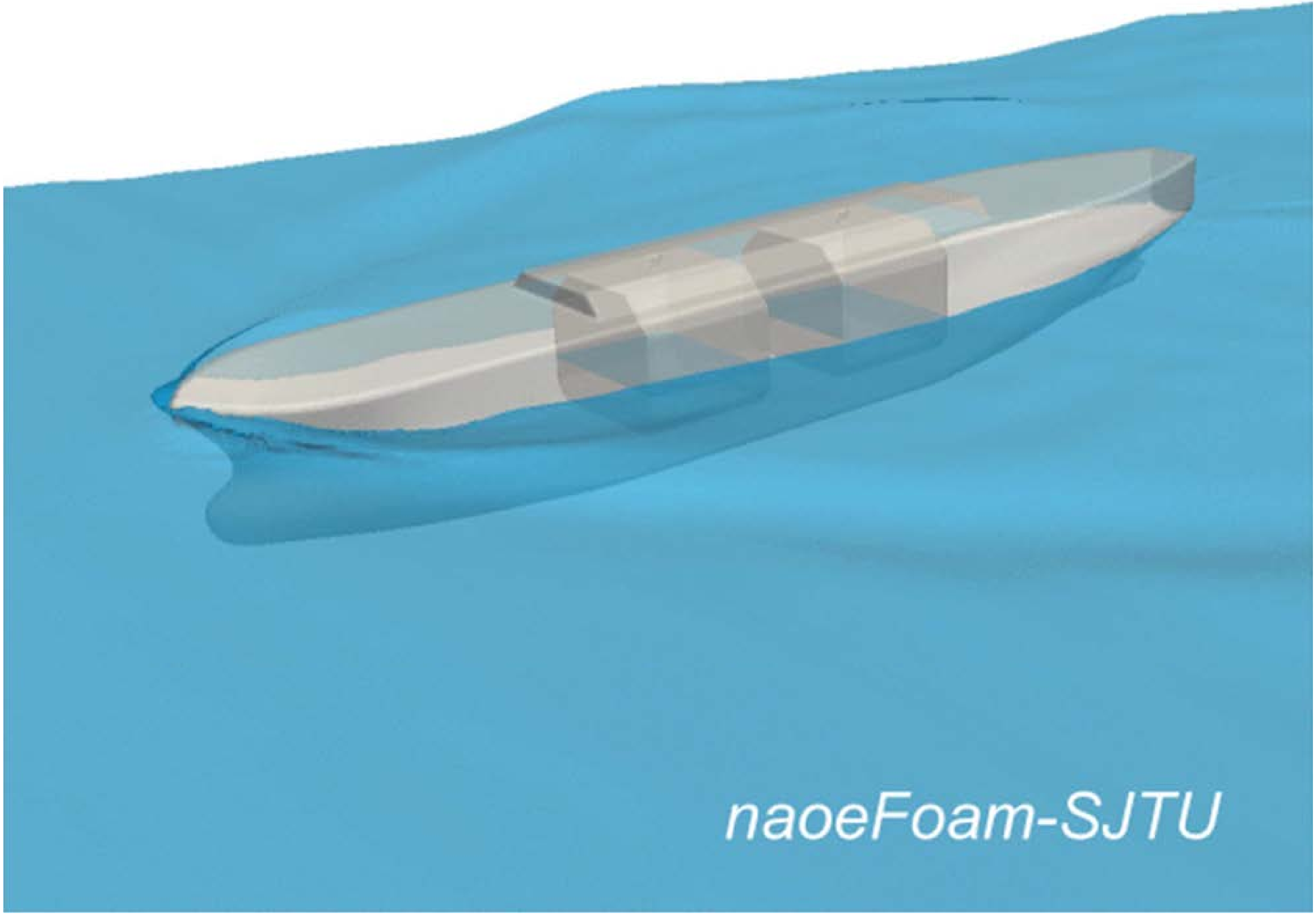
Numerical wave tank

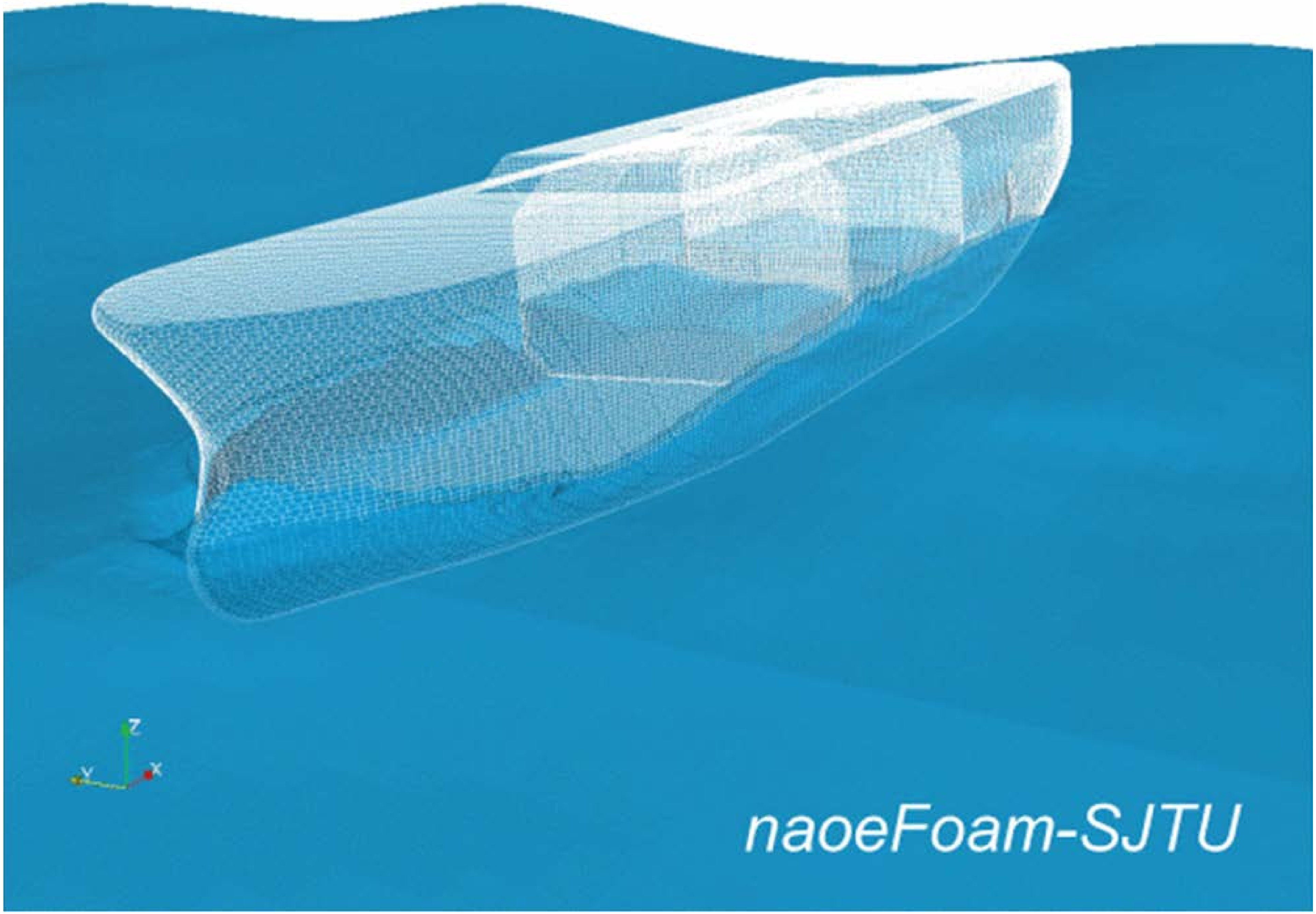


(a) head wave

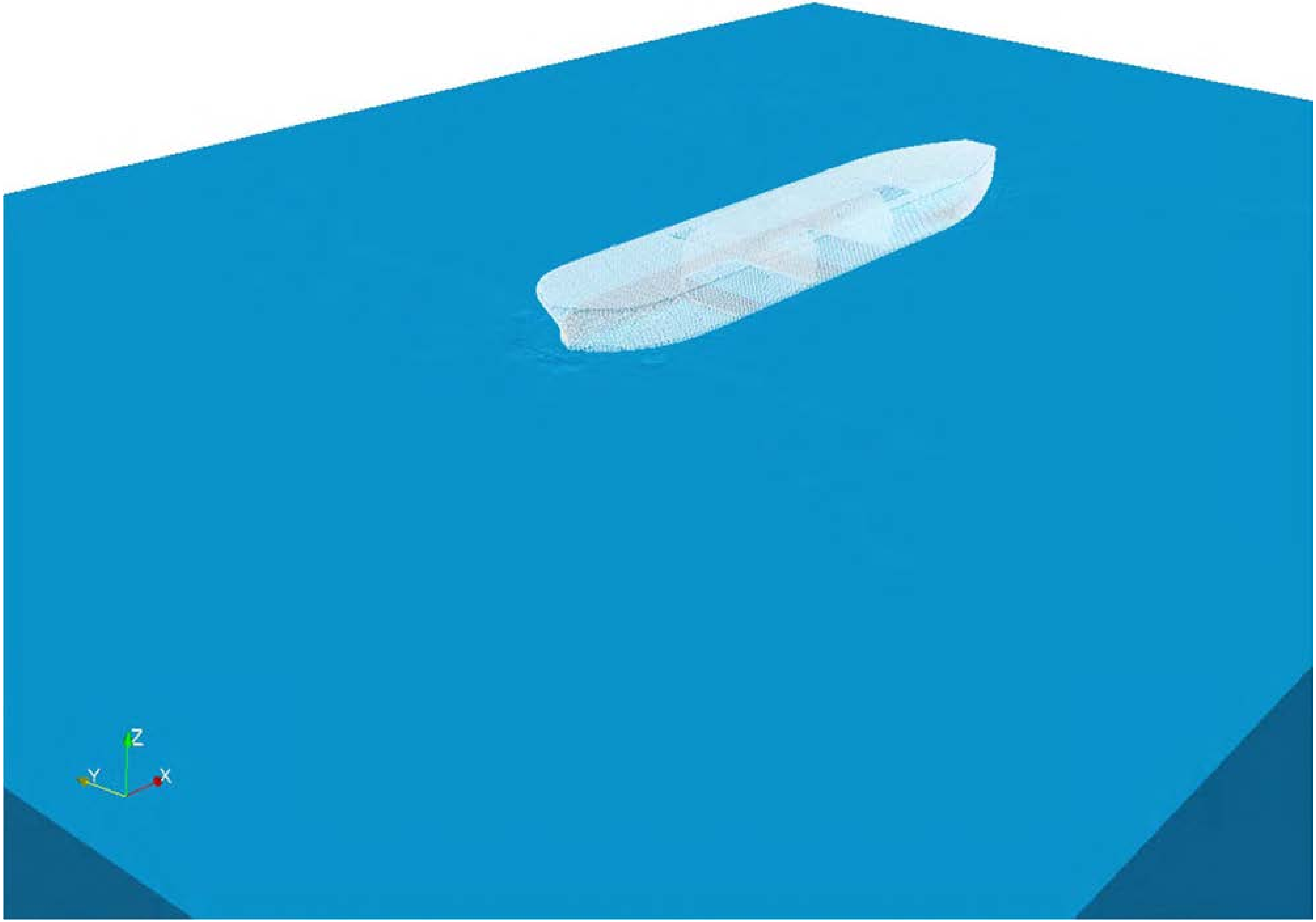


(b) beam wave


naoeFoam-SJTU



z
y
x
naoeFoam-SJTU



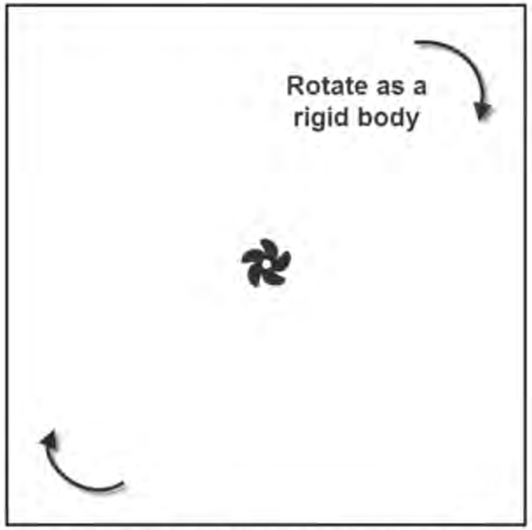
Z
Y
X

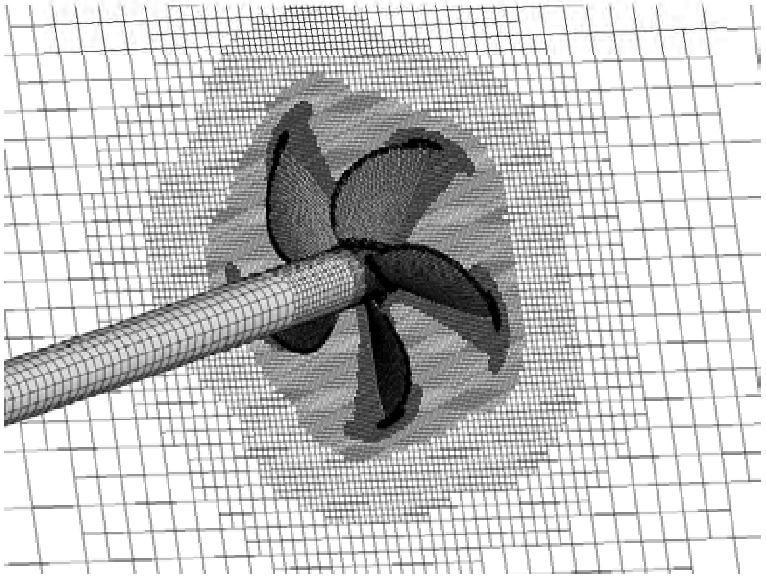
Propeller Flows and

Self-Propulsion of Ship Motion

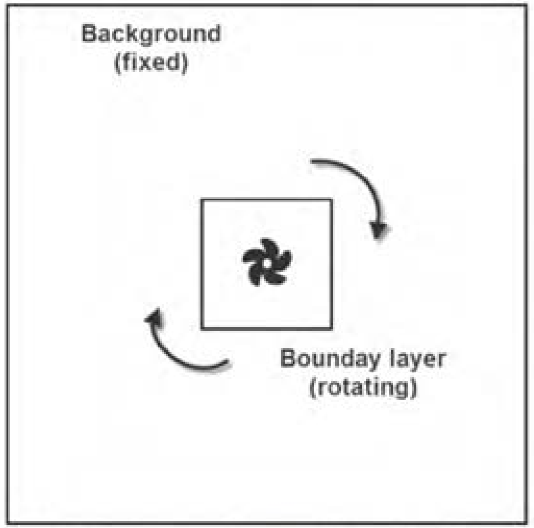
敞水计算

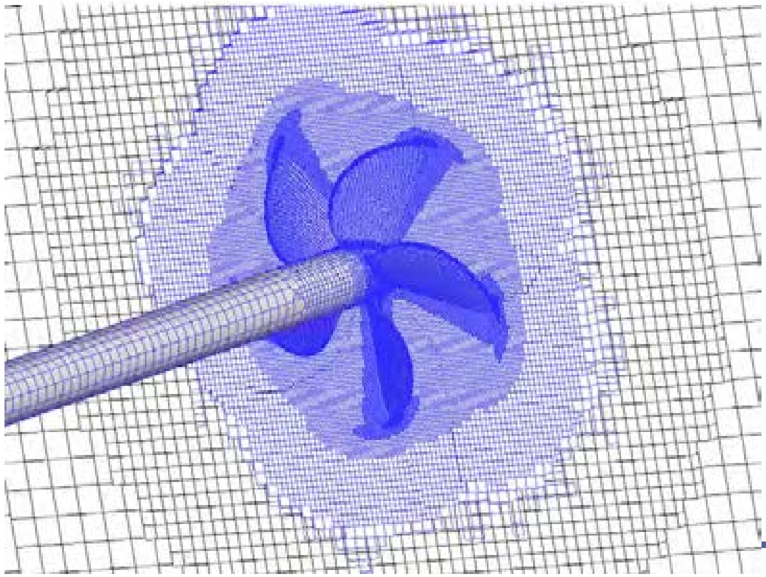
非重叠网格



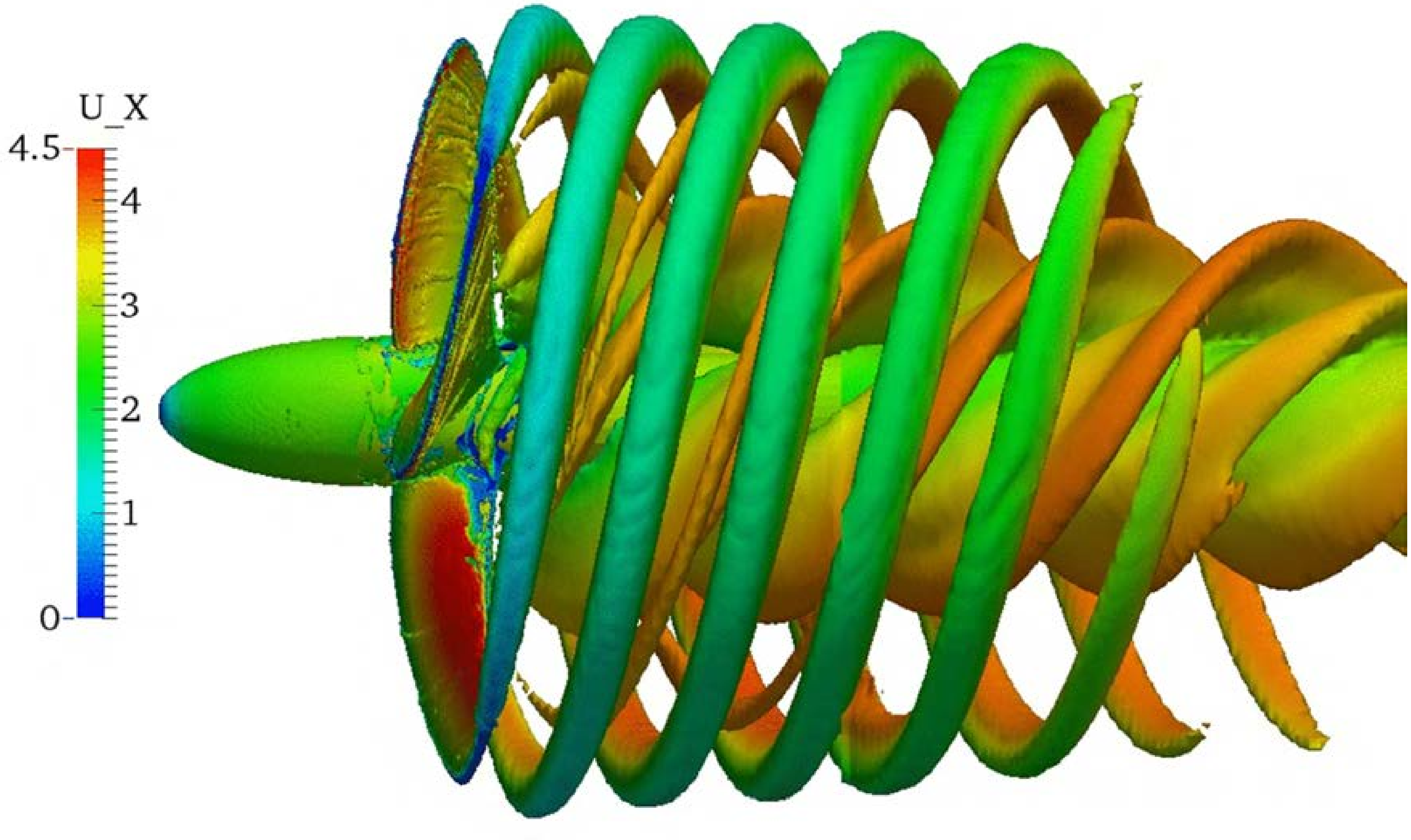


重叠网格

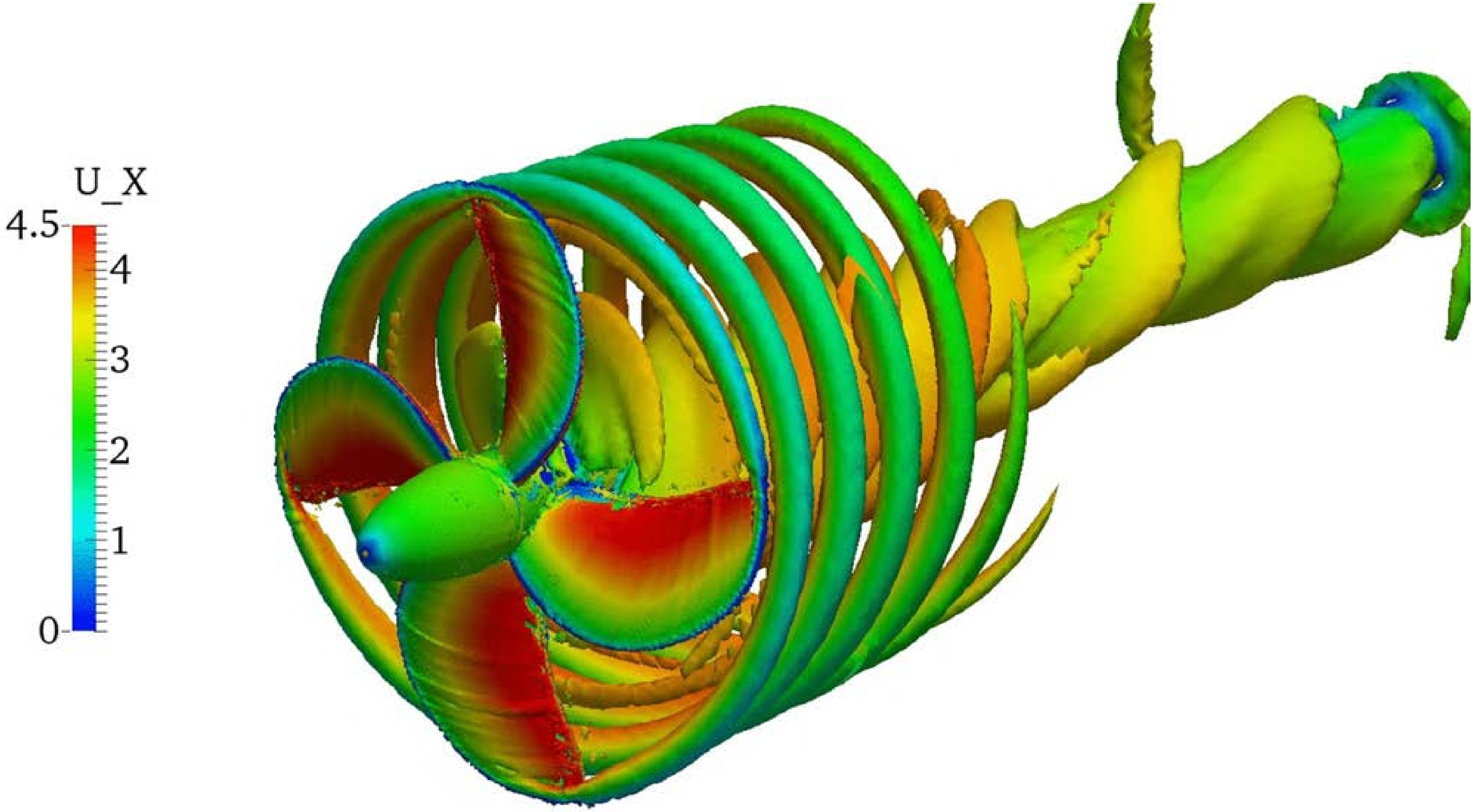


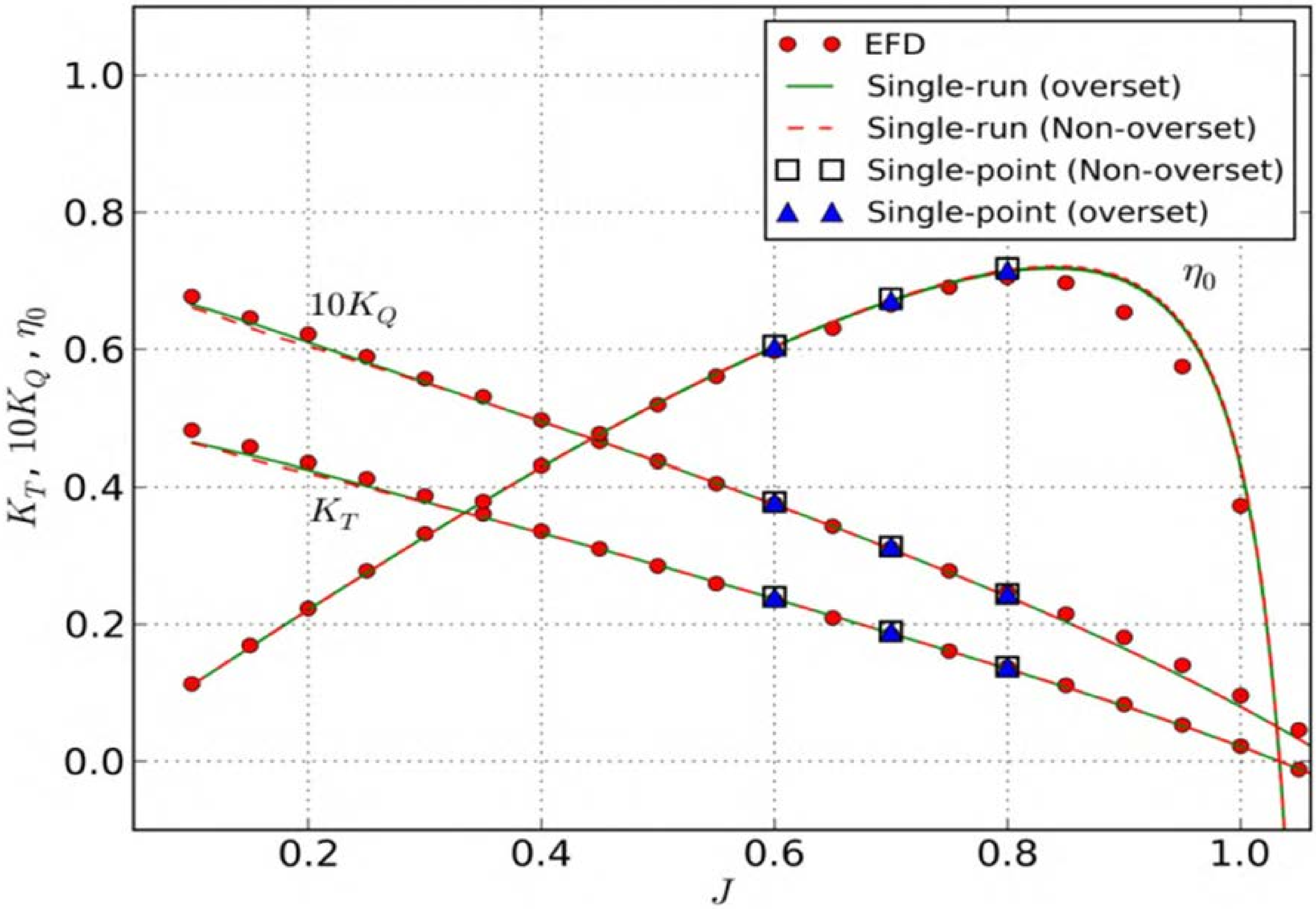


Rotating Propeller in Open Water

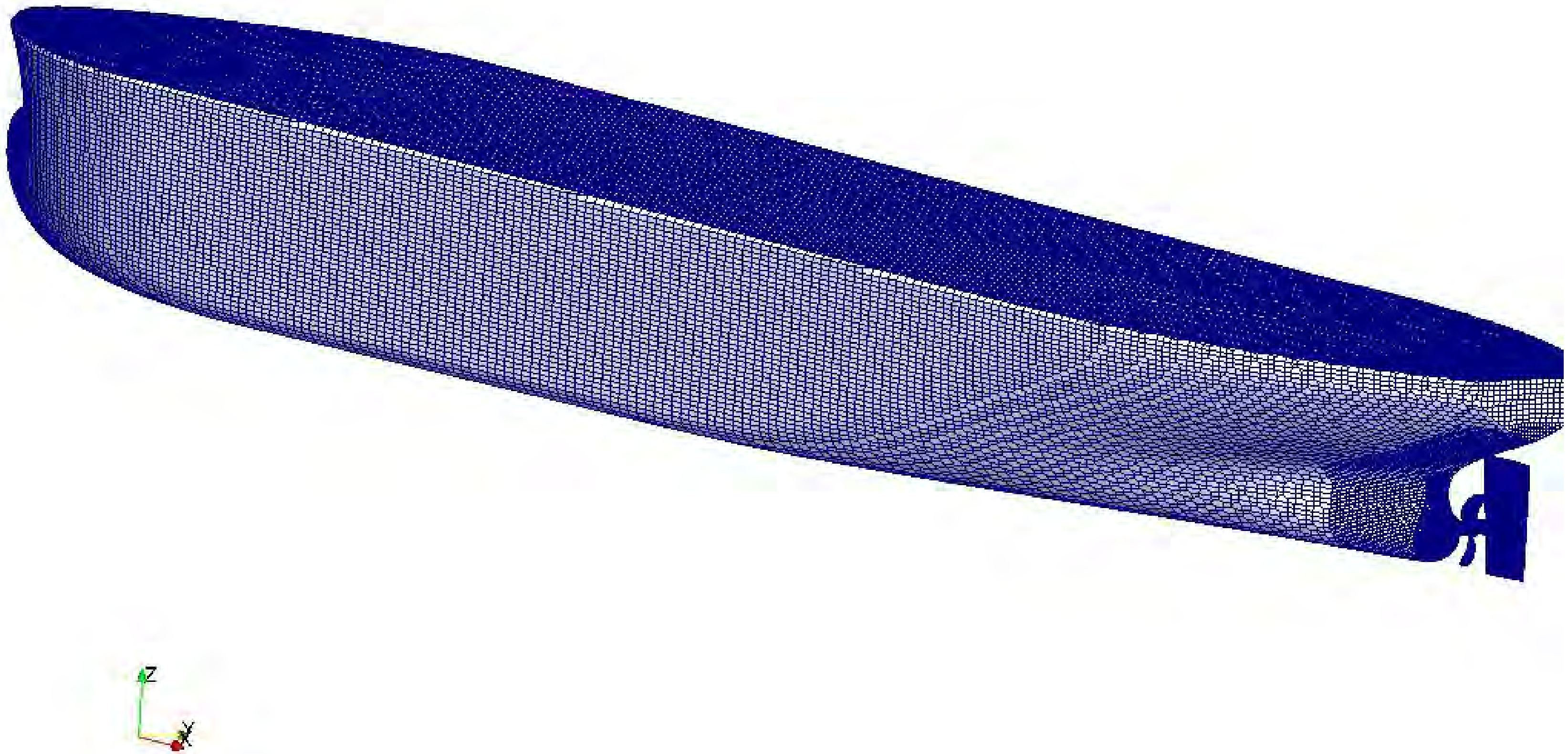


Rotating Propeller in Open Water

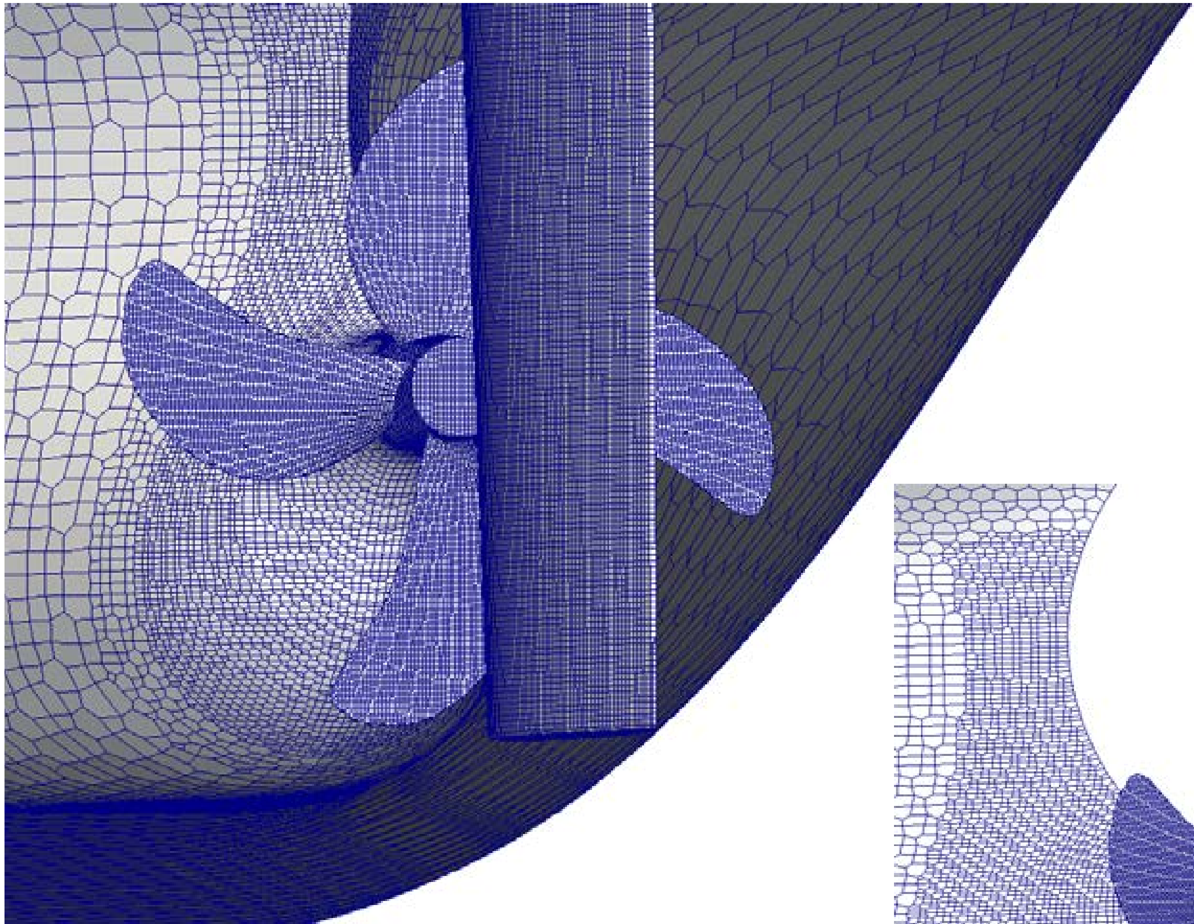


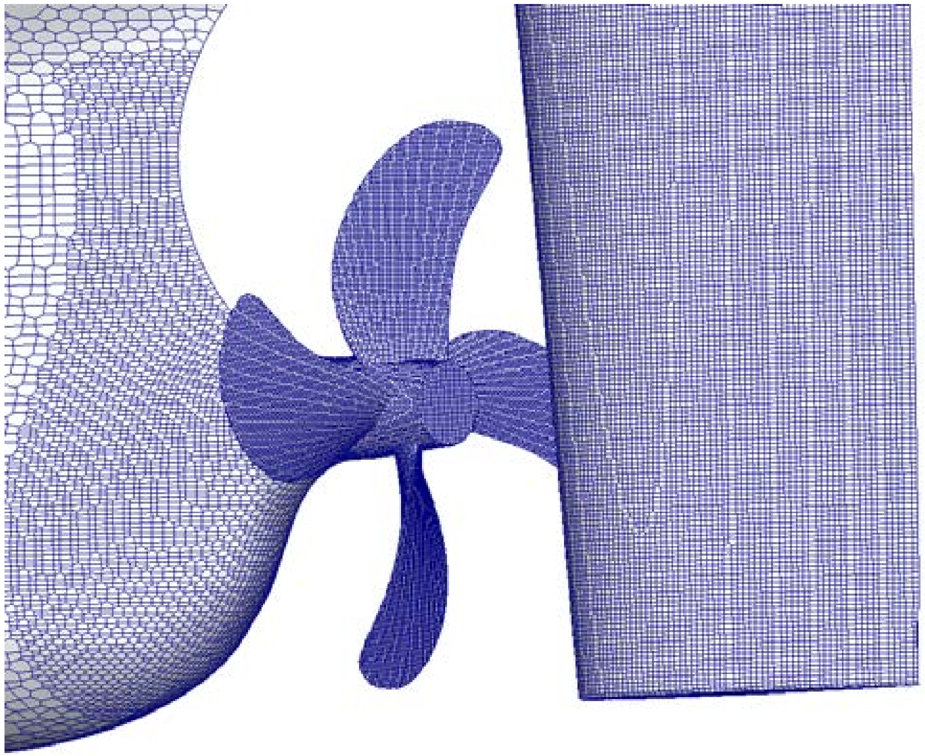

EFD
Single-run (overset)
Single-run (Non-overset)
Single-point (Non-overset)
Single-point (overset)
$10K_Q$
K_T
η_0
K_T, $10K_Q$, η_0
J
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0

Self-Propulsion of Ship Motion

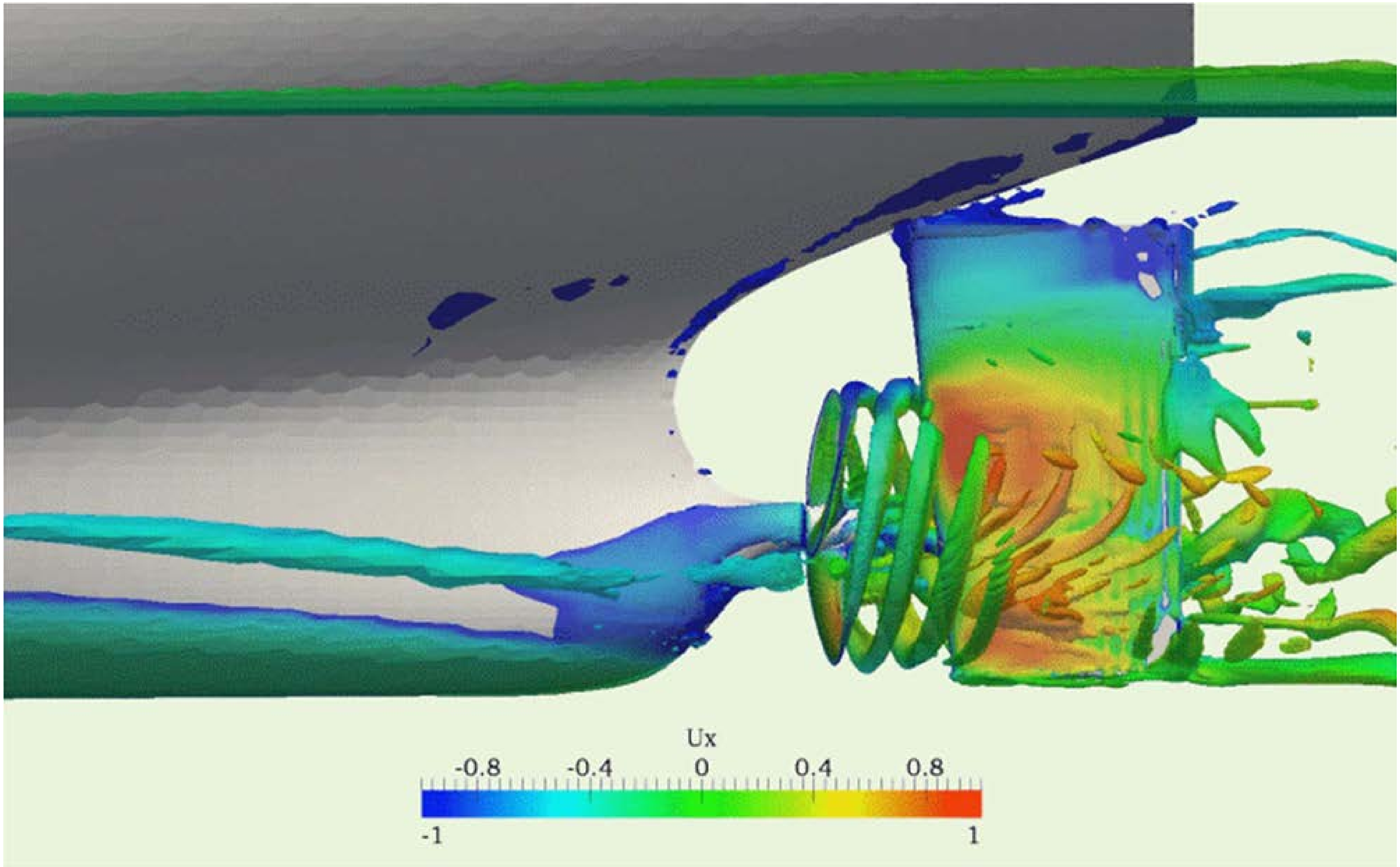


Self-Propulsion of Ship Motion





Self-Propulsion of Ship Motion



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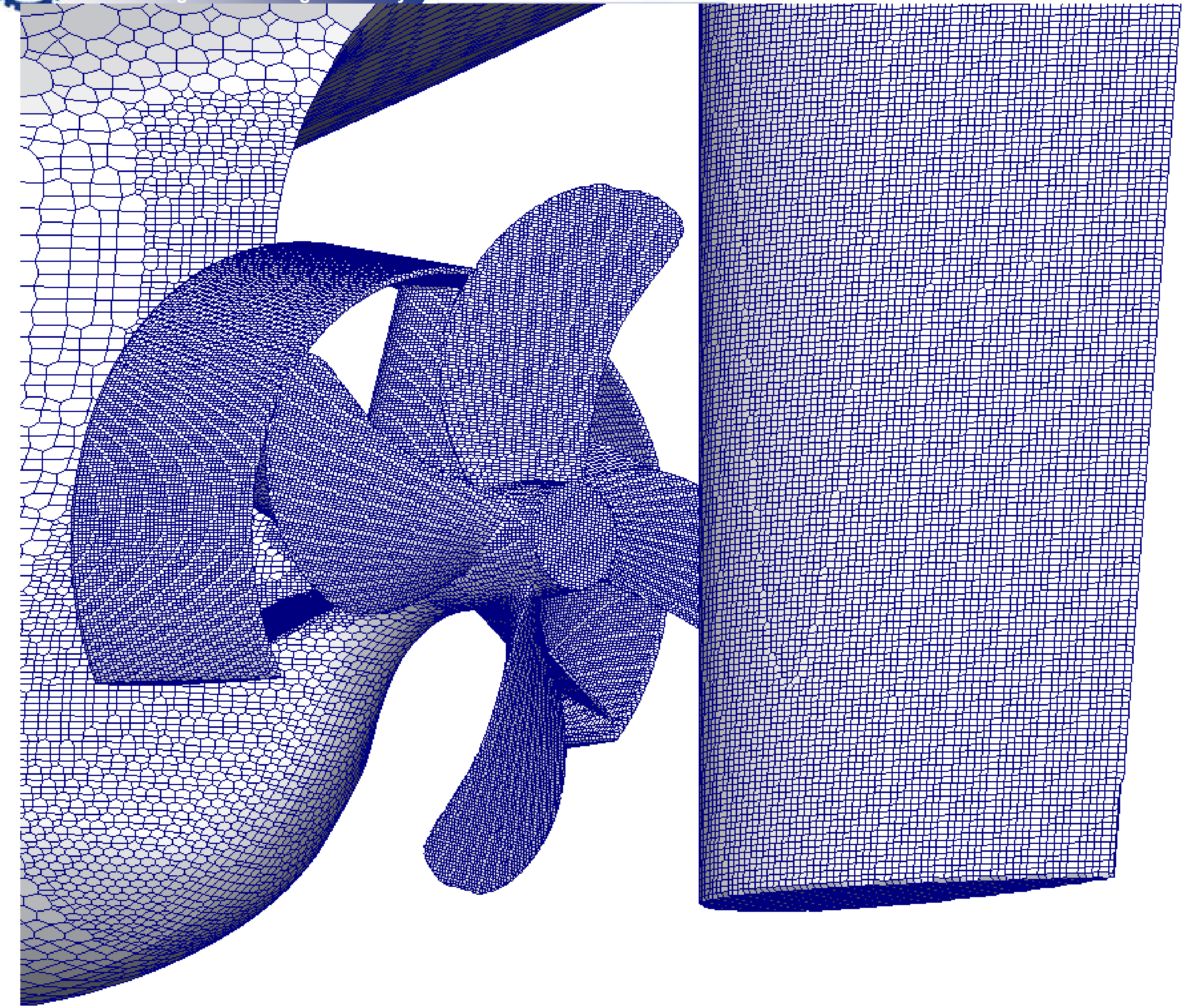
Self-Propulsion of Ship Motion



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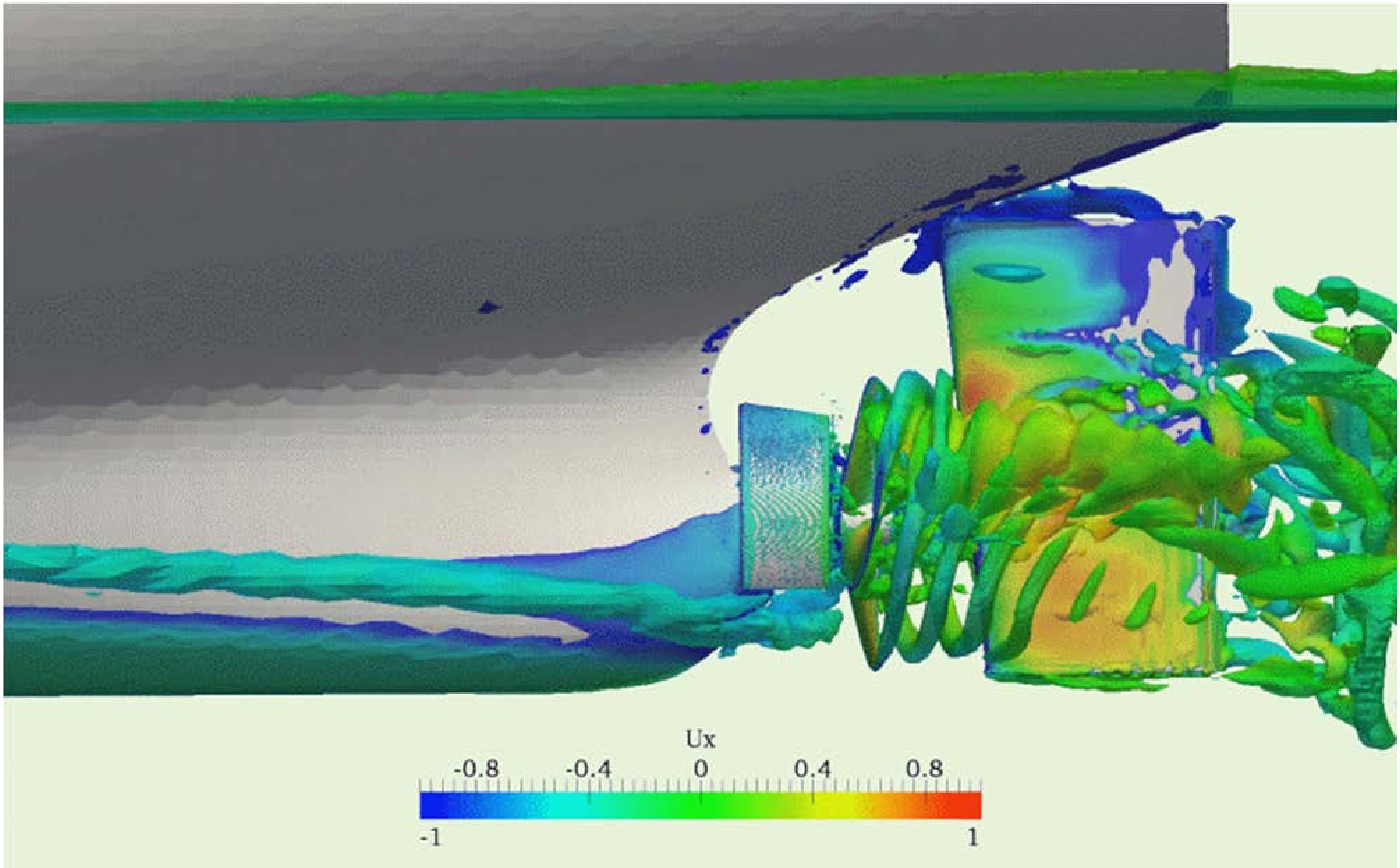
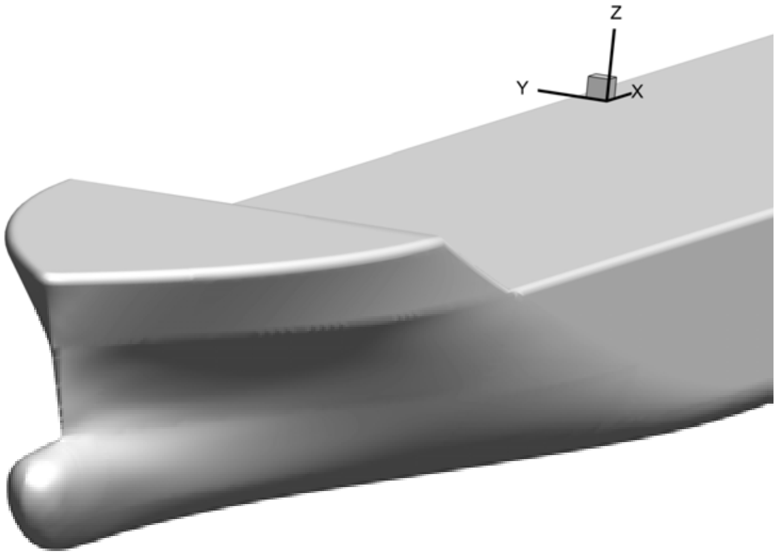
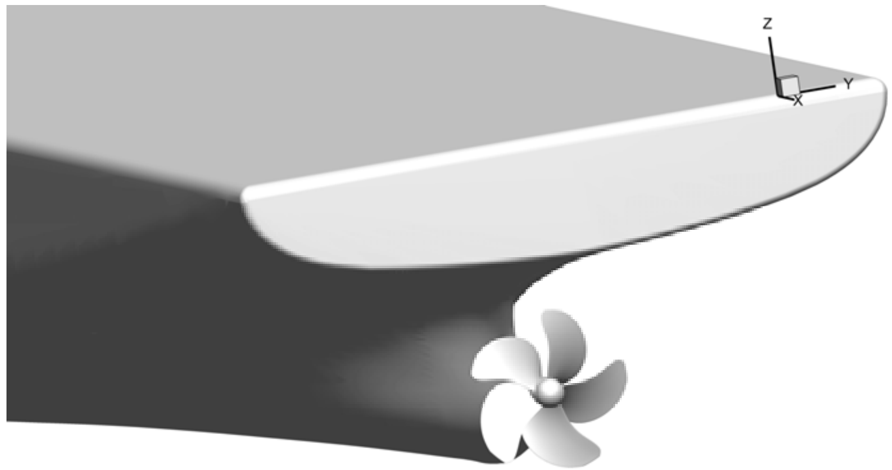
Self-Propulsion of Ship Motion

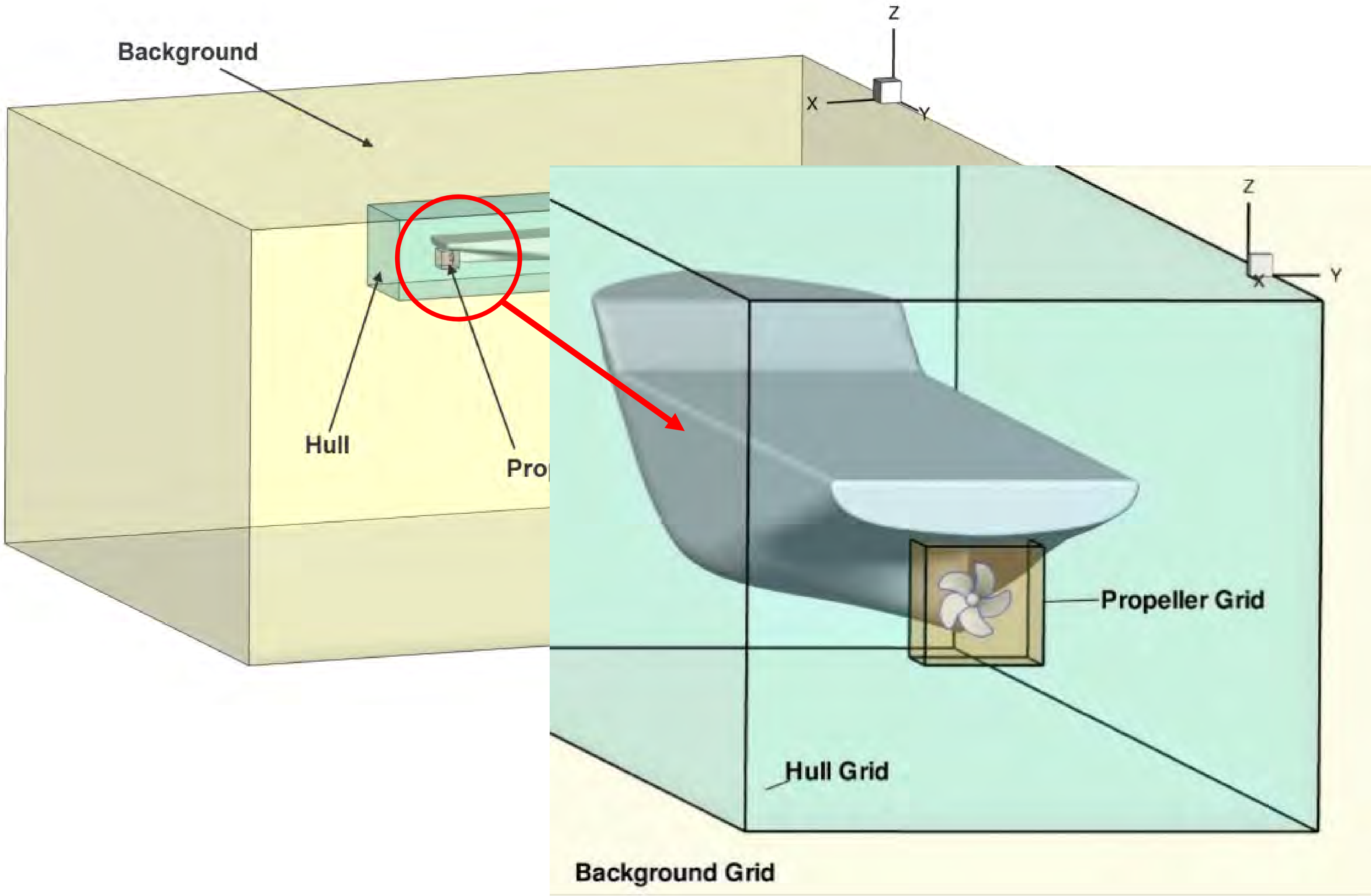


HSVA KCS Model

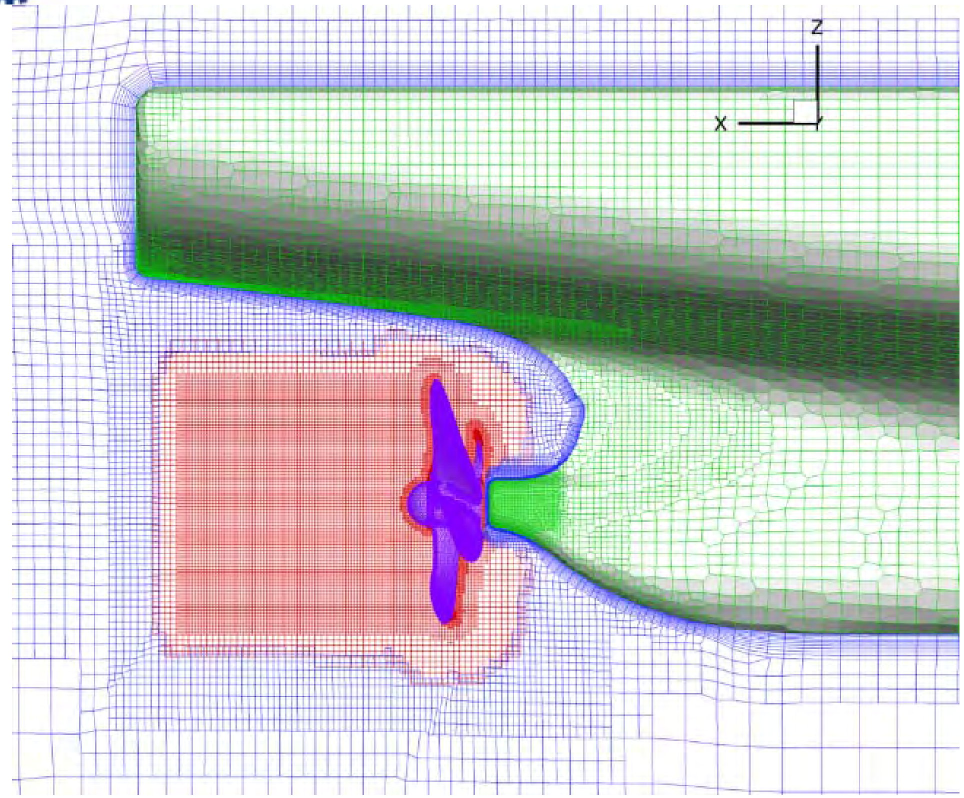


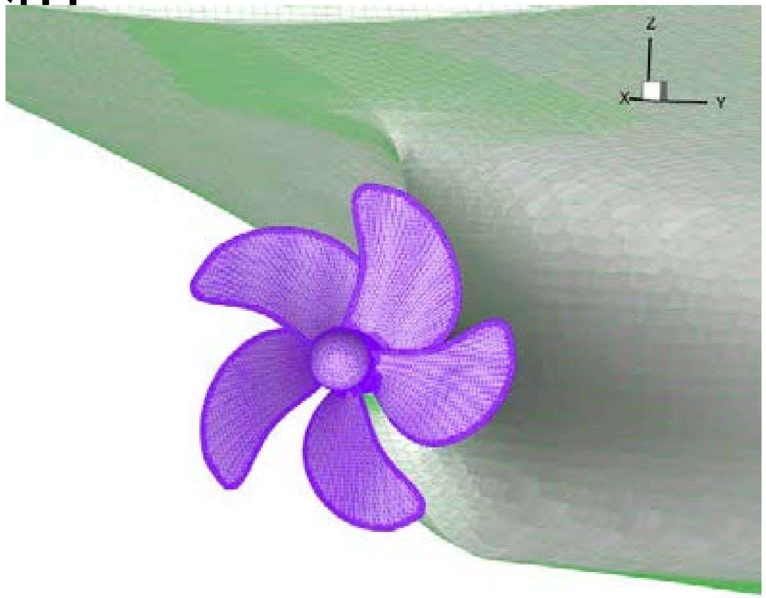


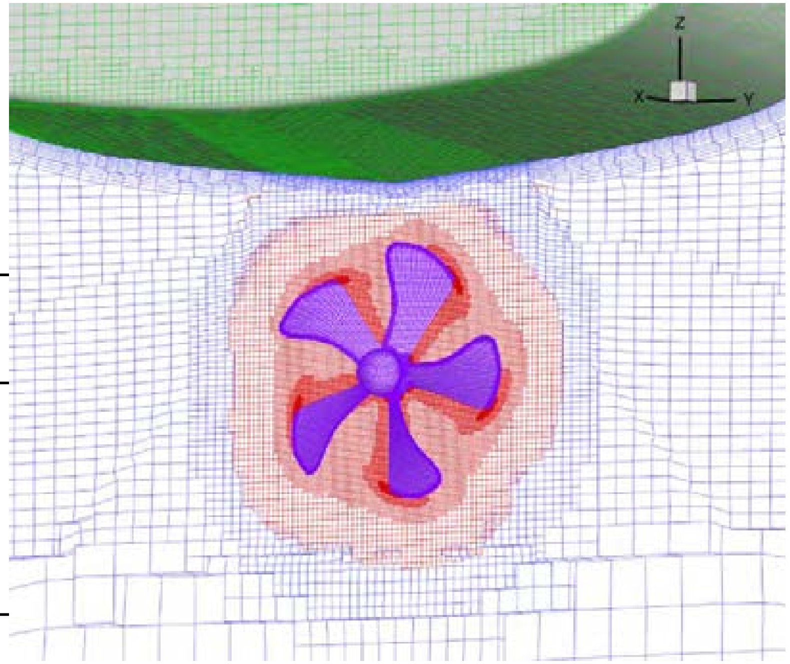
自航计算（有螺旋桨）


Background
Hull
Pro
Z
X
Y
Z
Y
X
Propeller Grid
Hull Grid
Background Grid

网格







网格	船体	背景	螺旋桨	总数
拖航	0.959 M	0.716 M	-	1.68 M
自航	1.129 M	0.716 M	1.368 M	3.21 M

KCS模型的Z形操纵计算

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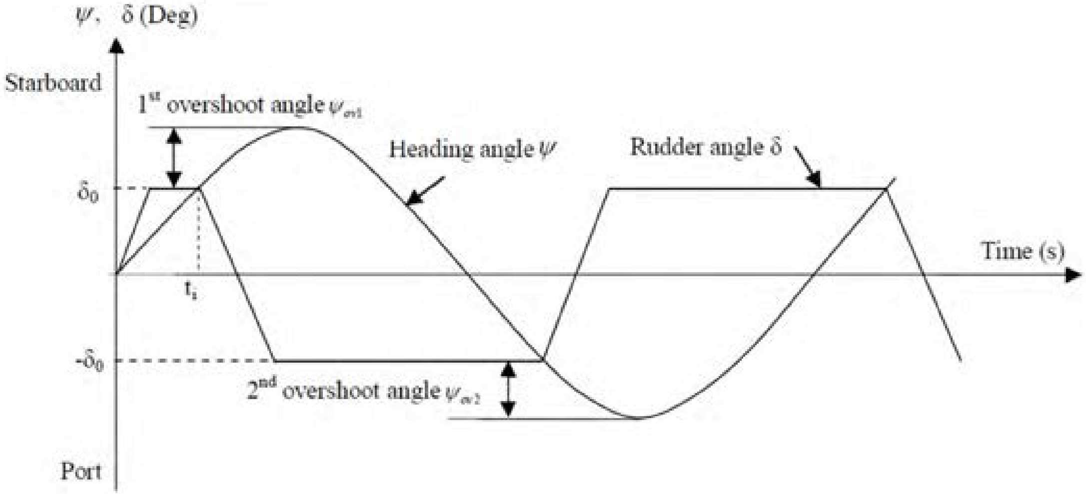
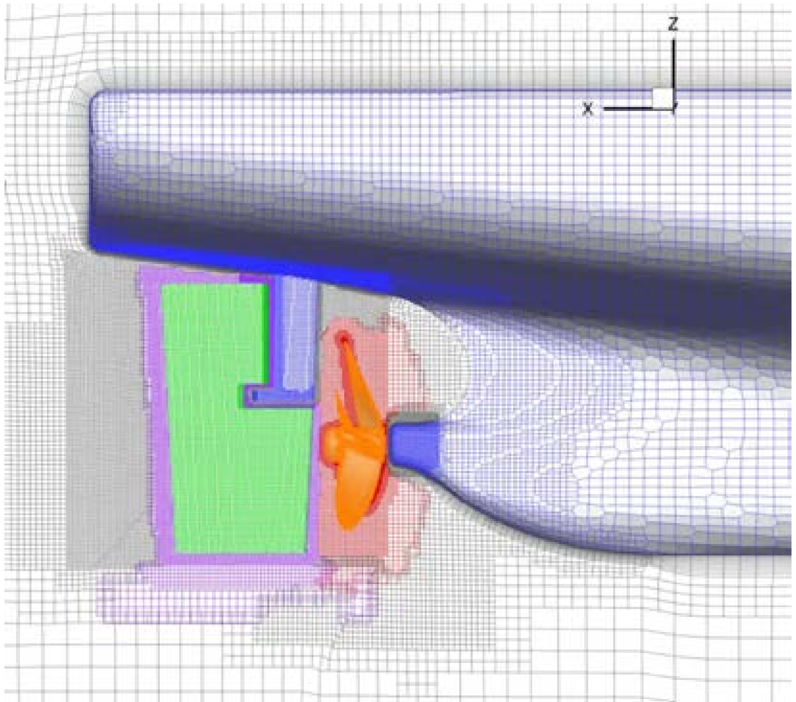
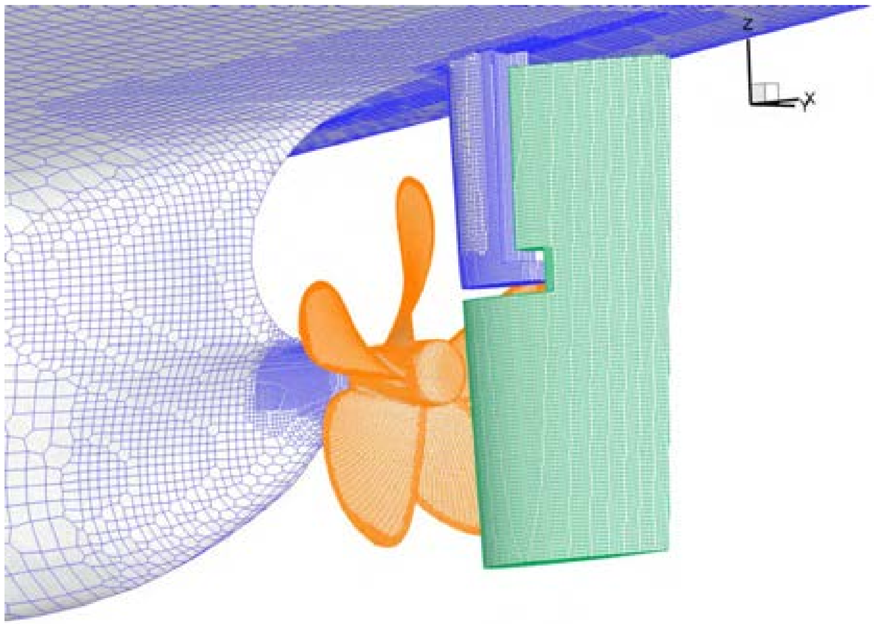
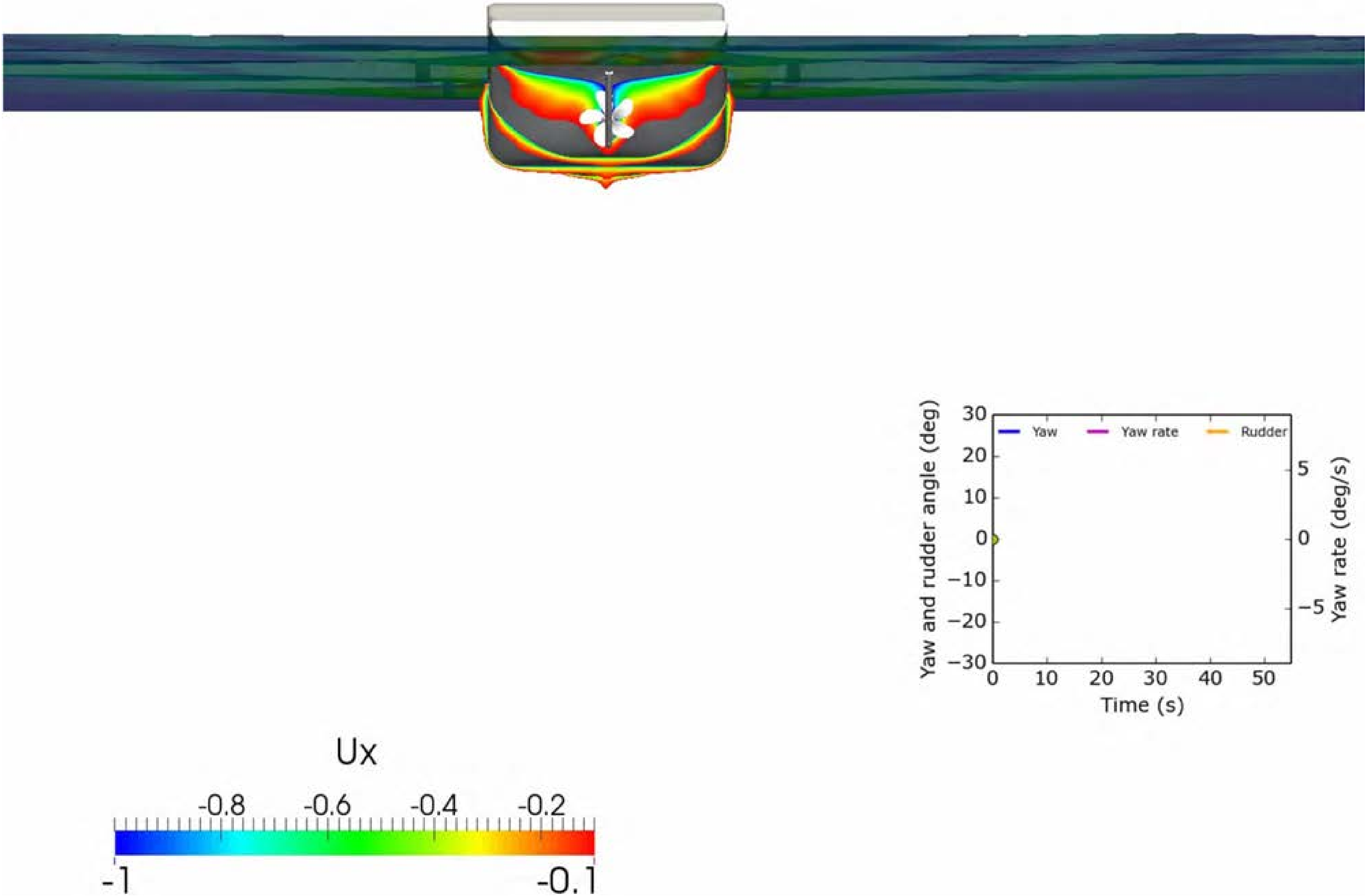






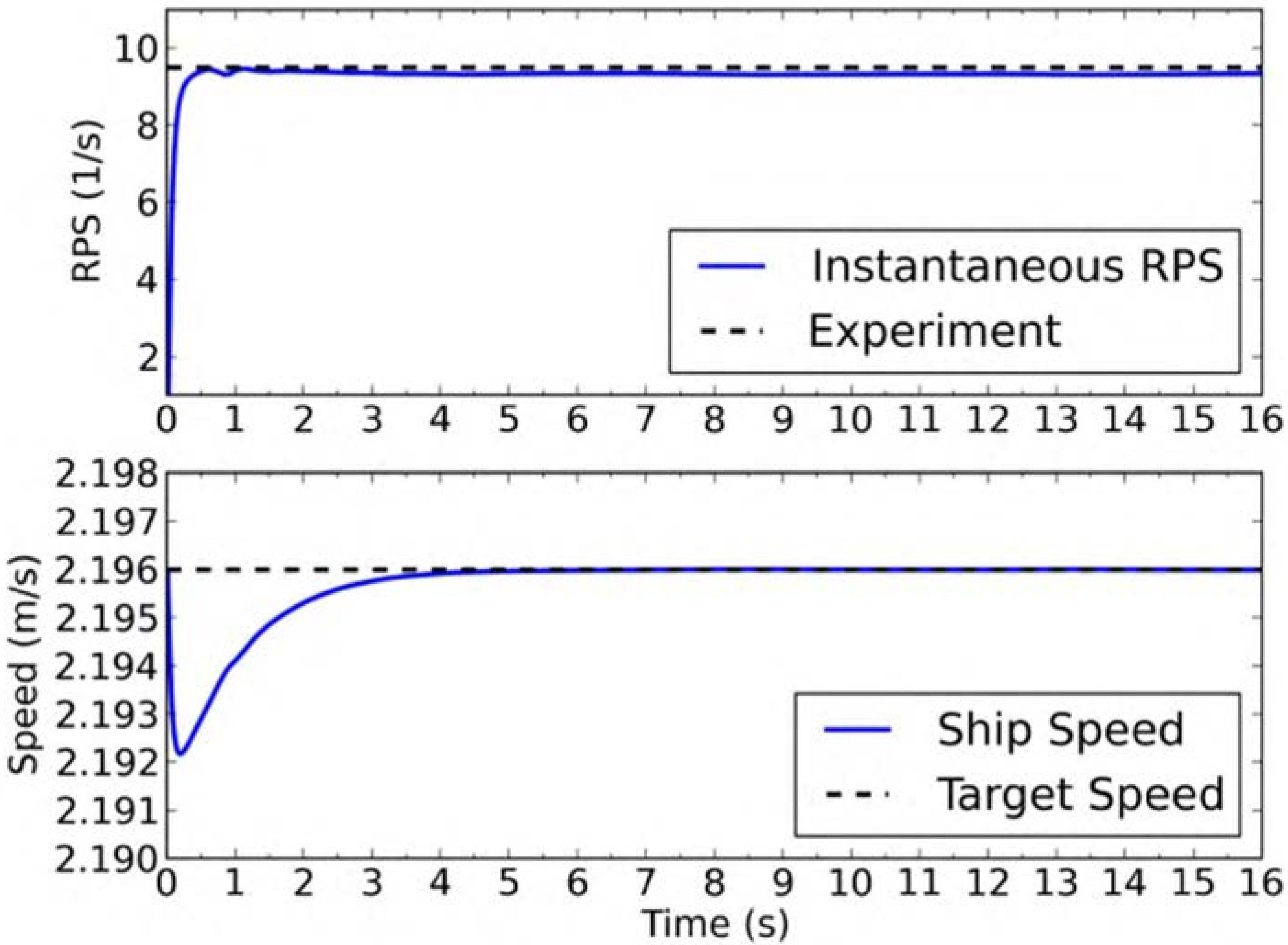


Yaw
Yaw rate
Rudder
Yaw and rudder angle (deg)
30
20
10
0
−10
−20
−30
5
0
−5
Yaw rate (deg/s)
0
10
20
30
40
50
Time (s)
Ux
-0.8
-0.6
-0.4
-0.2
-1
-0.1

Self-Propulsion of Ship Motion

Propeller speed

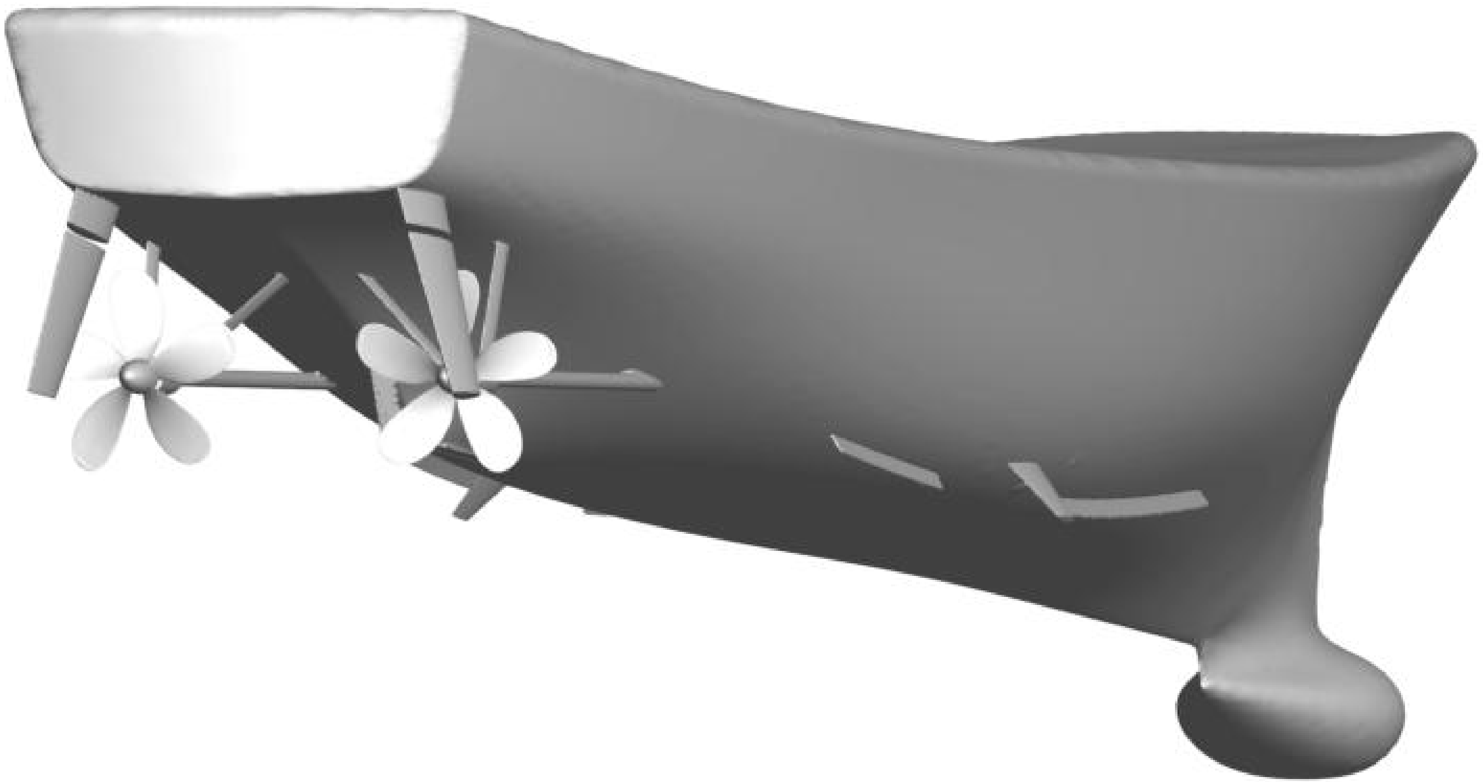
Ship speed

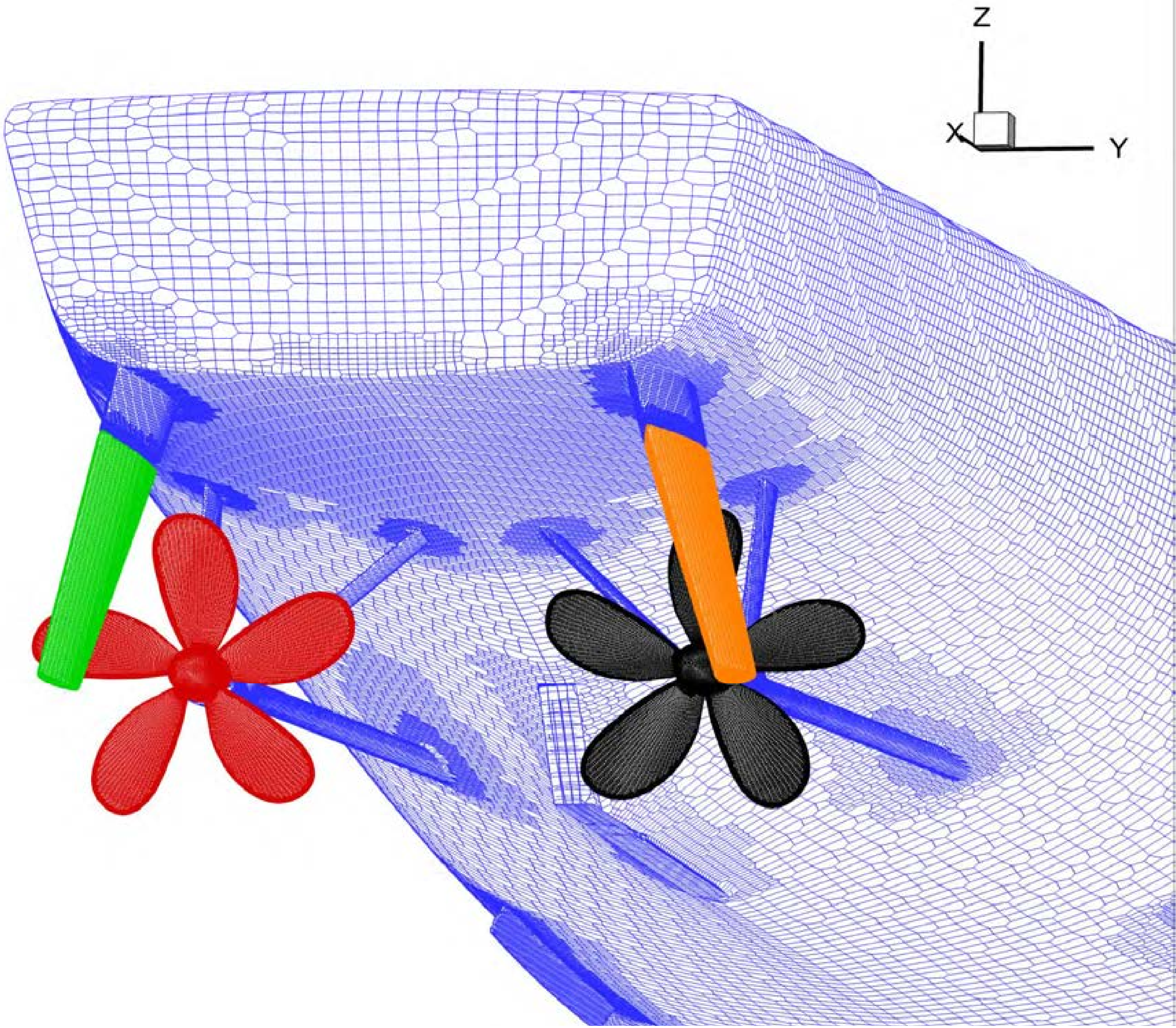


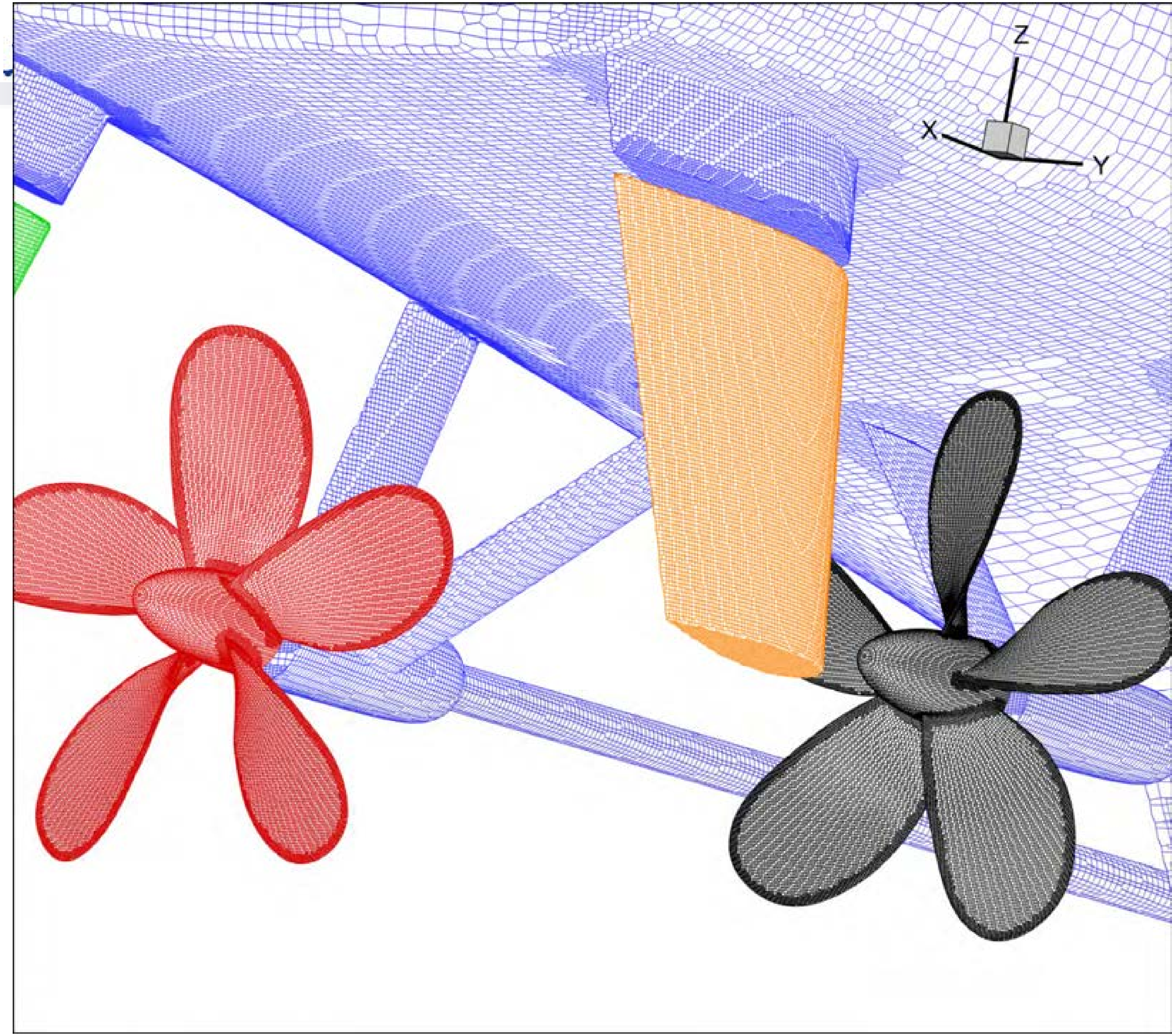
Self-Propulsion of Ship Motion

	Experiment	Present Work	% error	CFDShip-Iowa (DES)
C_T	3.942×10^{-3}	3.840×10^{-3}	-2.586%	4.011×10^{-3}
K_T	0.17	0.1682	-1.061%	0.1689
K_Q	0.0288	0.0290	0.863%	0.02961
$1-t$	0.853	0.8857	3.838%	0.8725
$1-W_t$	0.792	0.7815	-1.326%	0.803
η_o	0.682	0.6785	-0.507%	0.683
η_R	1.011	0.9811	-2.955%	0.976
J	0.728	0.7363	1.142%	0.733
n	9.5	9.3231	-1.862%	9.62
η	0.74	0.7545	1.963%	0.724

Self-Propulsion of Ship Motion

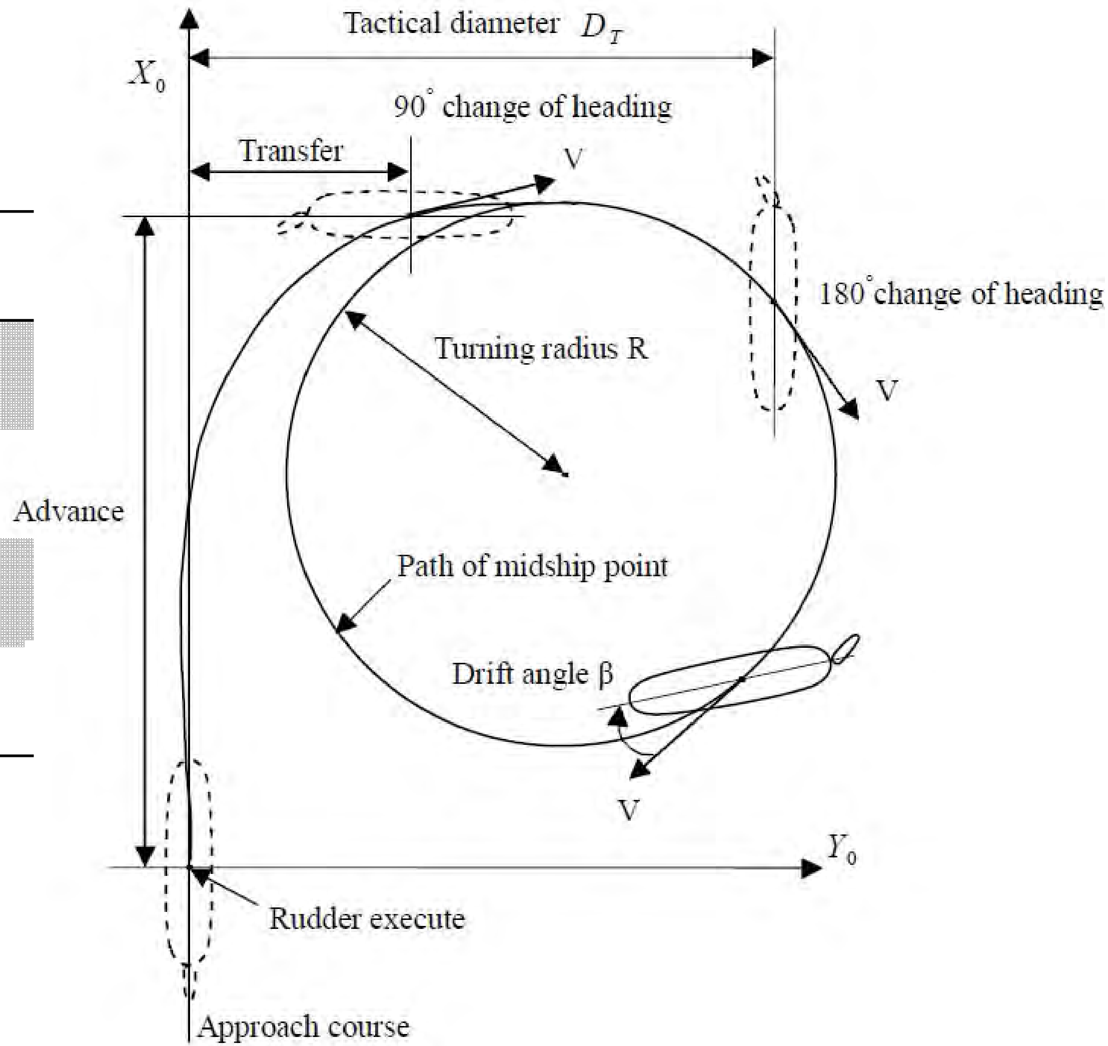


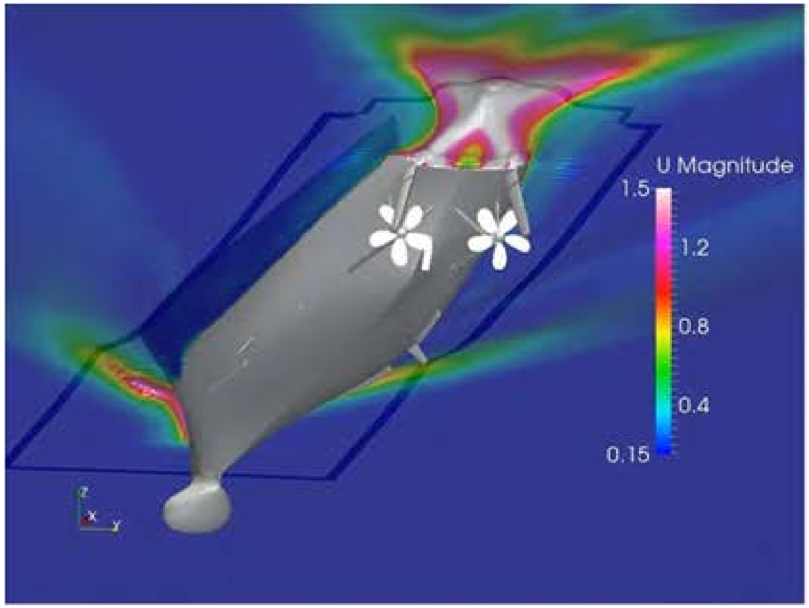

Z
X
Y

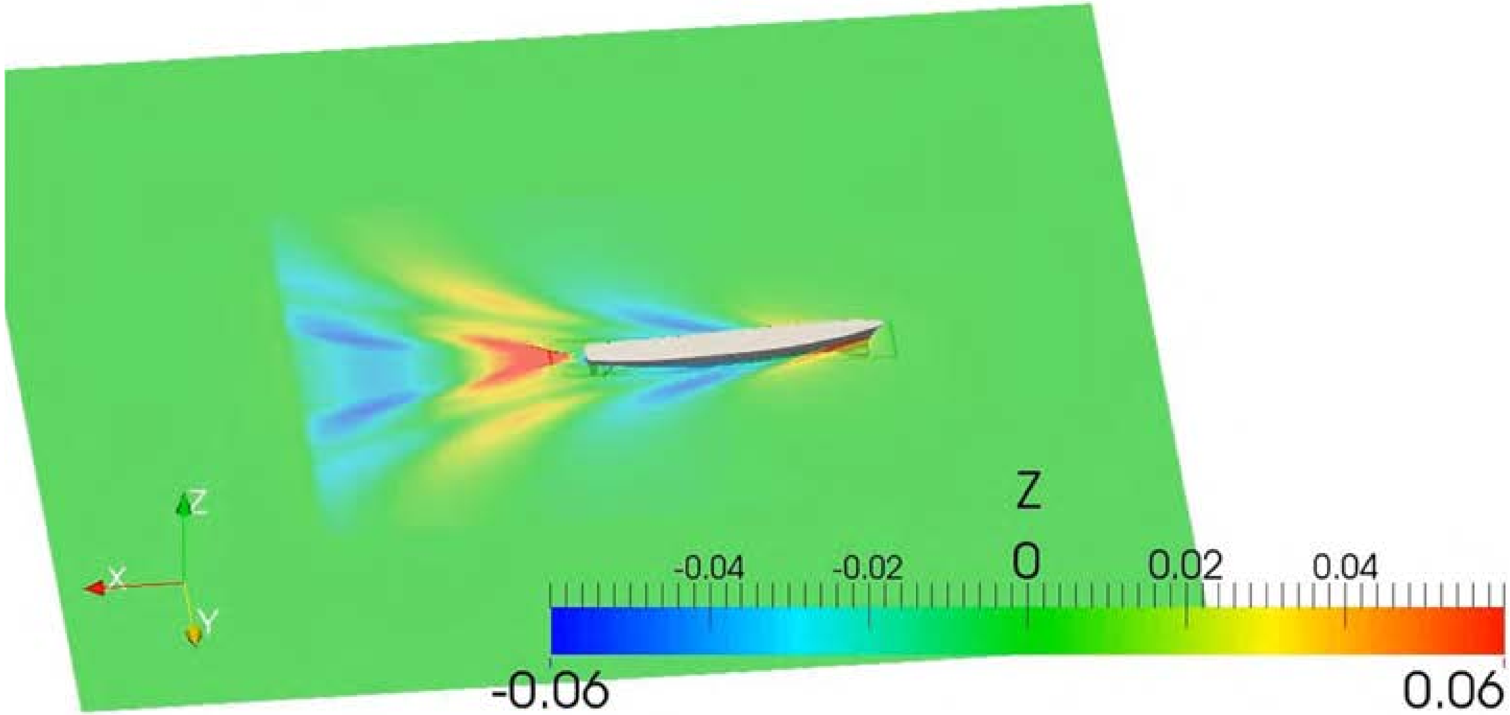

Z
X
Y

回转运动

工况	35° 舵角回转
航速	2.59 m/s
最大舵角	35°
转舵速度	53.6 °/s
首次操舵方向	左舷

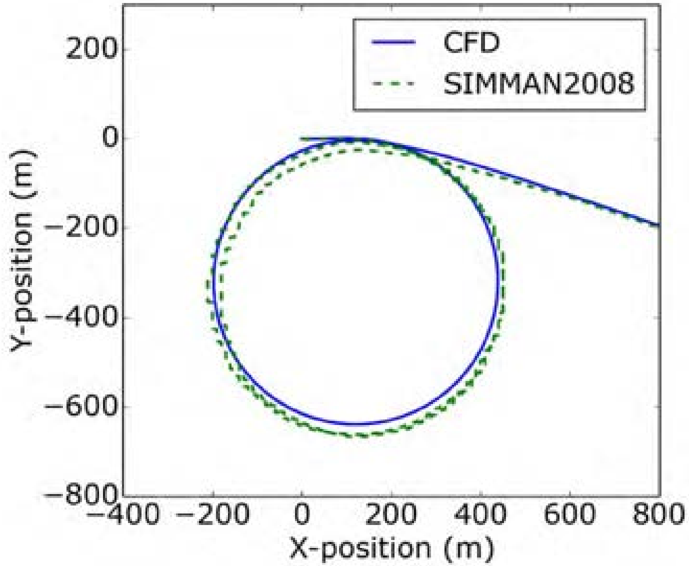



U Magnitude
1.5
1.2
0.8
0.4
0.15

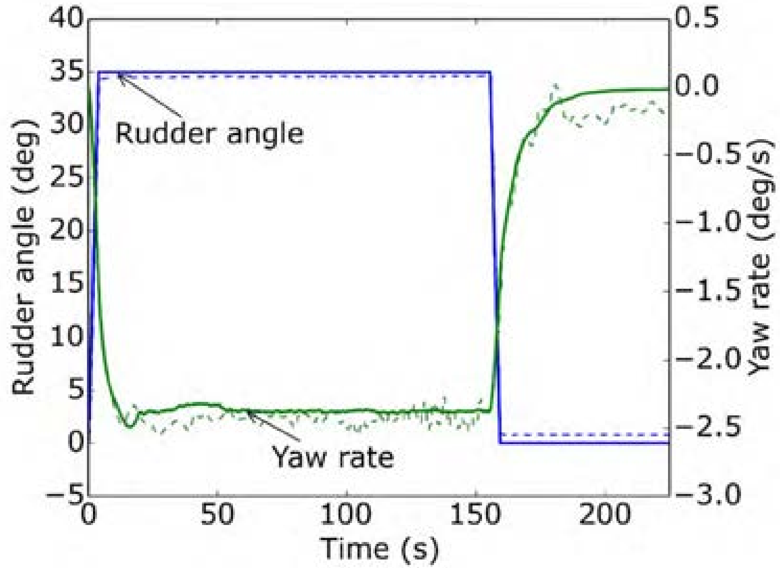

Z
-0.04
-0.02
0
0.02
0.04
-0.06
0.06

回转运动

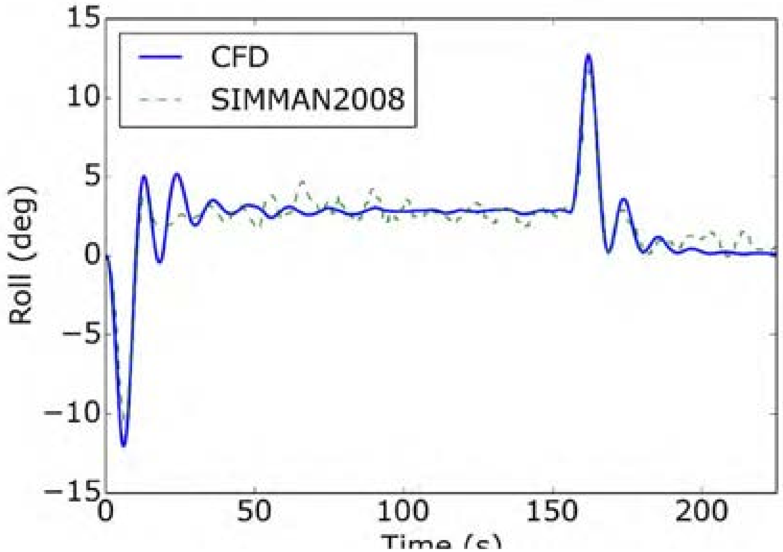
运动轨迹



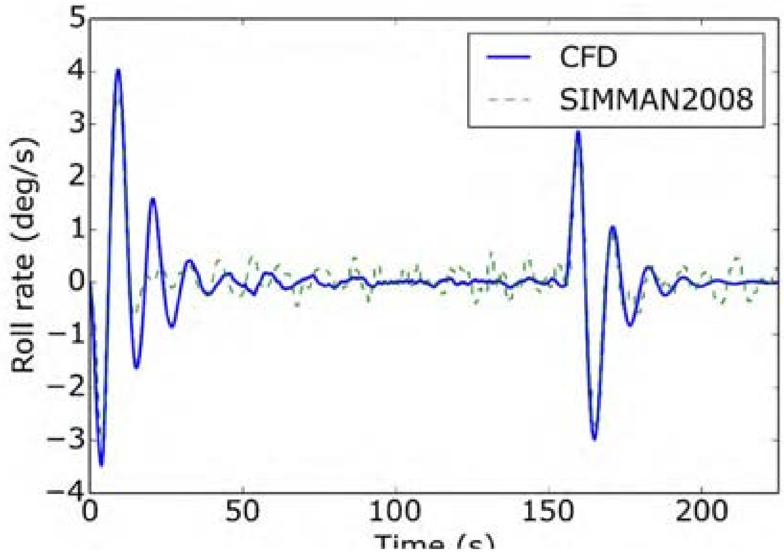
舵角、首向角



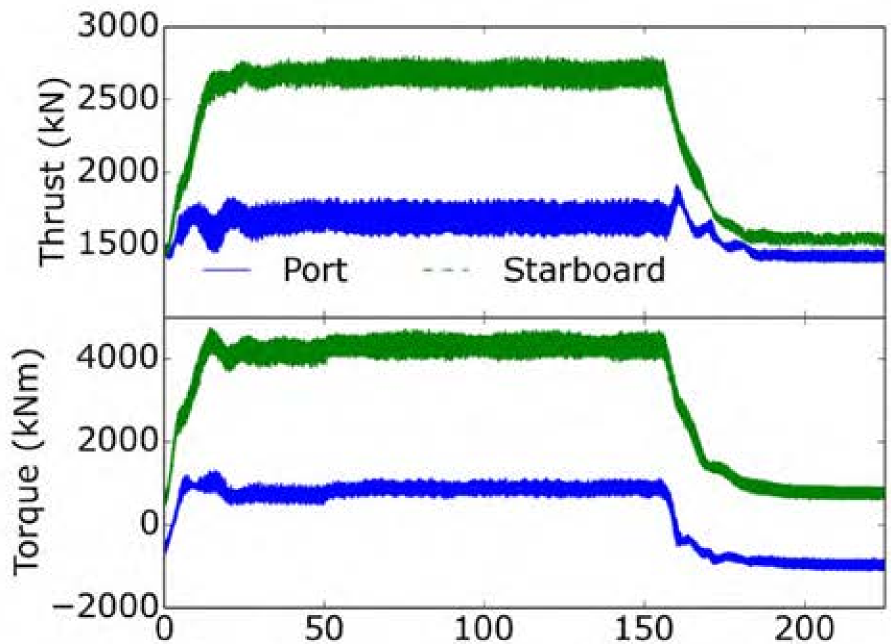
横摇角



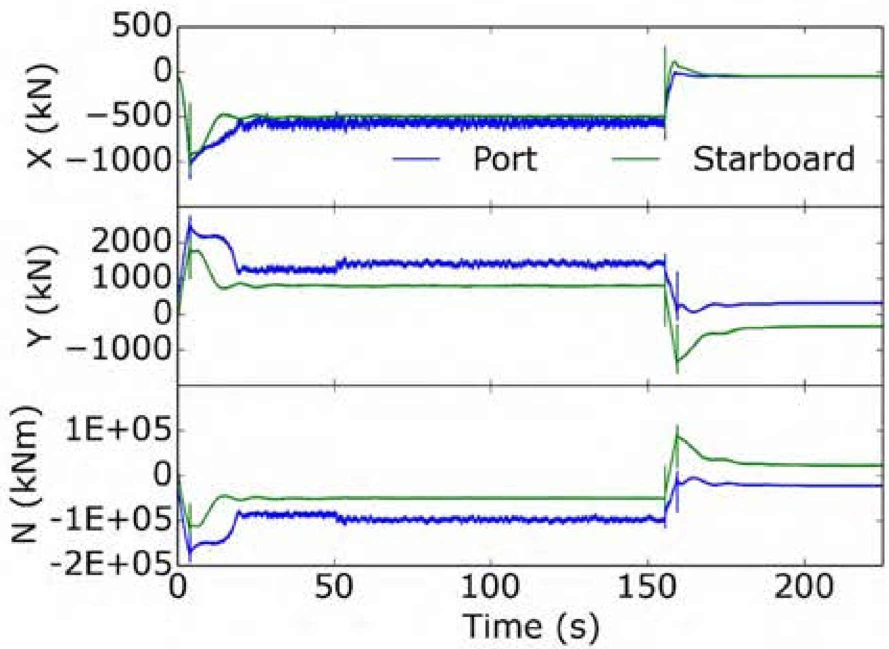
横摇角速度



回转运动



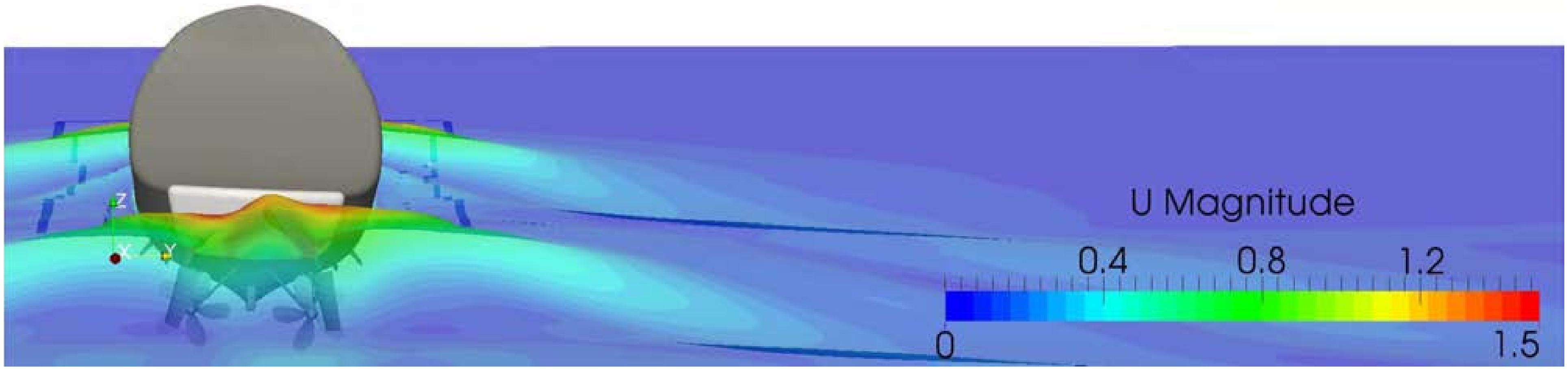
螺旋桨推力和扭矩



舵-阻力，侧向力
和转向力矩

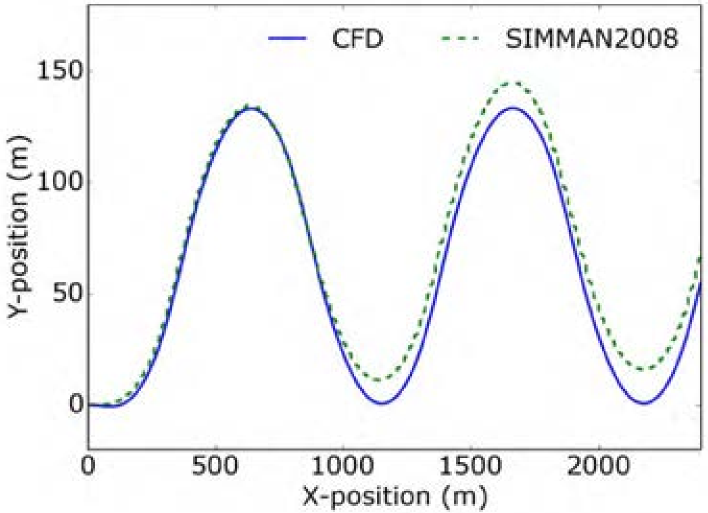
20/20 Z形操纵

工况	**20/20 Zigzag**
航速	2.59 m/s
最大舵角	20°
换舵首向角	20°
转舵速度	53.6 °/s
首次操舵方向	右舷

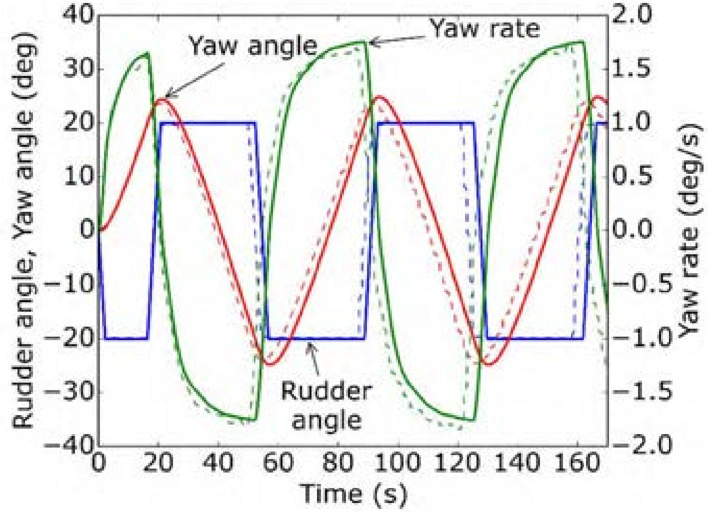


20/20 Z形操纵

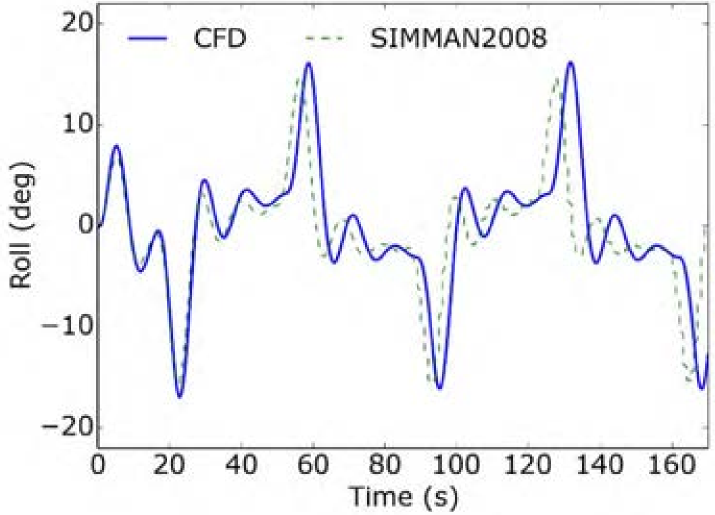
运动轨迹



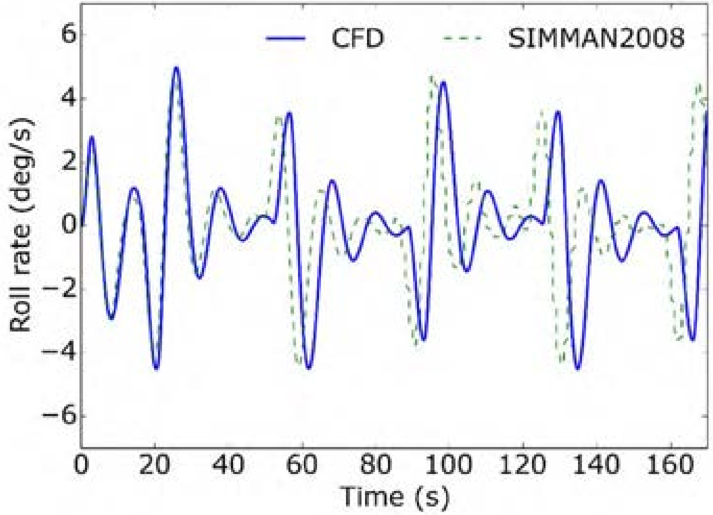
舵角、首向角



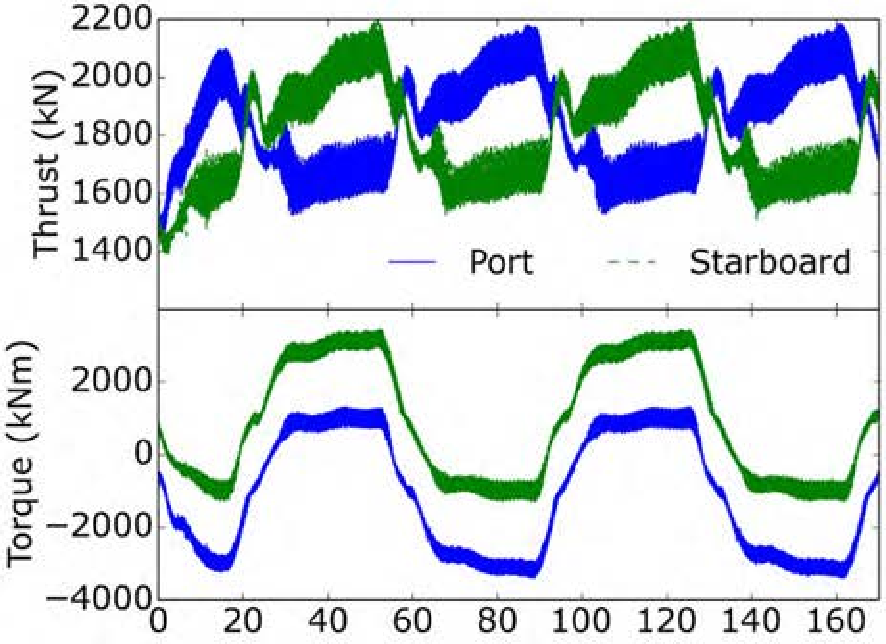
横摇角



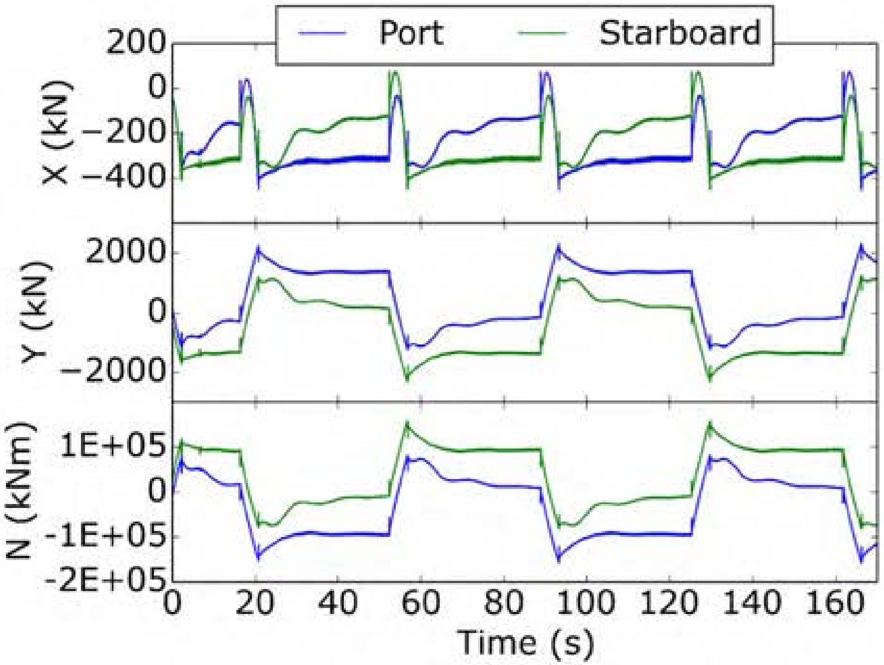
横摇角速度



20/20 Z形操纵

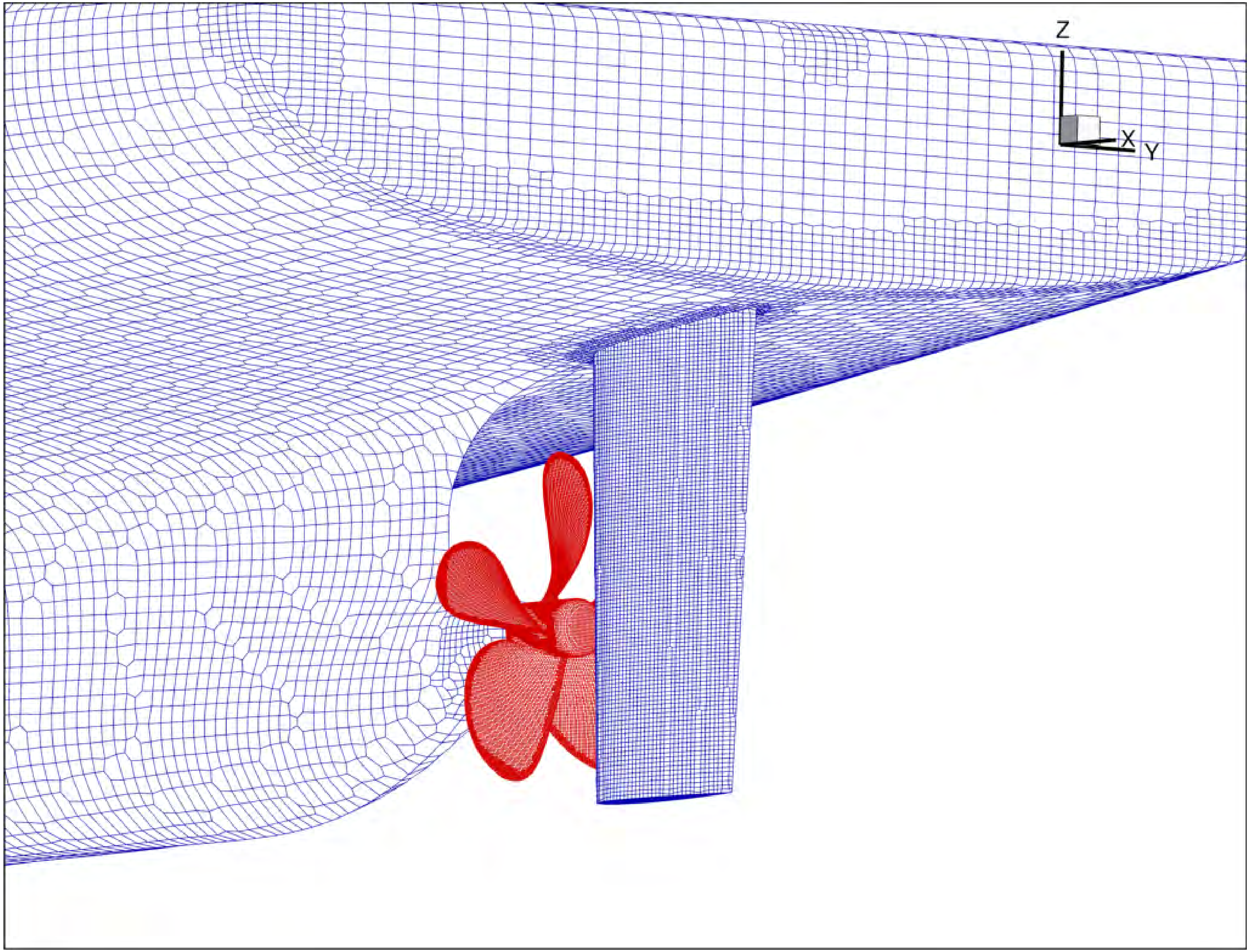


螺旋桨推力和扭矩

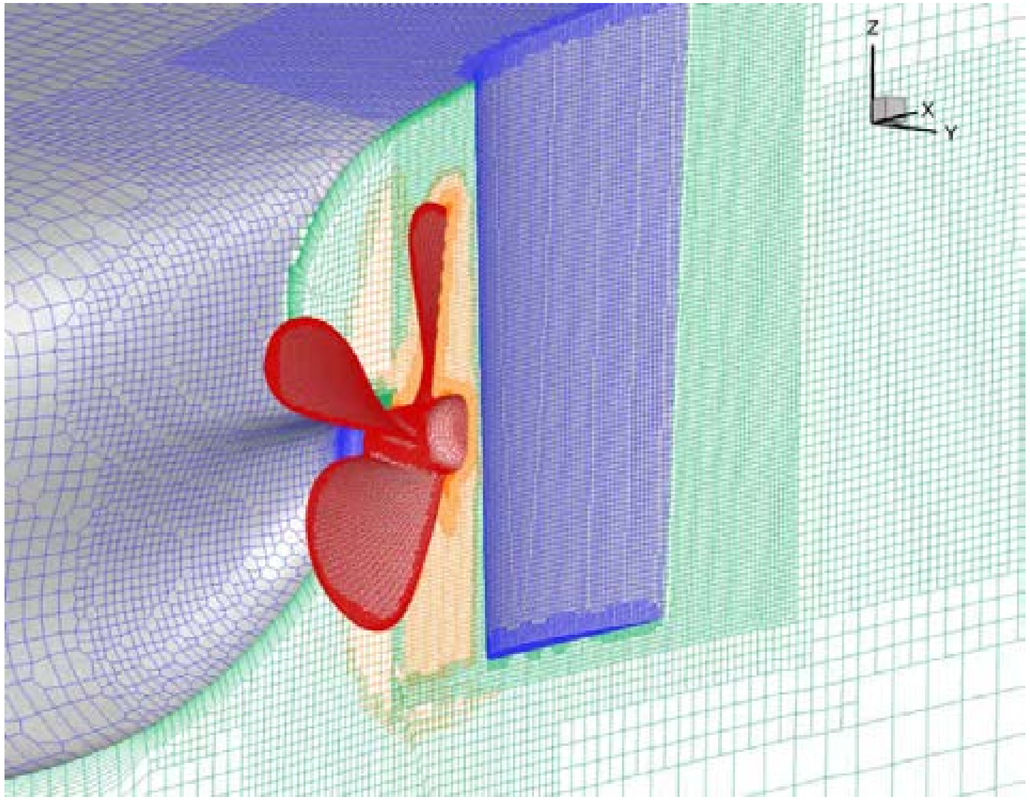


舵-阻力，侧向力
和转向力矩

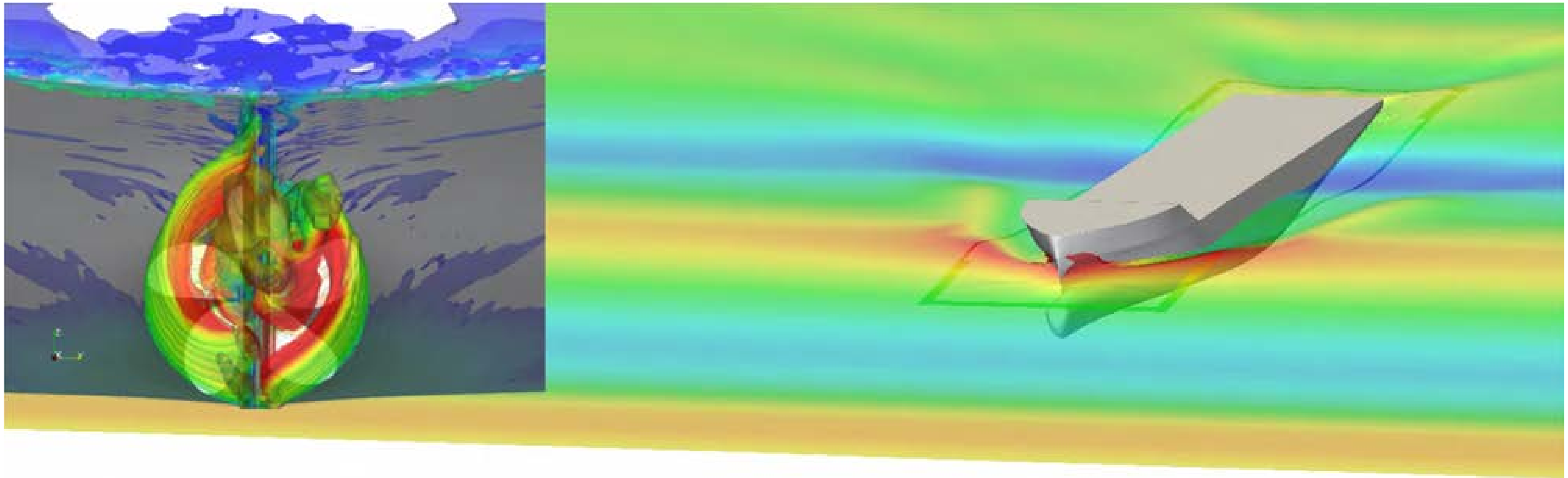
Ship self-propuslion motion in waves

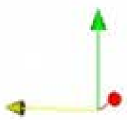


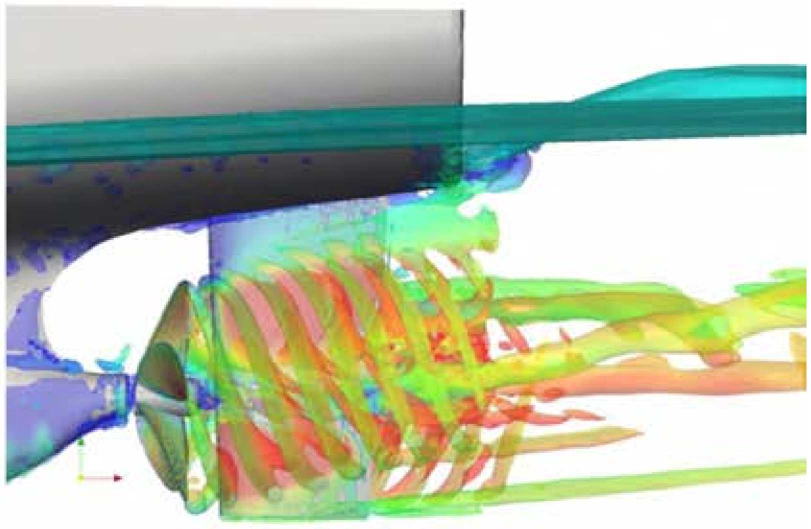
计算网格（带螺旋桨）



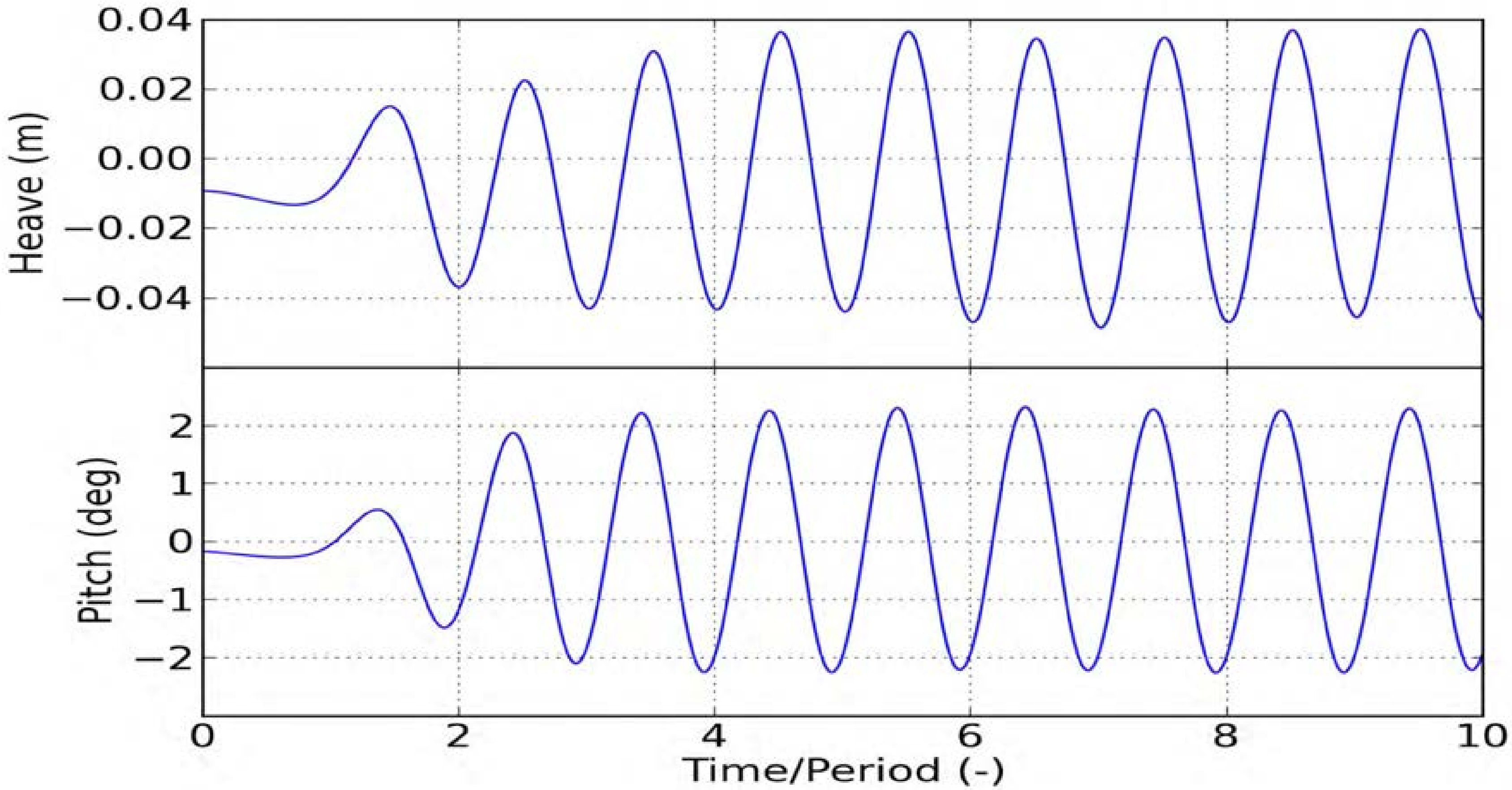
	船体网格	螺旋桨	背景	总数
网格数量	2,931,764	758,989	1,098,416	4,789,169







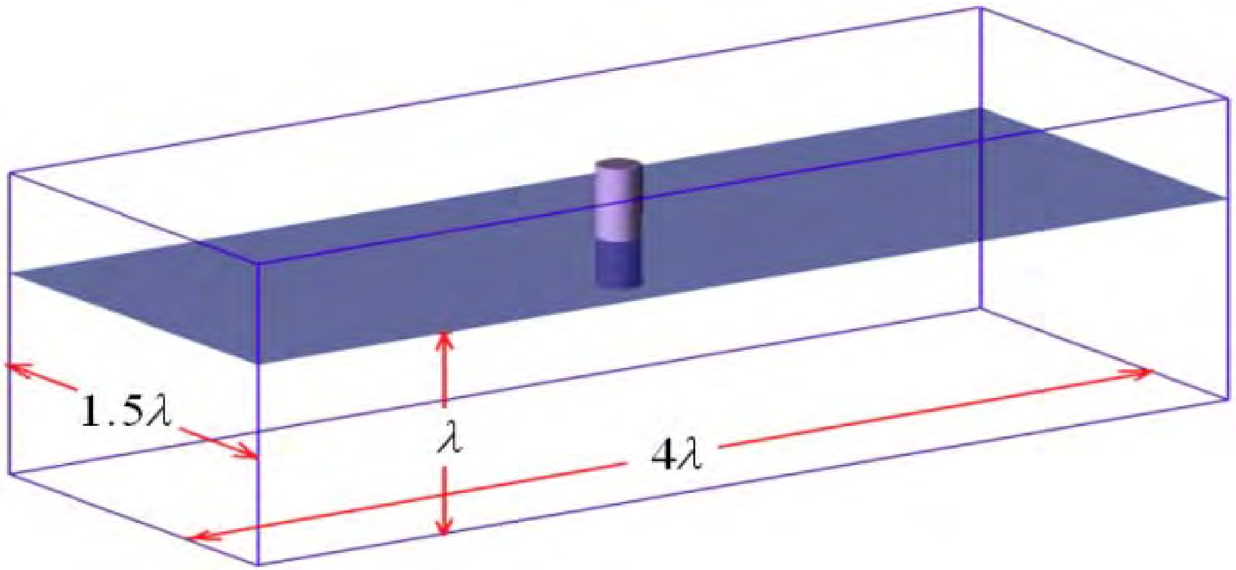
Motion histories

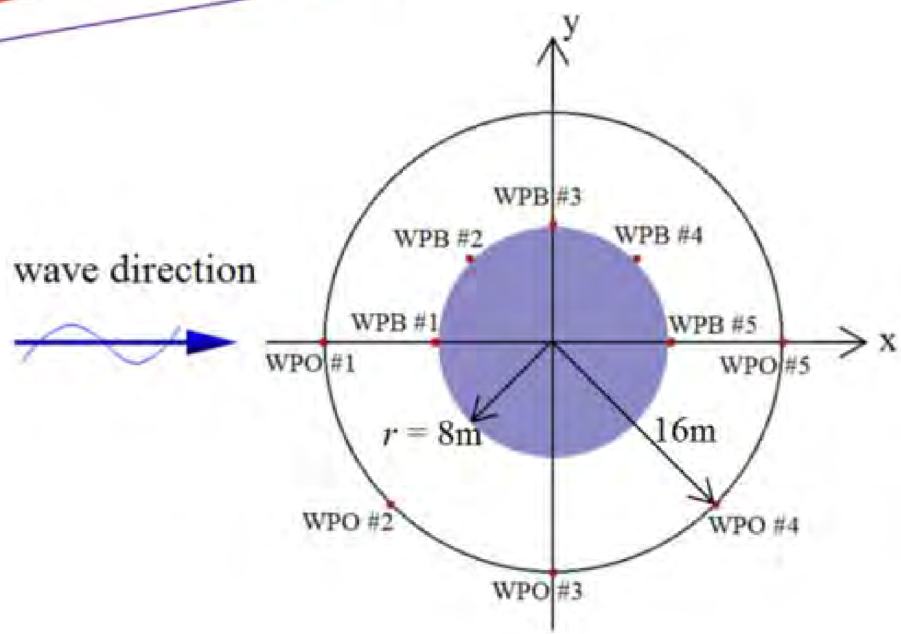


	TF3	TF5
CFD	0.9785	0.7406
EFD	1.039	0.669

Wave Run-up and impact

Wave Run-up on Cylinder





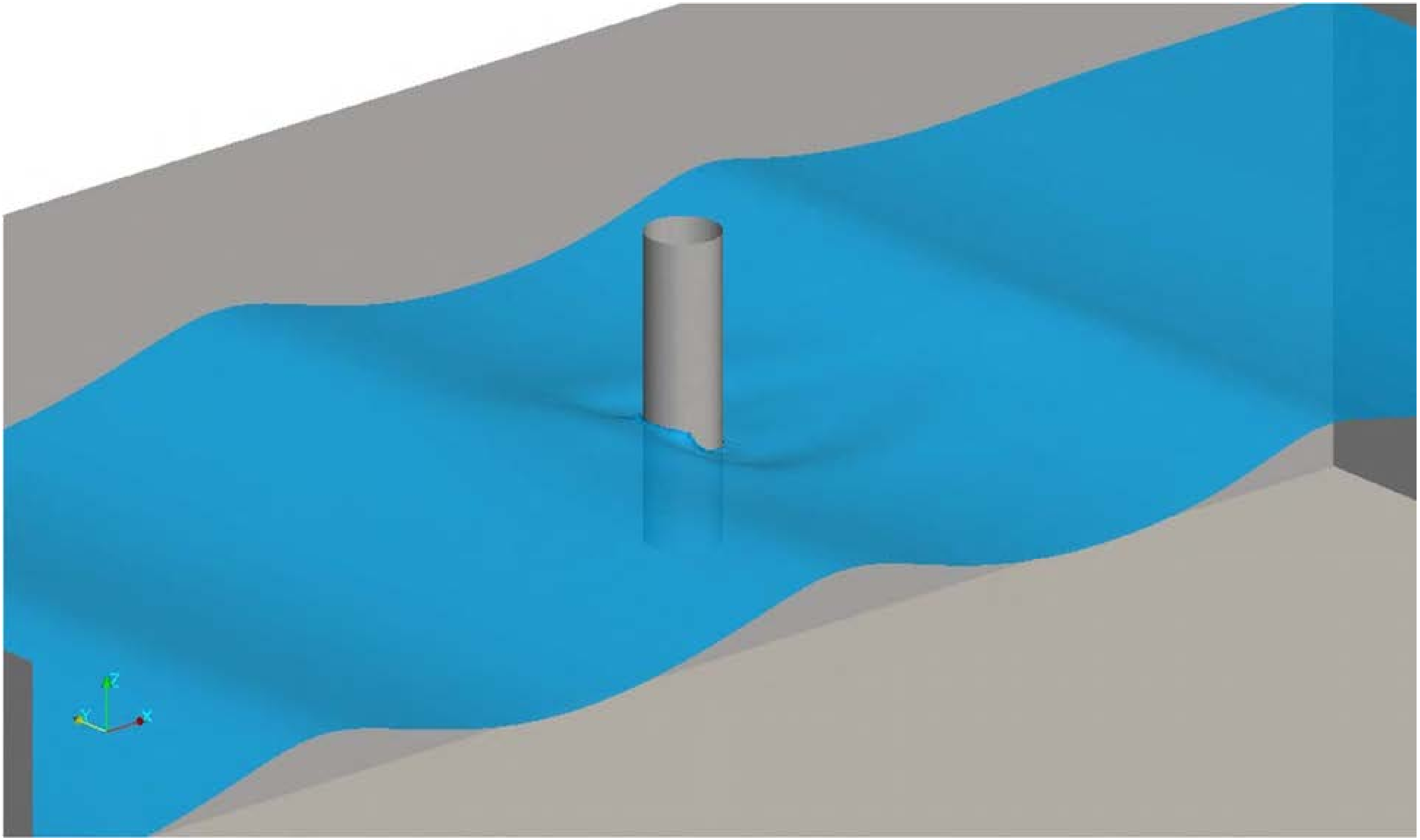
Wave Run-up on Cylinder

Wave conditions

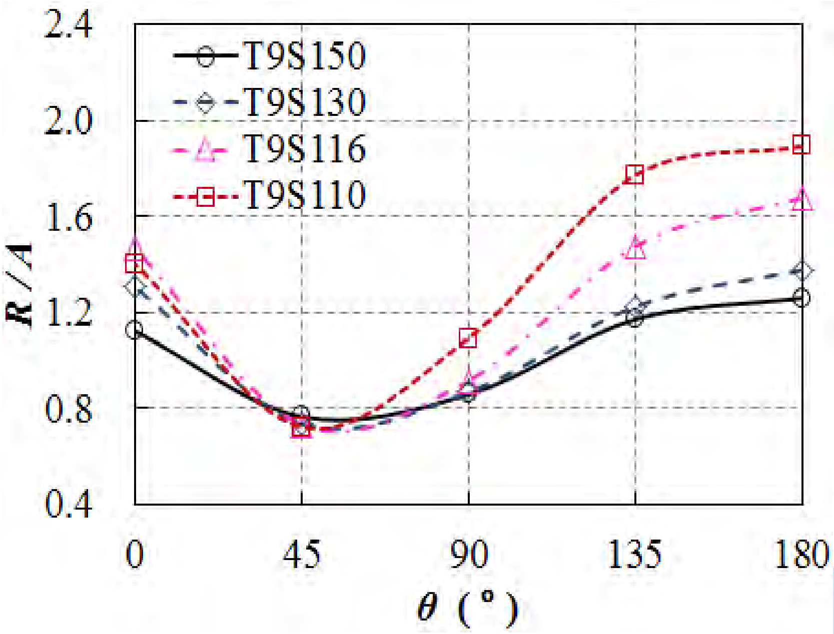
3 periods， 4 wave hieghts

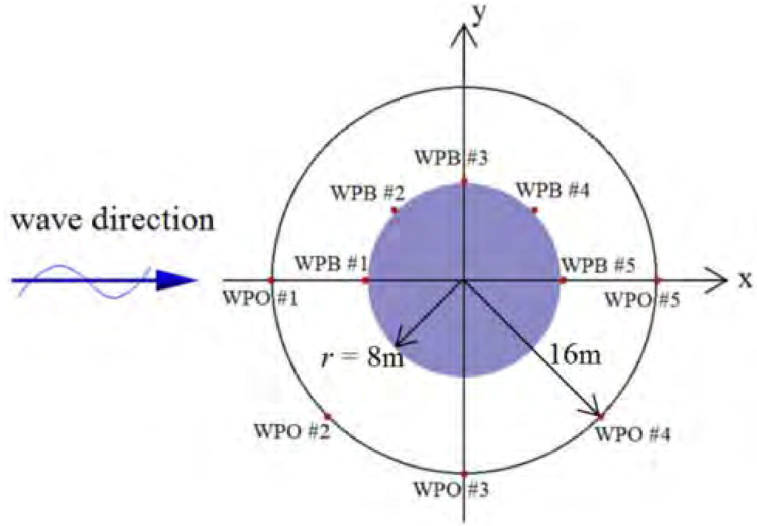
	T = 7s	T = 9s	T = 12s
H/λ= 1/50	T07S150	T09S150	T12S150
H/λ = 1/30	T07S130	T09S130	T12S130
H/λ = 1/16	T07S116	T09S116	T12S116
H/λ = 1/10	T07S110	T09S110	T12S110

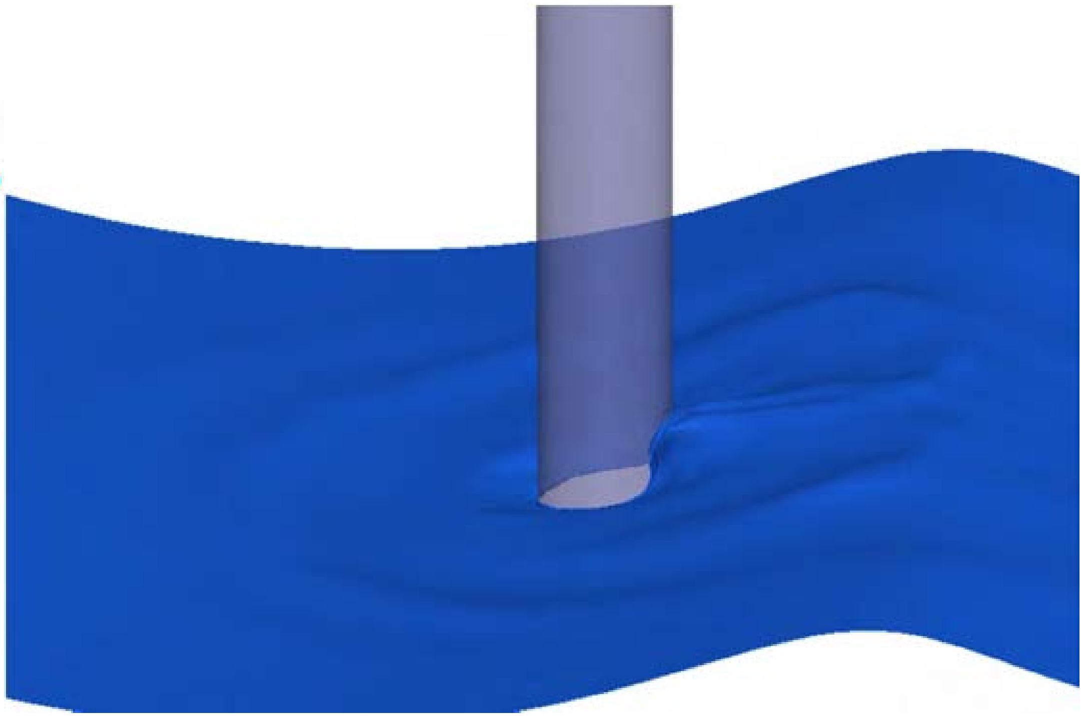
T9S110



Maxium values of wave runup







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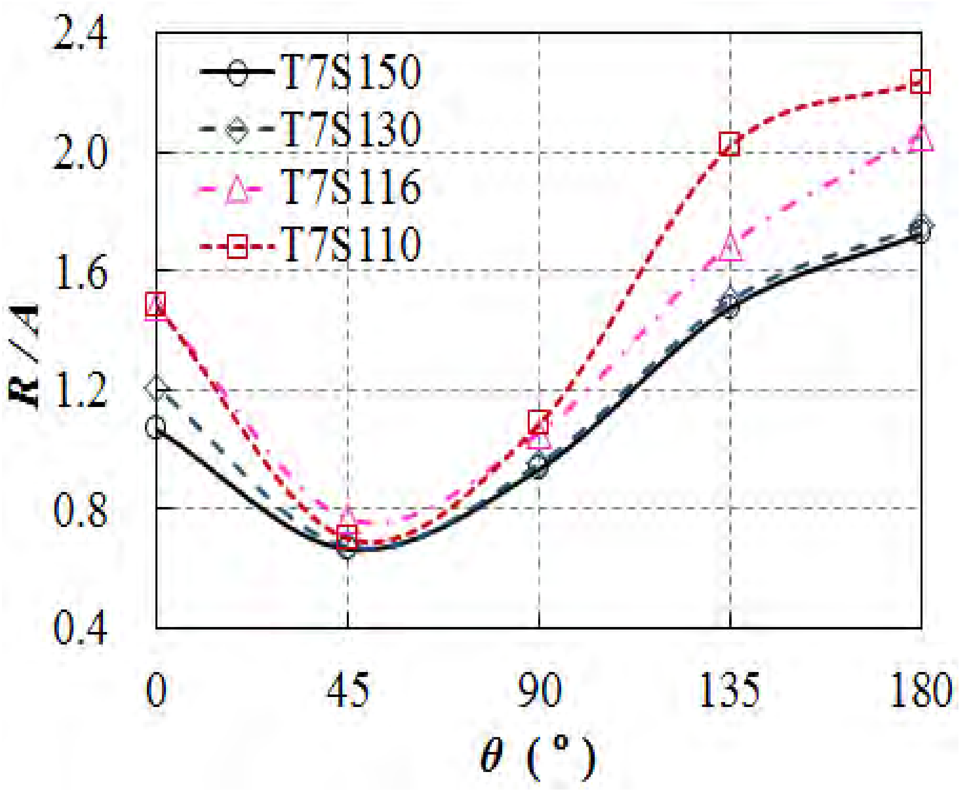
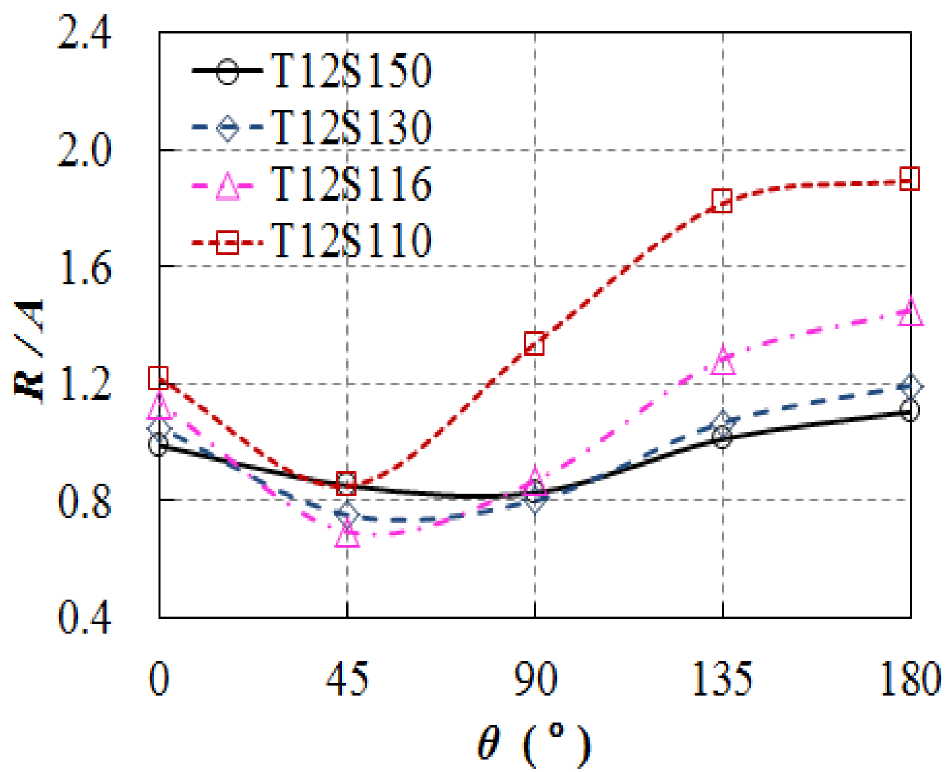
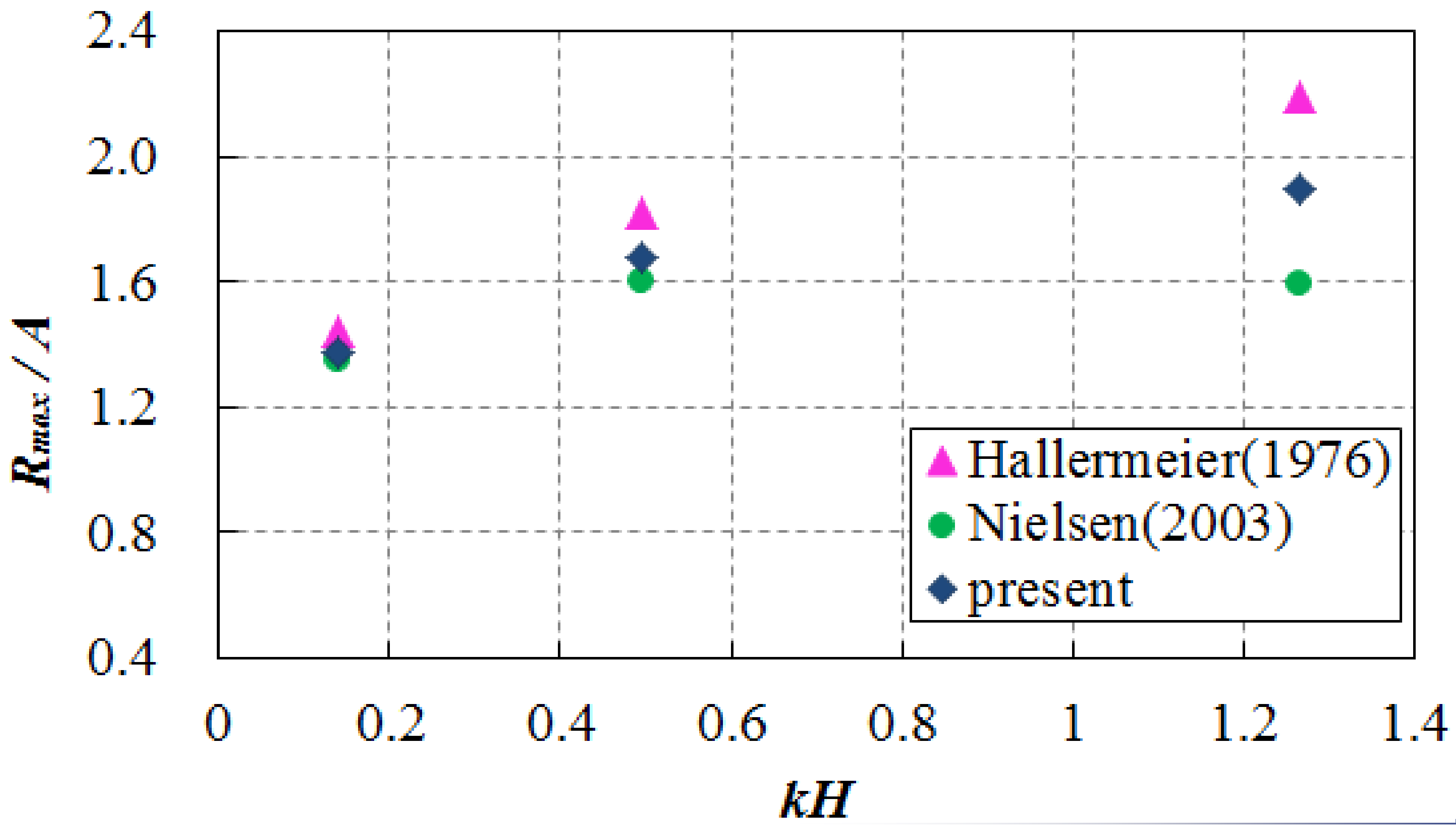
Maxium values of wave runup

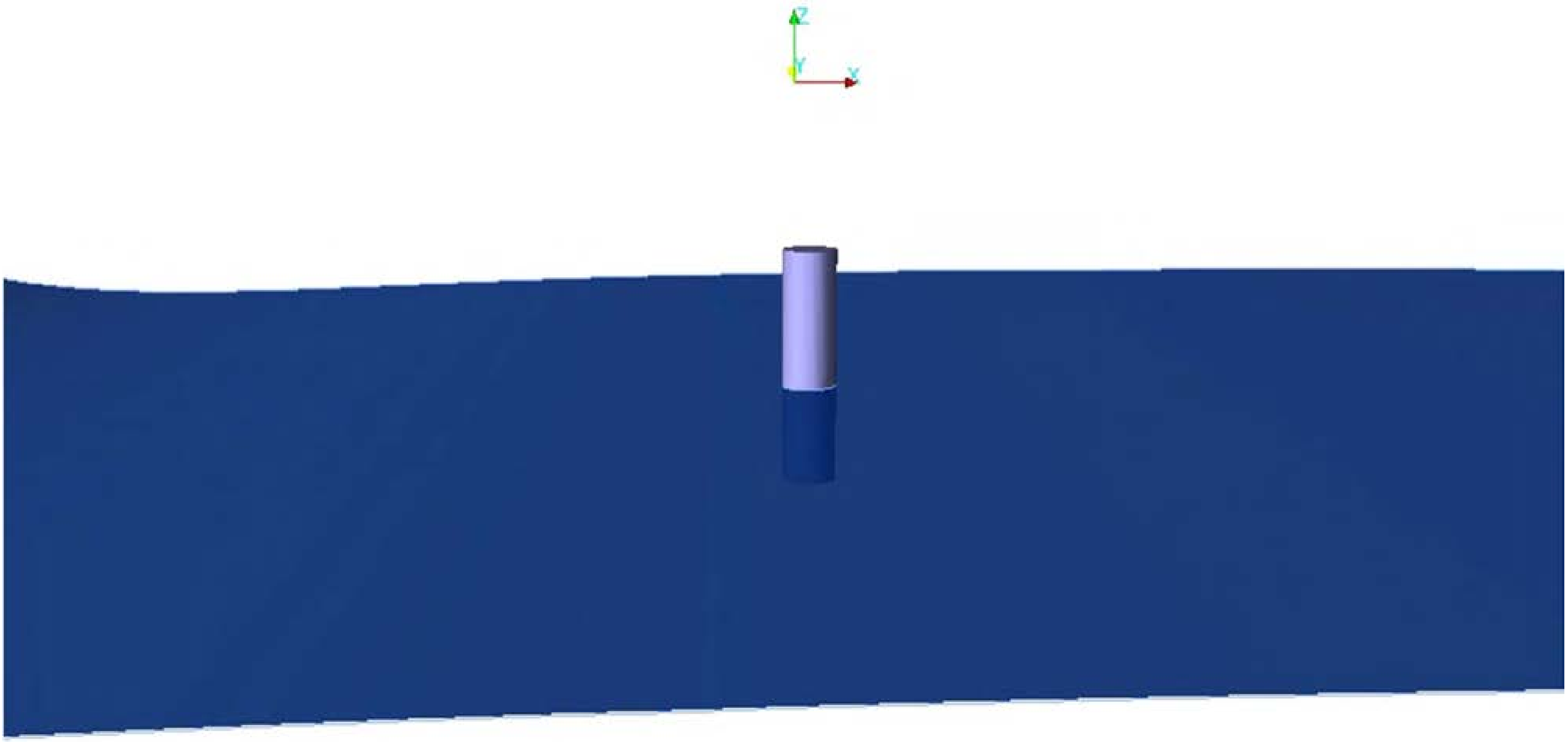




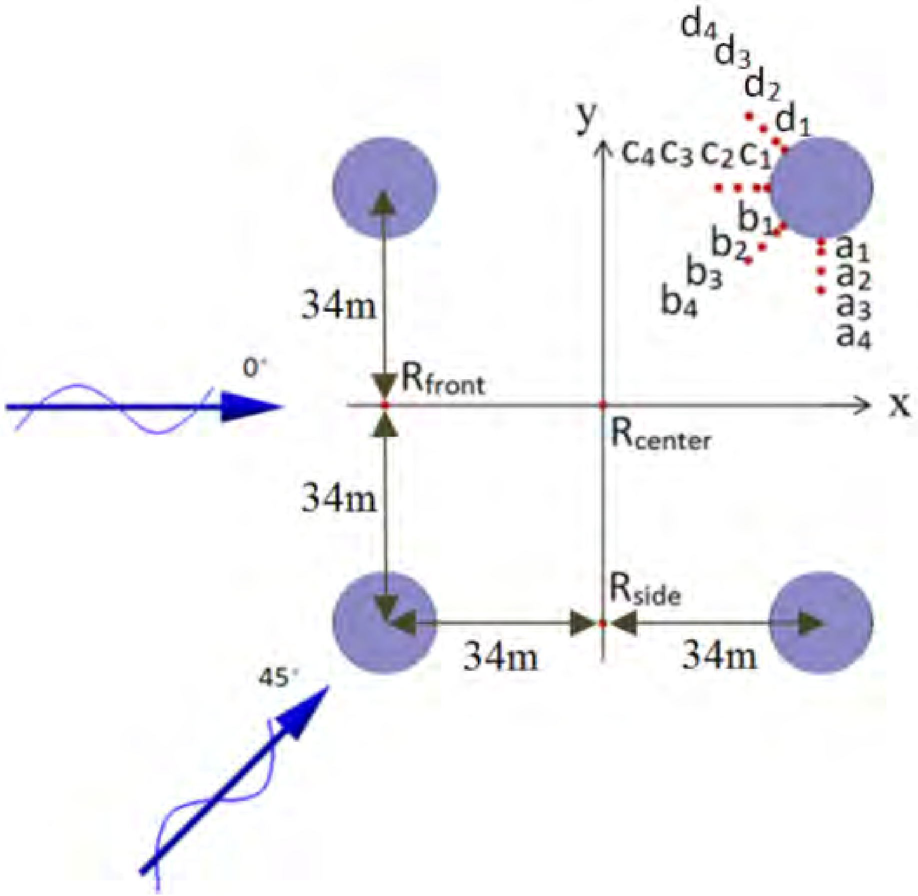
Maxium values of wave runup（T=9s）

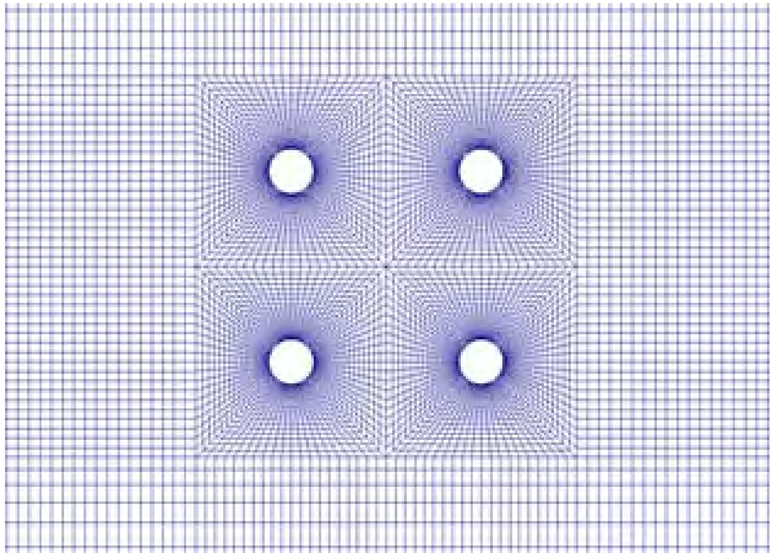


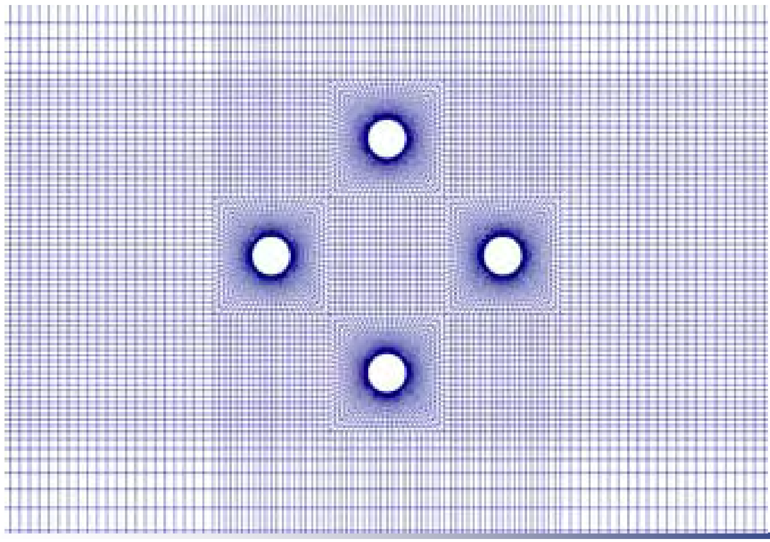
Extrem Wave Run-up on Cylinders



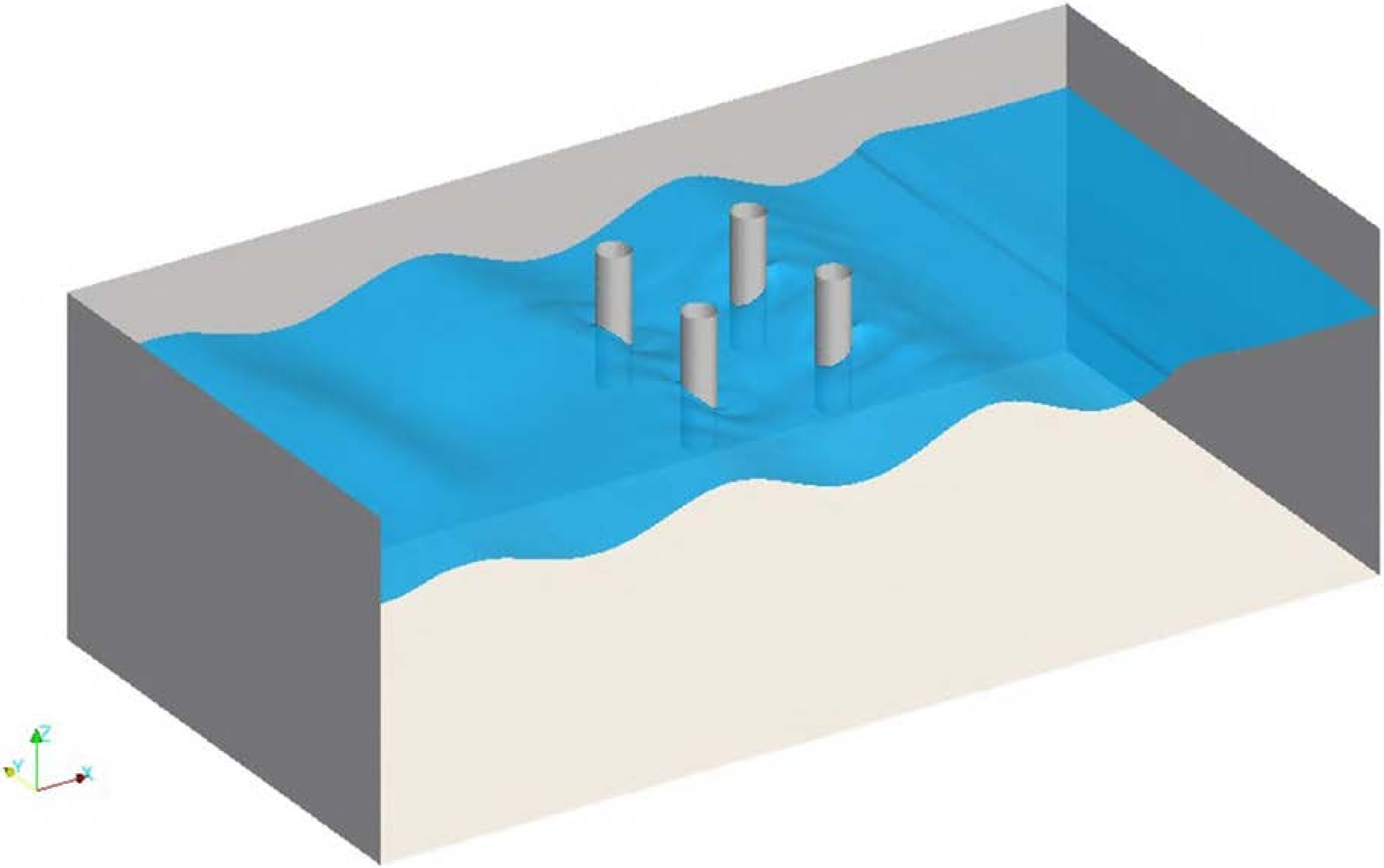
Wave Run-up on four Cylinders



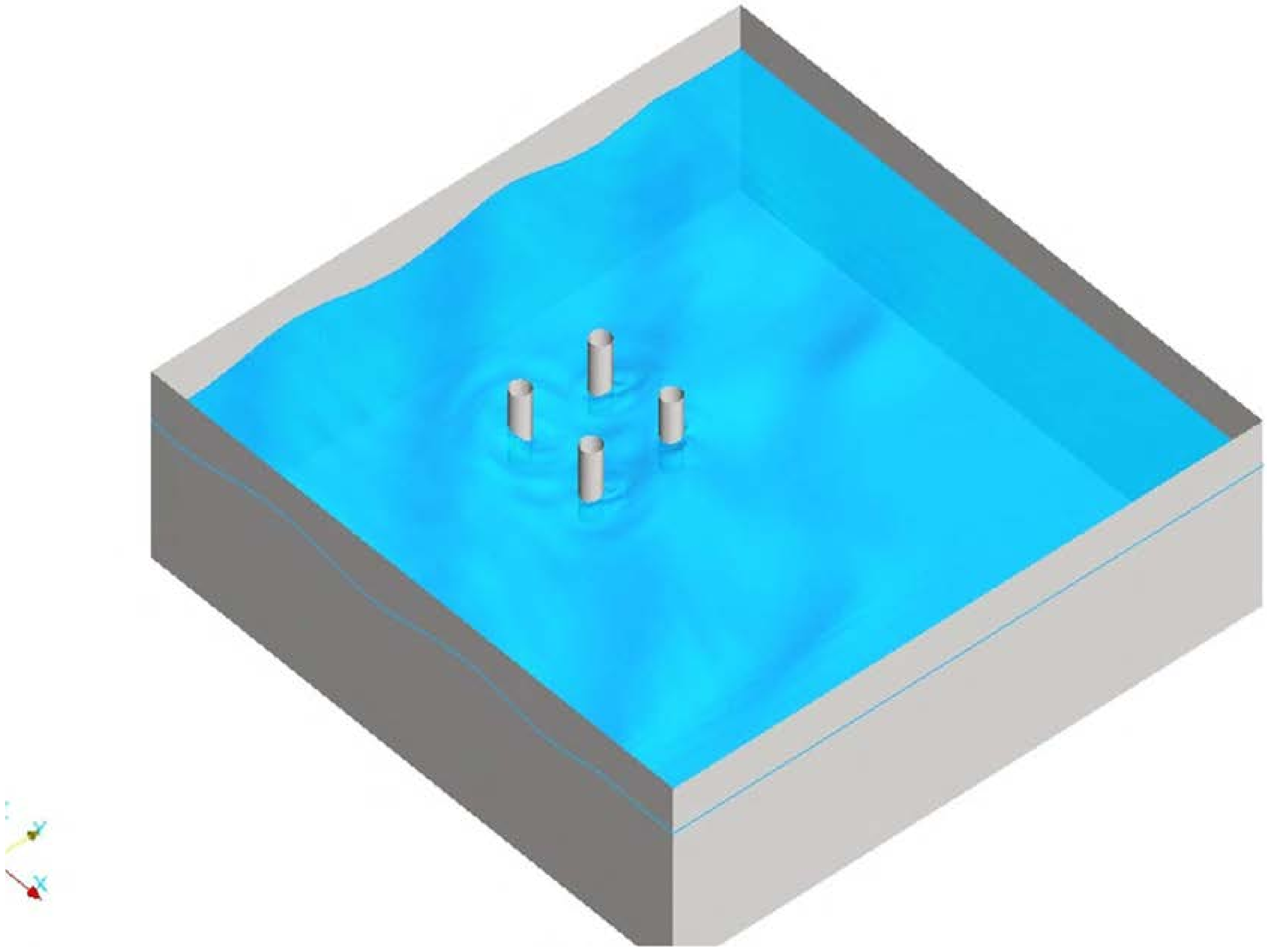




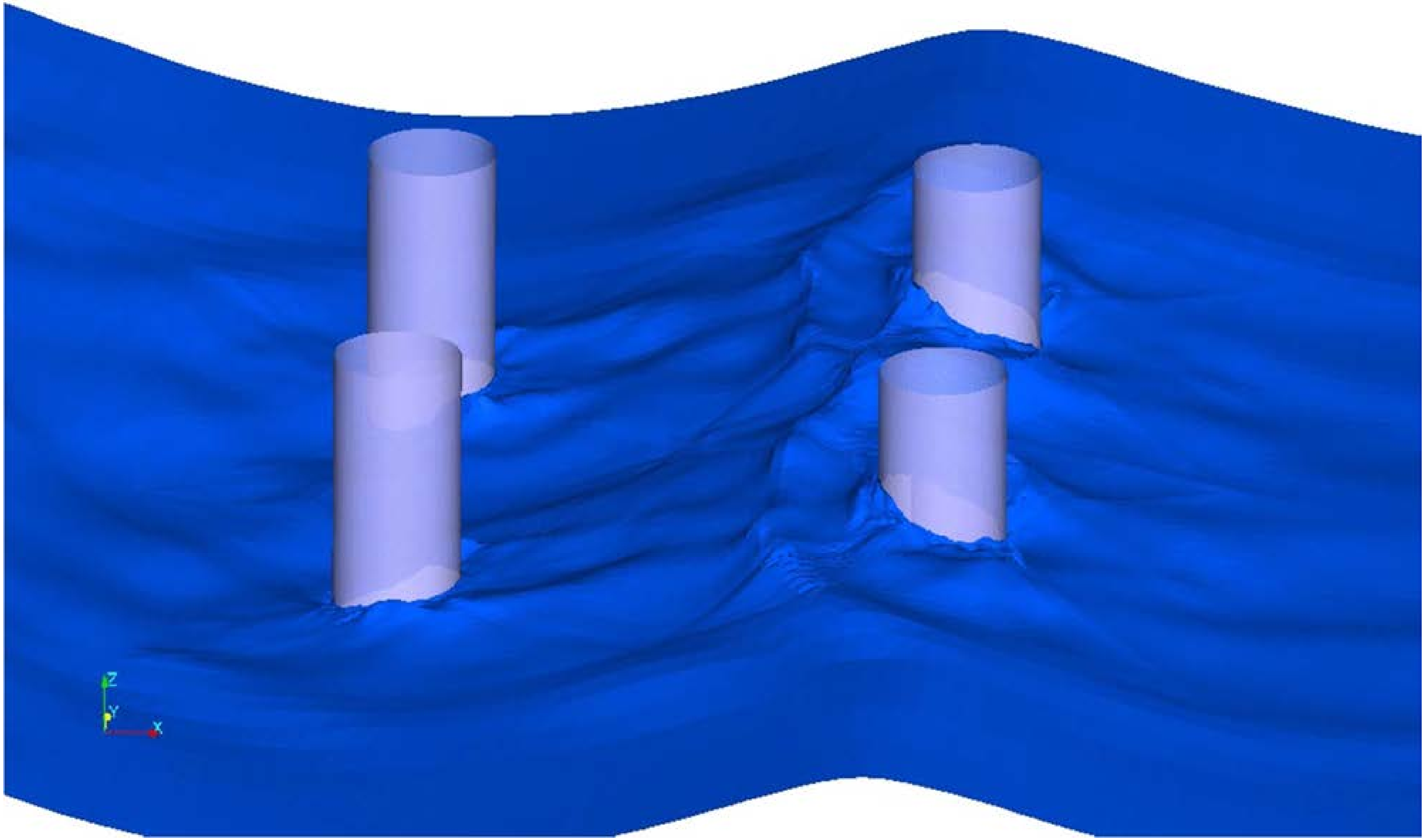
T9S130



T9S130

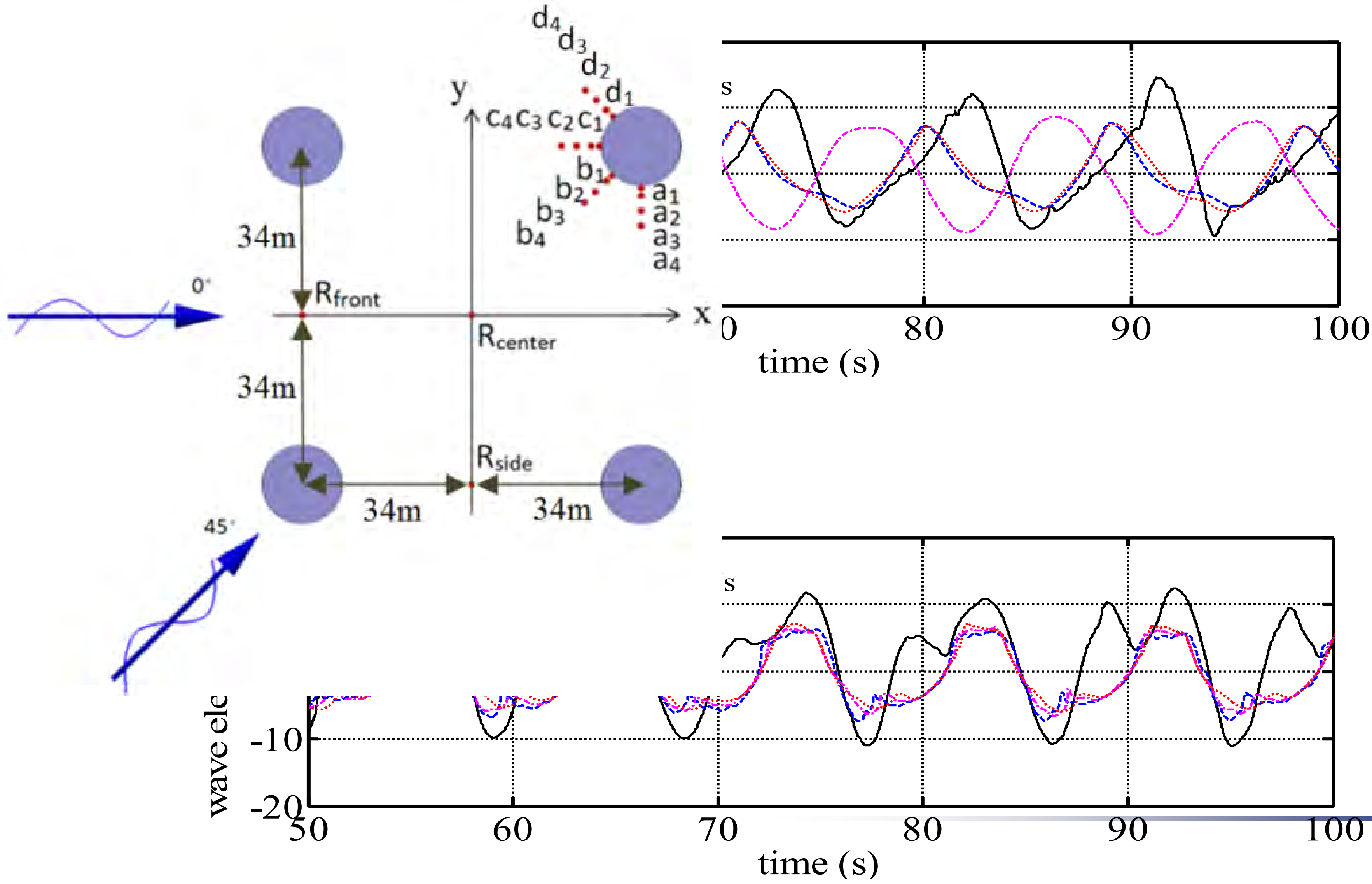


T9S110



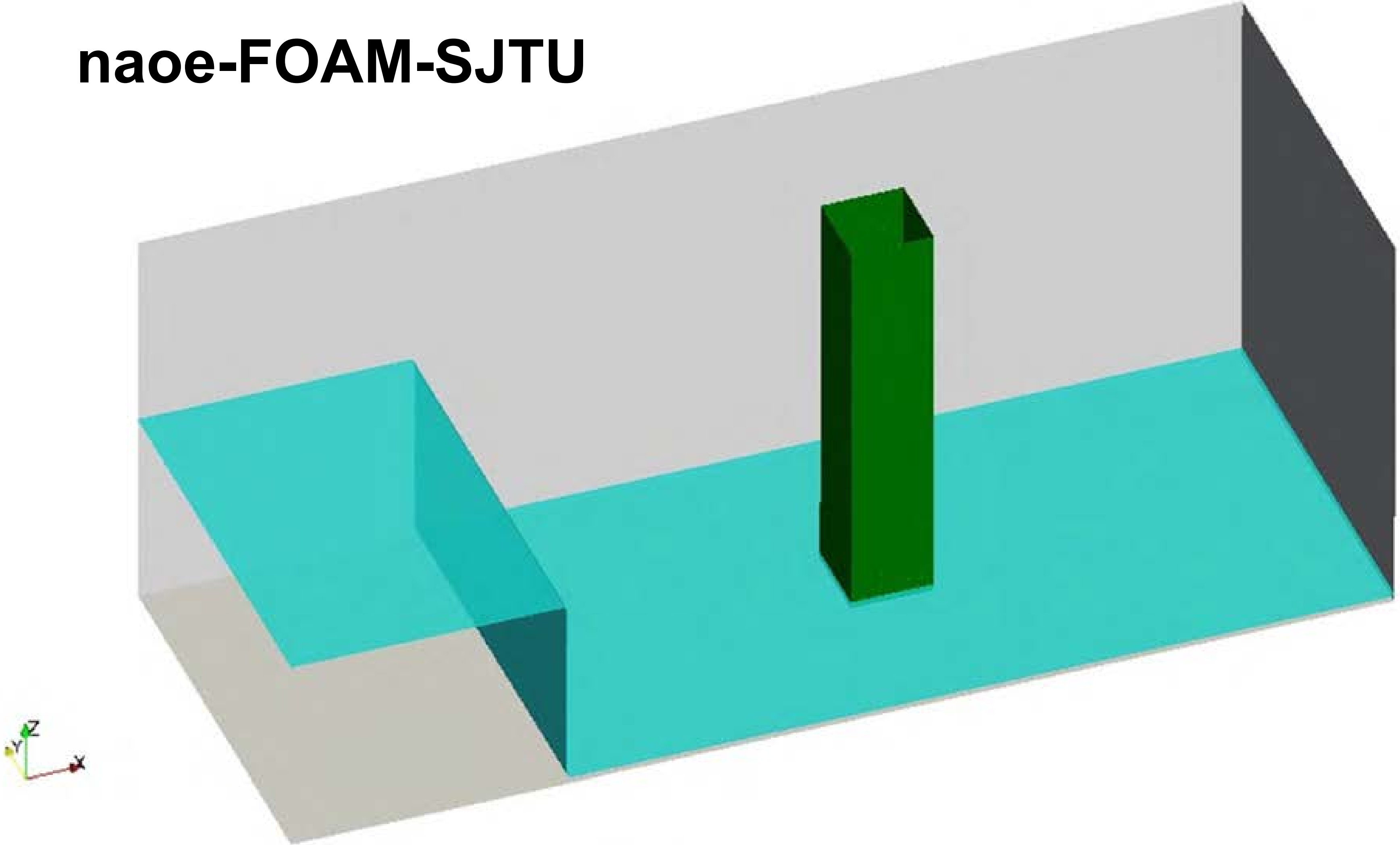
T9S110

- θ=0°



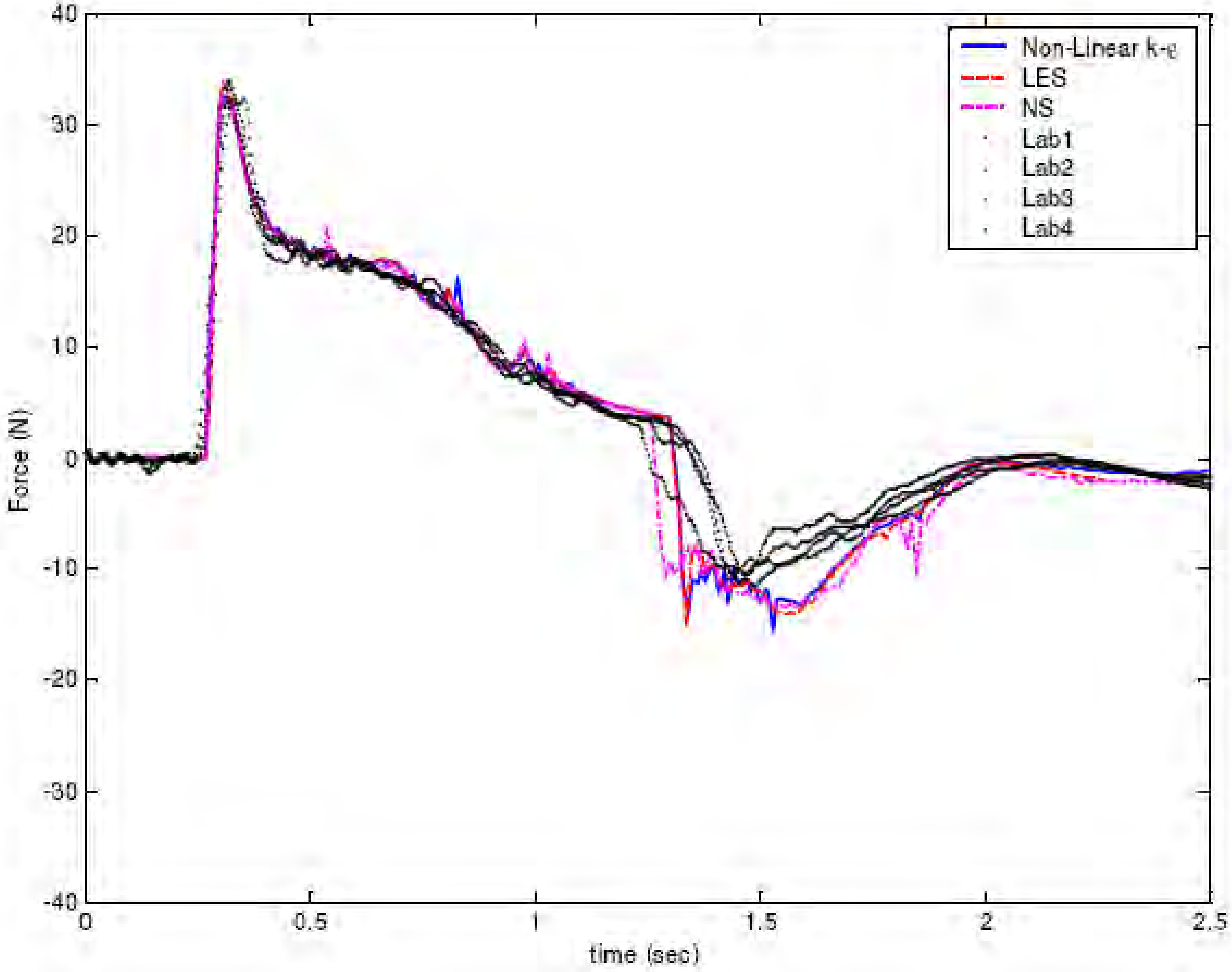
Violent Wave Impact on Cylinders

naoe-FOAM-SJTU



t= 0.00s

Violent Wave Impact on Cylinders



Violent Wave Impact on Cylinders

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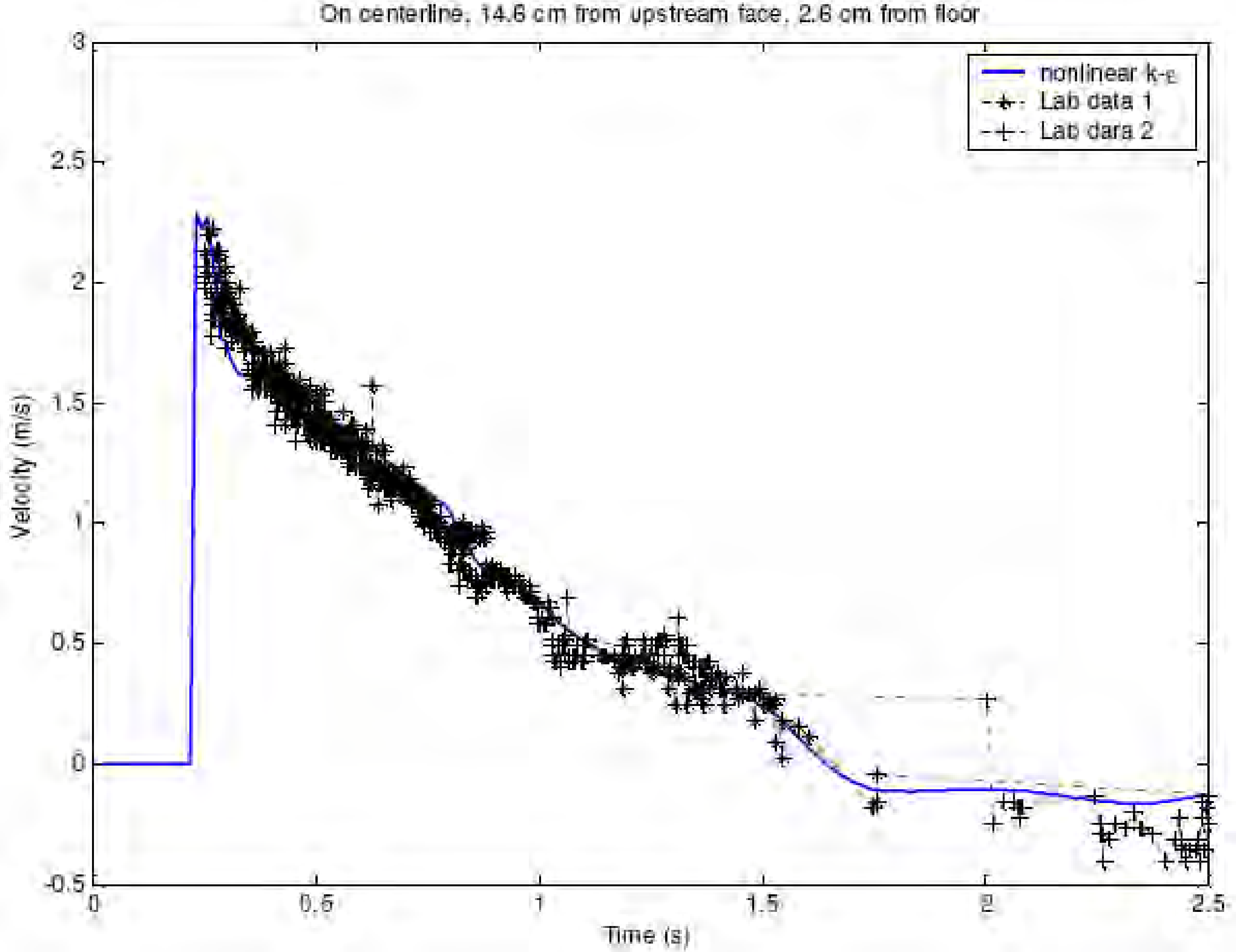
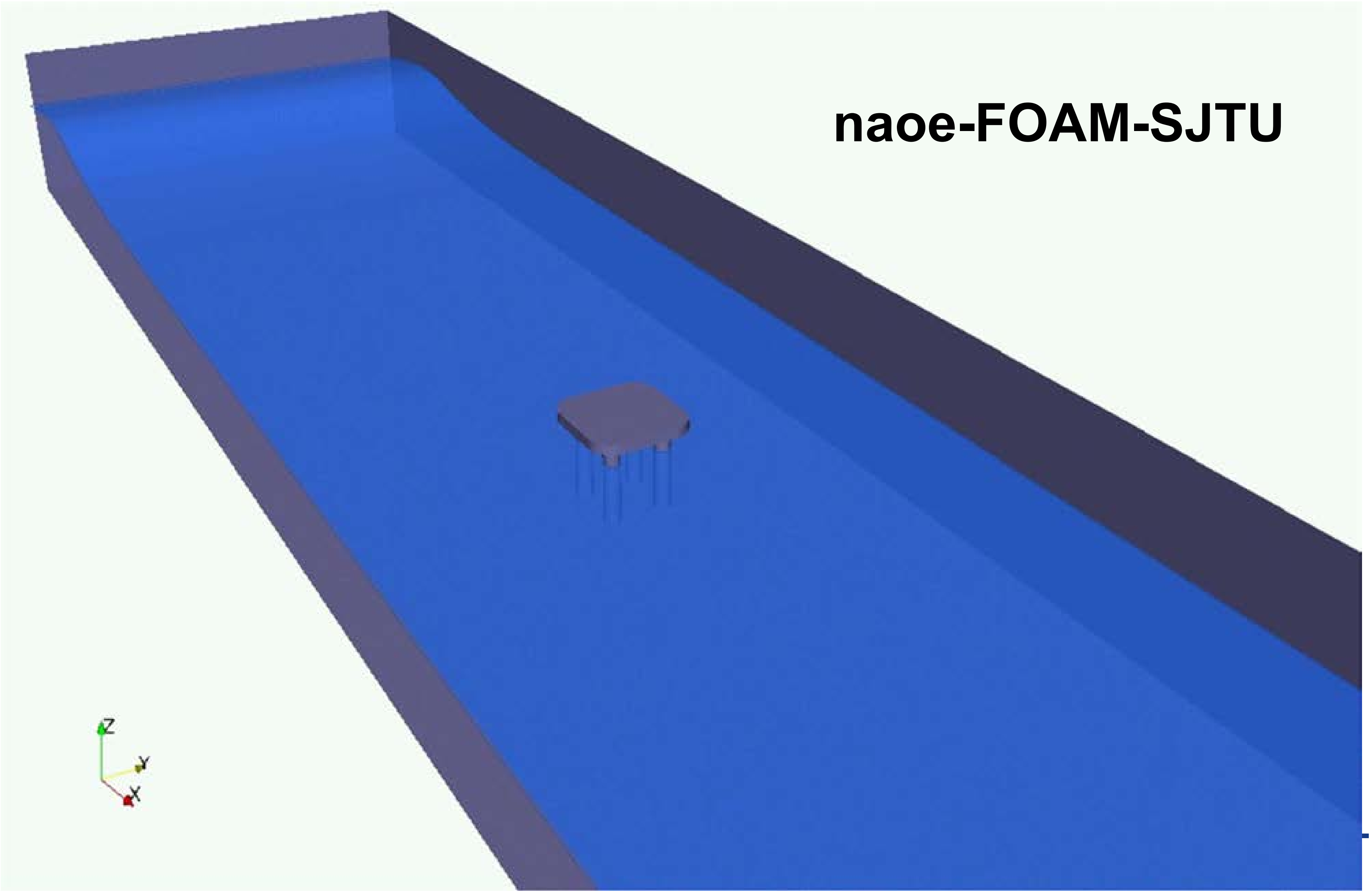
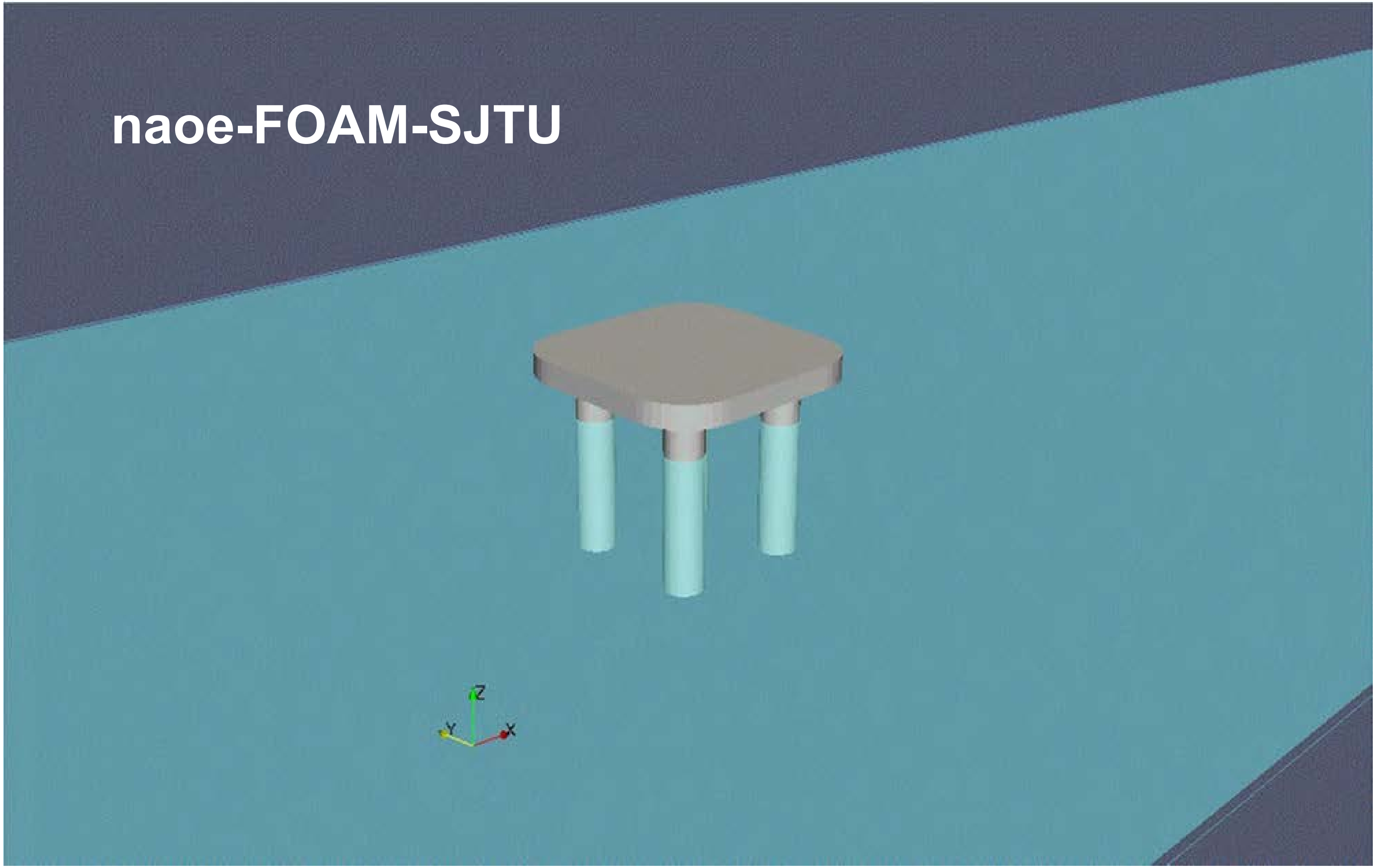


Wave Run-up on Fixed Platform

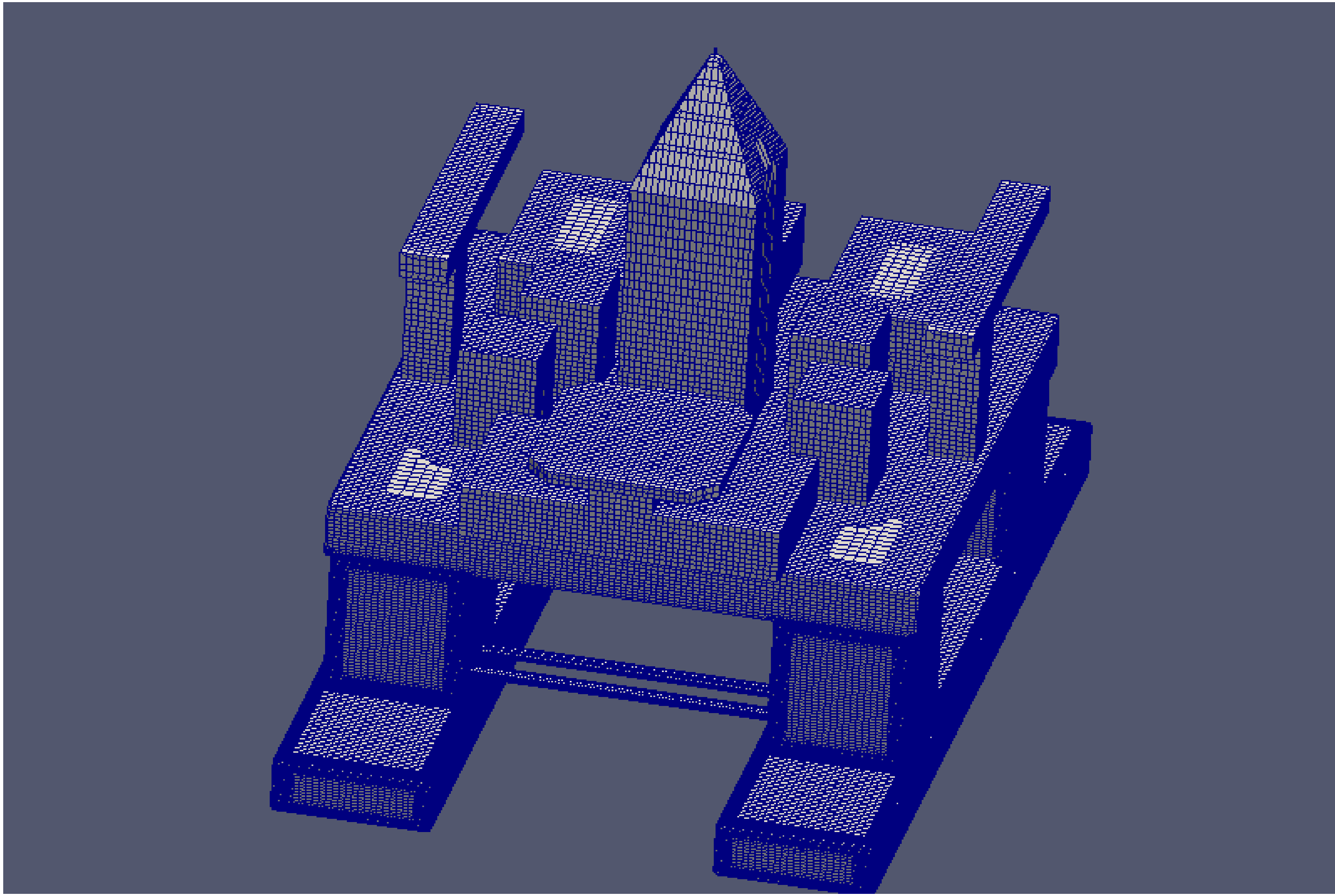


Wave Run-up on Fixed Platform



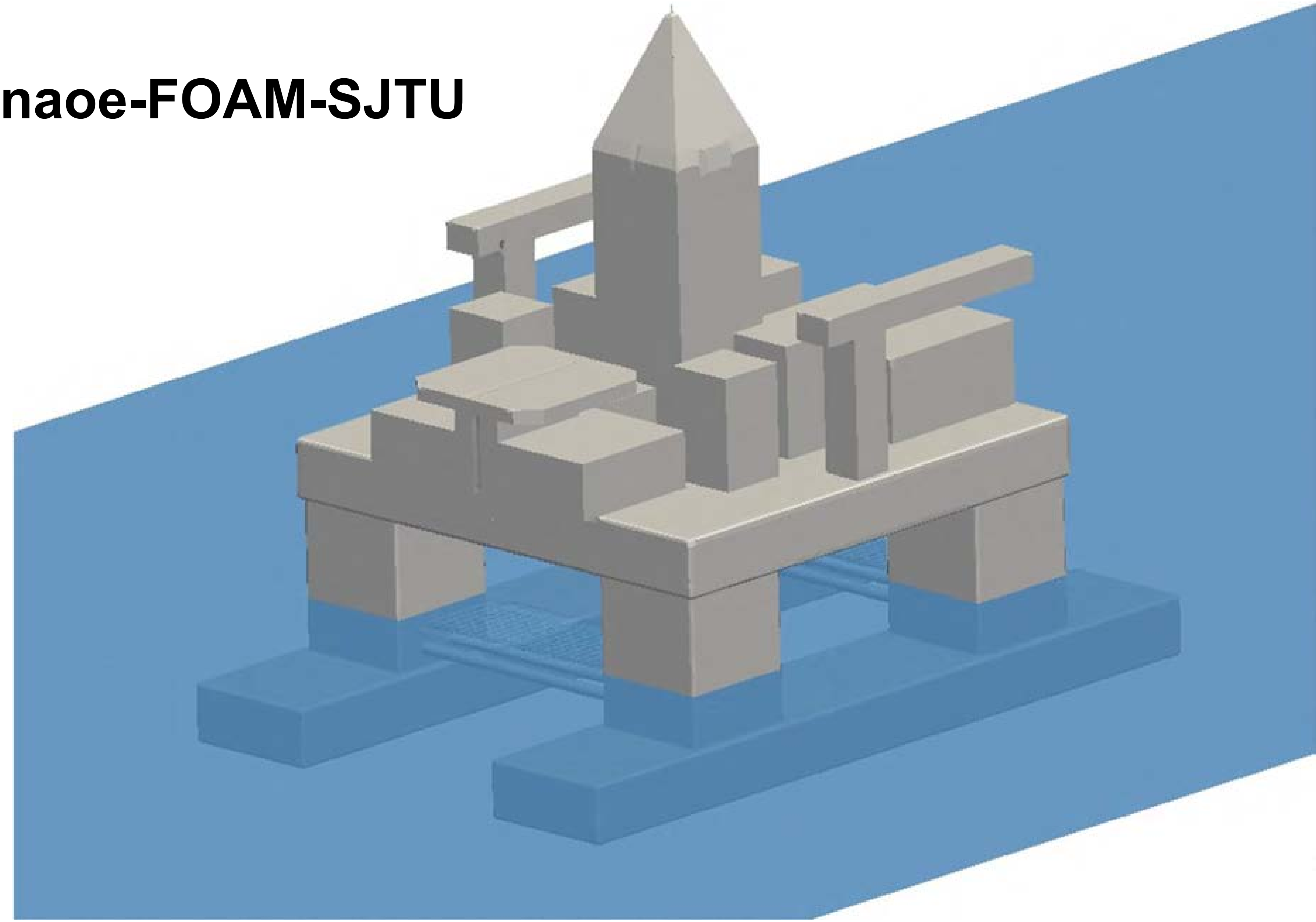
Floating body and mooring system

981 semimersible Platform Motion in Waves

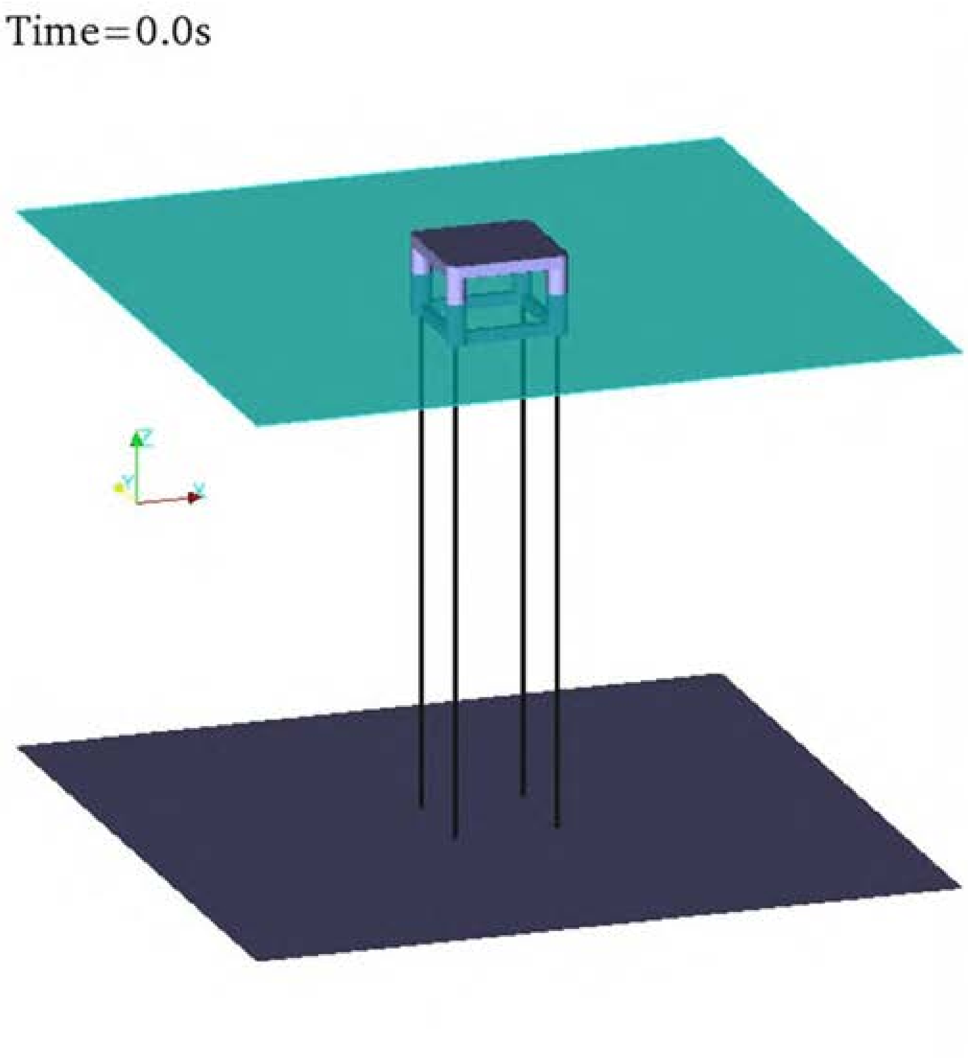


981 semimersible Platform Motion in Waves

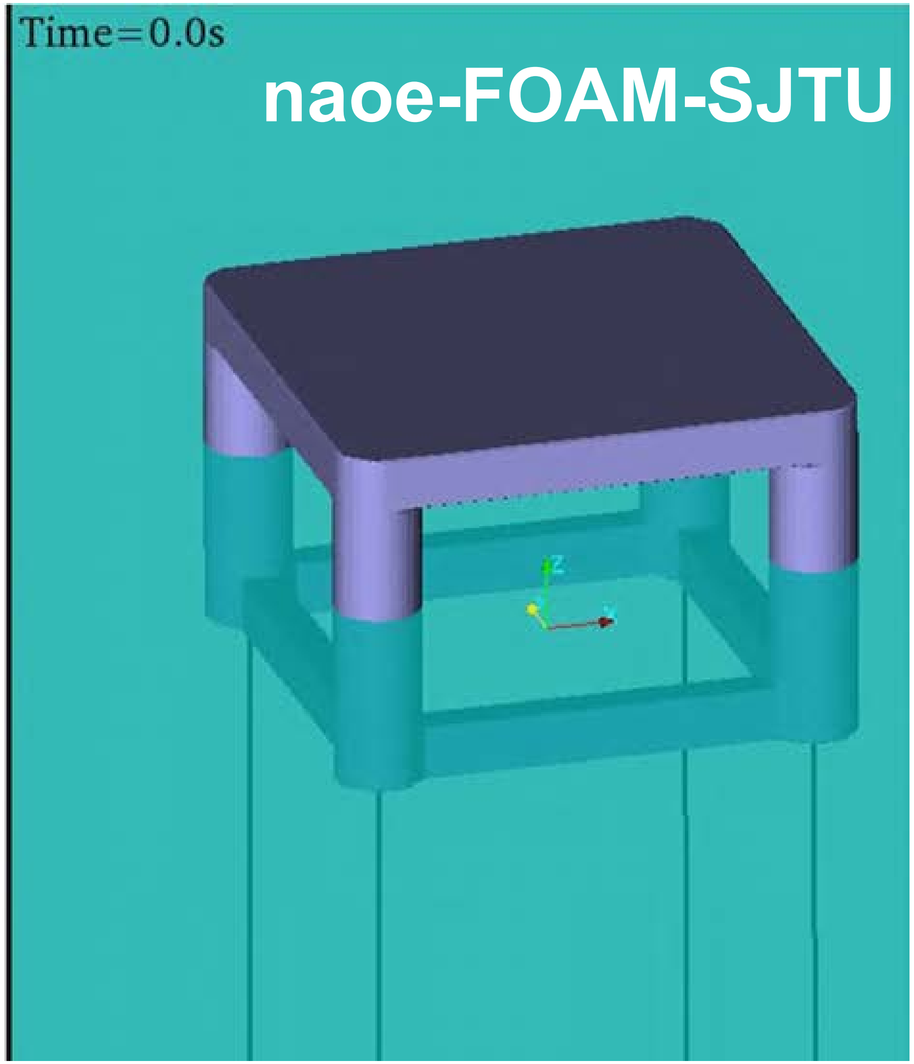
naoe-FOAM-SJTU



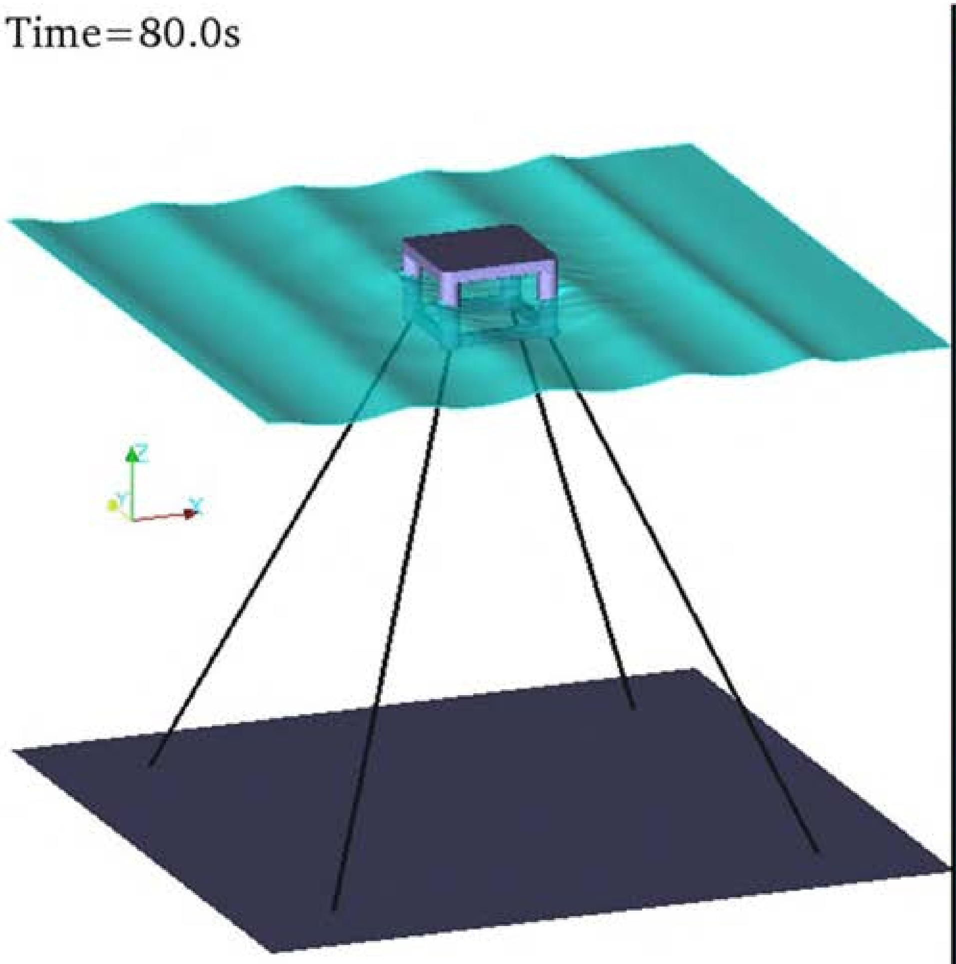
在垂直张紧锚链作用下平台在波浪上运动

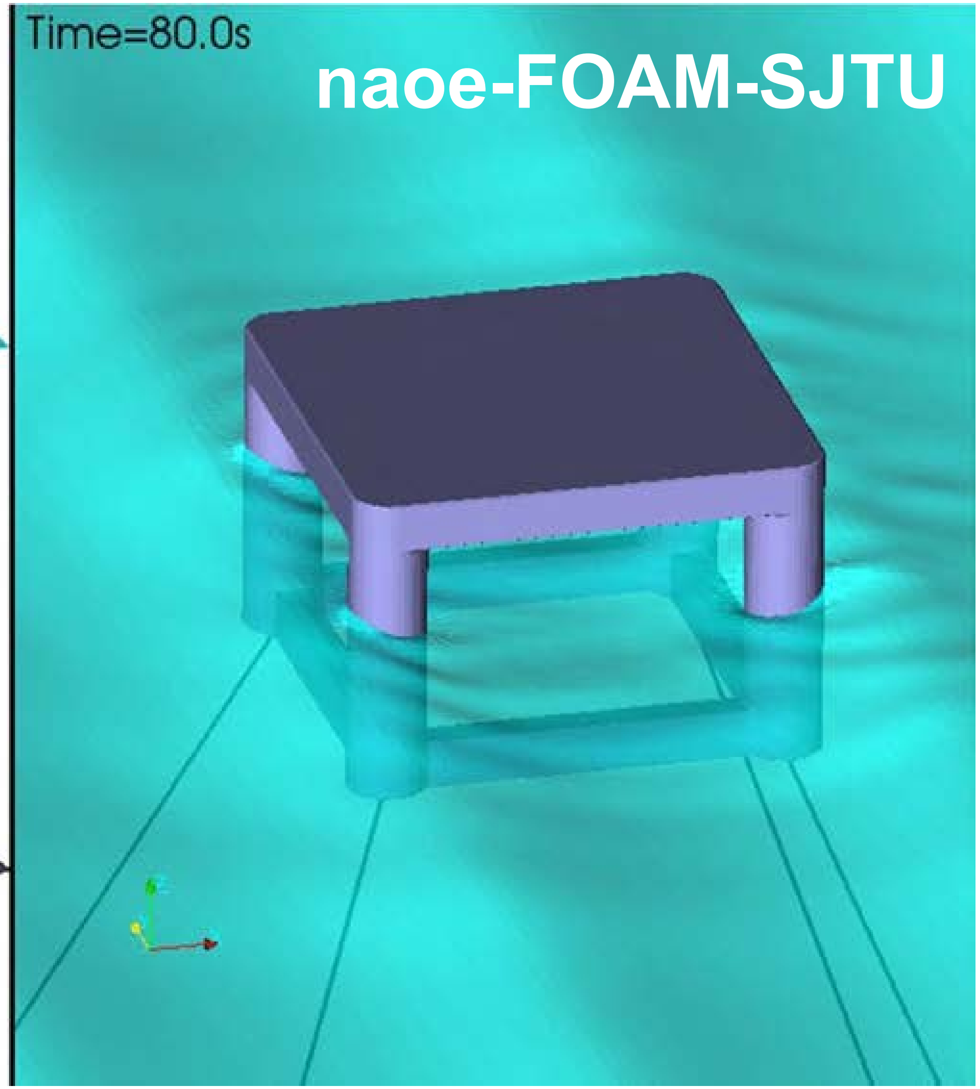


naoe-FOAM-SJTU



在斜张紧锚链作用下平台在波浪上运动





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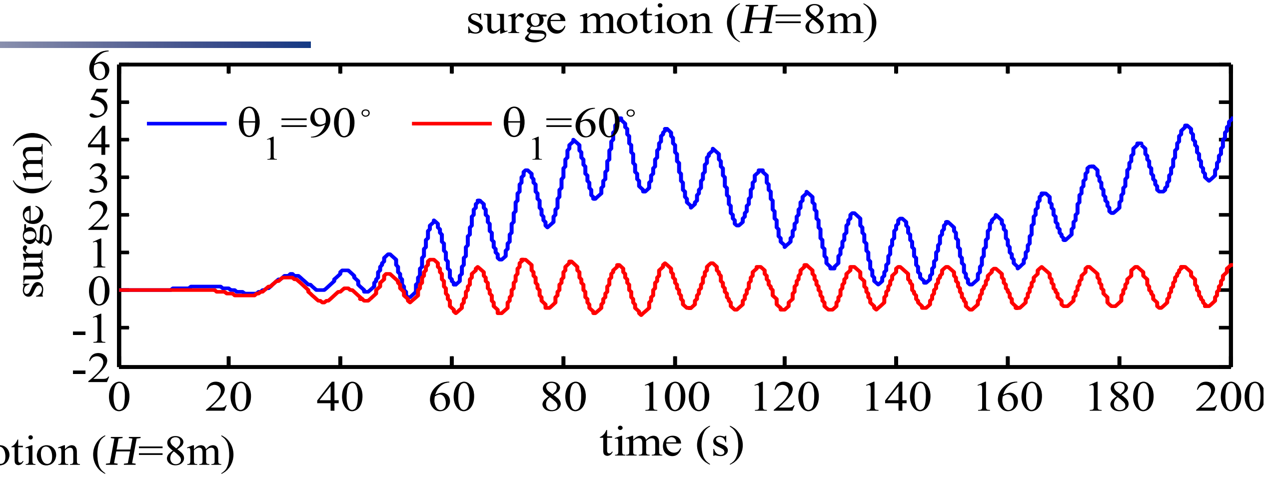
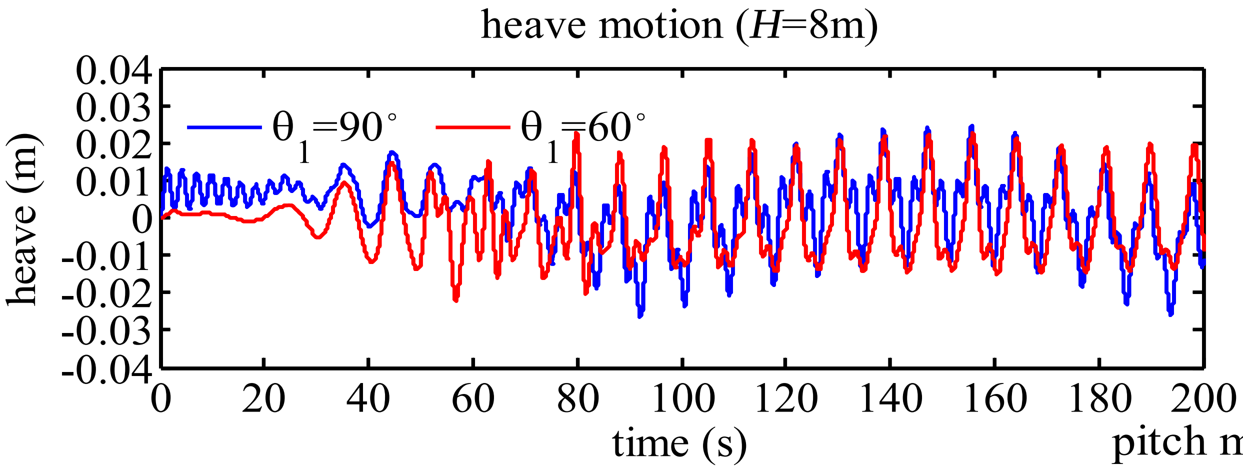
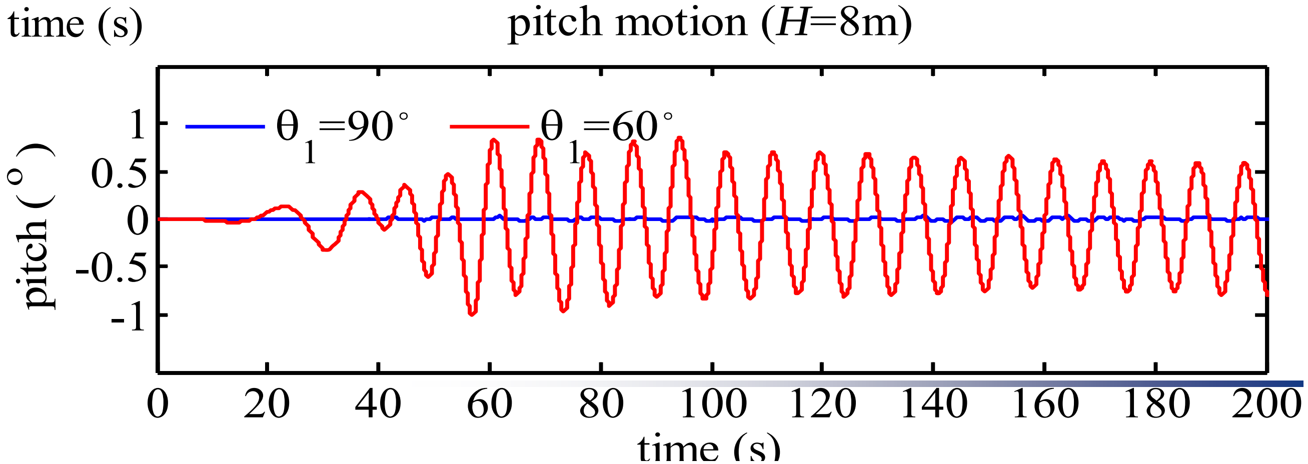
张紧锚链作用下平台在波浪上运动







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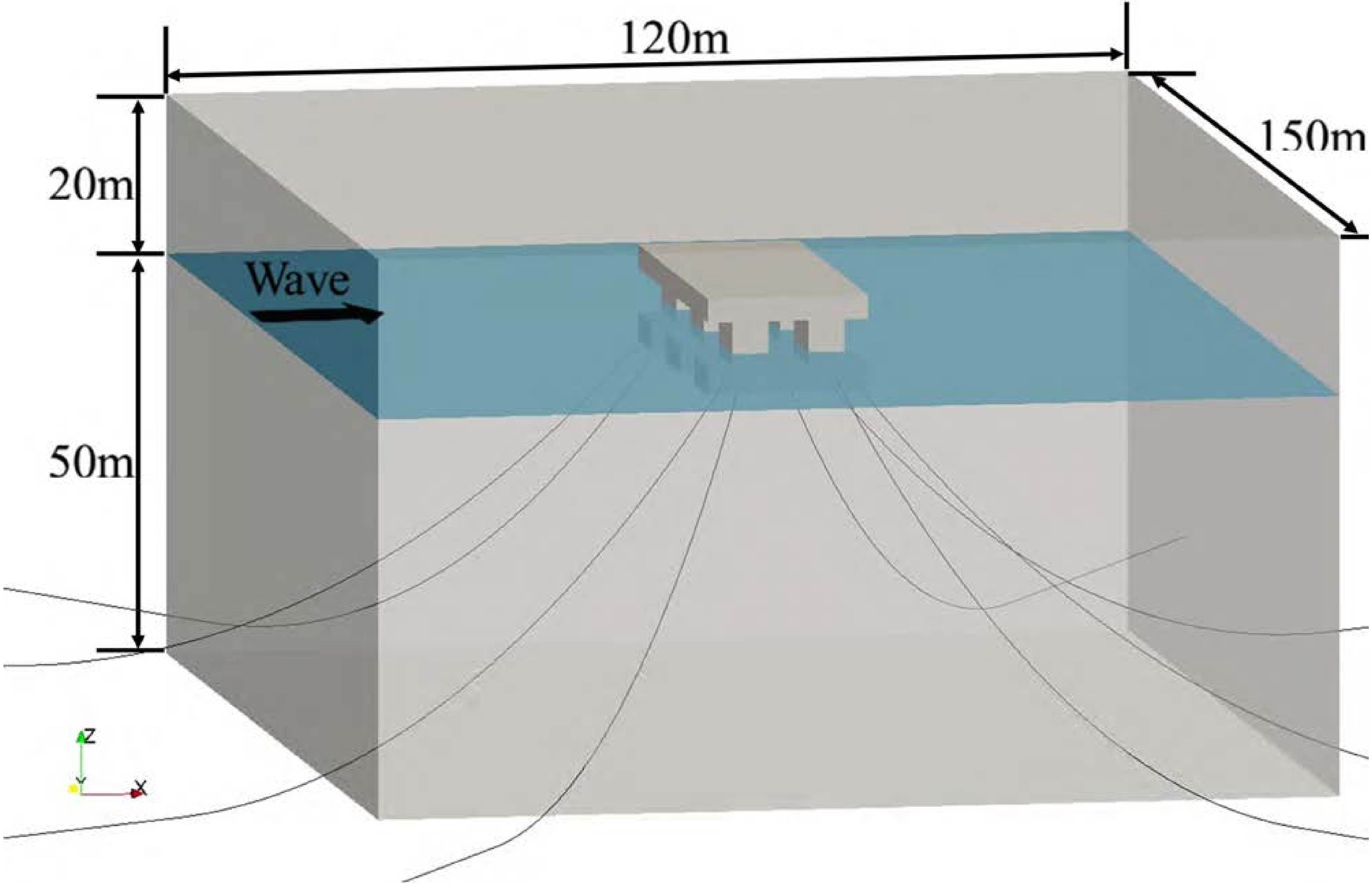

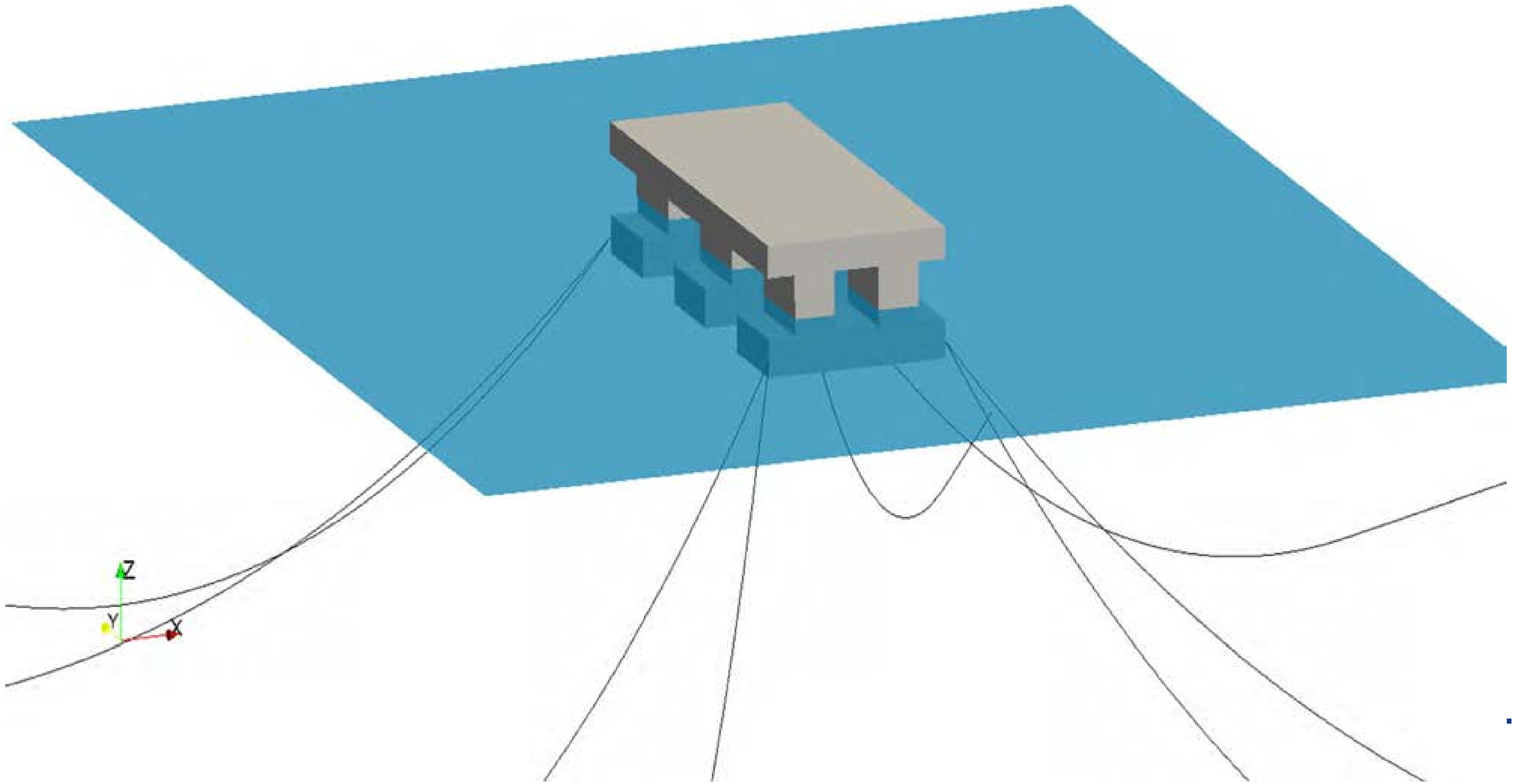
Z
Y
X

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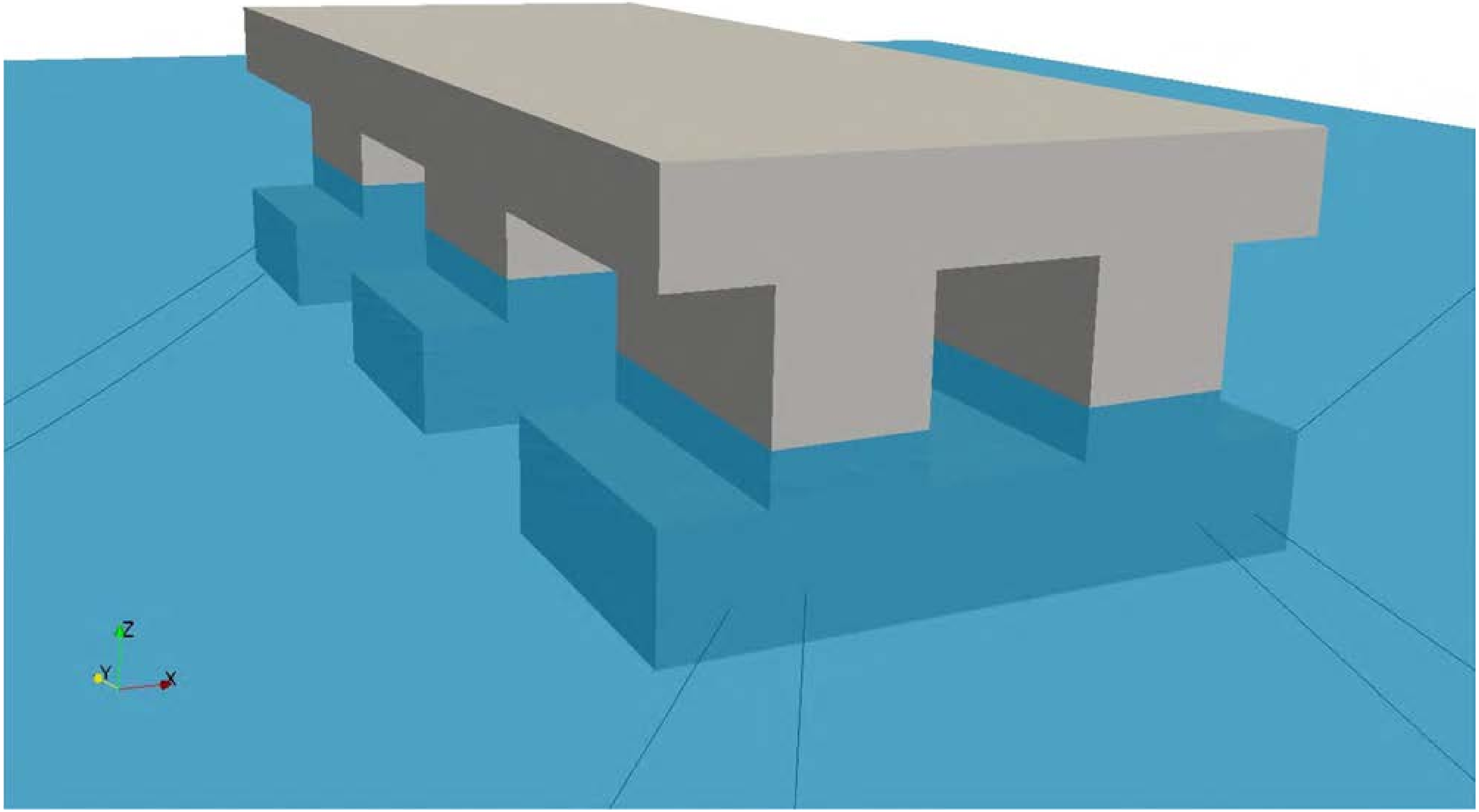
Time: 0.0s



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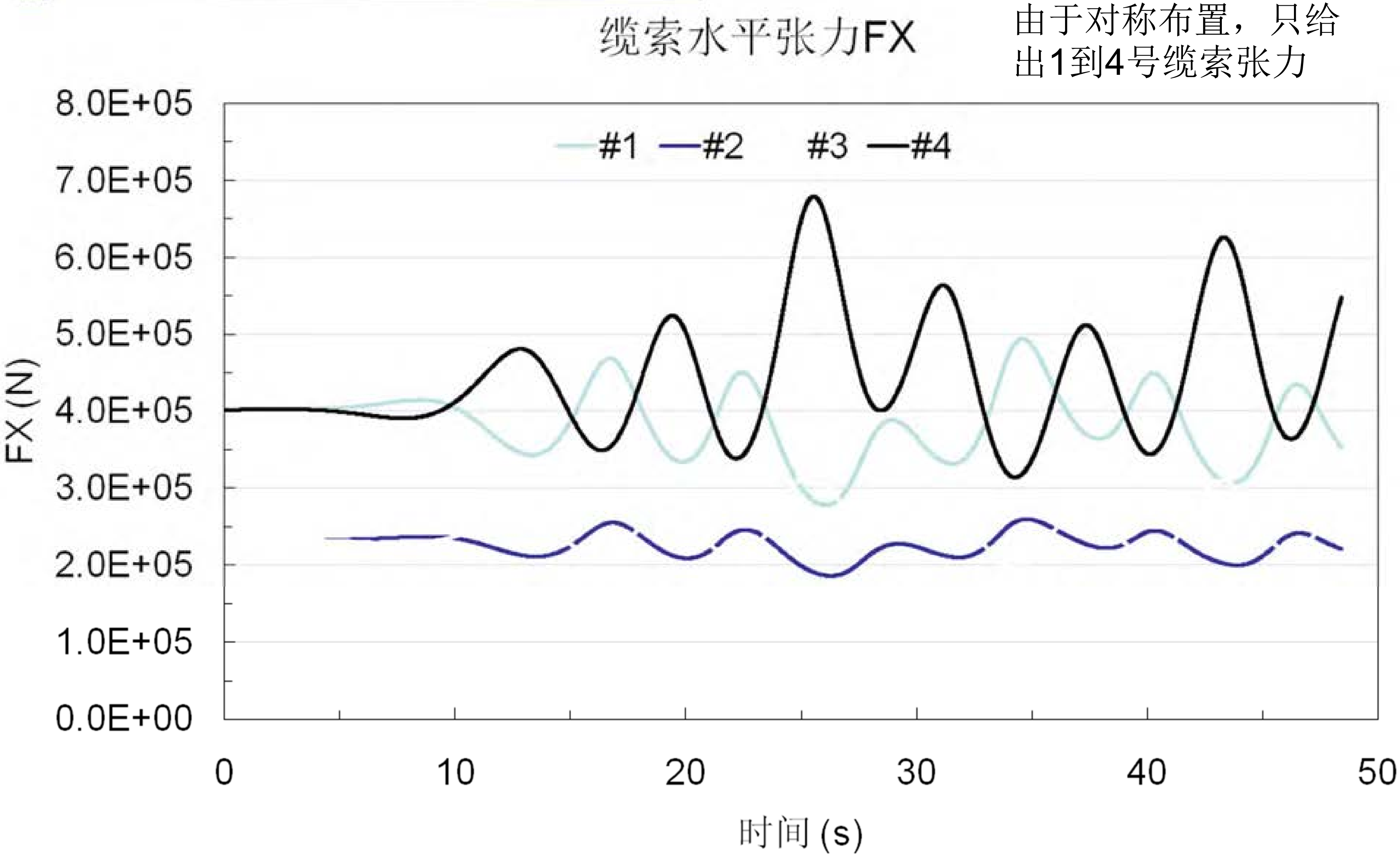
缆索张力曲线

由于对称布置，只给出1到4号缆索张力



缆索张力曲线

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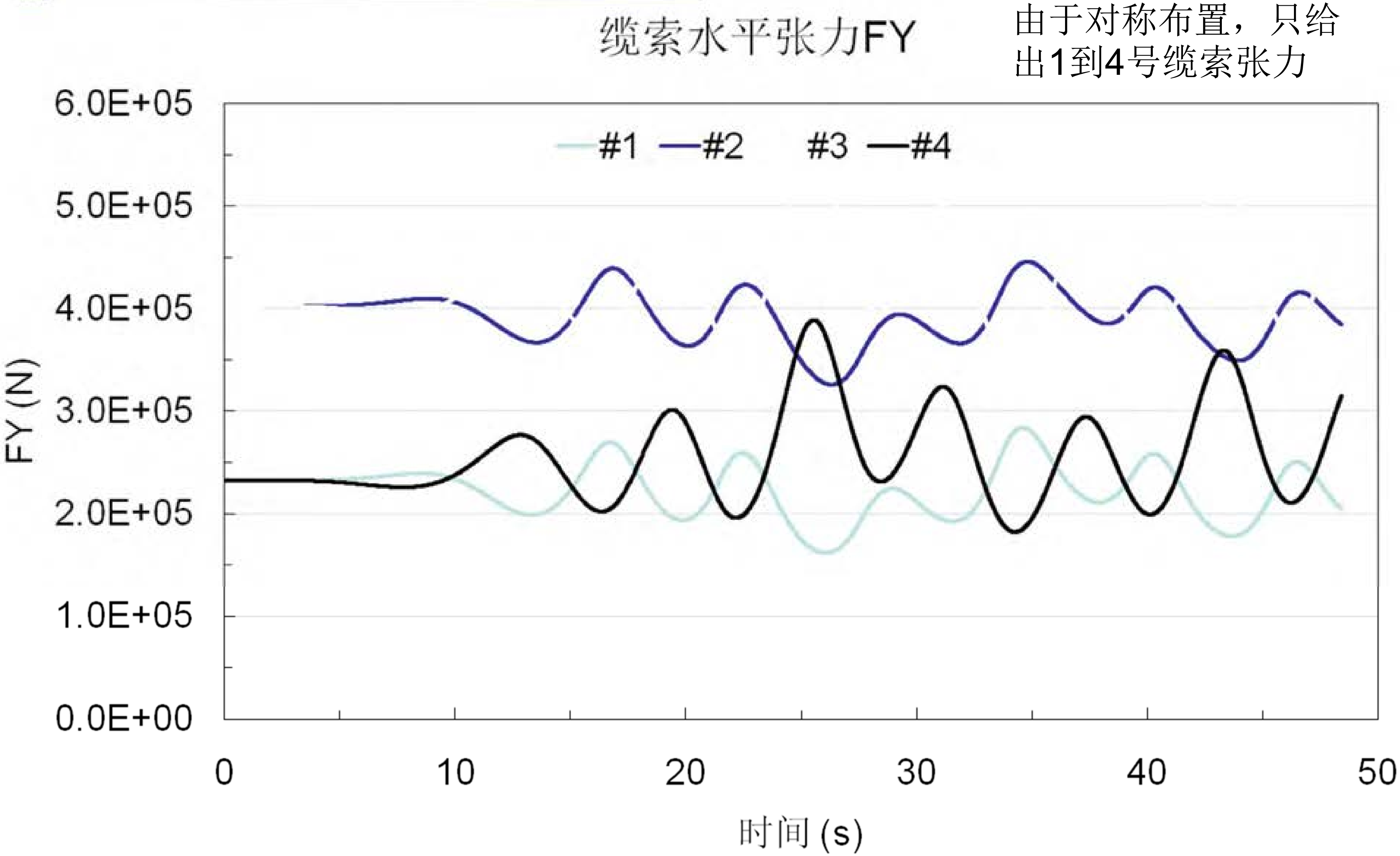
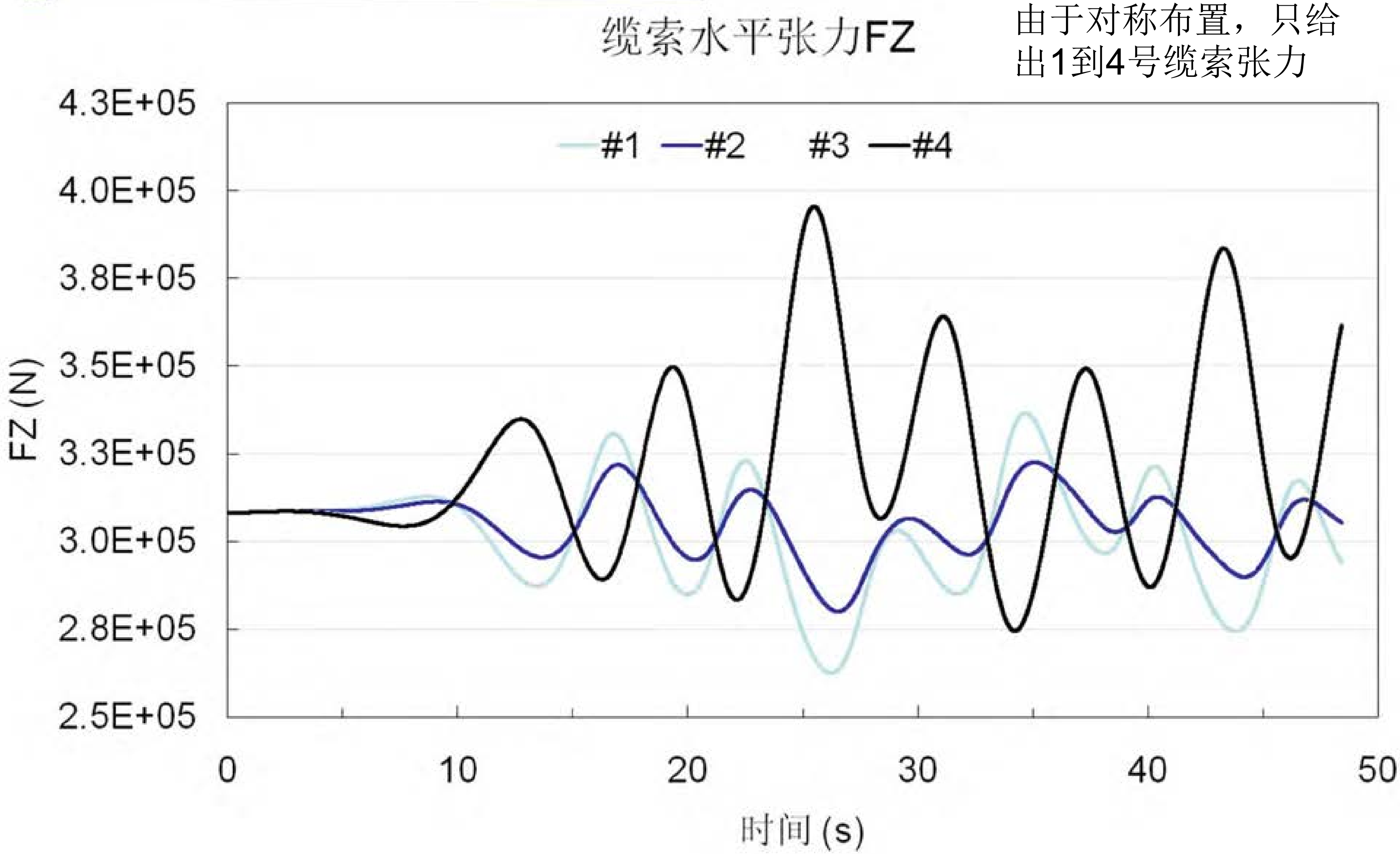
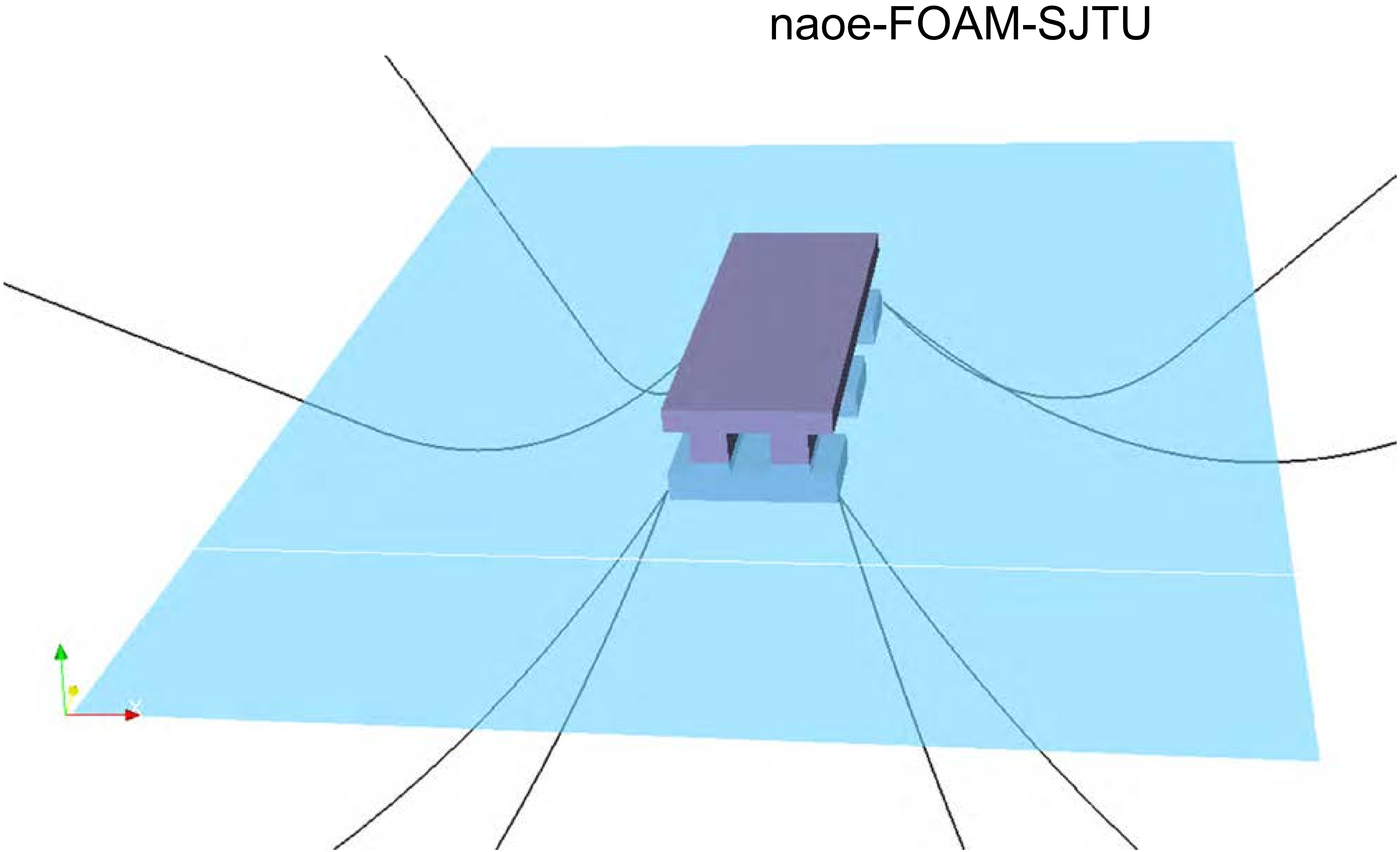


缆索张力曲线

由于对称布置，只给出1到4号缆索张力

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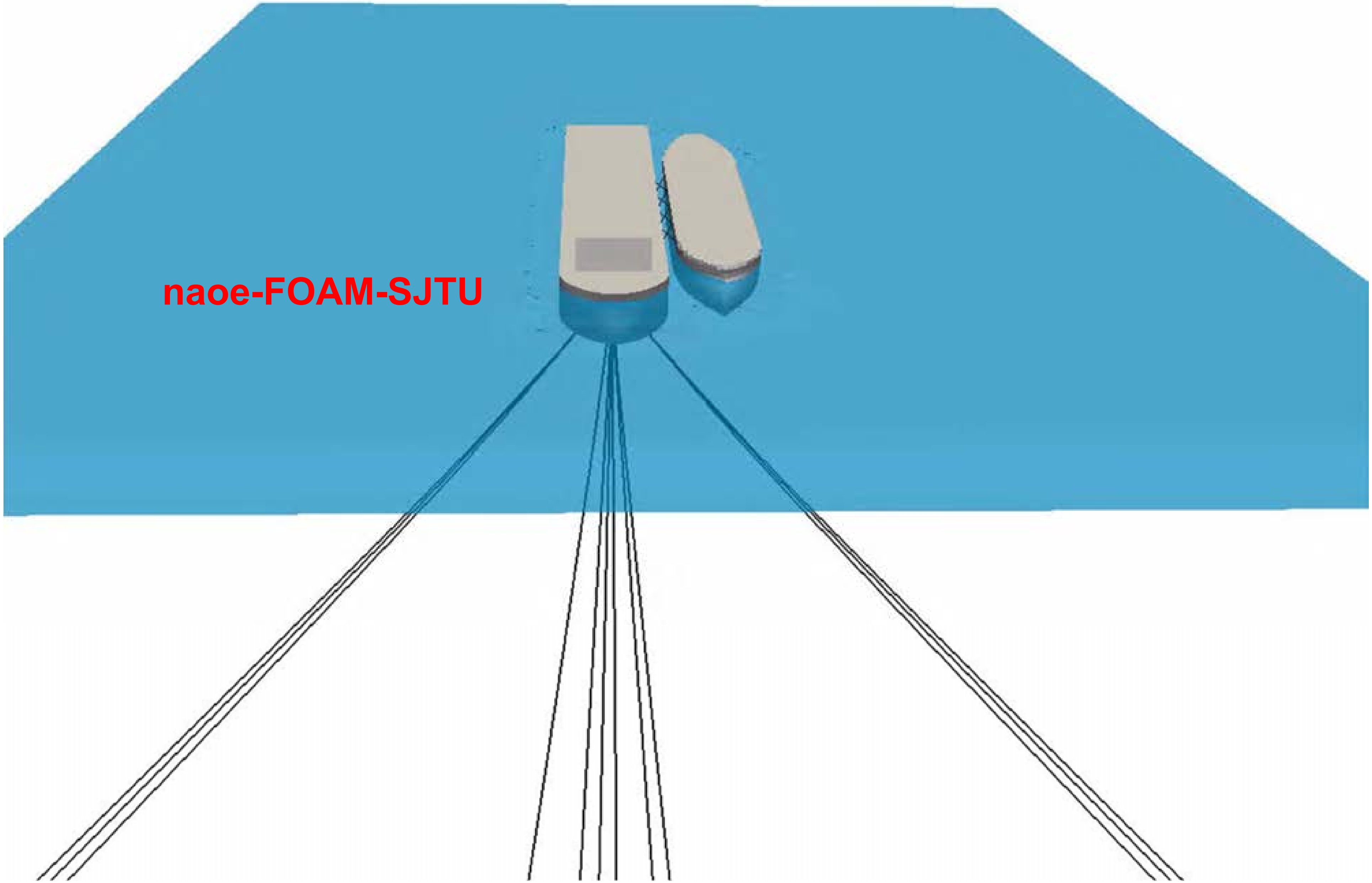
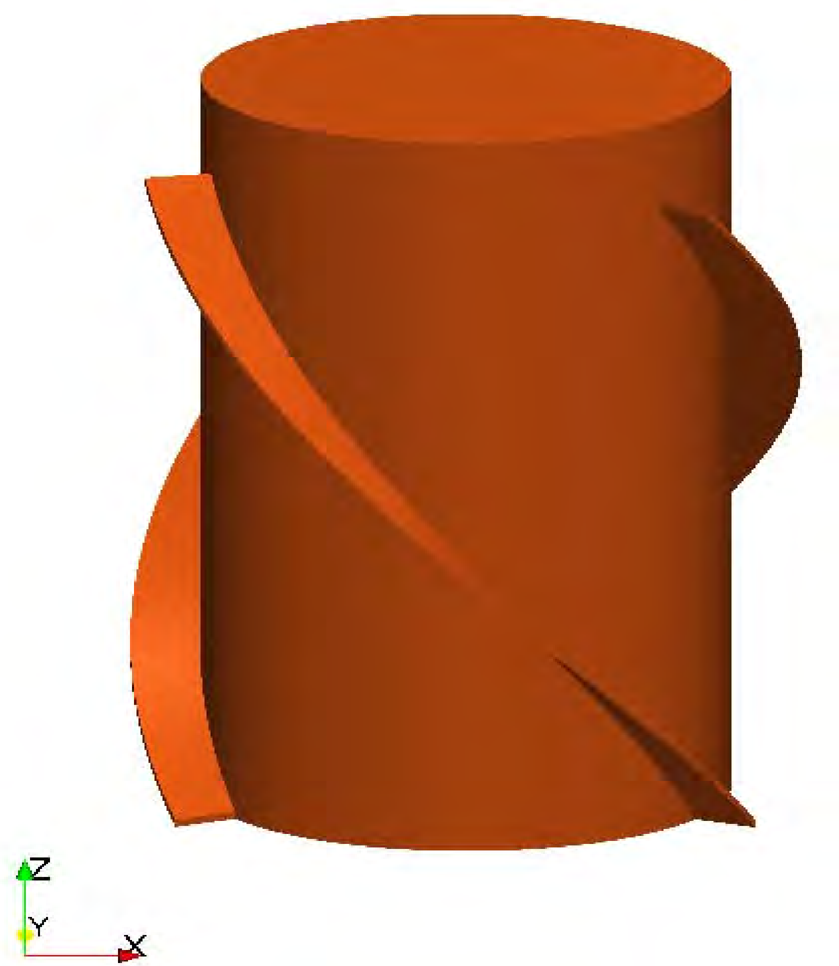
FLNG

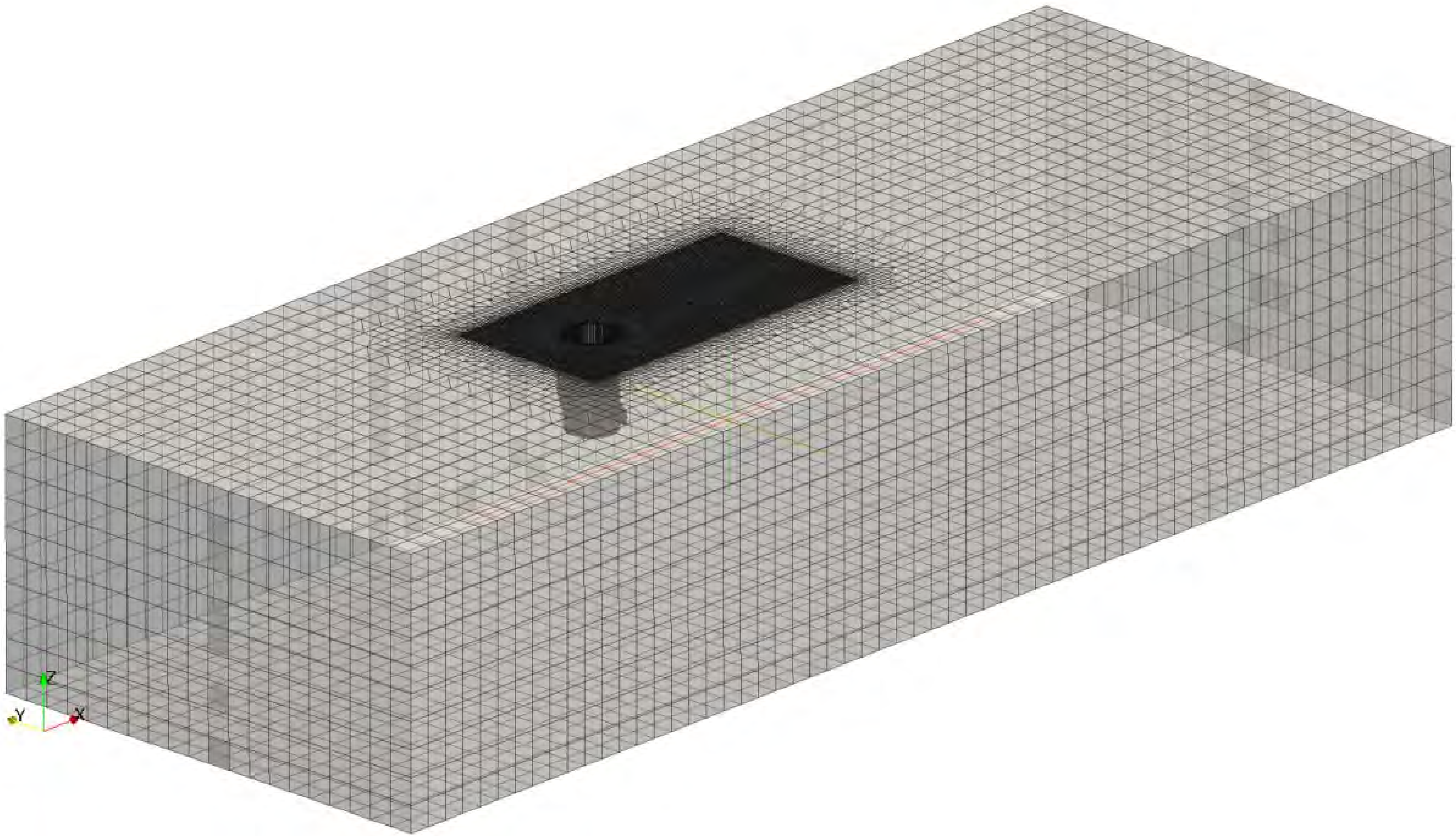


Numerical simulation of Spar VIM

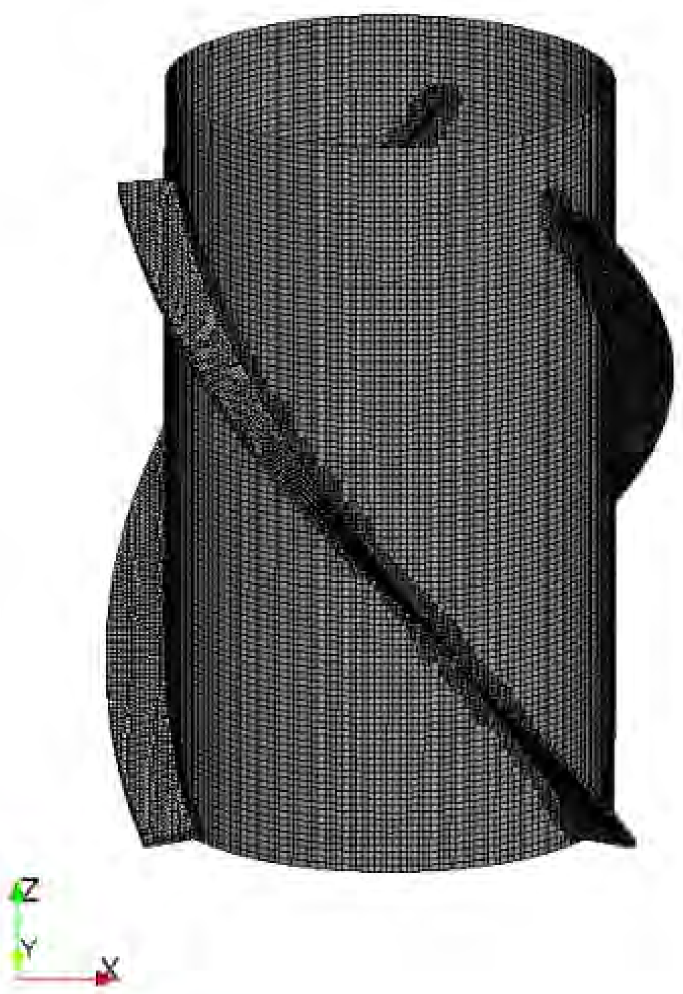


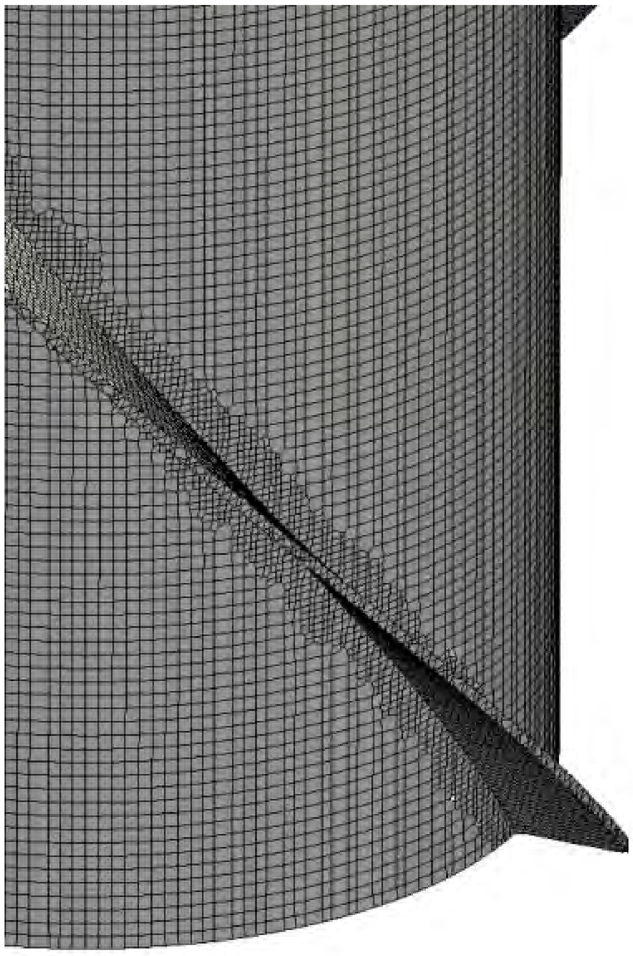
DTMB Spar

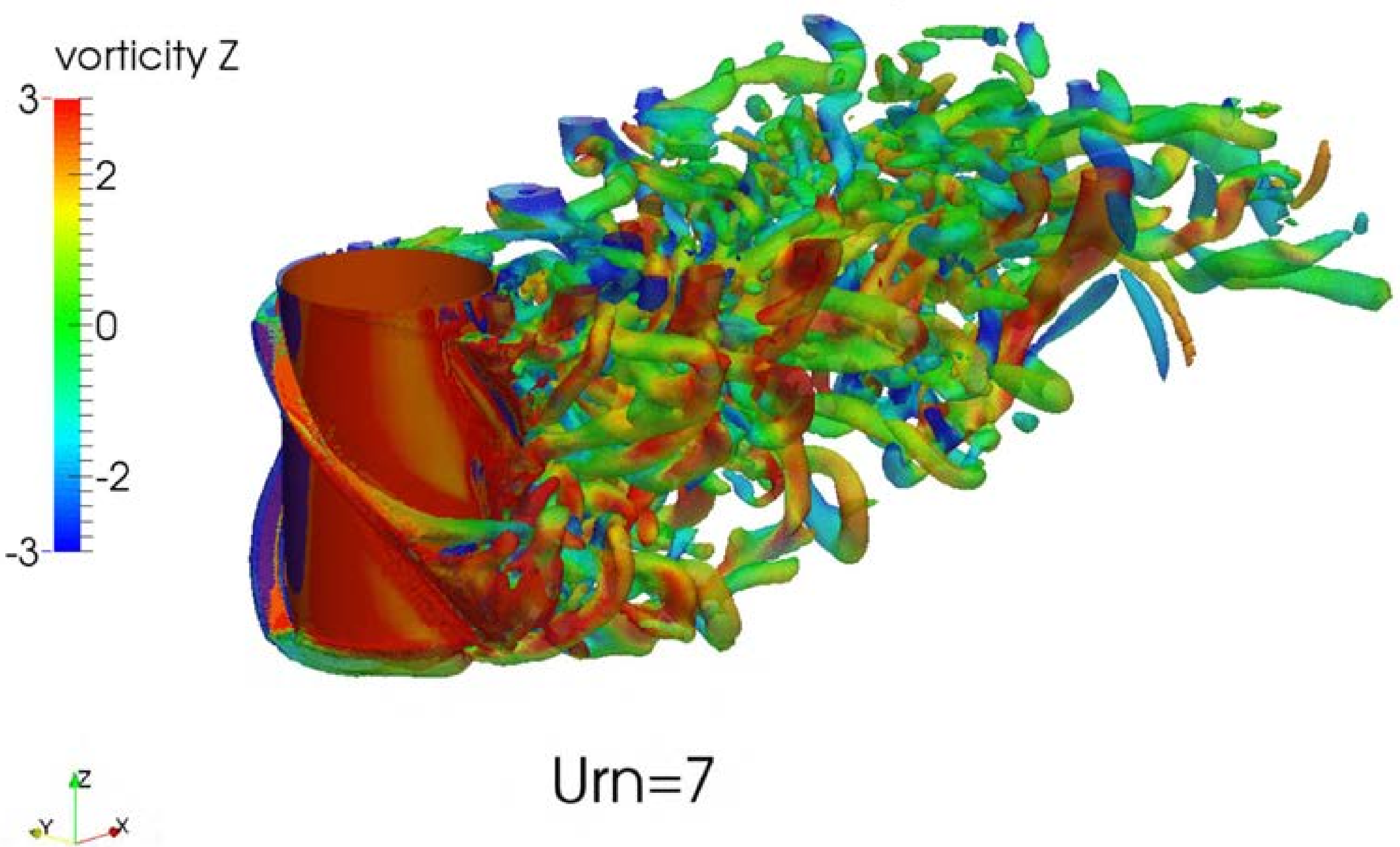
mesh



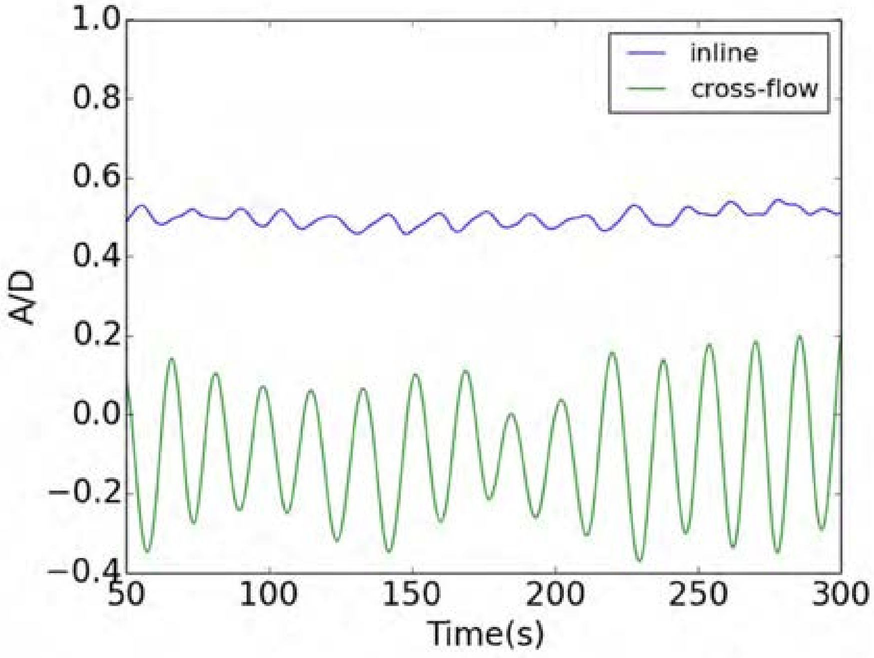
mesh



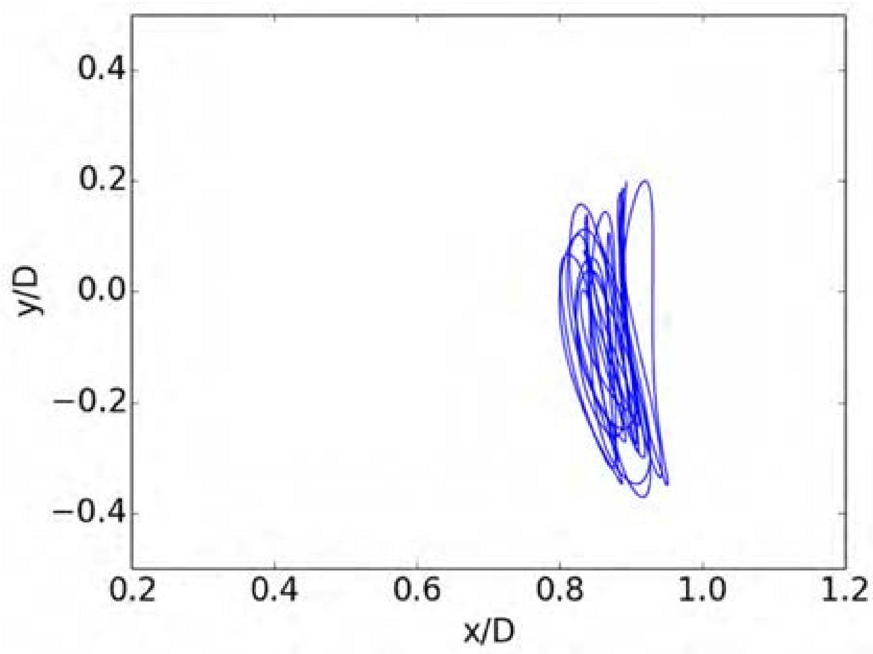



vorticity Z
3
2
0
-2
-3
Urn=7
Z
Y
X

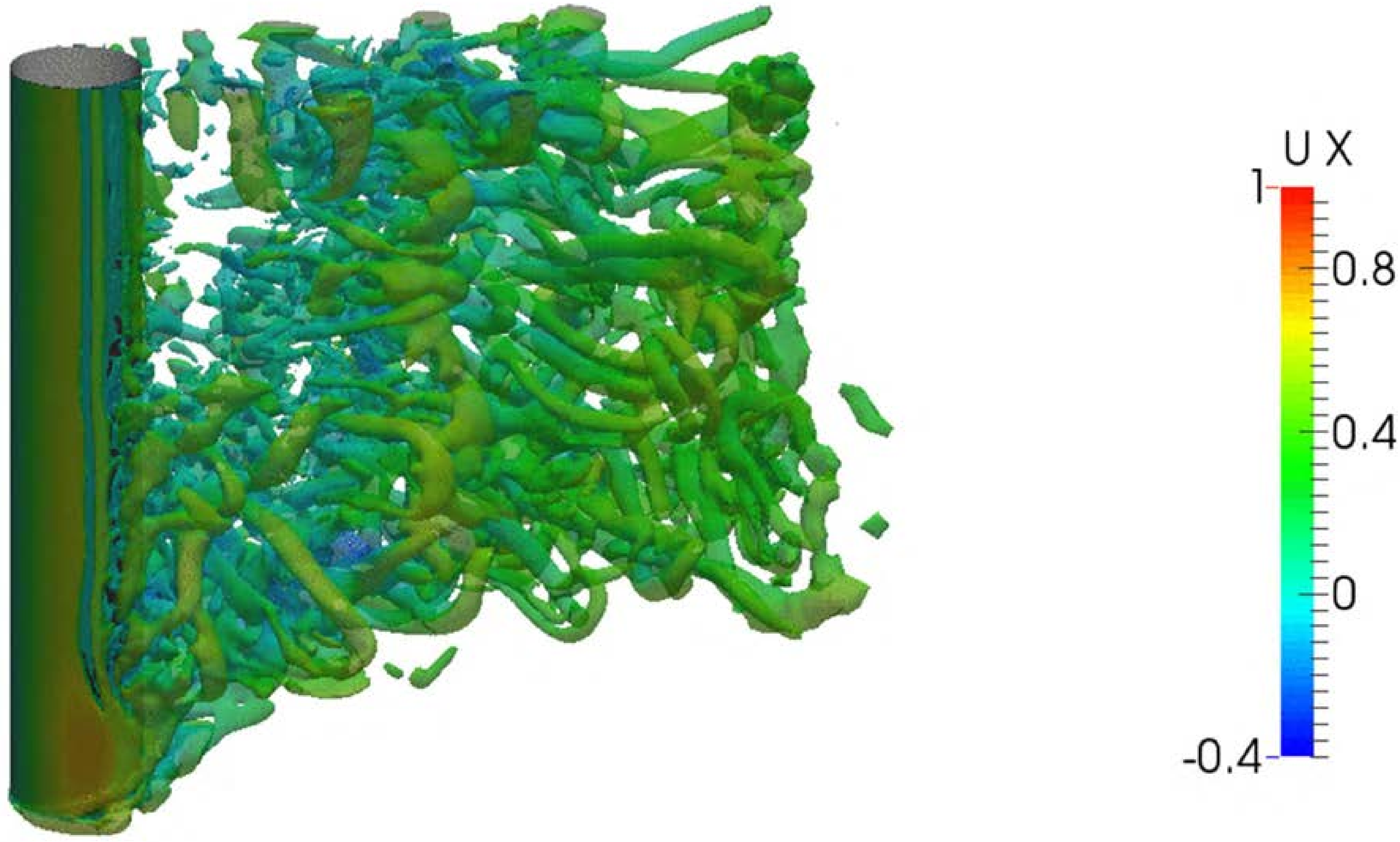
DTMB Spar模型计算结果（U_{rn}=8）



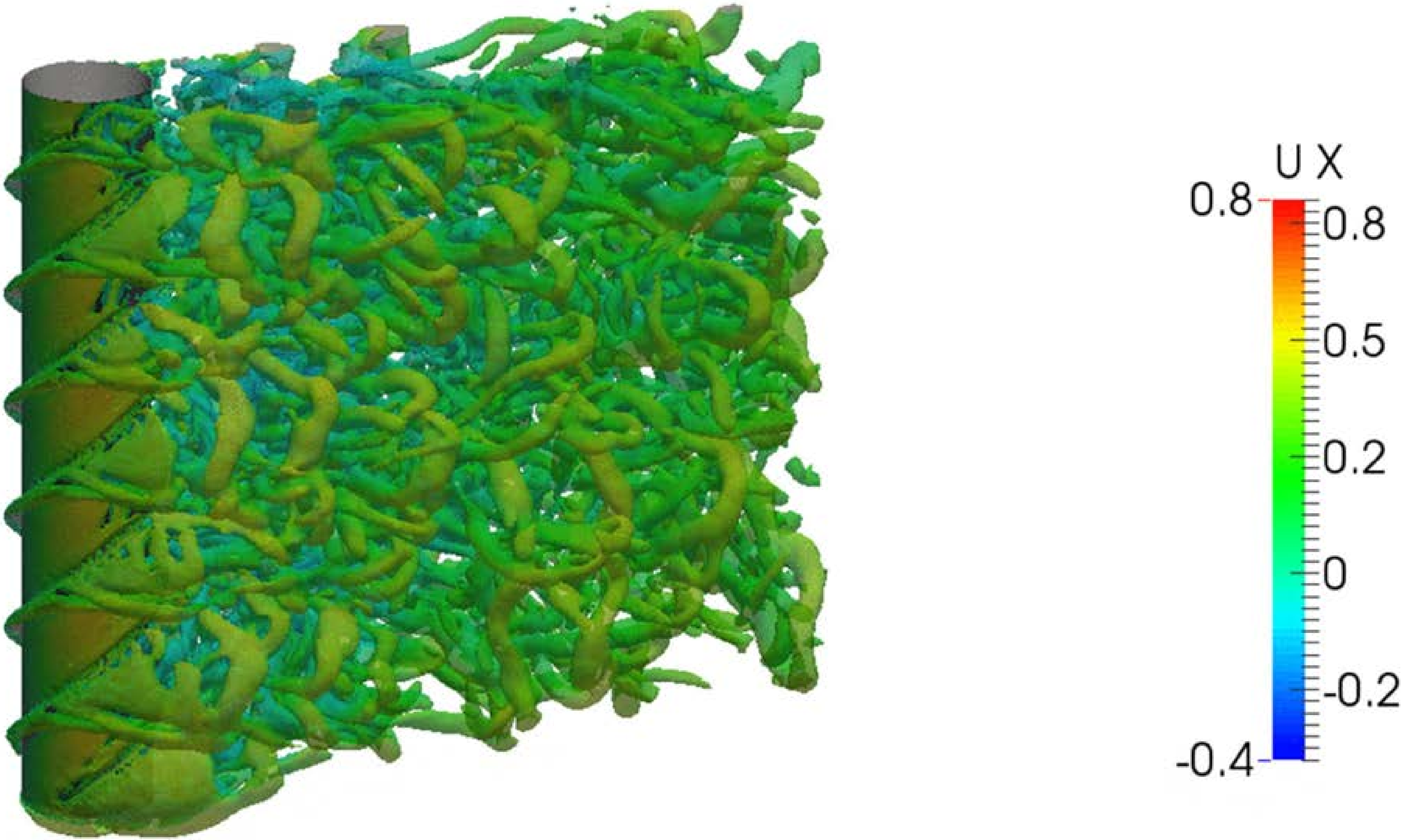
位移随时间变化图



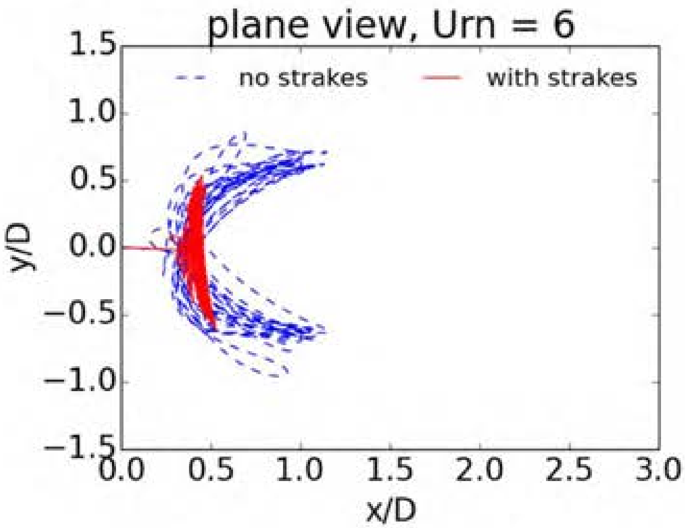
运动轨迹

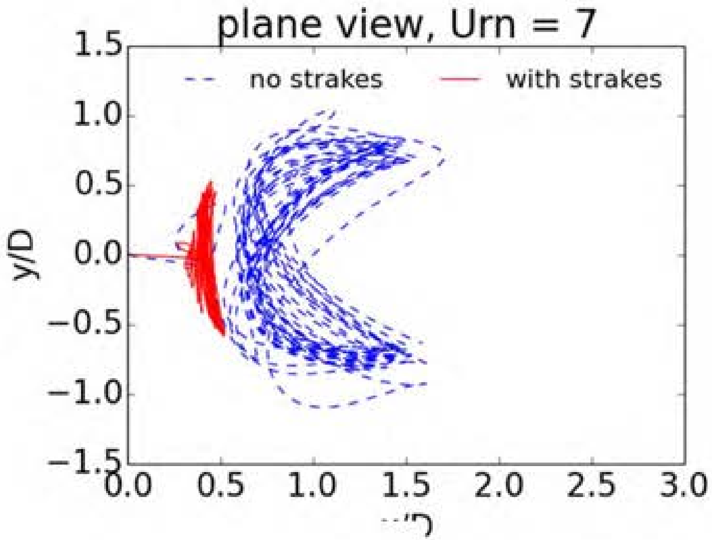


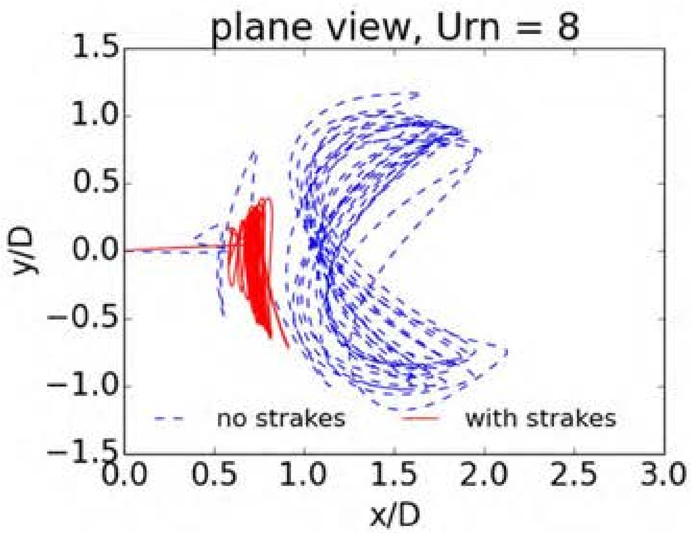
Urn=7, without strakes

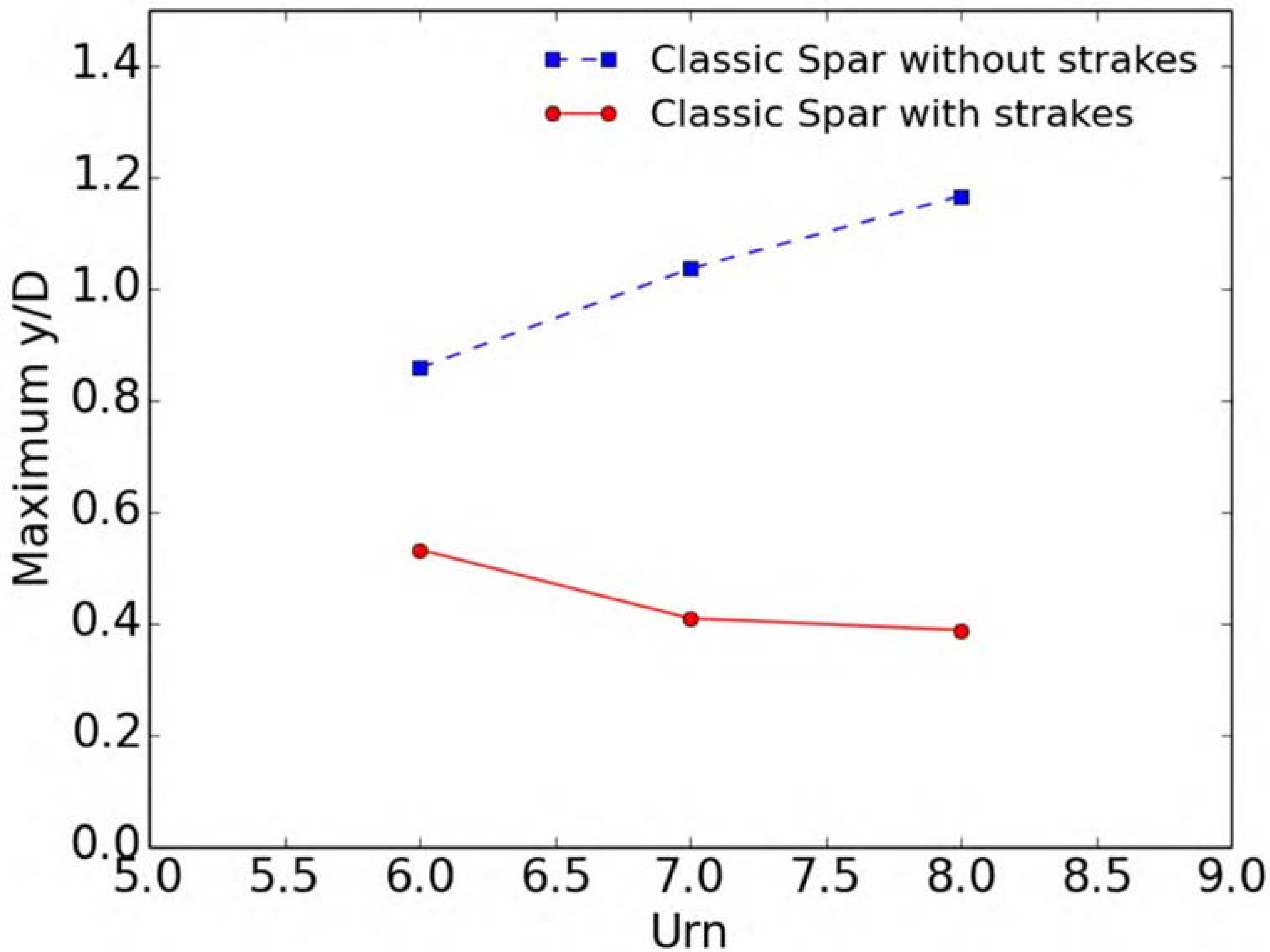


Urn=7, with strakes


plane view, Urn = 6
no strakes
with strakes
y/D
x/D
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.0 0.5 1.0 1.5 2.0 2.5 3.0

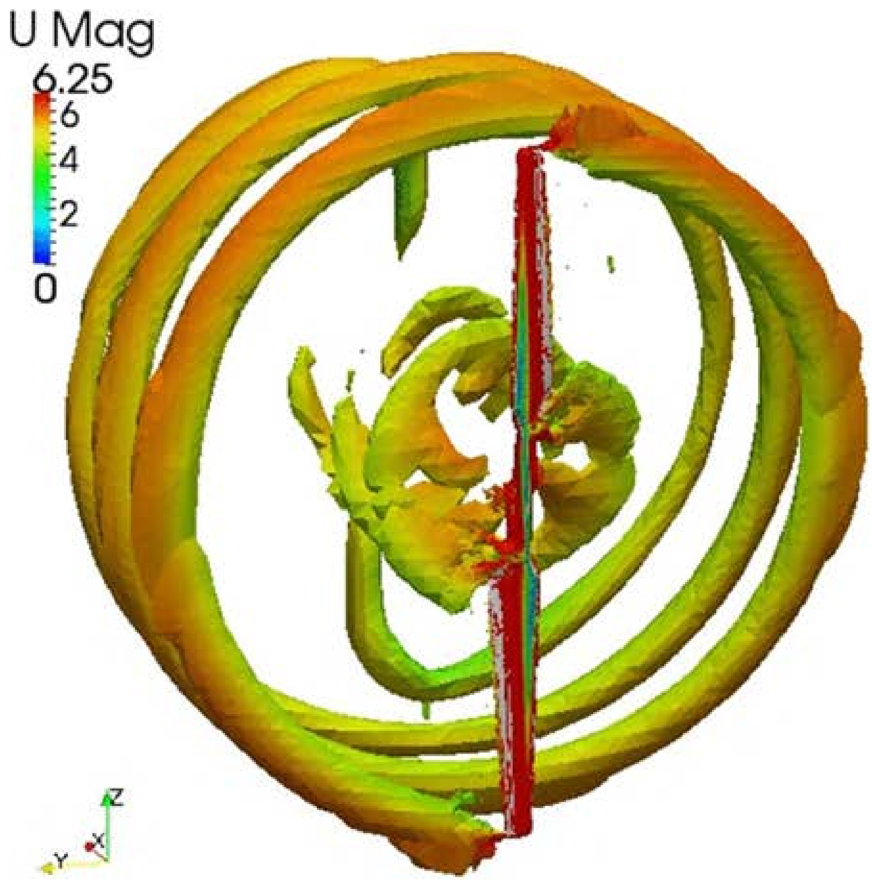

plane view, Urn = 7
no strakes
with strakes
y/D
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.0 0.5 1.0 1.5 2.0 2.5 3.0


plane view, Urn = 8
no strakes
with strakes
y/D
x/D
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.0 0.5 1.0 1.5 2.0 2.5 3.0

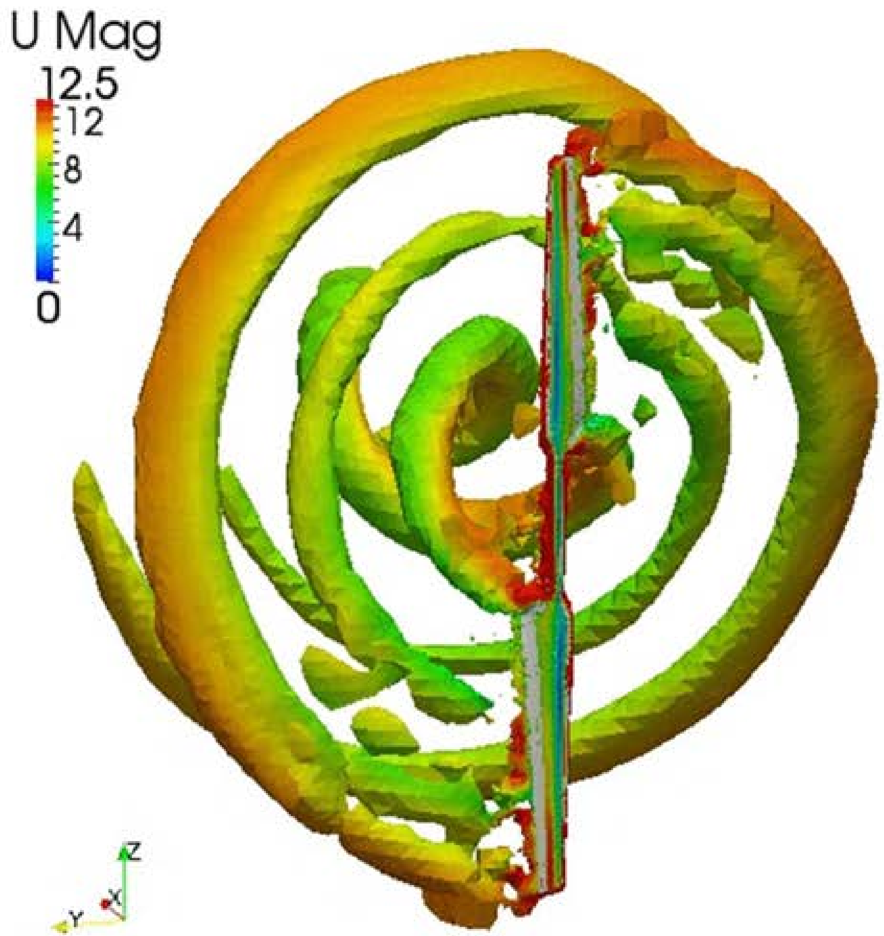

Classic Spar without strakes
Classic Spar with strakes
Maximum y/D
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
Urn

Offshore Wind Turbine Flows

Two Blades of Wind Turbine



U=5m/s Q=1.2



U=10m/s Q=5

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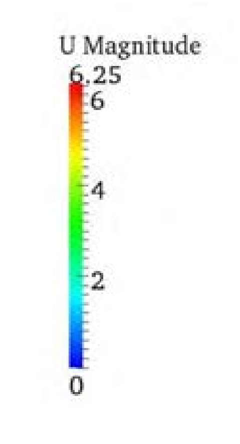
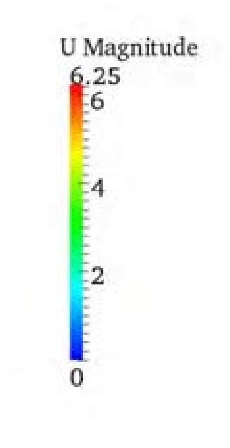
Two Blades of Wind Turbine

U = 10m/s, inlet angle =10

U=25m/s, inlet angle=10

Two Blades of Wind Turbine





U = 5m/s, inlet angle =10

U=5m/s, inlet angle=30

Three Blades of Wind Turbine

V=5m/s

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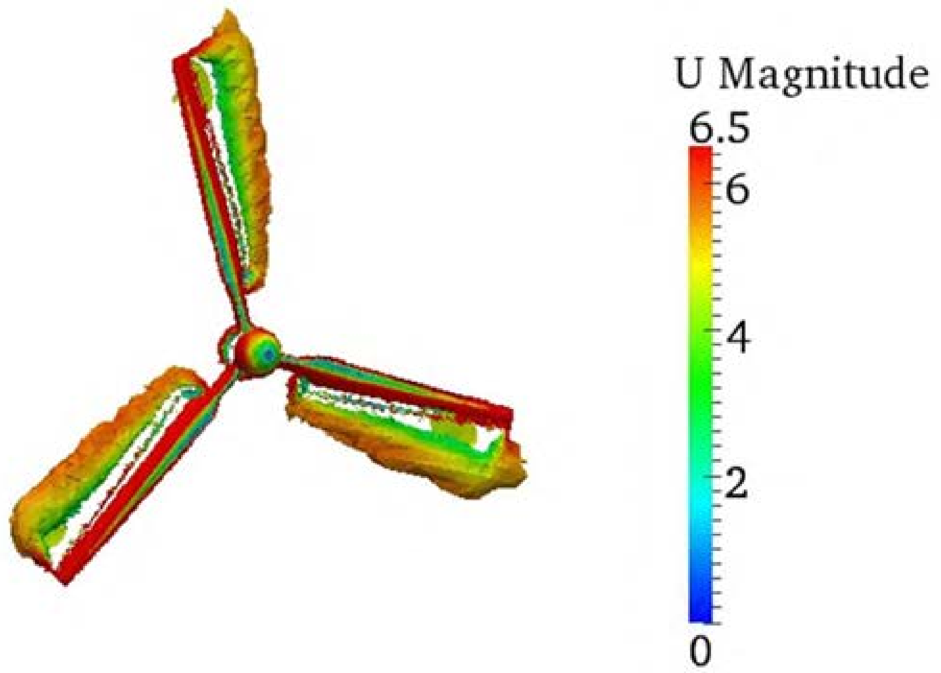

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Three Blades of Wind Turbine

V=15m/s

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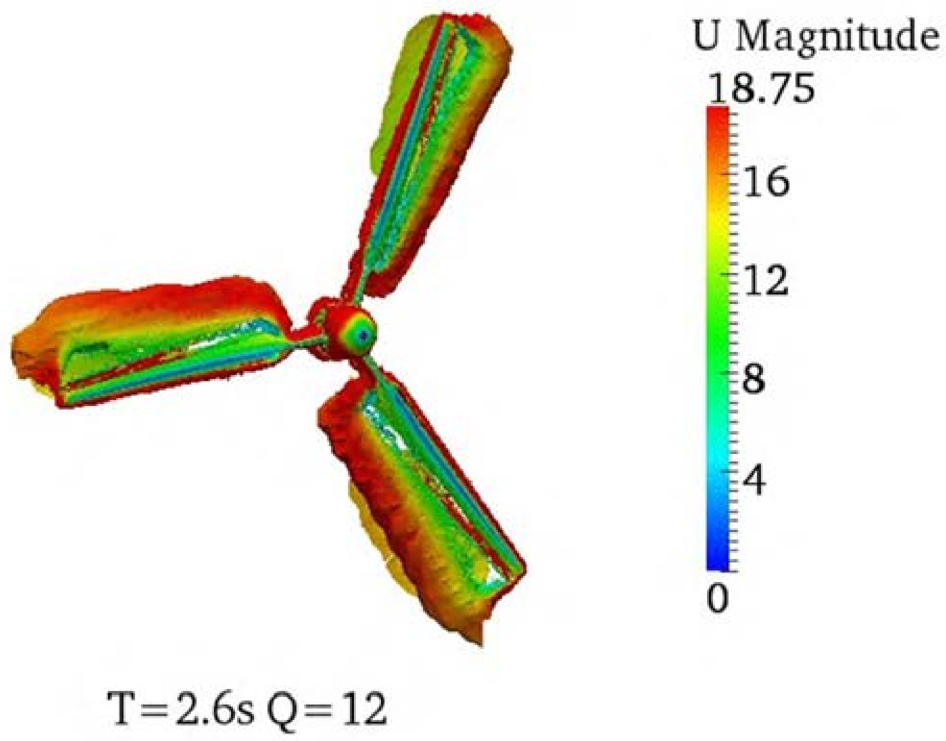

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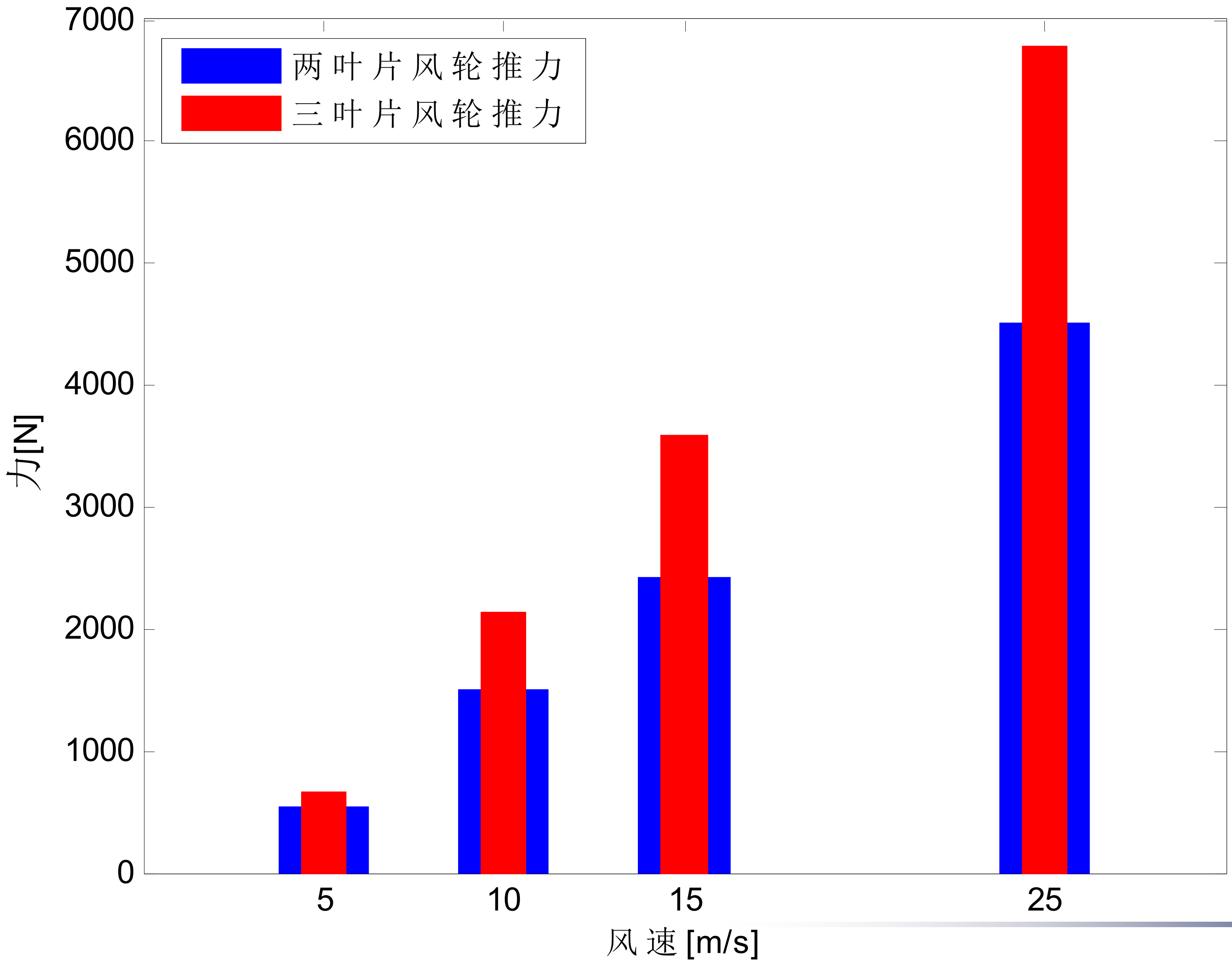
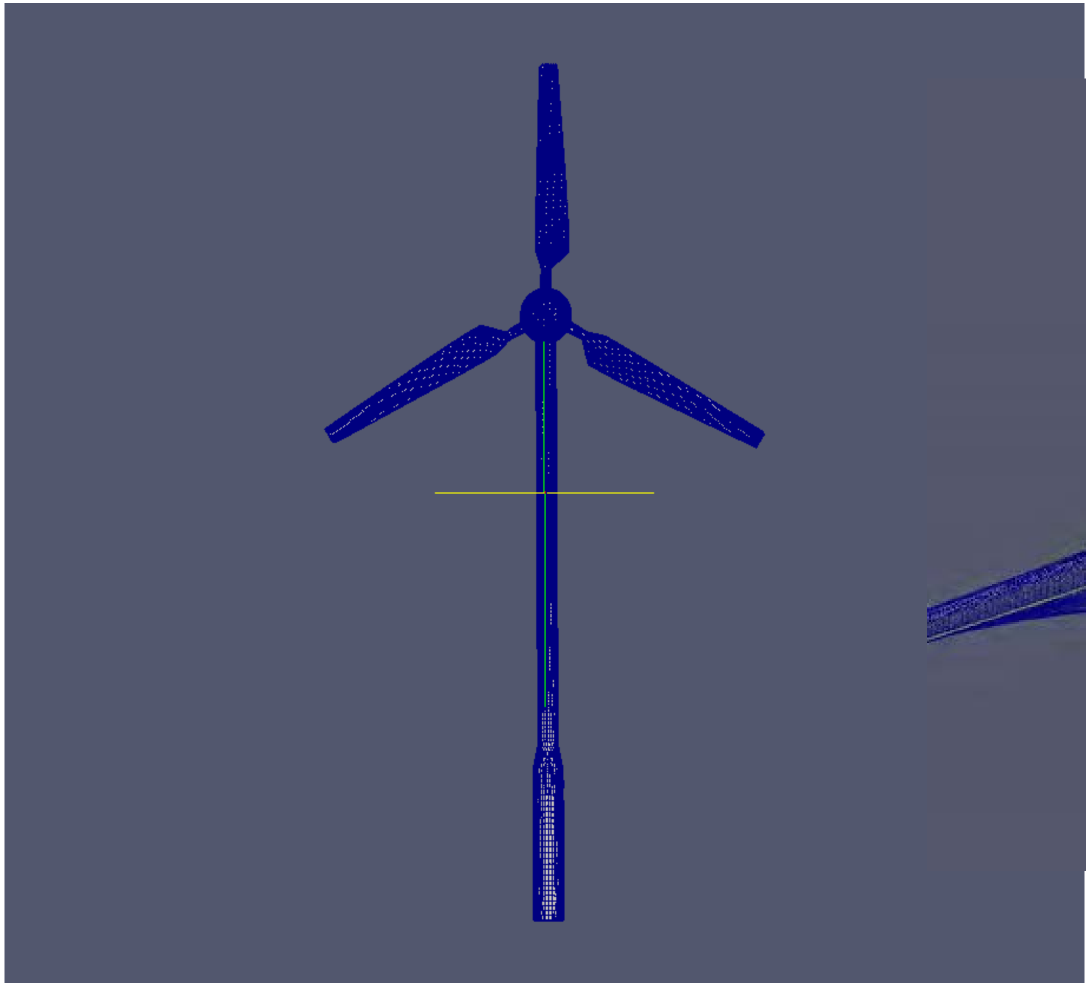
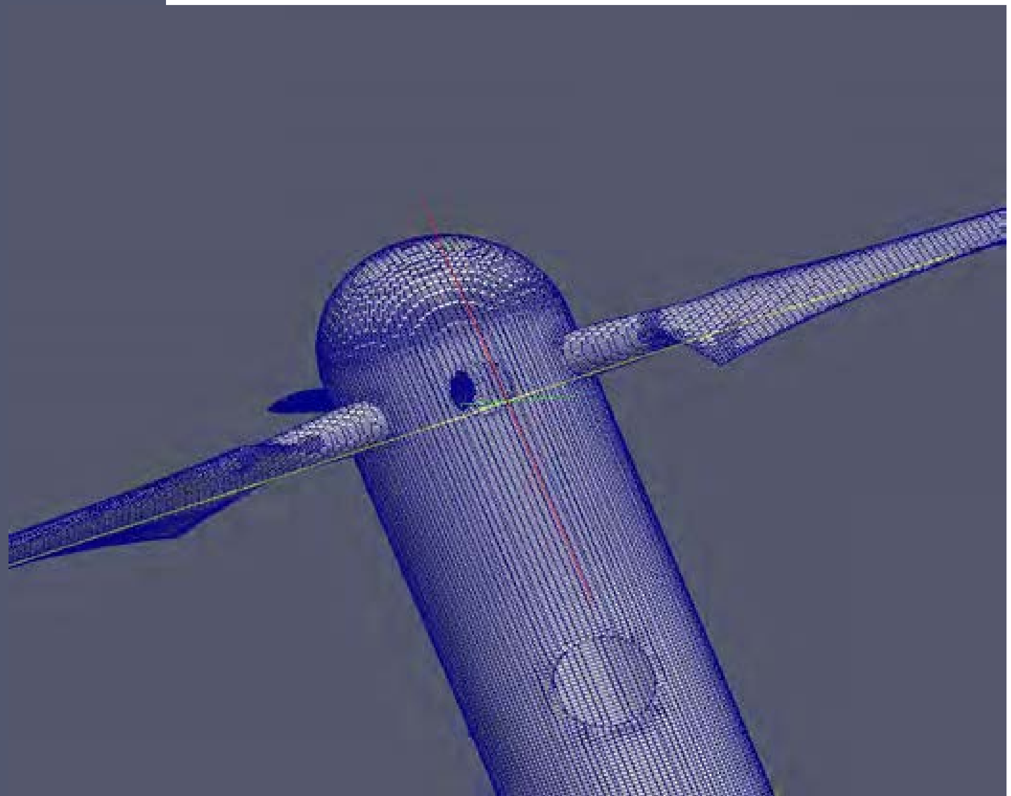
Three Blades



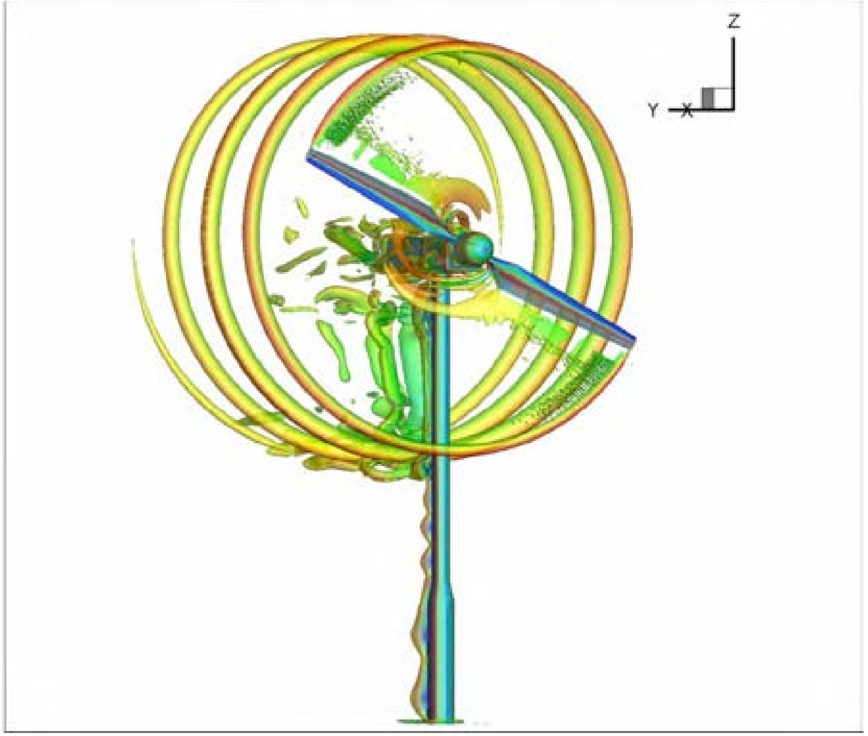
Wind Turbine with supporting Tower





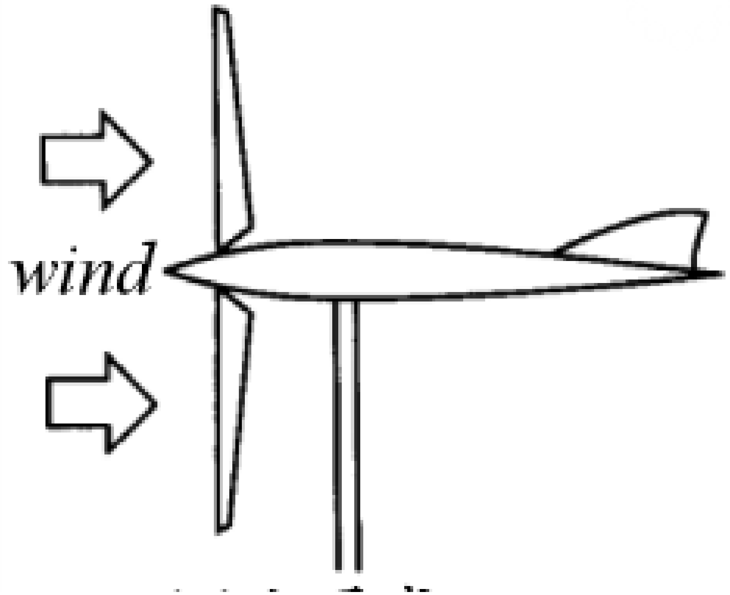
Wind Turbine with supporting Tower

Flow visualization

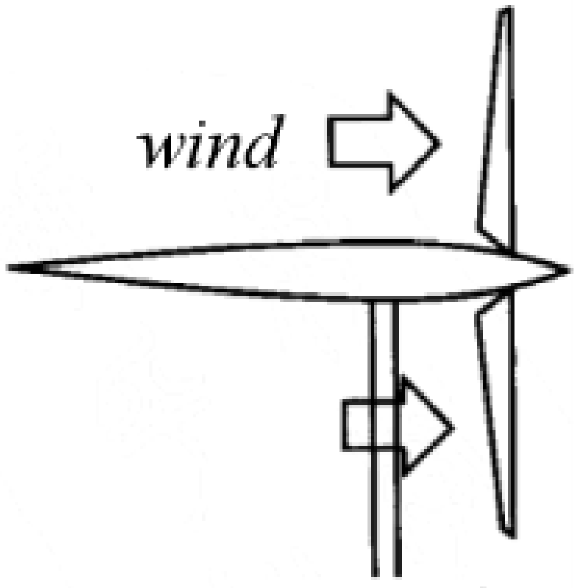


Wind speed = 5 m/s

Downwind configuration

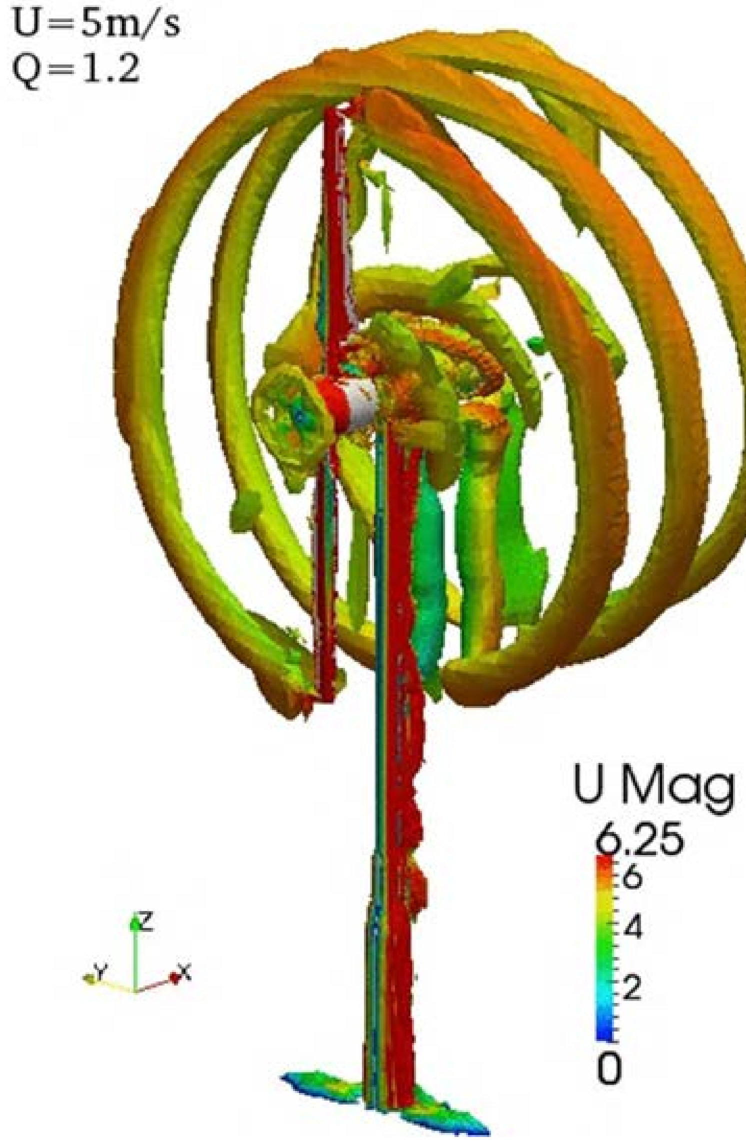


Upwind turbine



Downwind turbine

Wind Turbine with supporting Tower



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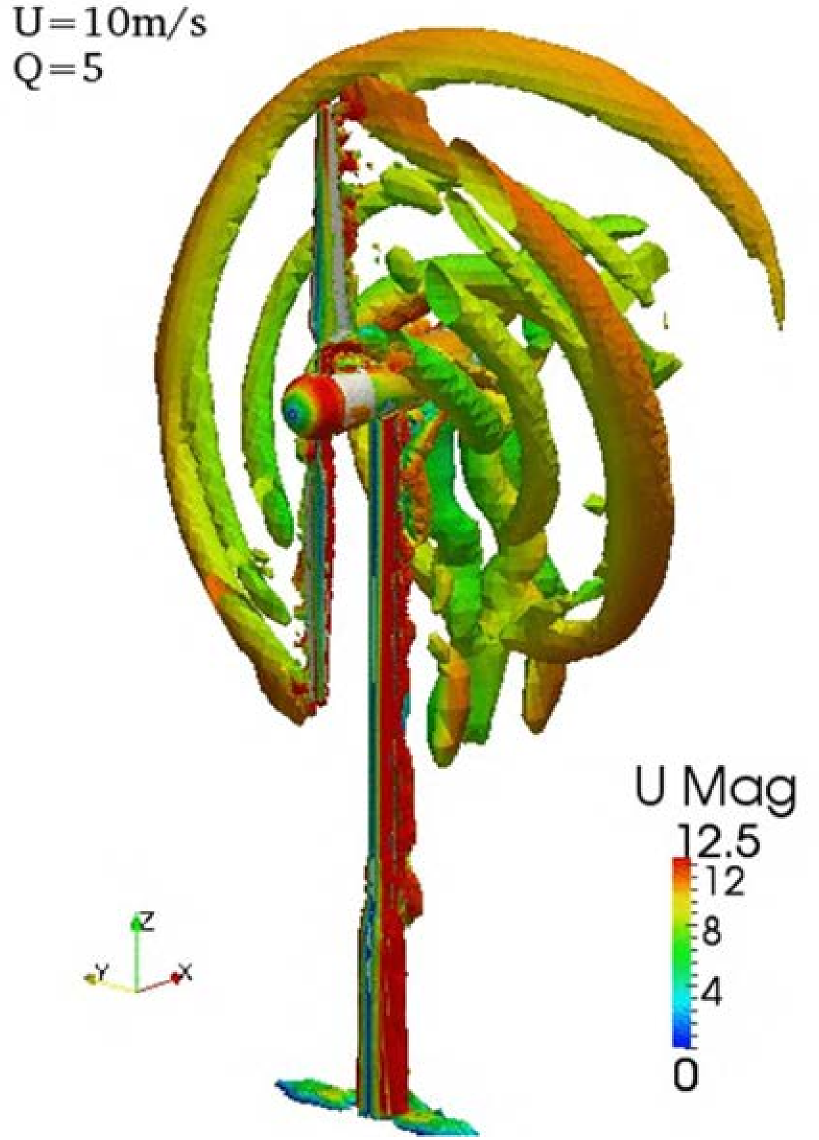
Wind Turbine with supporting Tower



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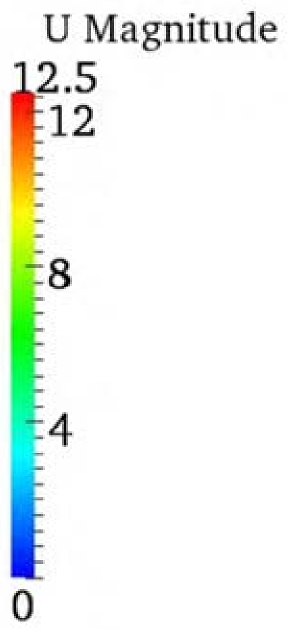
Wind Turbine with supporting Tower



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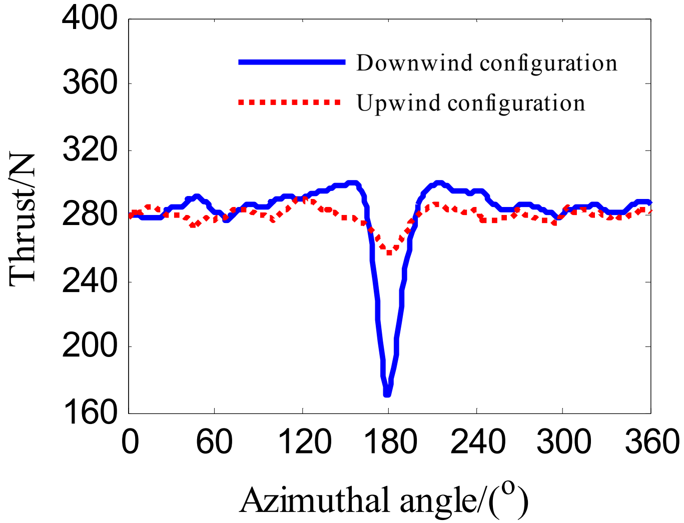
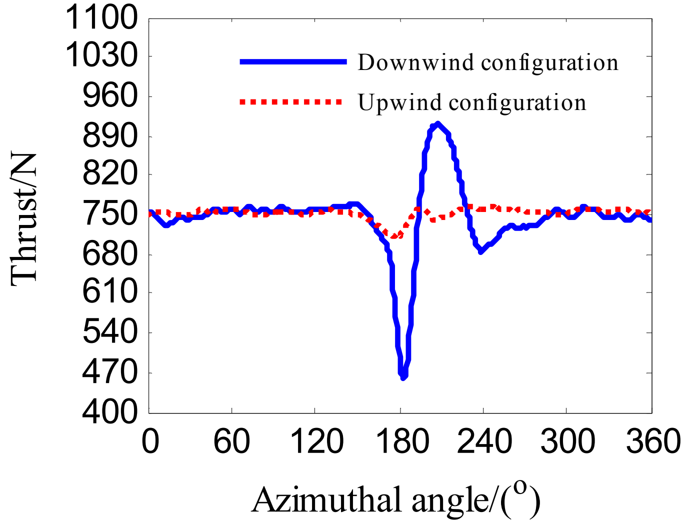
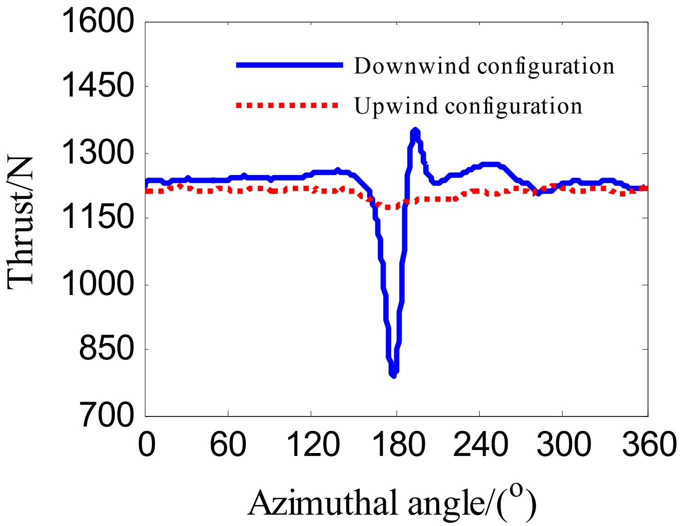
Wind Turbine with supporting Tower



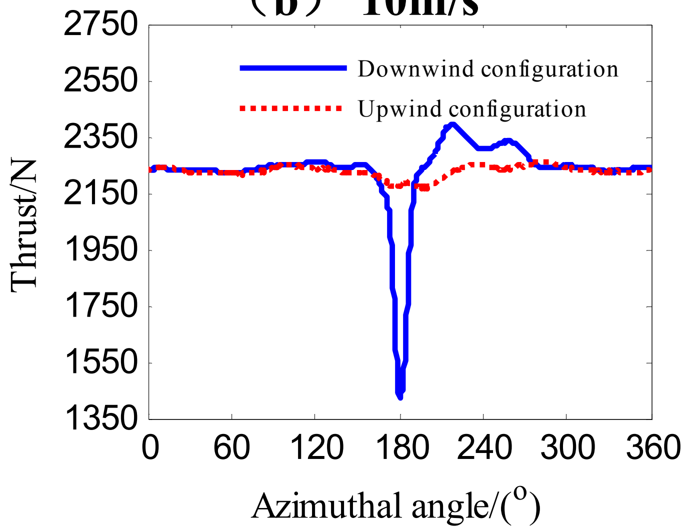
（a） 5m/s



（b） 10m/s

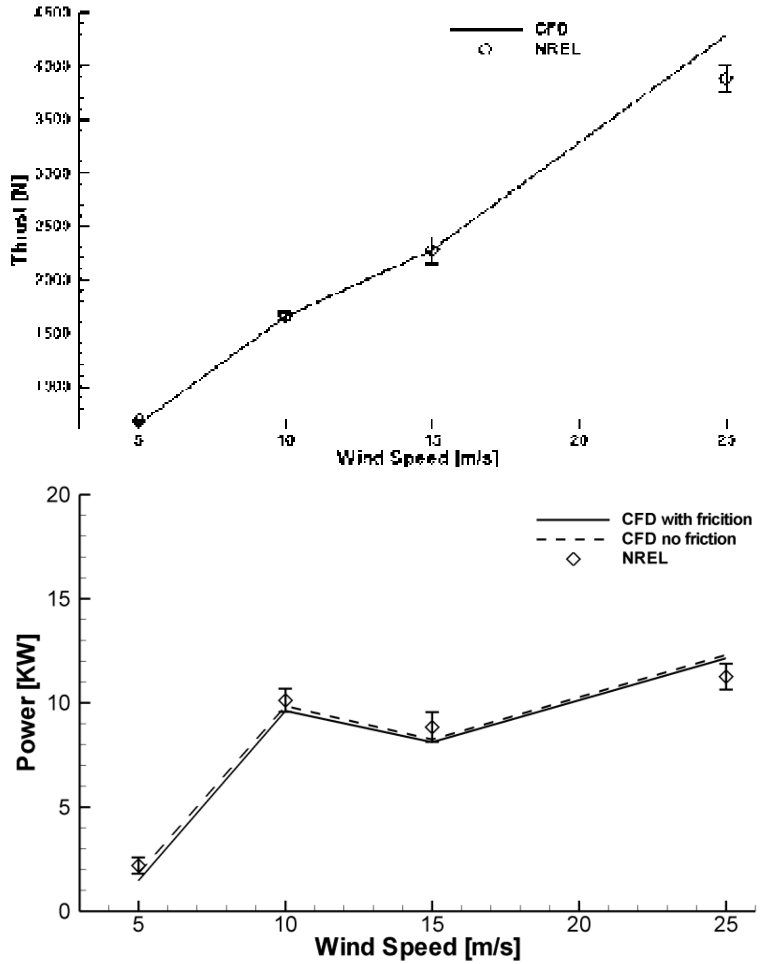


（c） 15m/s

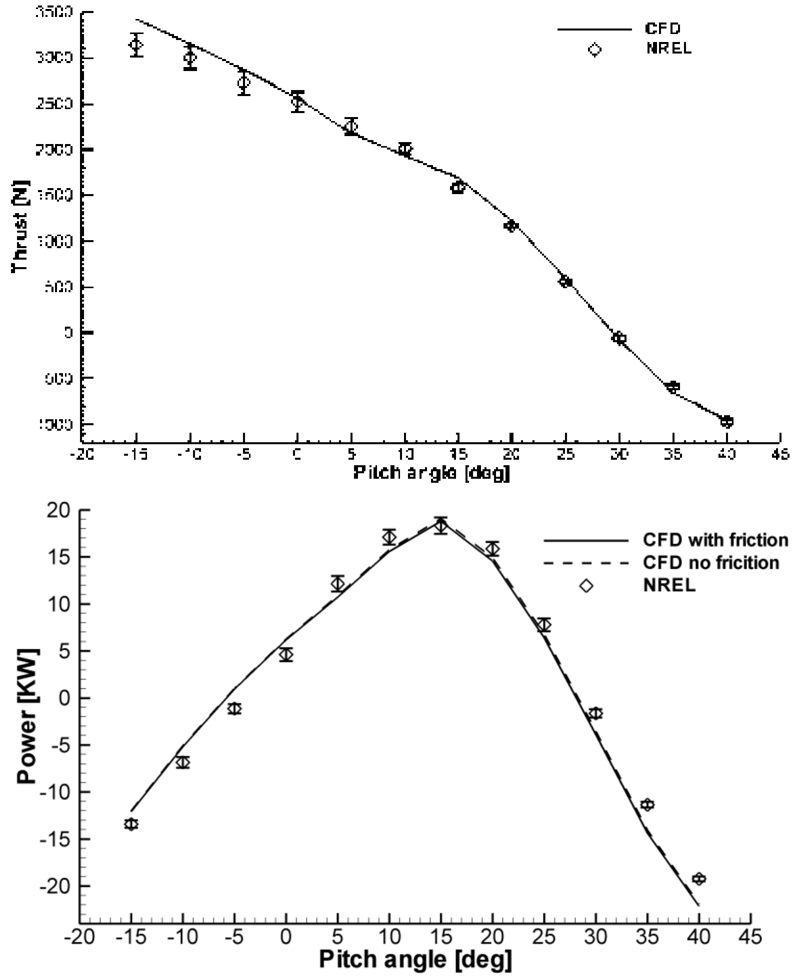


（d） 25m/s

Thrust and power

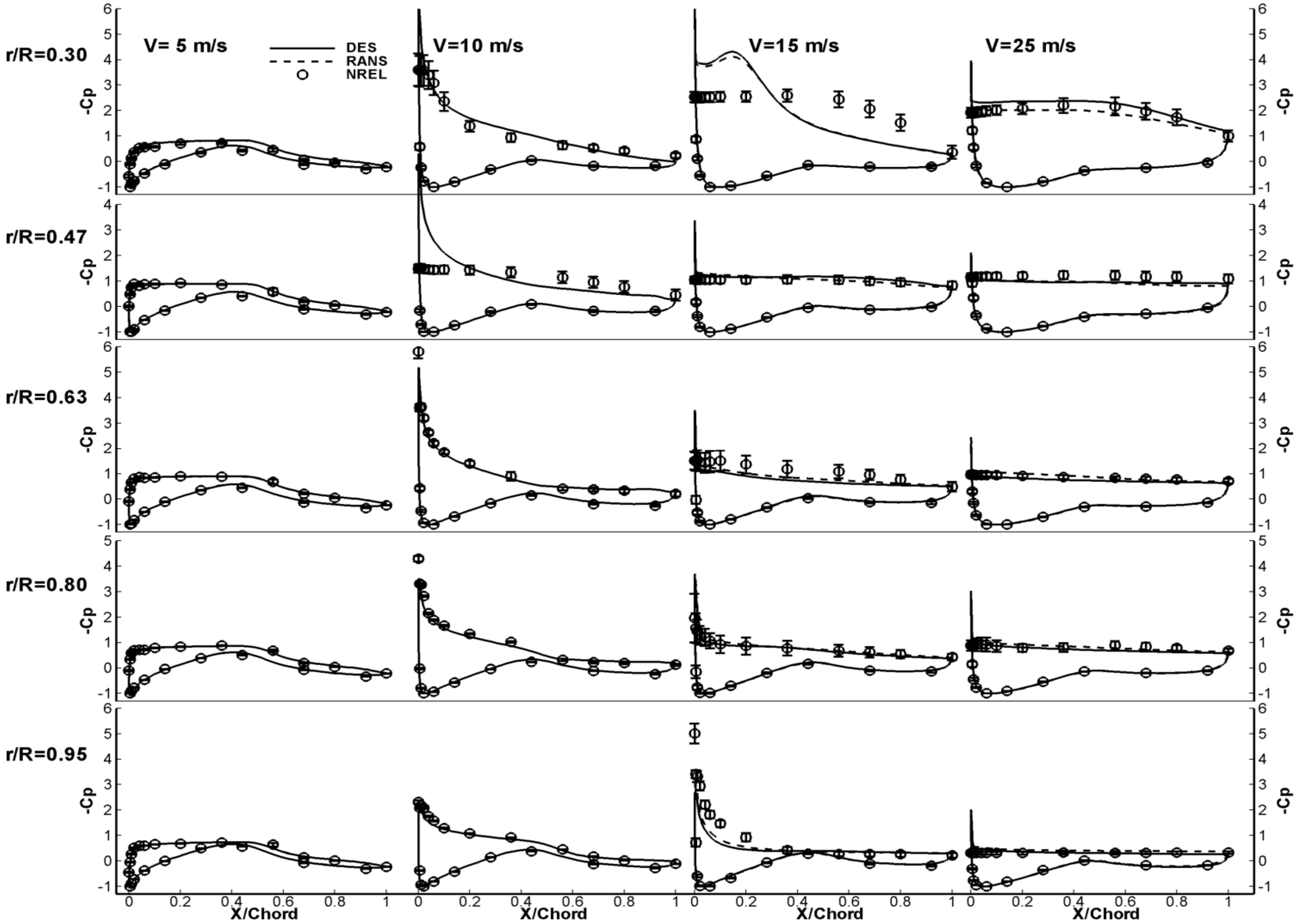


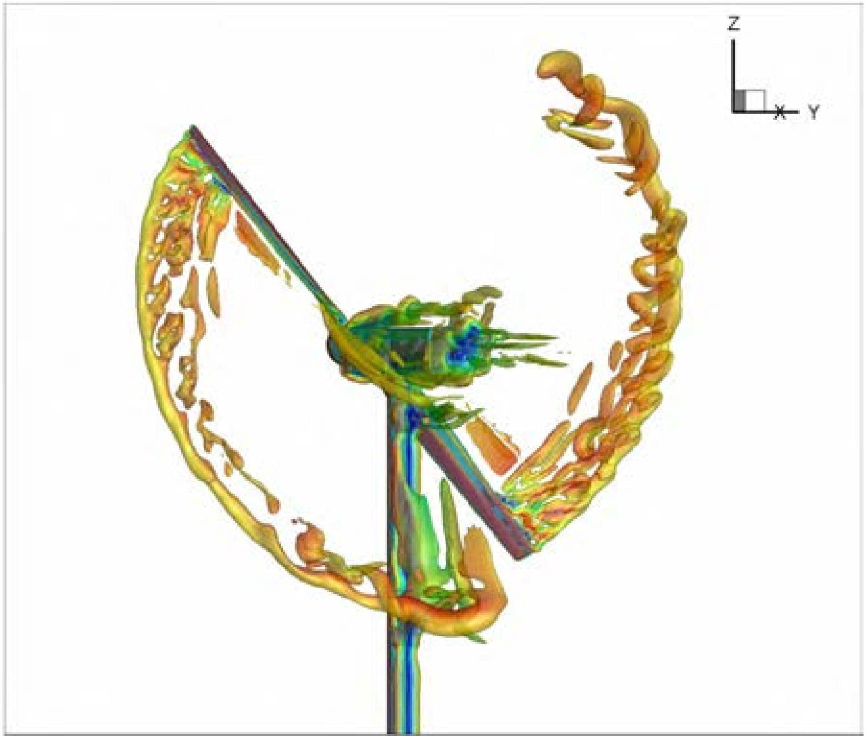
Effect of wind velocity (Sequence S)



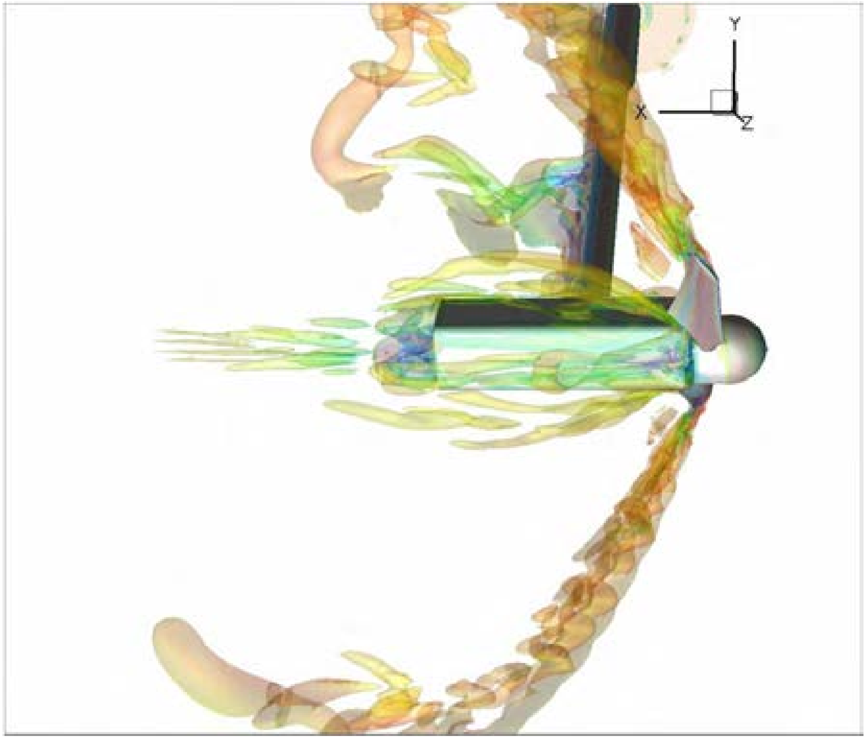
Effect of pitch angle (Sequence K)

Local Aerodynamic Performance (Cp)



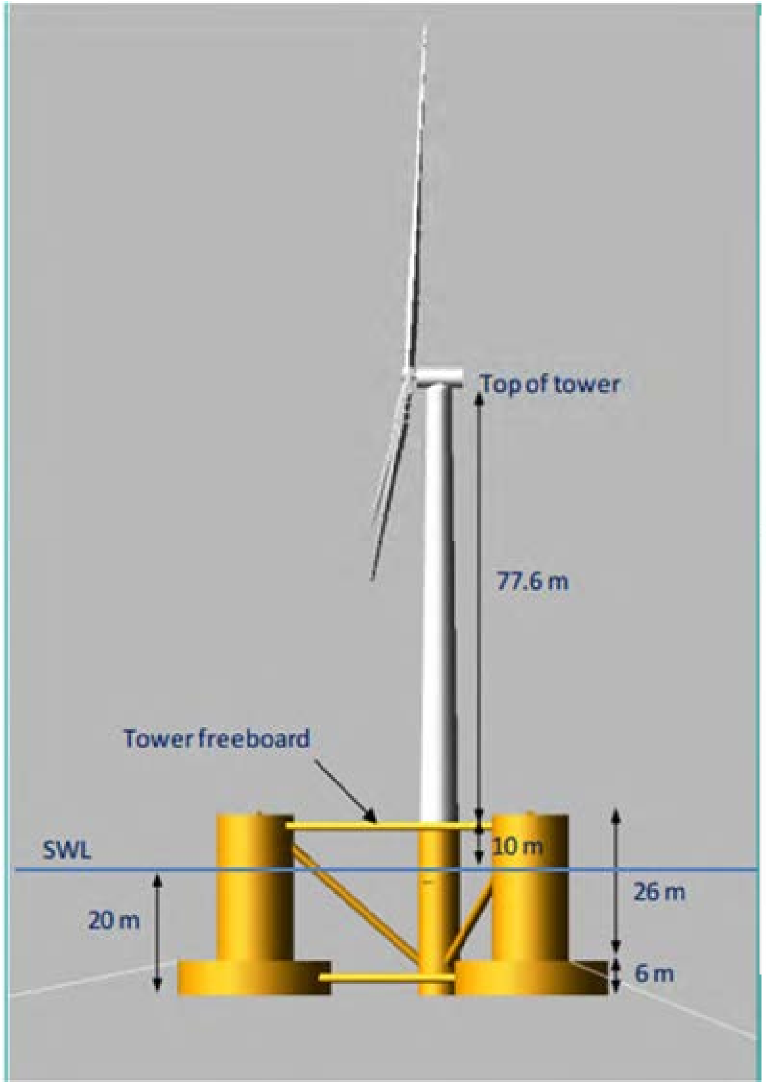


Variation of blade pitch angle
(rear view, earth system)

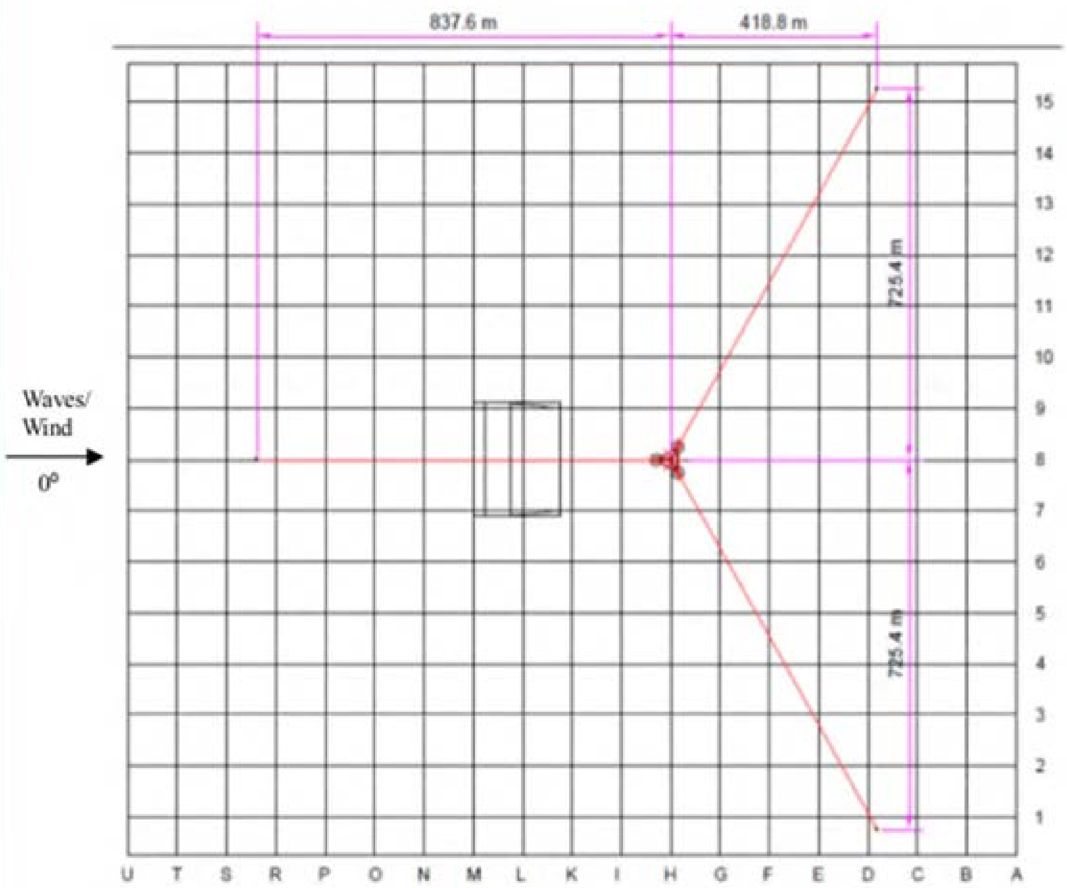


Variation of blade pitch angle
(blade system)

Floating offshore wind turbine

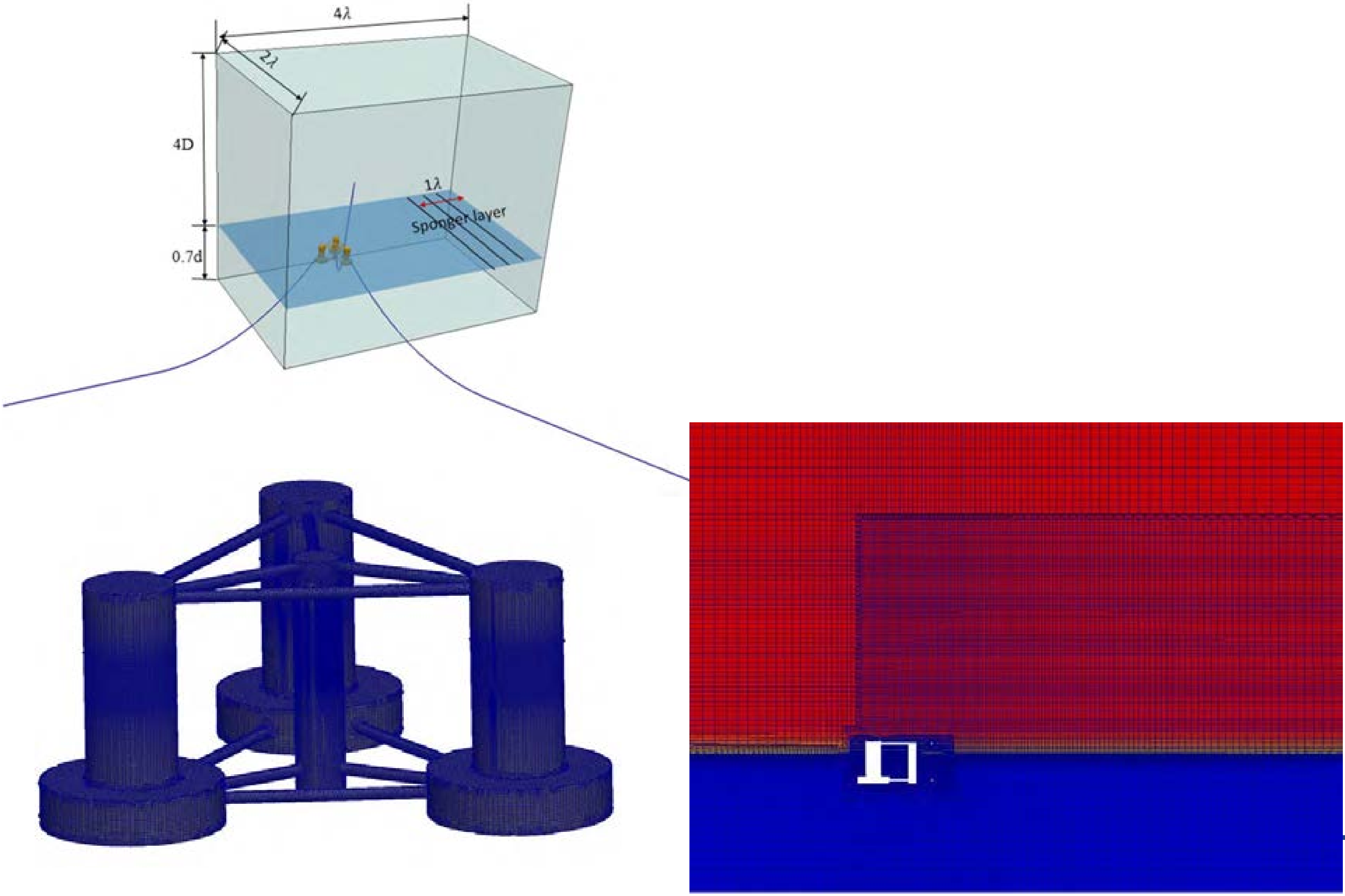


OC4 DeepCWind



Mooring system

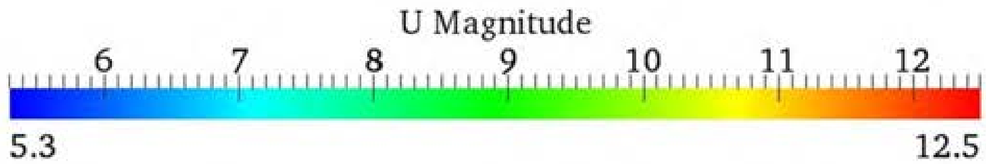
Floating offshore wind turbine



Floating offshore wind turbine

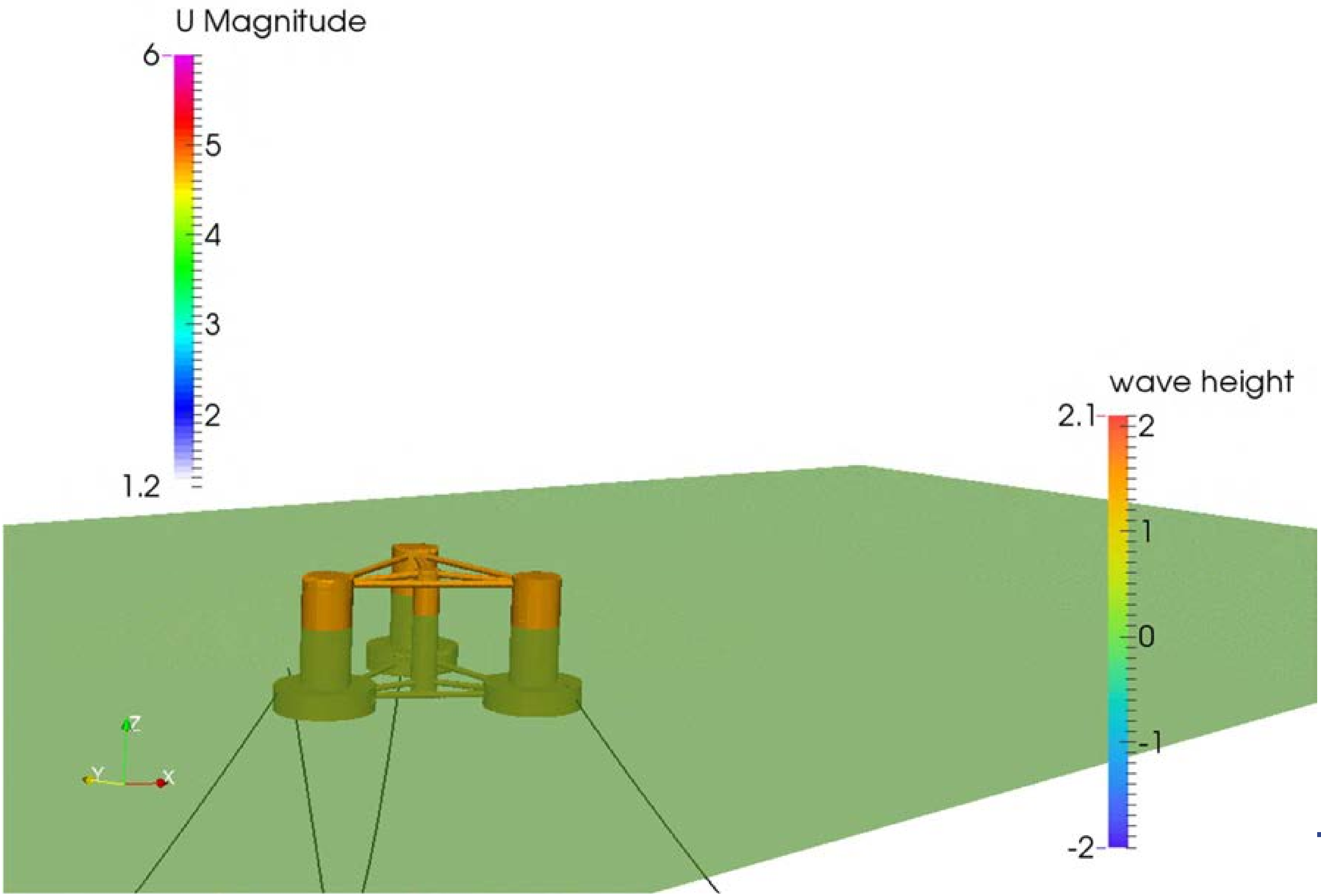
尾涡演化图:Pitch $amplitude{=}4^{\circ}, frequncy = 0.314\,rad/s$

Floating offshore wind turbine



尾涡演化图：surge $amplitude{=}16m, frequncy = 0.314\, rad/s$

Floating offshore wind turbine



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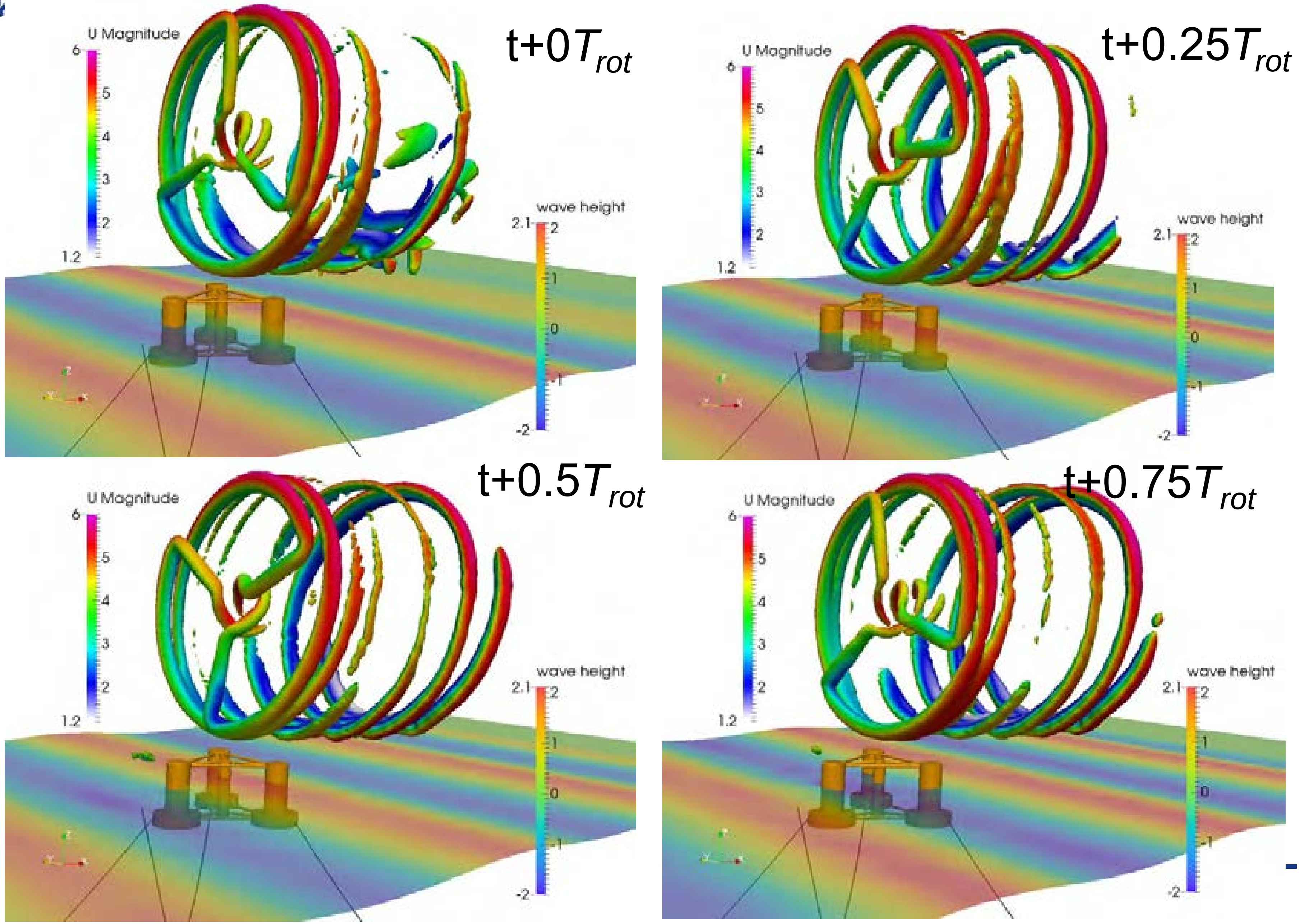
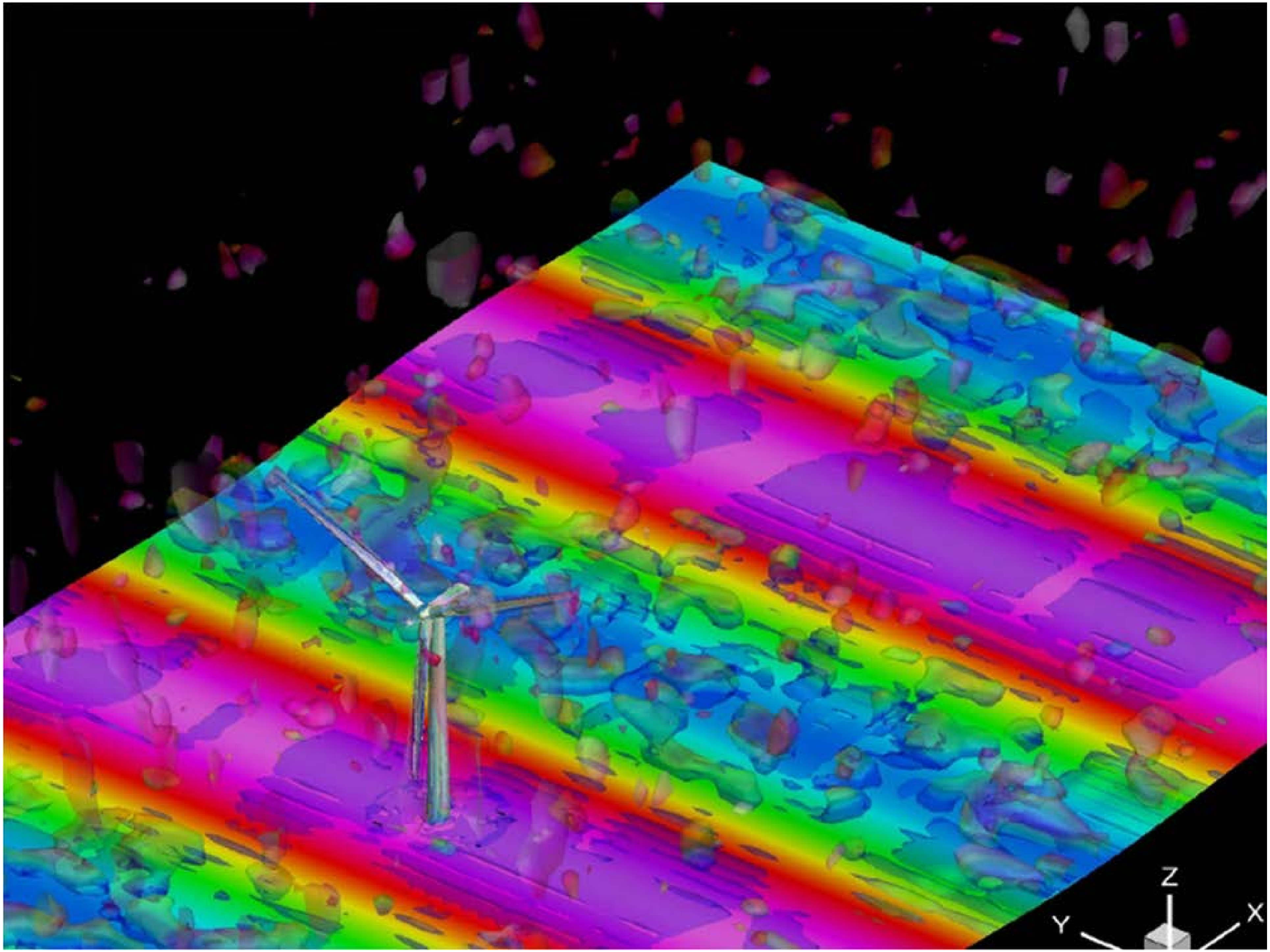
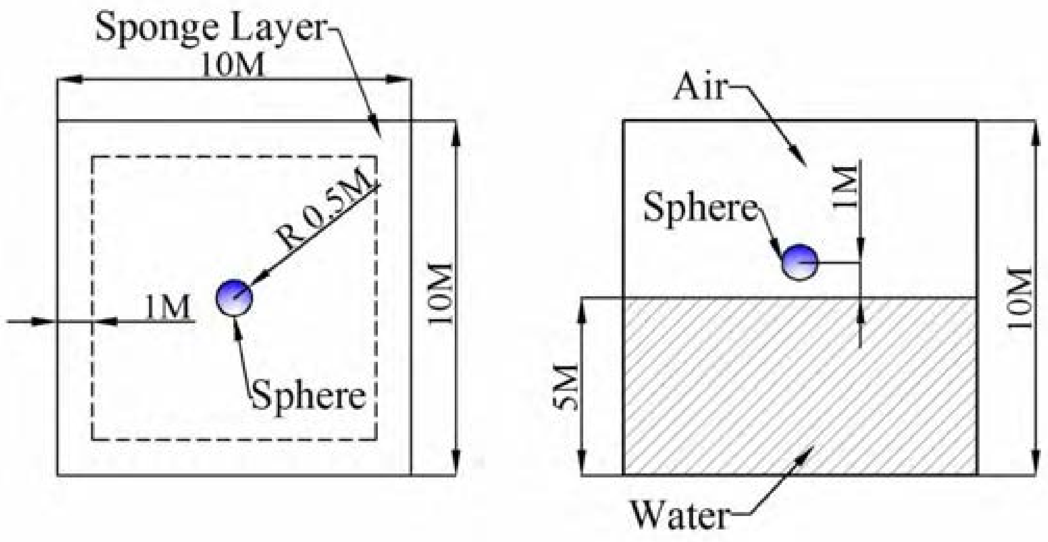
Floating offshore wind turbine

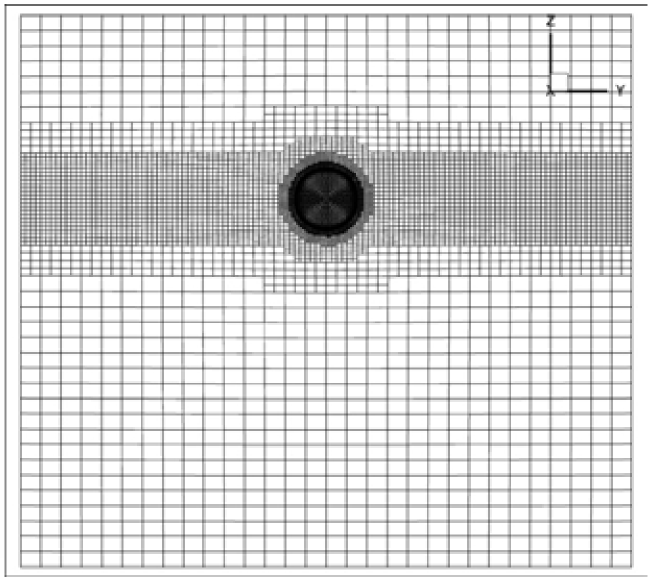


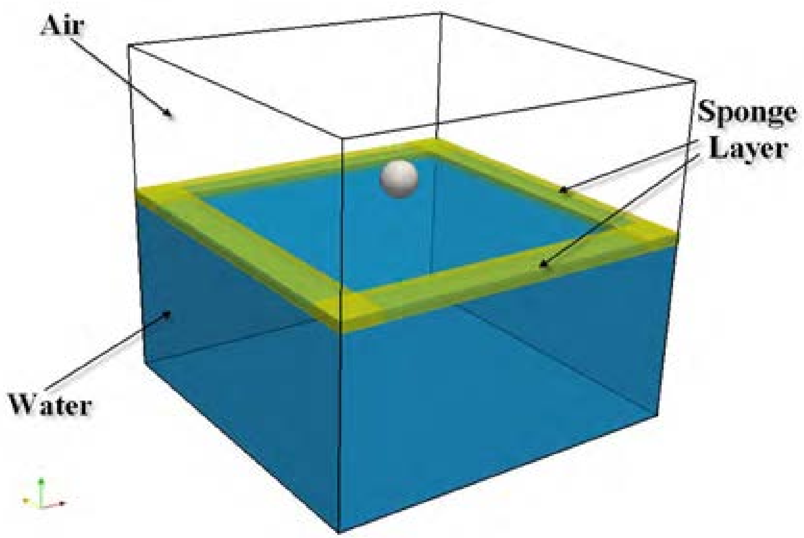

Z
Y
X

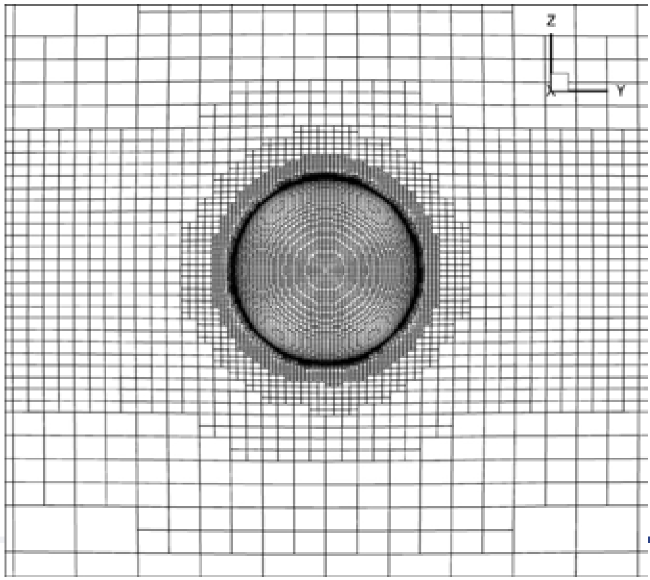
Water Entry and Exit for Balls

A ball drops into calm water

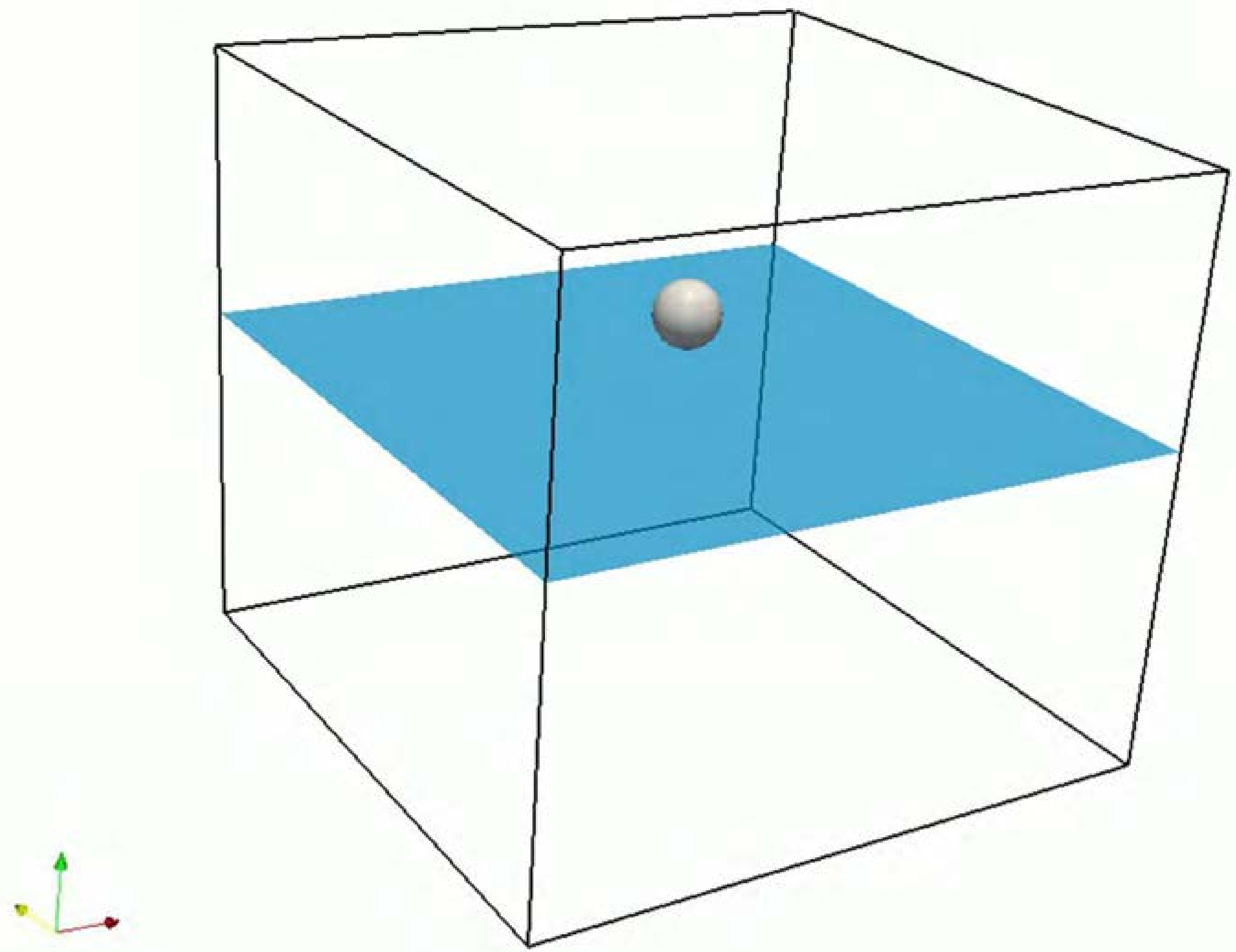




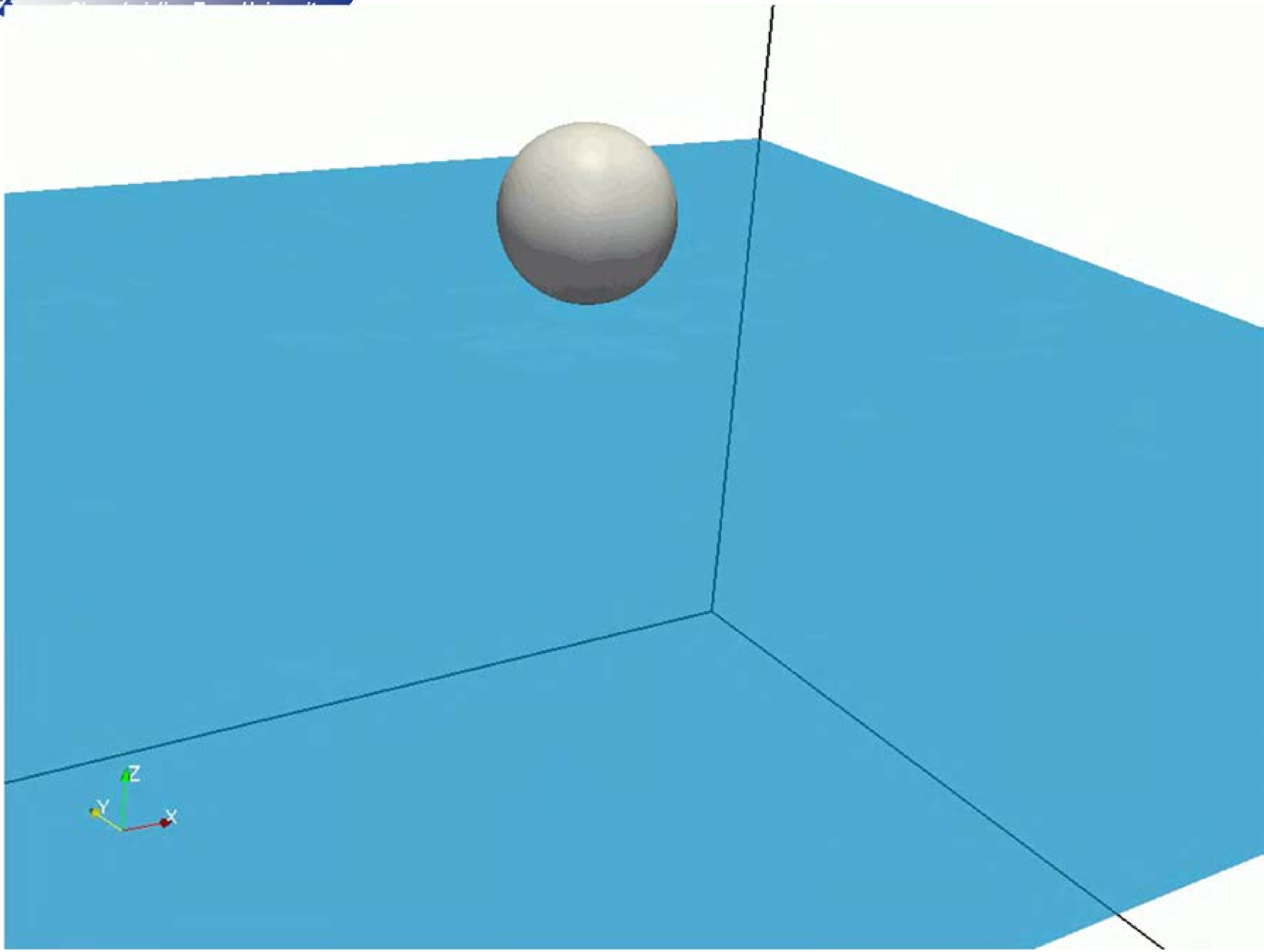




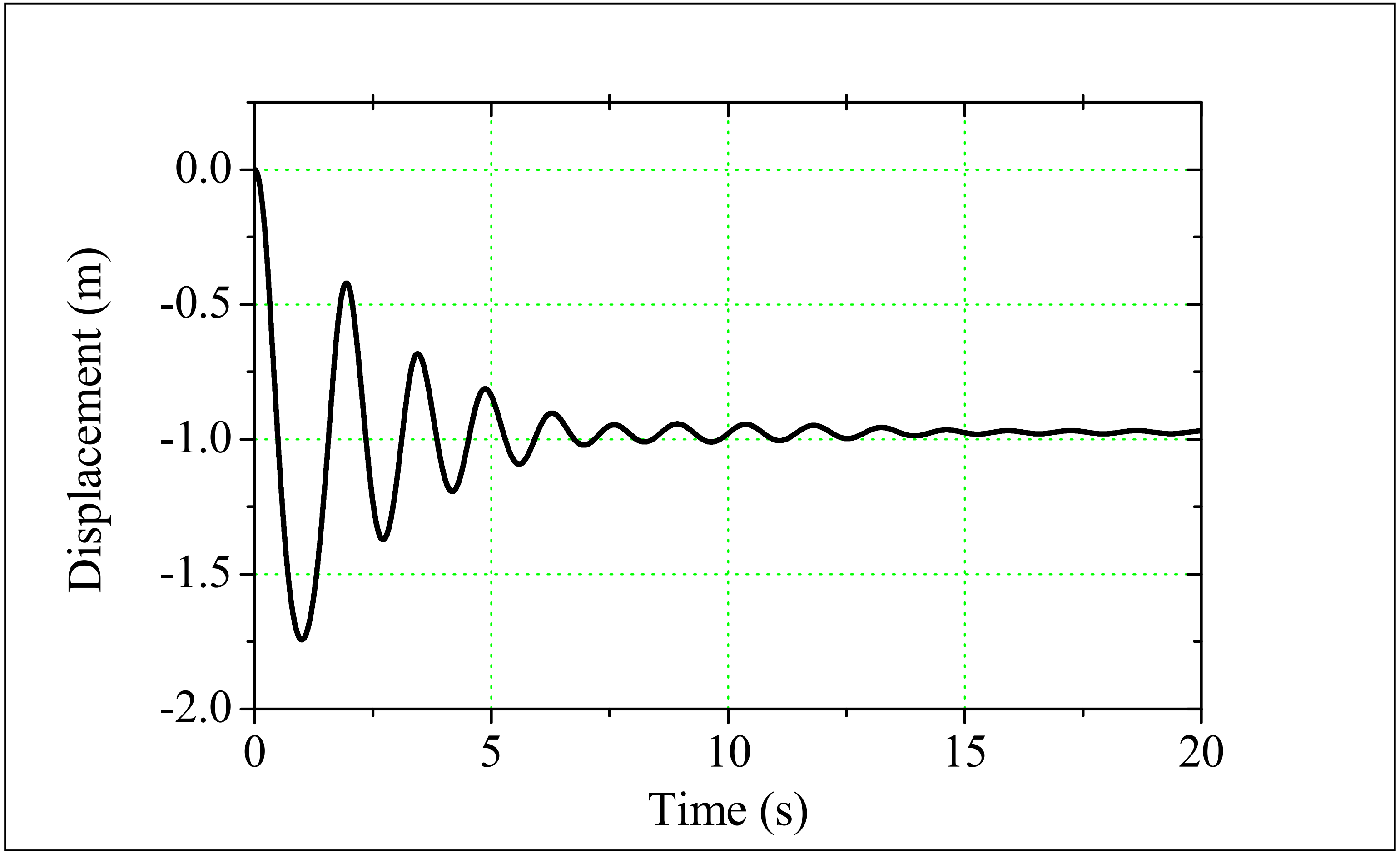
A ball drops into calm water



A ball drops into calm water



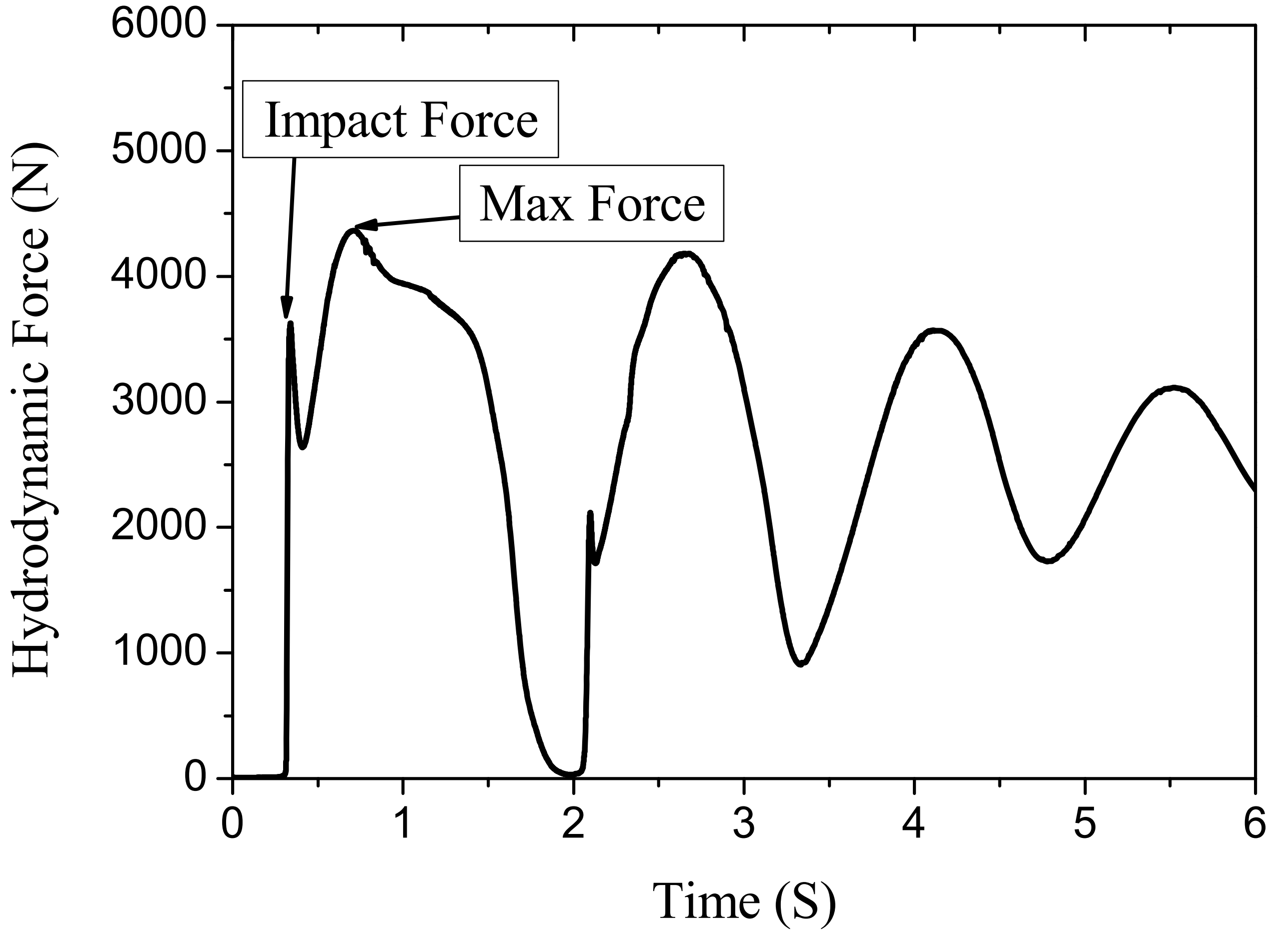
A ball drops into calm water



Transient behavior of Sphere Movement

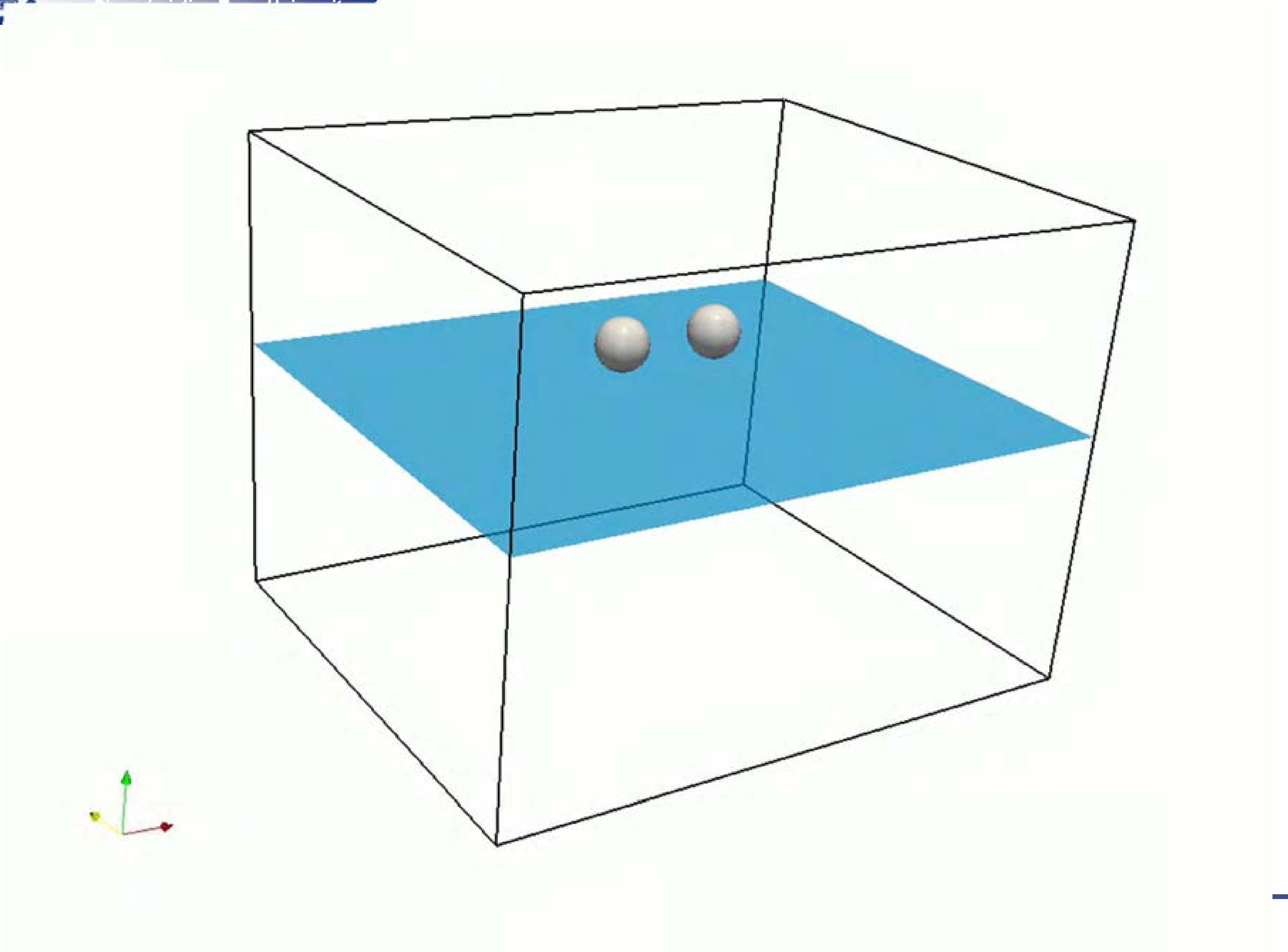
A ball drops into calm water

Impact force and Max Force

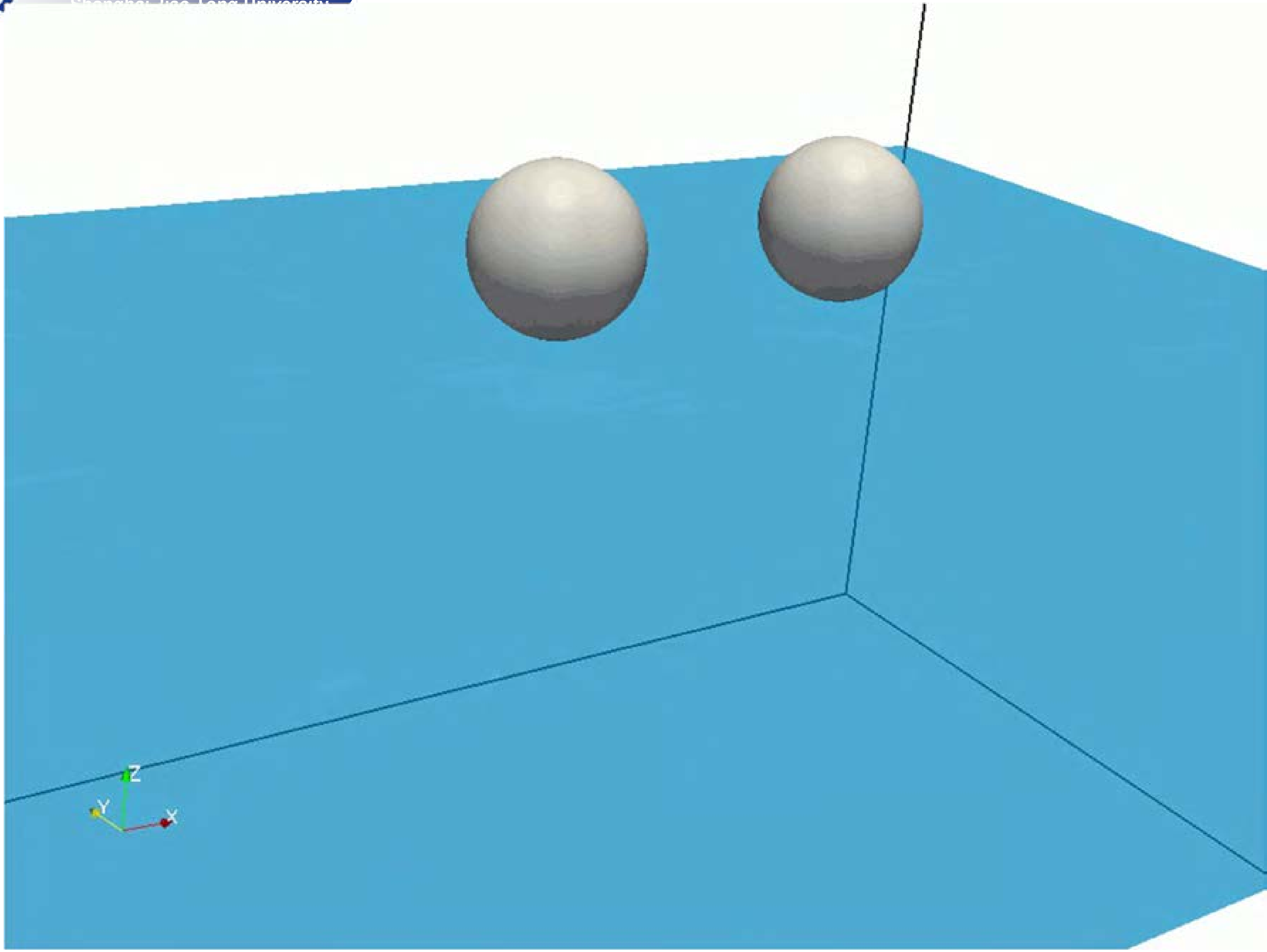


Time History of Hydrodynamic Forces

Two balls drop into calm water



Two balls drop into calm water

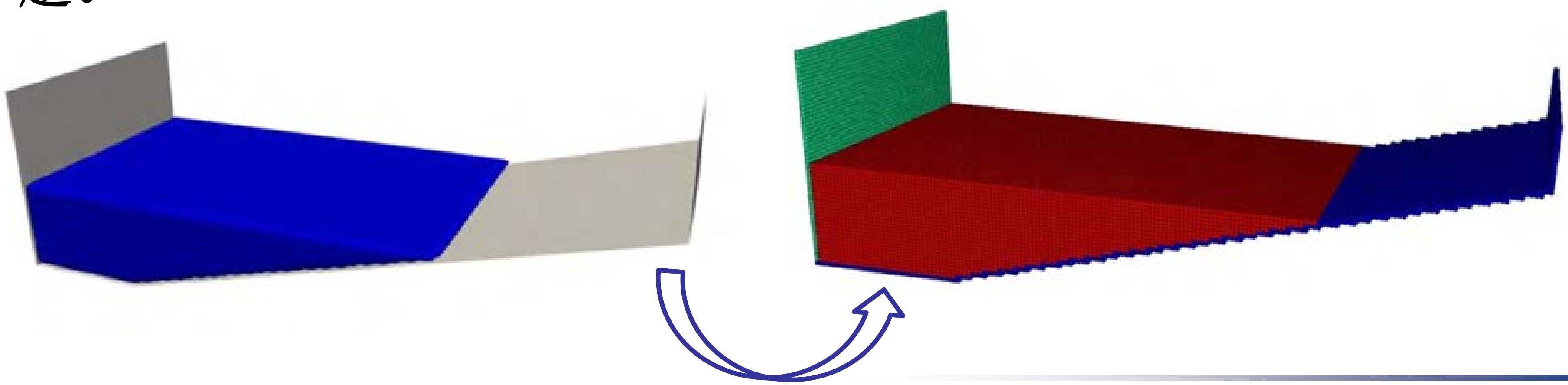


Introduction to

Meshless Solver: MLParticle-SJTU

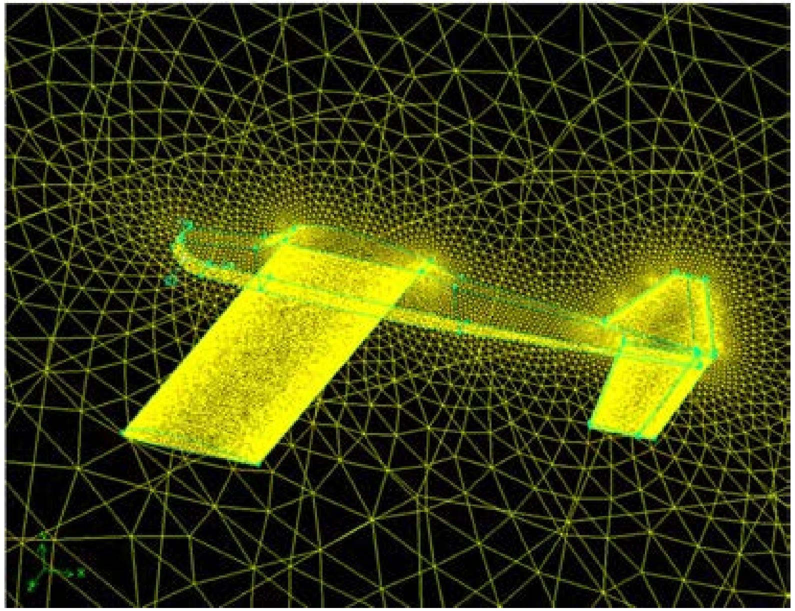
无网格方法

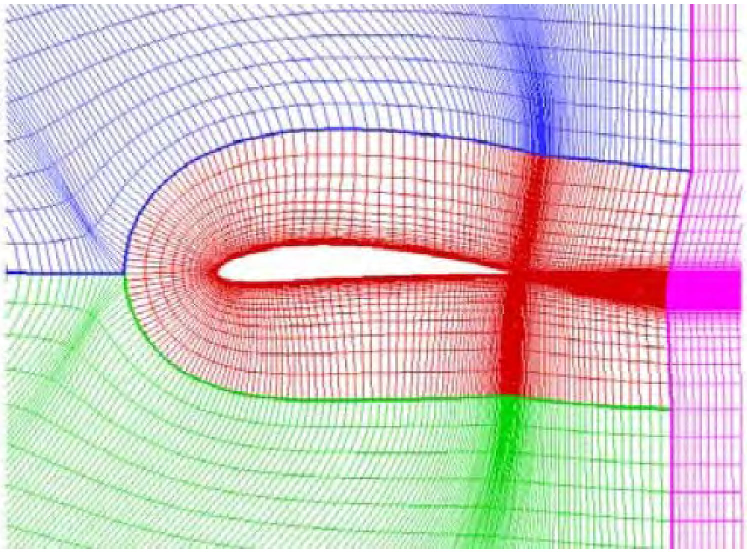
基于拉格朗日方法，将连续的流体域离散成一系列粒子，这些粒子具有质量、动量和能量等物理量，粒子间的相互影响是通过“核函数”的积分来实现的，且控制方程也被写成粒子形式，计算粒子的受力并追踪粒子的移动即可模拟整个流动问题。

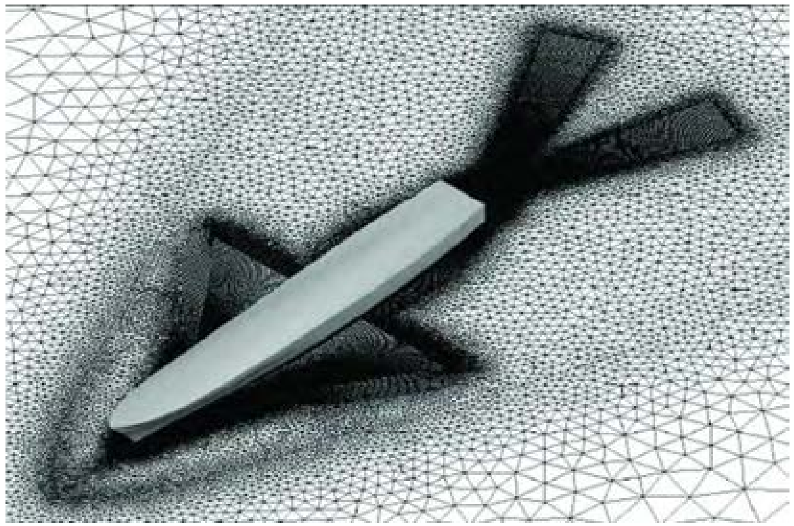


传统的网格类方法

- 需要对计算域划分网格
- 控制方程在网格节点上离散
- 网格质量会影响计算精度
- 边界运动时需要更新网格







网格法常遇到的问题

1.模型复杂，难以划分出高质量网格

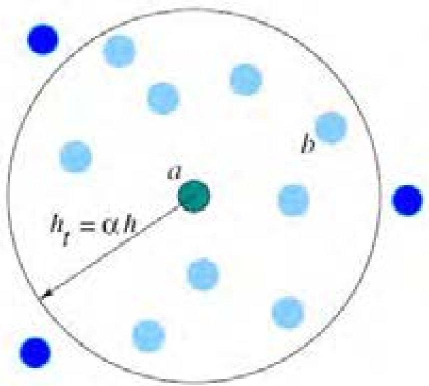
2.实现动网格困难

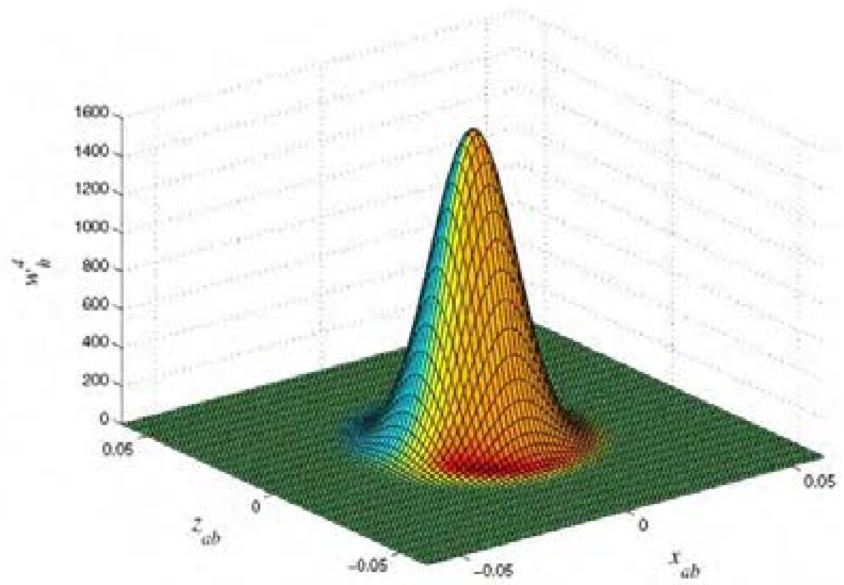
3.需要采用辅助方法处理自由面

无网格粒子法

基本思想

1. 将流场用一系列Lagrange粒子表达
2. 控制方程离散成粒子形式
3. 追踪粒子的移动即可模拟整个流动问题





粒子法的优势：

1. 无需生成网格；

2. 易于追踪复杂的自由面问题，不存在界面耗散。

2. 易于处理动边界问题。

SPH计算结果（Ihmsen, 2010)

- 船舶海洋工程中流体问题：
    1. 物体几何形状复杂
    2. 动边界
    3. 自由面变形大

- 研究无网格粒子法具有重要的科研意义和工程应用价值。

本课题主要研究的粒子法

- 光滑粒子法

(**S**moothed **P**article **H**ydrodynamics，**SPH**)

L.B.Lucy 1977

R.A.Gingold 1977

- 移动粒子半隐式法

(**M**oving **P**article **S**emi-**I**mplicit, **MPS**)

S.Koshizuka 1996

为什么要研究SPH和MPS这两种粒子法

- SPH方法和MPS方法是两种常用的无网格拉格朗日粒子法，在处理自由面大变形问题方面都有较大的灵活性。

- SPH和MPS在数值计算方面有各自的独特之处，值得研究。

SPH方法和MPS方法的不同点

SPH与MPS的不同

压力的计算

离散格式

1. 压力的计算:

SPH :

$$p = B\left(\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right)$$

where : $B = \frac{\rho_0 c^2}{\gamma}$ c is sound speed

MPS :

$$< \nabla^2 P^{n+1} >_i = -\frac{\rho}{\Delta t^2} \frac{< n^* >_i - n^0}{n^0}$$

2. 计算格式:

时间积分:

SPH :
- **Explicit scheme**
- **Predictor-Corrector scheme**
- **Leap-Frog scheme**

MPS : **Projection scheme**

梯度模型:

SPH :

$$< \nabla \phi >_i = \sum_j \frac{m_j}{\rho_j} (\phi_j + \phi_i) \cdot \nabla_i W(r_{ij})$$

MPS :

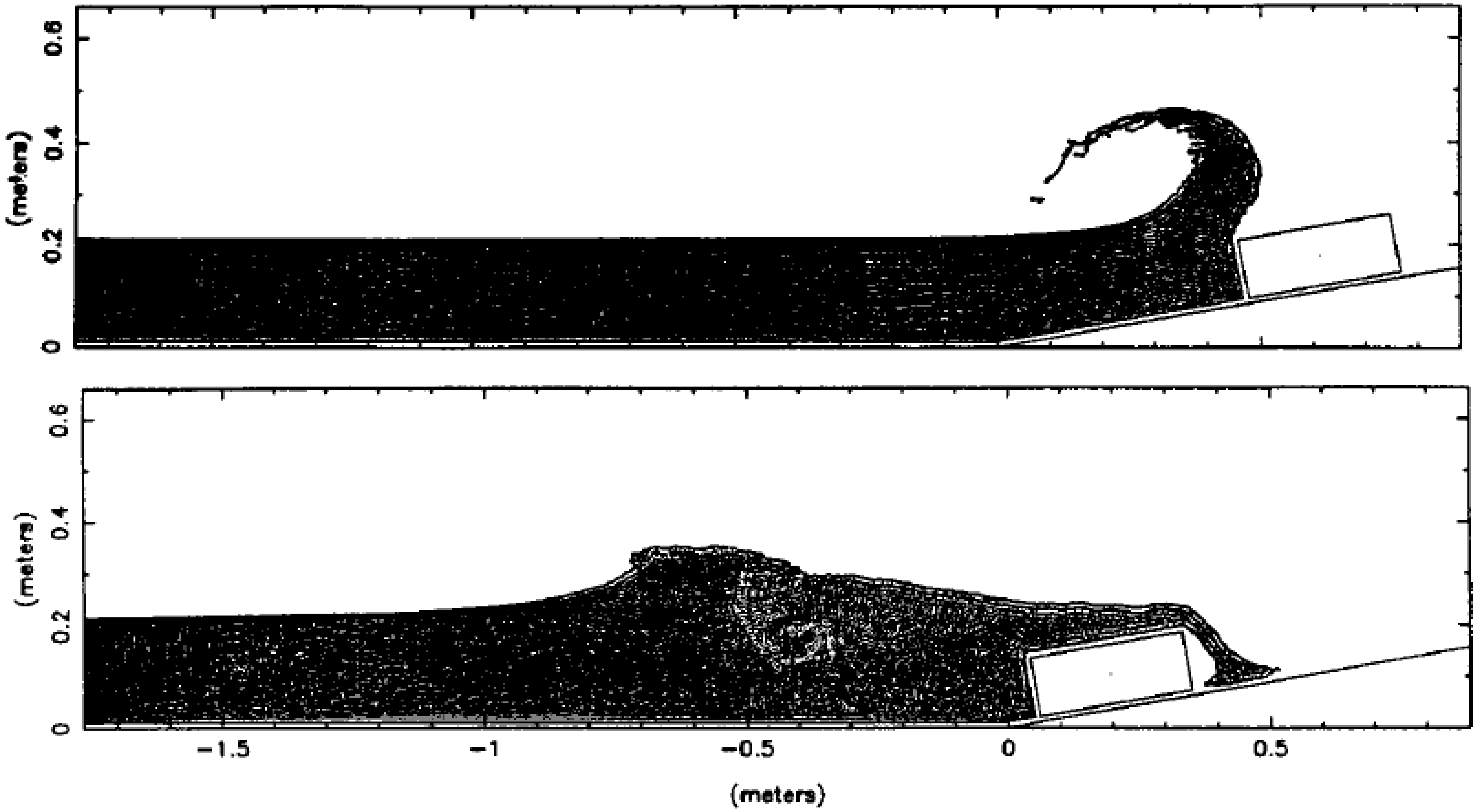
$$< \nabla \phi >_i = \frac{D}{n^0} \sum_{j \neq i} \frac{\phi_j - \phi_i}{r_{ij}^{\ 2}} (\vec{r}_j - \vec{r}_i) \cdot W(r_{ij})$$

其中:$W(r_{ij})$为核函数，D为空间尺度， n^0 为初始粒子数密度.

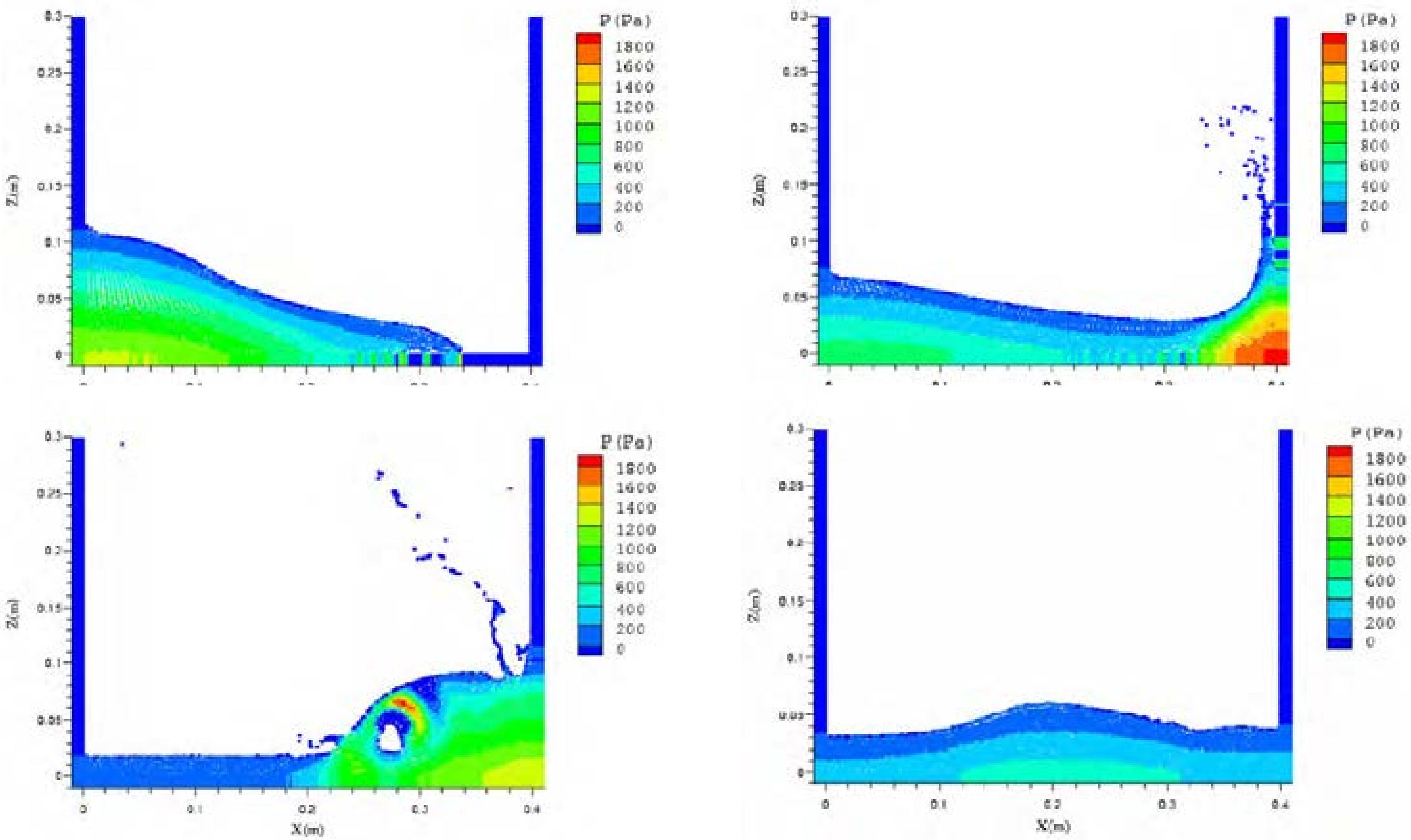
粒子法的应用范围：

- 天体物理
- 磁流体力学
- 高速抨击
- 水下爆炸
- 船舶与海洋工程
- 核工程
- 电影、游戏制作

Monaghan. Fluid Motion Generated by Impact. Journal of Waterway, Port, Coastal, and Ocean Engineering, *2003*

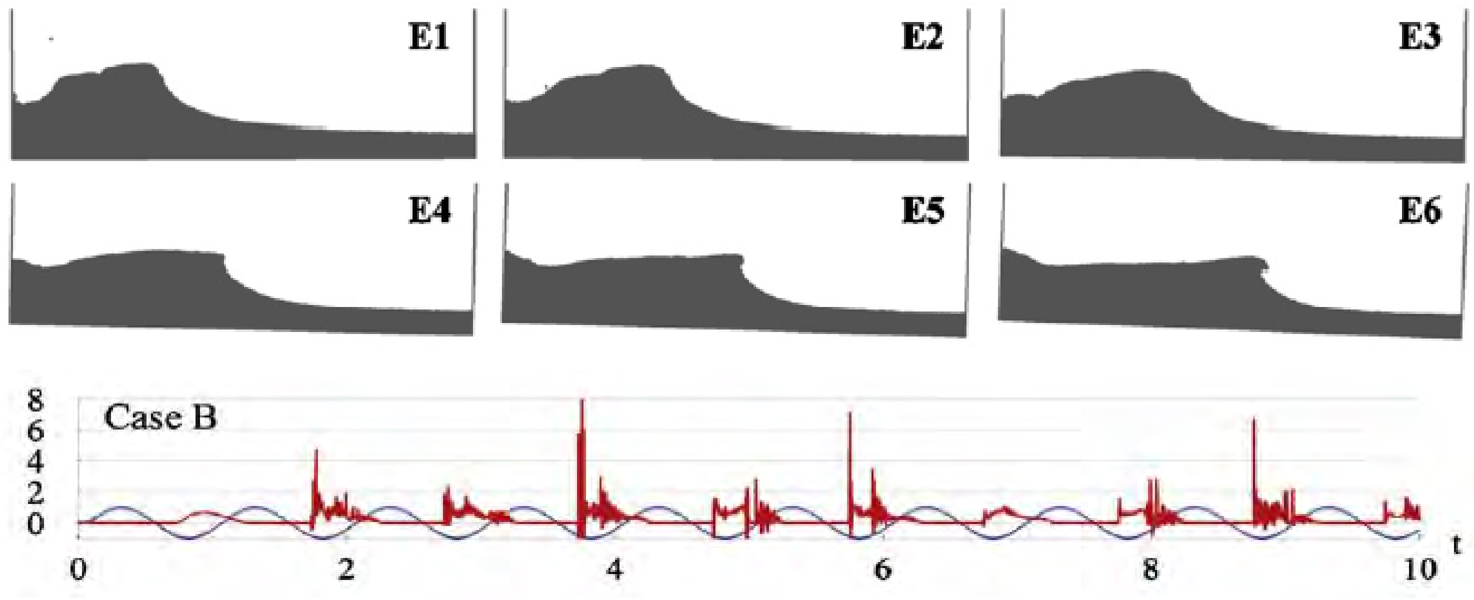


E. S. Lee. *Comparisons of weakly compressible and truly incompressible algorithms for the SPH mesh free particle method. Journal of Computational Physics, 2008*

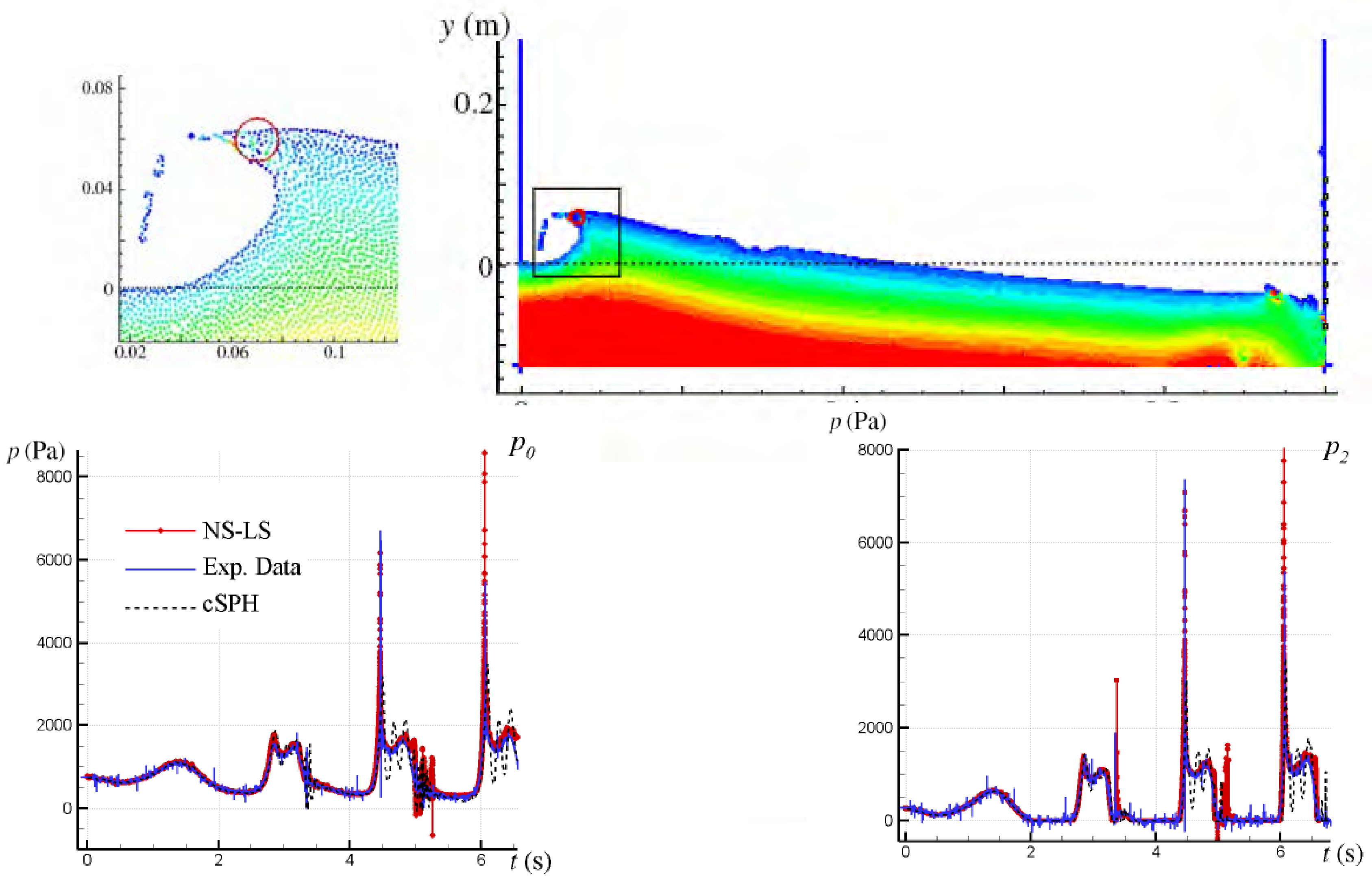


上海交通大学 Shanghai Jiao Tong University

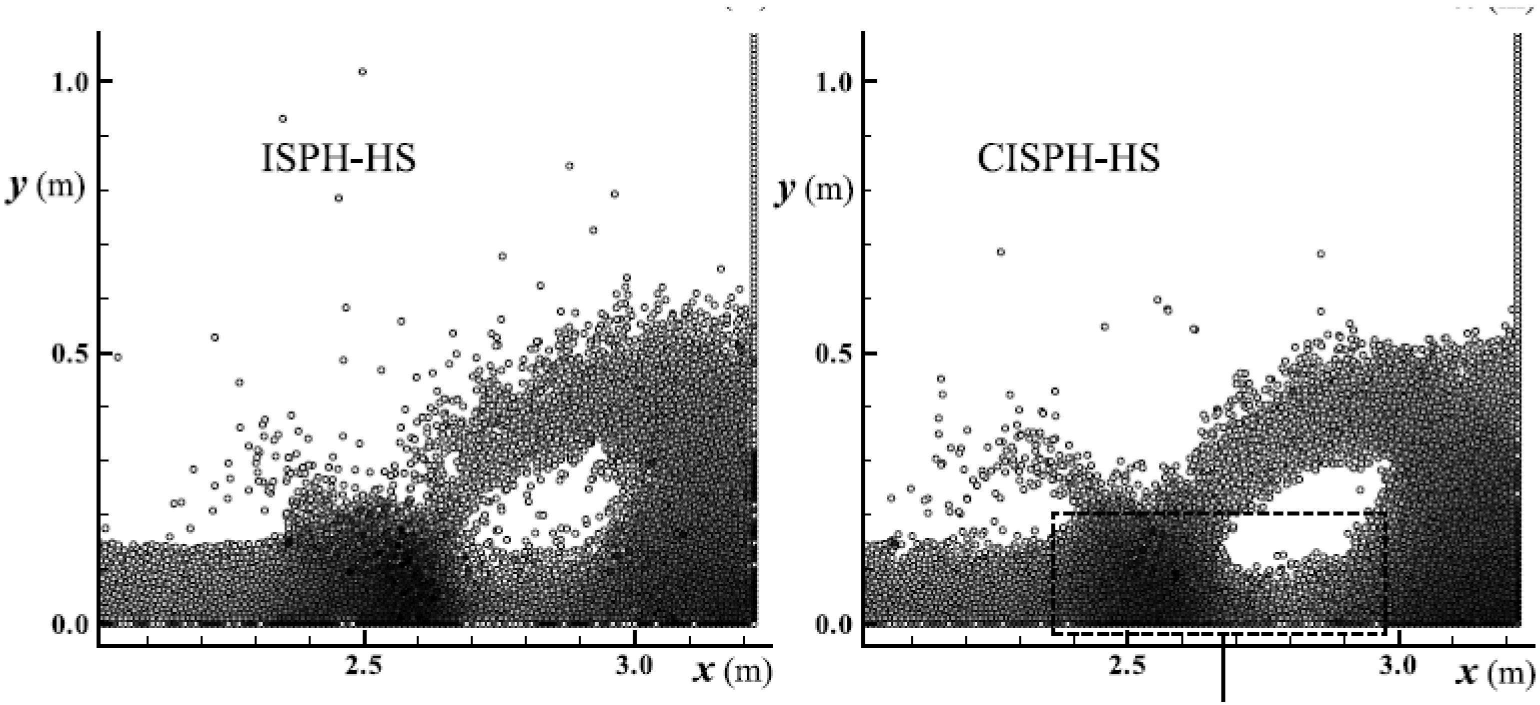
L. Delorme. *A set of canonical problems in sloshing, Part I: Pressure field in forced roll-comparison between experimental results and SPH. Ocean Engineering, 2009*



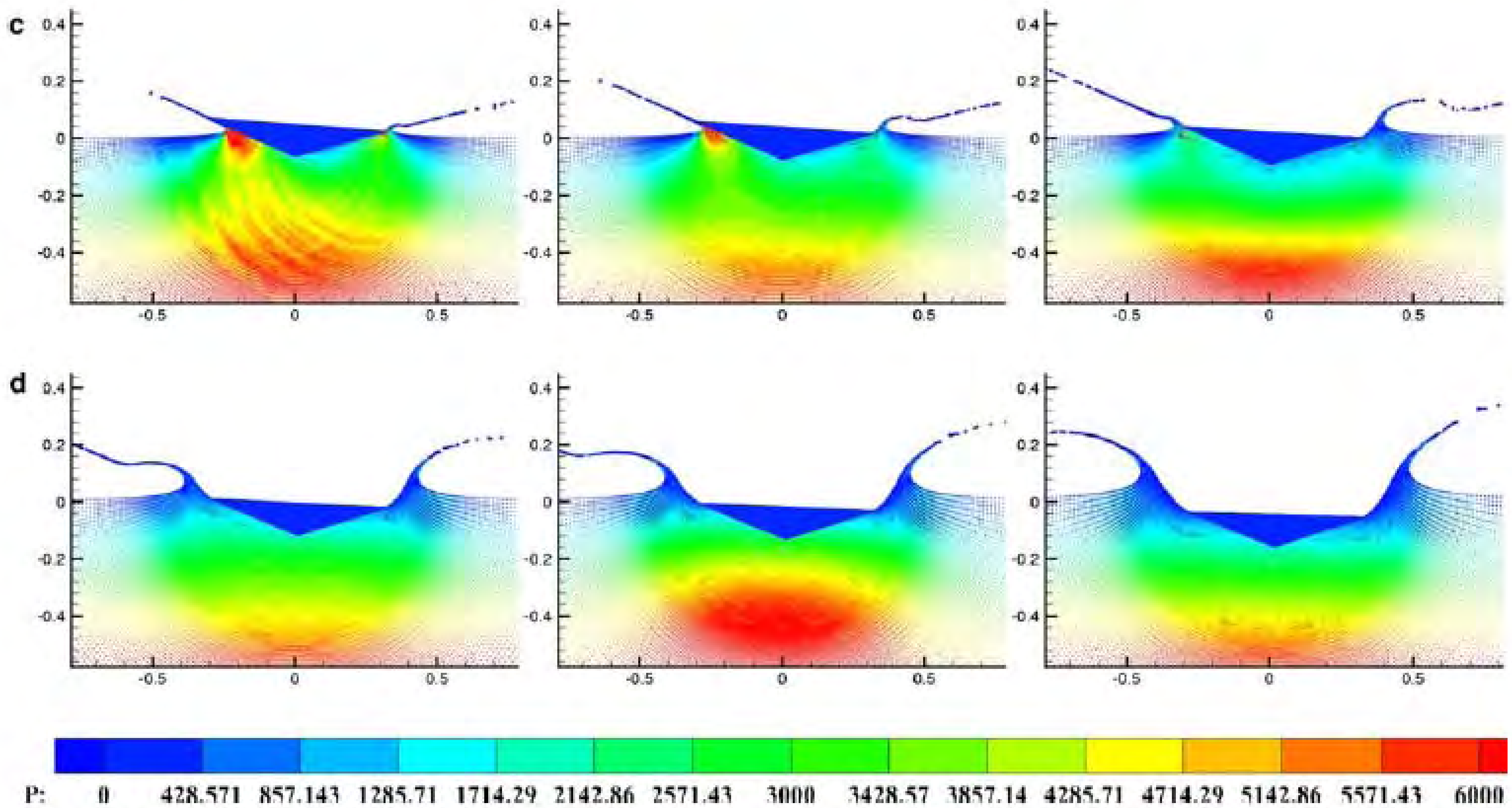
Colagrossi. A study of violent sloshing wave impacts using an improved SPH method. Journal of Hydraulic Research, *2010*



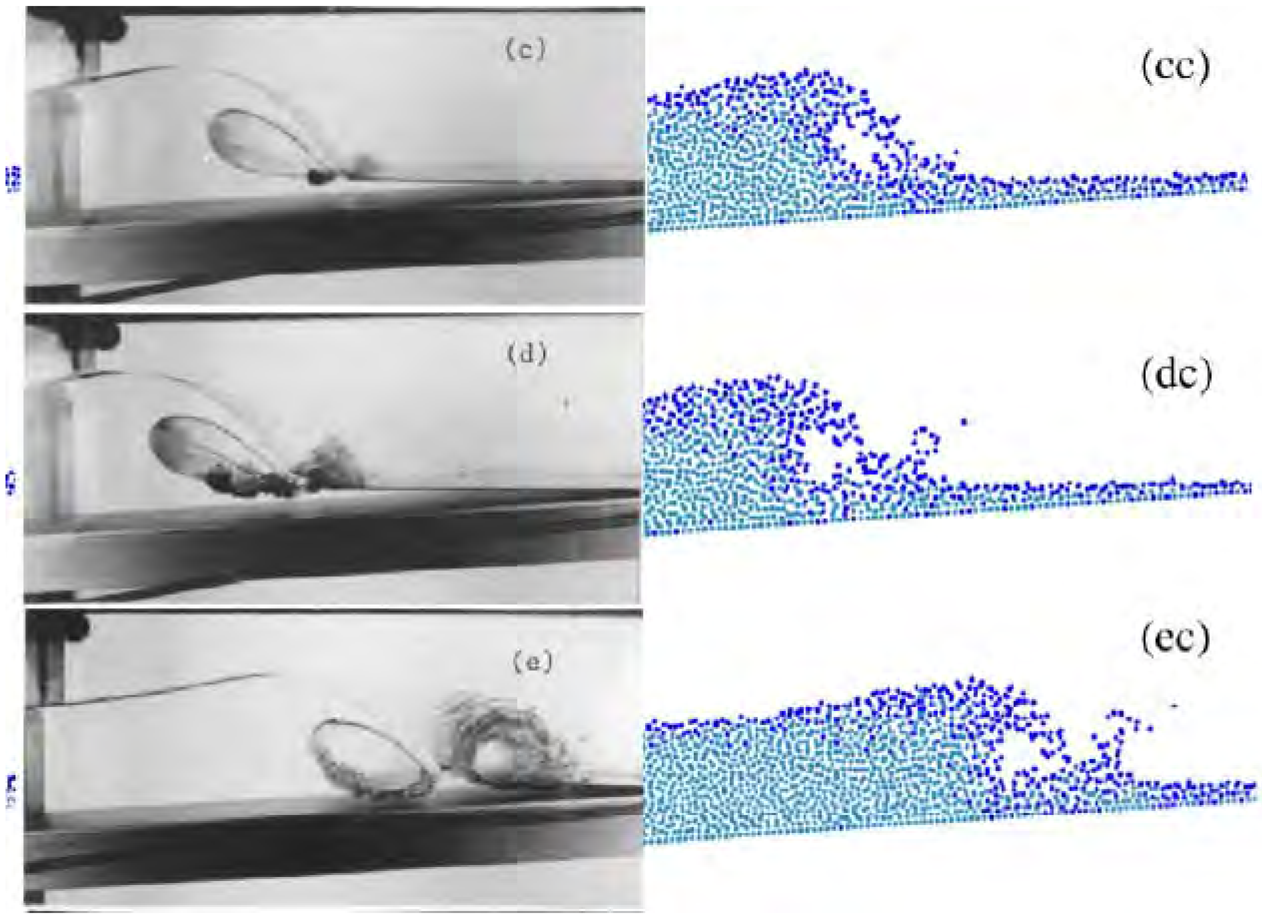
Khayyer. Enhanced predictions of wave impact pressure by improved incompressible SPH methods. Applied Ocean Research, *2009*



G. Oger. Two-dimensional SPH simulations of wedge water entries. Journal of Computational Physics, 2006

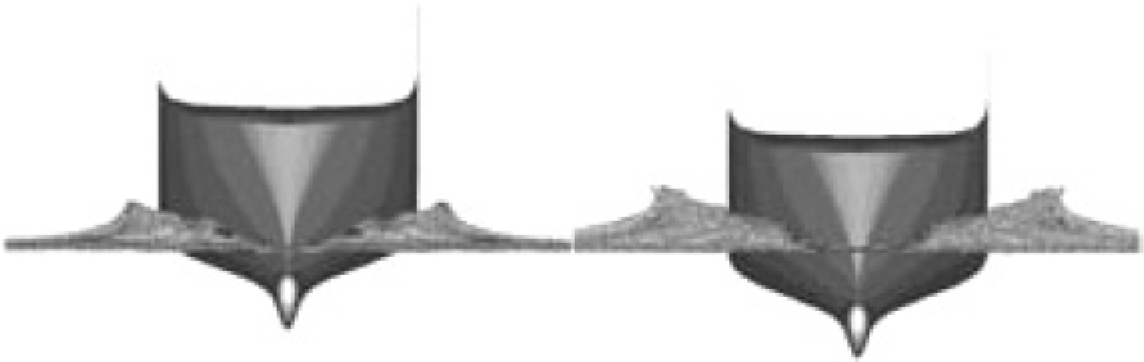


Khayyer. Corrected Incompressible SPH method for accurate water-surface tracking in breaking waves. Coastal Engineering, *2008*



P. Maruzewski. SPH high-performance computing simulations of rigid solids impacting the free-surface of water. Journal of Hydraulic Research, 2010

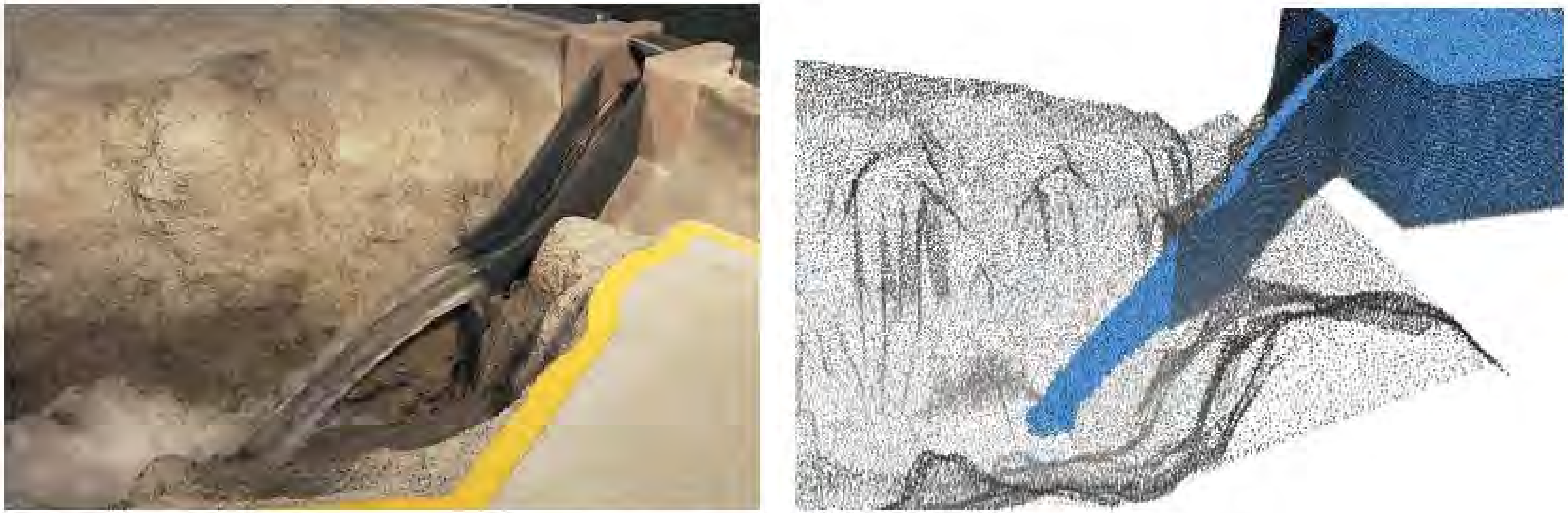
$t = 0.12$ s and $t = 0.16$ s



$t = 0.18$ s and $t = 0.24$ s

Figure 19 Ship hull impact process

E. Lee. Application of weakly compressible and truly incompressible SPH to 3-D water collapse in waterworks. journal of Hydraulic Research, 2010



Experiment WCSPH

Figure 9 An example of the 3-D river dam spillway snapshot from the physical (left) and numerical (right) models

H. Gotoh. Lagrangian particle method for simulation of wave overtopping on a vertical seawall. Coastal Engineering Journal, 2005

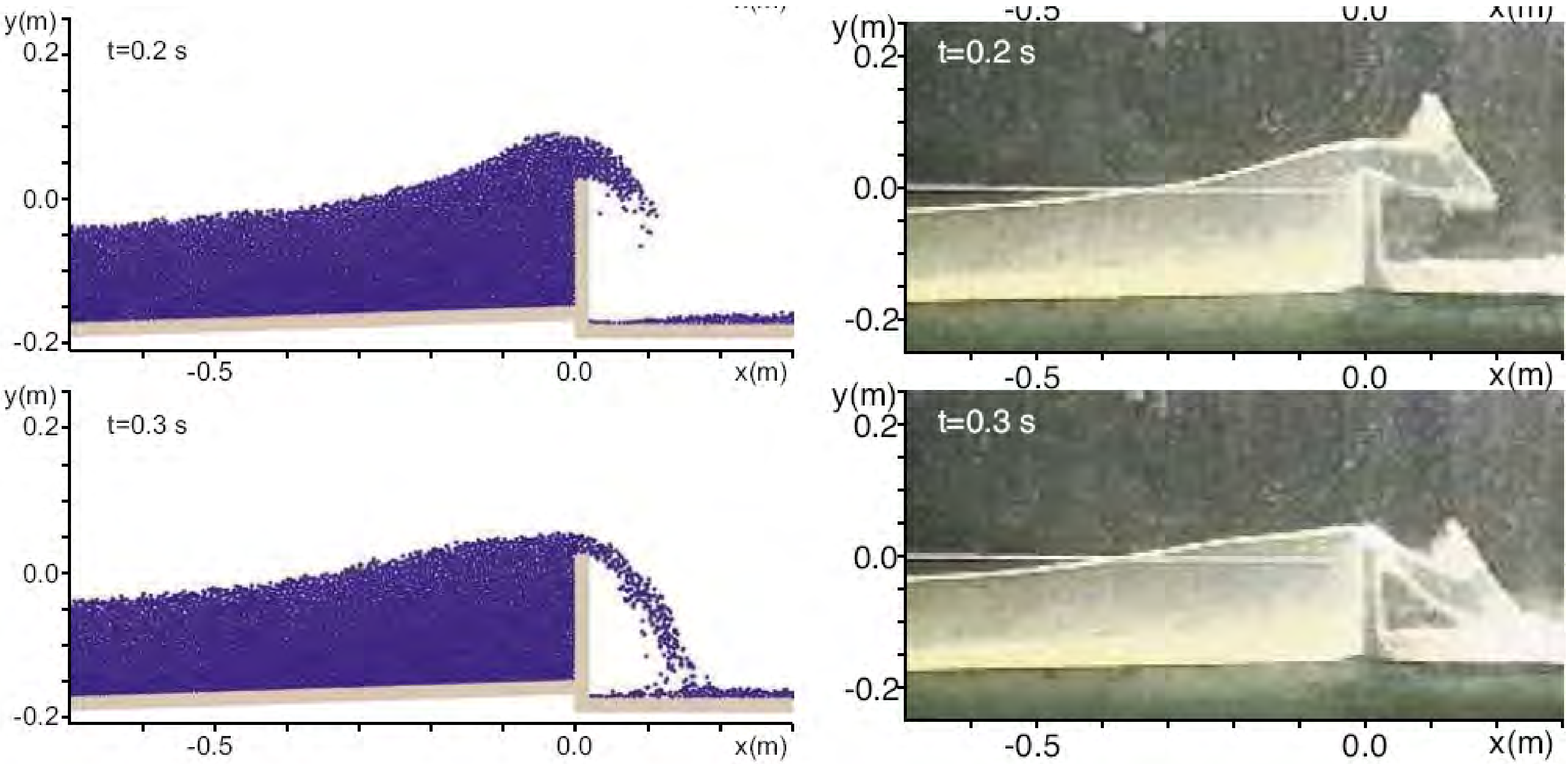
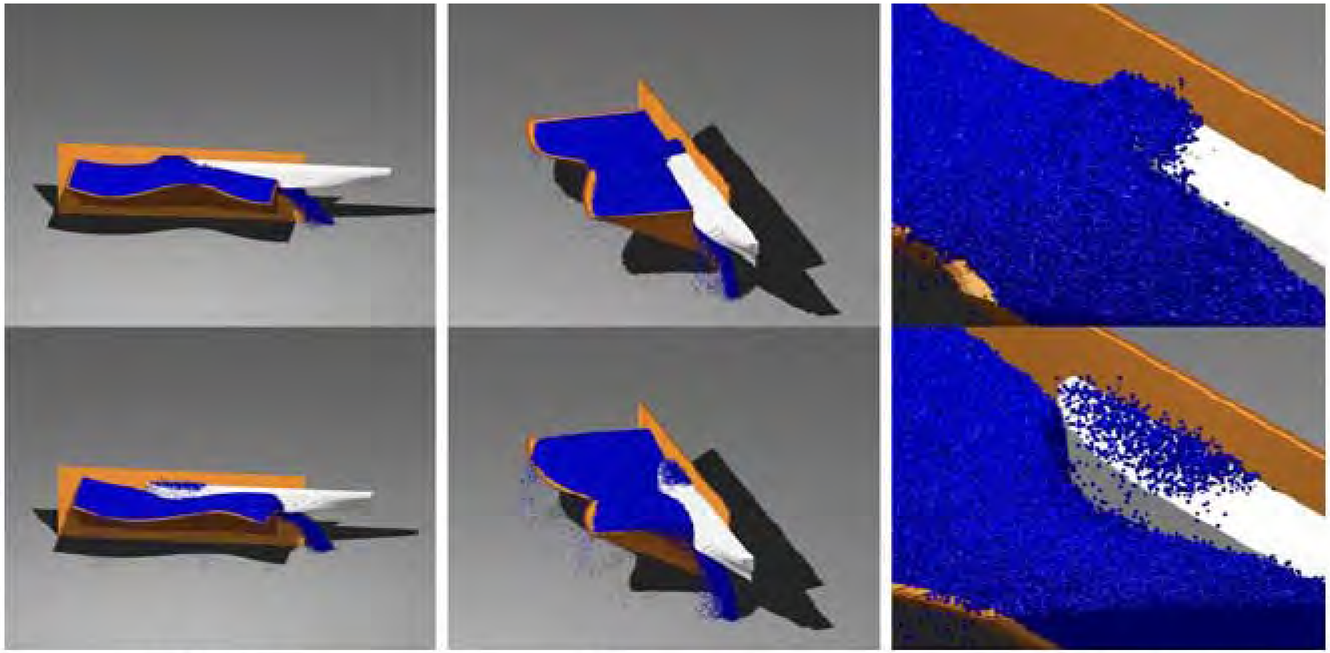


Fig. 9. Snapshots of wave overtopping (non-breaking wave).

K. Shibata. Three-dimensional numerical analysis of shipping water onto a moving ship using a particle method. Journal of Marine Science and Technology, *2009*

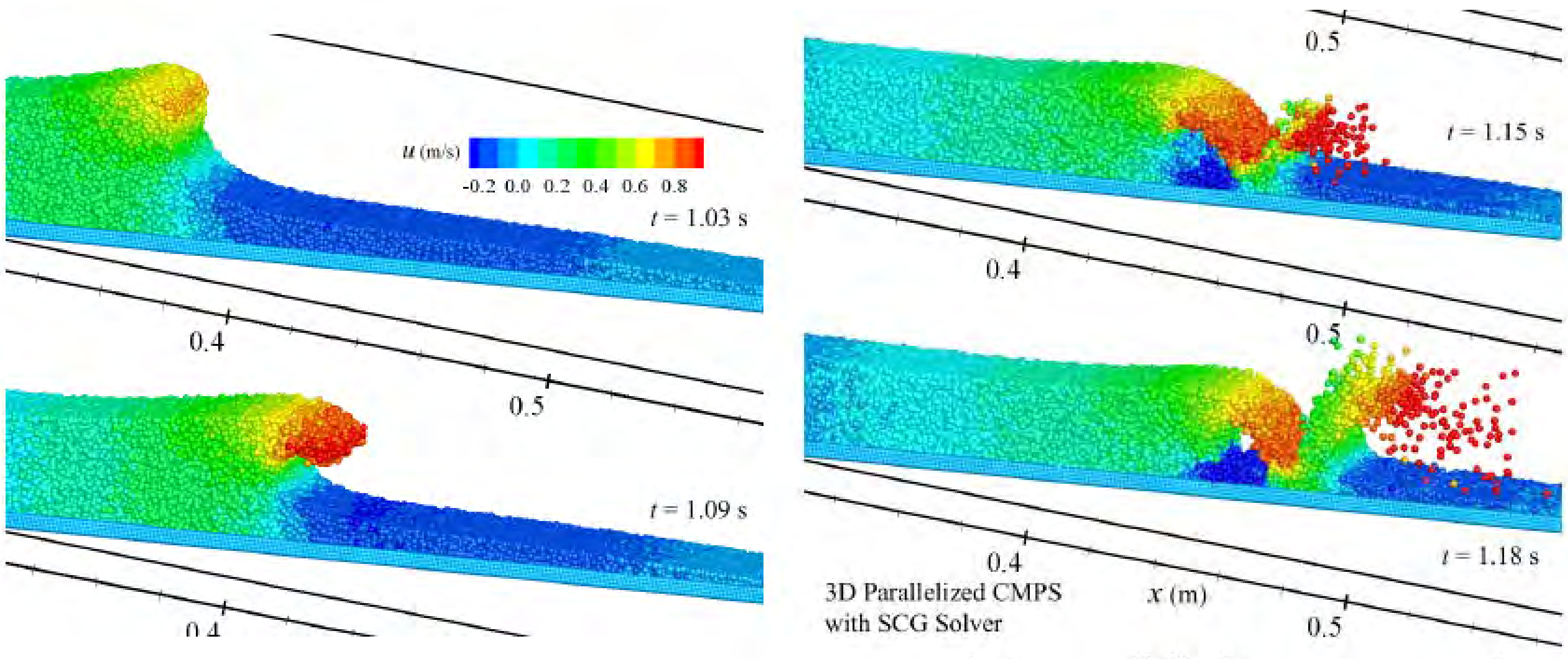


0.6sec

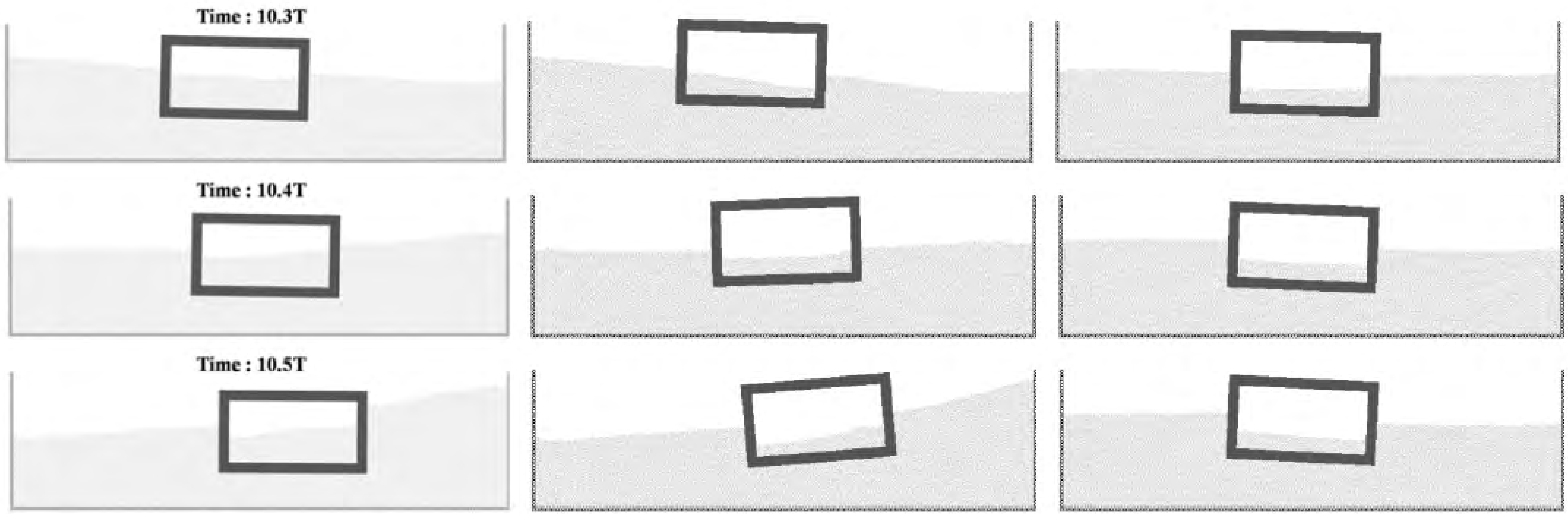
0.9sec

Side view | Back view | Enlarged deck view

H. Gotoh. Refined reproduction of a plunging breaking wave and resultant splash-up by 3D-CMPS method. ISOPE, 2009



B. H. Lee. Two-dimensional vessel-motion/liquid-sloshing interactions and impact loads by using a particle method. OMAE, 2010



- 关于粒子法的文献迅速增加，应用越来越广。
- SPH的研究工作较多，MPS相对较少。
- 大部分集中在二维问题，三维问题较少。
- 国内的研究在深度、广度、前沿性上都与国际有一定差距。

问题背景

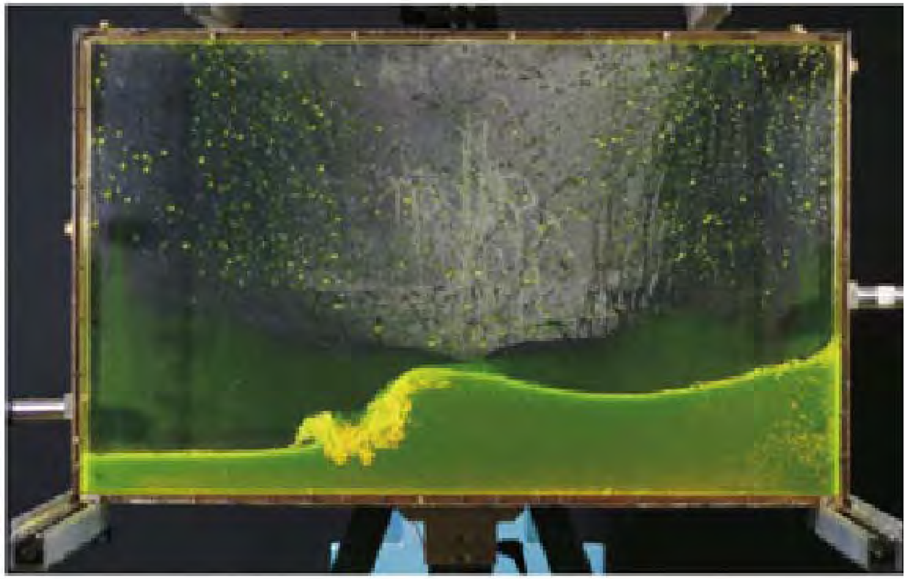
海洋工程和海岸工程中广泛存在自由面剧烈流动问题：

涌潮波
Bore waves

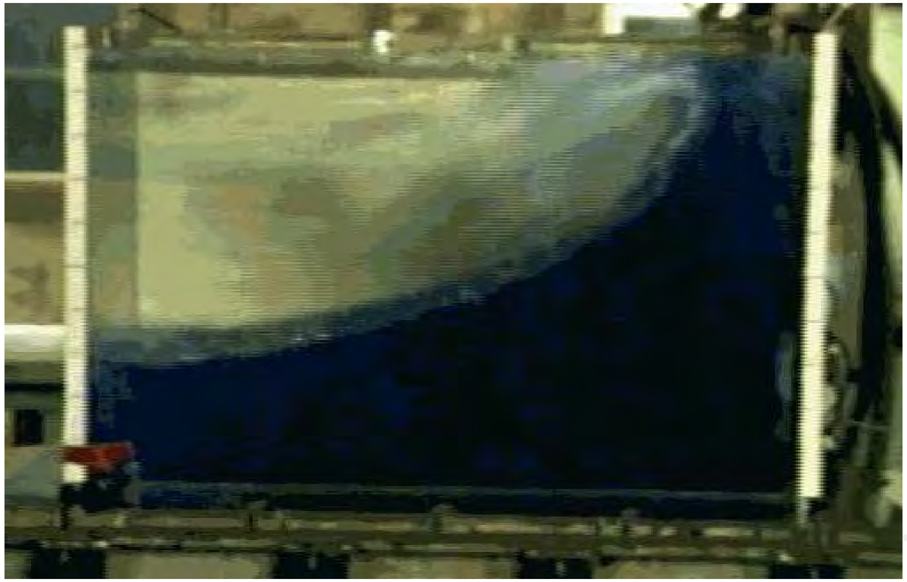
畸形波
Freak waves

波浪破碎
Wave breaking

问题背景

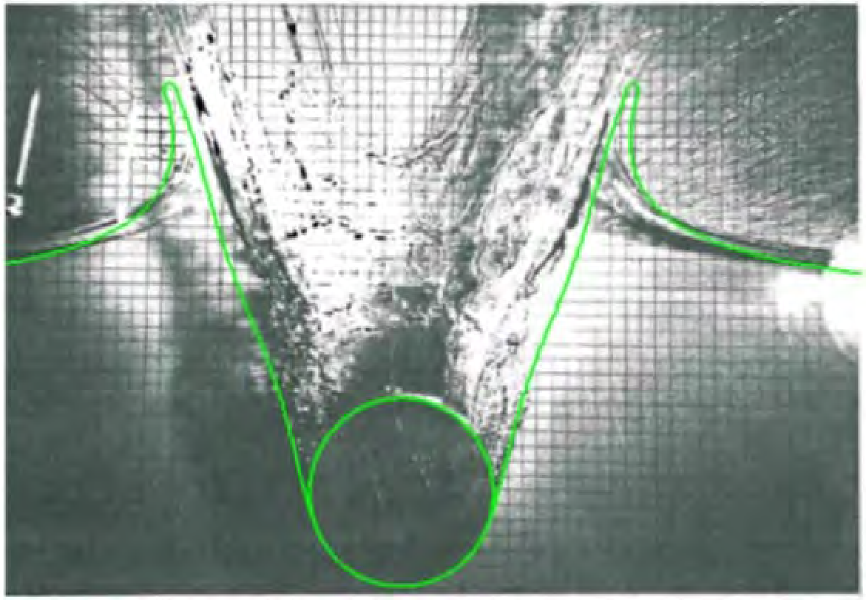


溃坝波
Dam breaking



液舱晃荡
Sloshing flows

问题背景



物体出入水问题
Water entry flows

甲板上浪
Green water flows
波浪拍击
Slamming

问题背景

自由面剧烈流动问题的特点：

- **自由面大变形**

  (Large deformed free surface)

- **剧烈波浪冲击力**

  (High impact pressure)

- **物体六自由度大幅度运动**

  (6DOF motion with large amplitude)

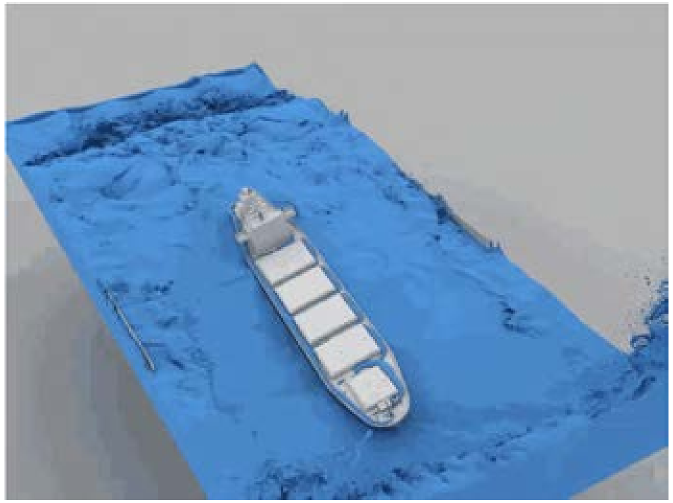
问题背景

数值求解自由面剧烈流动问题途径：

1. 非线性势流方法（频域和时域）
2. 粘性流方法
   - 有网格方法(VOF, Level set)
   - 无网格方法(SPH, MPS)

无网格方法

- 无需生成网格
- 善于追踪大变形的自由面
- 容易处理动边界问题
- 演示效果较好



无网格方法

- **Smoothed Particle Hydrodynamics (SPH)**

  L.B. Lucy(1977), R.A. Gingold(1977)

- **Moving Particle Semi-Implicit (MPS)**

  S. Koshizuka (1996)

	SPH	MPS
Kernel function	Weight function Smooth function	Weight function
Integration	Explicit scheme	Semi-implicit
Pressure	Artificial compressible equation	Possion pressure equation
Flow	Both Incompressible and compressible flows	Incompressible Flows

MPS Method

- Kernel function

$$W(r) = \begin{cases} \dfrac{r_e}{r} - 1 & 0 < r \leq r_e \\ 0 & r_e < r \end{cases}$$

where: r_e is radius of interaction area.

- In particle methods, differential operators are modeled by integration of values at particles and kernel function. In MPS method, the kernel function plays a role of weight function.

MPS Method

- Particle number density

$$\langle n \rangle_i = \sum_{j \neq i} w\left(\left| r_j - r_i \right|\right)$$

$$\langle n \rangle_i = \langle N \rangle_i \left(\int_v w(r)\, dv \right)$$

$$\langle \rho \rangle = m \langle N \rangle_i = \frac{m \langle n \rangle_i}{\int_v w(r)\, dv}$$

MPS Method

- Gradient model

$$<\nabla\phi>_i=\frac{d}{n^0}\sum_{j\neq i}\frac{\phi_j-\phi_i}{r_{ij}{}^2}(\vec{r}_j-\vec{r}_i)\cdot W(r_{ij})$$

$$<\nabla P>_i=\frac{d}{n^0}\sum_{j\neq i}\frac{P_j+P_i}{|\boldsymbol{r}_j-\boldsymbol{r}_i|^2}(\boldsymbol{r}_j-\boldsymbol{r}_i)\cdot W(|\boldsymbol{r}_j-\boldsymbol{r}_i|)$$

Laplacian model

$$\langle \nabla^2 \phi \rangle_i = \frac{2d}{n^0 \lambda} \sum_{j \neq i} (\phi_j - \phi_i) \cdot W(|\boldsymbol{r}_j - \boldsymbol{r}_i|)$$

$$\lambda = \frac{\sum_{j \neq i} W(|\boldsymbol{r}_j - \boldsymbol{r}_i|) \cdot |\boldsymbol{r}_j - \boldsymbol{r}_i|^2}{\sum_{j \neq i} W(|\boldsymbol{r}_j - \boldsymbol{r}_i|)}$$

Projection method

Compute temporal velocity and position of particles

$$\vec{V}_i^{*} = \vec{V}_i^{n} + \Delta t(\nu \nabla^2 \vec{V}^{n} + \vec{f}^{n})$$

$$\vec{r}_i^{*} = \vec{r}_i^{n} + \Delta t \cdot \vec{V}_i^{*}$$

Solve Poisson equation

$$< \nabla^2 P^{n+1} >_i = -\frac{\rho}{\Delta t^2} \frac{< n^* >_i - n^0}{n^0}$$

Modify velocity

$$\vec{V}_i^{n+1} = \vec{V}_i^{*} - \frac{\Delta t}{\rho} \nabla P^{n+1}$$

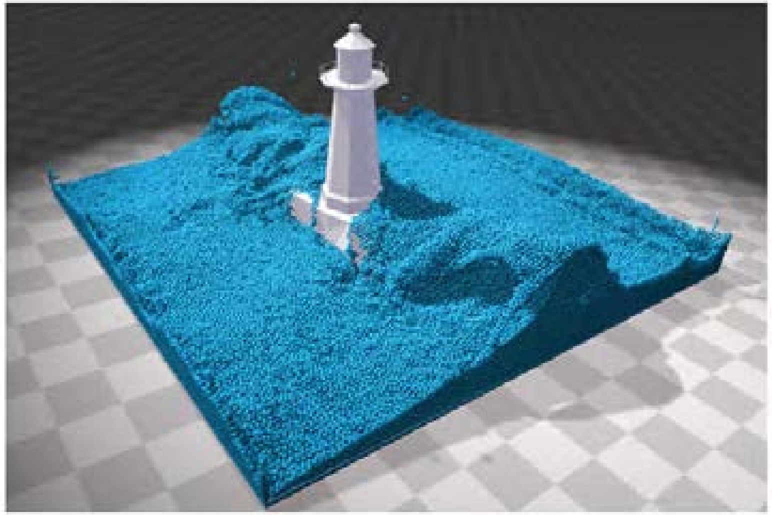
Update position of particles

$$\vec{r}_i^{n+1} = \vec{r}_i^{n} + \vec{V}_i^{n+1} \Delta t$$

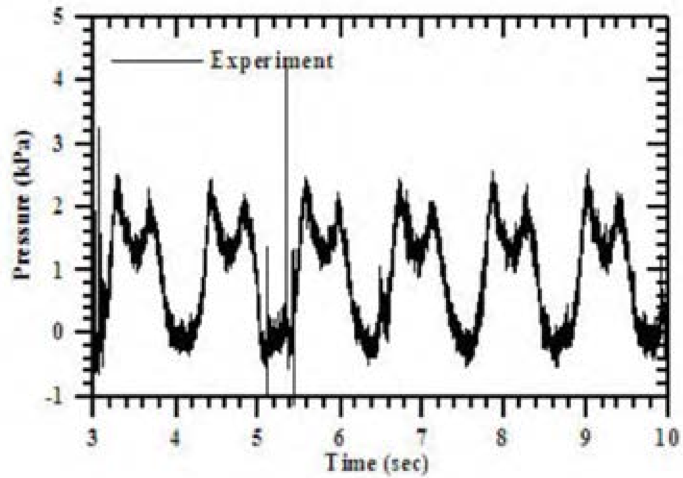
MPS方法

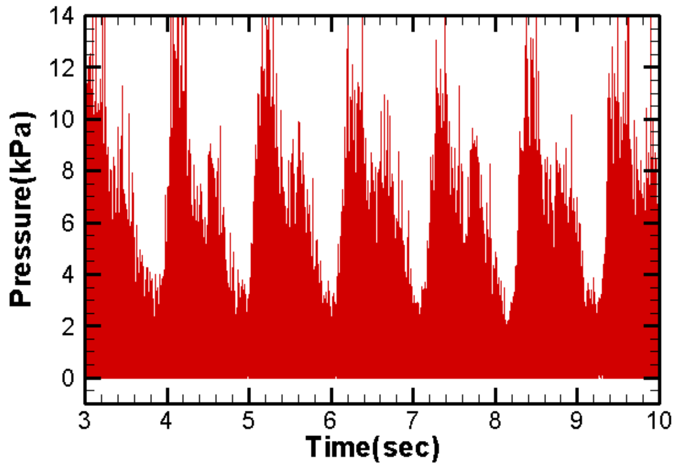
MPS应用的关键技术：

- 抑制压力振荡
- 提高三维计算效率



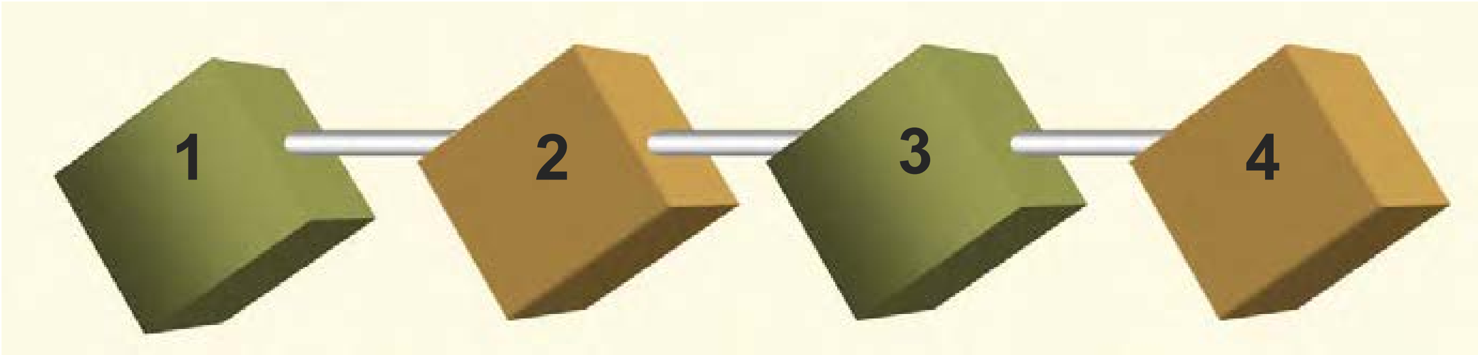
1.0×10^{9}（Fluid particles）





Meshless Solver: MLParticle-SJTU

无网格粒子法关键性问题



计算稳定性	压力振荡	计算精度	计算效率

上海交通大學 Shanghai Jiao Tong University

MLParticle-SJTU solver

MLParticle-SJTU : Meshless Particle at Shanghai Jiao Tong University

MLParticle-SJTU

Methods

- Improved MPS

Acceleration techniques

- GPU acceleration
- Parallel computations
- Overlapping technique
- Multi-Resolution

Applications

- Solitary wave
- Dam break
- Green water
- Ship-wave interaction

- 基于C++语言编写求解程序；
- 通过对一些标准算例的计算验证程序的可靠性；
- 将好的改进方法吸收进来，建立一套更加精确可靠的三维粒子法求解器。
- 程序设计将采用模块化思想，按计算任务将程序并行化，基于OpenMPI、CUDA语言实现CPU+GPU计算系统的高效并行计算。
- 将这套求解器应用到船舶和海洋工程中一些复杂的流动问题，如船舶、海洋平台在波浪中的运动。

- 主要采取从简单到复杂、从二维到三维、从串行到并行的技术路线。具体实施过程如下：

1）首先编写SPH和MPS的二维串行求解程序，对一些典型问题进行求解，如二维溃坝、晃荡，验证程序的可靠性。

2）将程序扩展到三维问题，同时采用更加高效的计算方法，如用Link-List方法进行邻居粒子的搜寻，BiCG –Stab方法求解Poisson方程等，并对程序进行验证。

3）将一些更精确、合理的改进方法加入到程序中，并通过算例进行验证，构建一个更加可靠、稳定的求解程序。

4）基于OpenMPI语言将程序并行化。

5）结合CUDA语言实现对GPU的调用。

6）将程序应用到船舶与海洋工程中的实际问题。

压力振荡现象与缓解方法

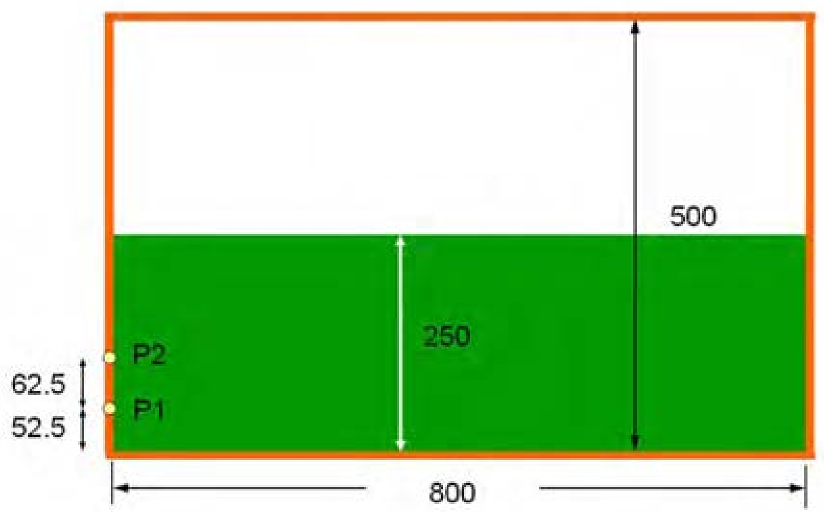
- 压力振荡现象
- 已有的改进方法
- 对已有改进方法的验证和分析
- 一种新的自由面判断方法
- 改进的MPS方法
- 小结

压力振荡现象

数值测试：　二维矩形液舱晃荡

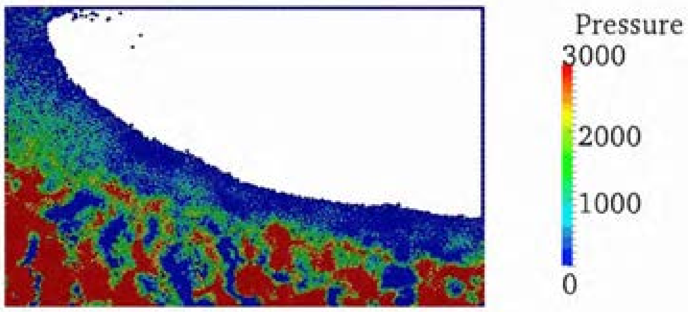
液舱运动方式：　$x = a \cdot \sin(\omega t)$

其中：　$a = 0.02\ \mathrm{m}$　$\omega = \omega_n$　$\omega_n^2 = \frac{g\pi}{L} \cdot \tanh\left(\frac{\pi h}{L}\right)$

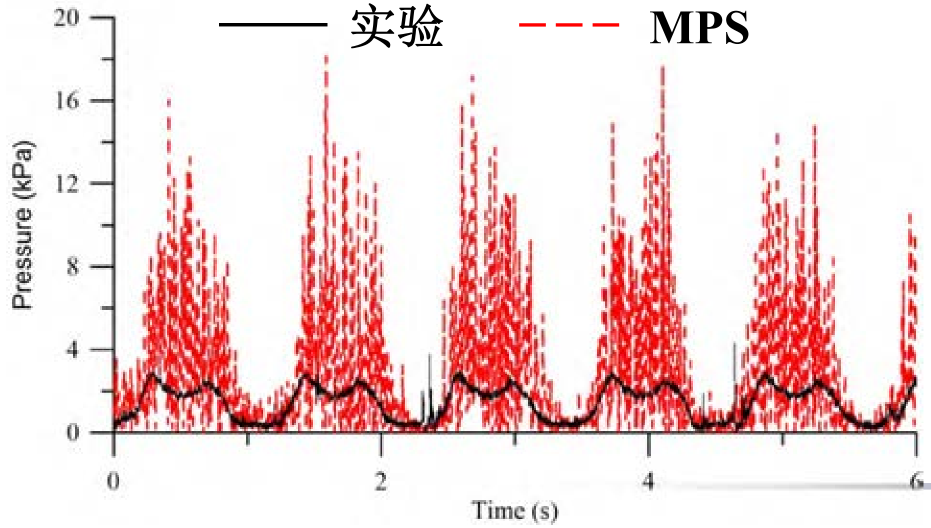


液舱几何模型（单位：mm）

压力振荡产生的原因



P2点压力 ⇨



压力振荡产生的原因

- 压力梯度
- 压力Poisson方程源项
- 自由面判断

压力梯度改进方法

- 原始MPS方法

$$<\nabla P>_i = \frac{D}{n^0}\sum_{j\neq i}\frac{P_j - P_i^{'}}{|\boldsymbol{r}_j - \boldsymbol{r}_i|^2}(\boldsymbol{r}_j - \boldsymbol{r}_i)\cdot W(|\boldsymbol{r}_j - \boldsymbol{r}_i|)$$

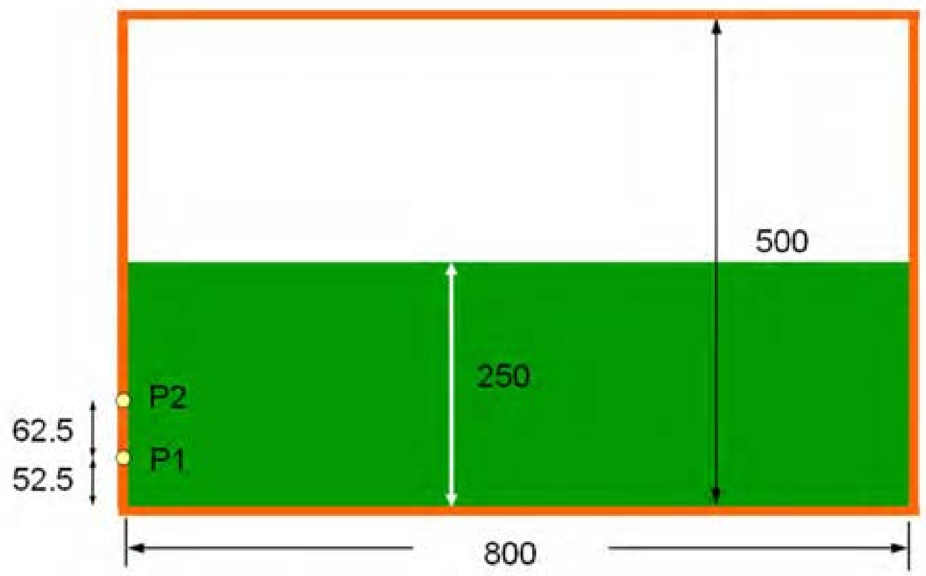
- 改进方法：

$$<\nabla P>_i = \frac{D}{n^0}\sum_{j\neq i}\frac{P_j + P_i}{|\boldsymbol{r}_j - \boldsymbol{r}_i|^2}(\boldsymbol{r}_j - \boldsymbol{r}_i)\cdot W(|\boldsymbol{r}_j - \boldsymbol{r}_i|)$$

Tanaka et al. Journal of Computational Physics, 2010, 229(11): 4279-4290.

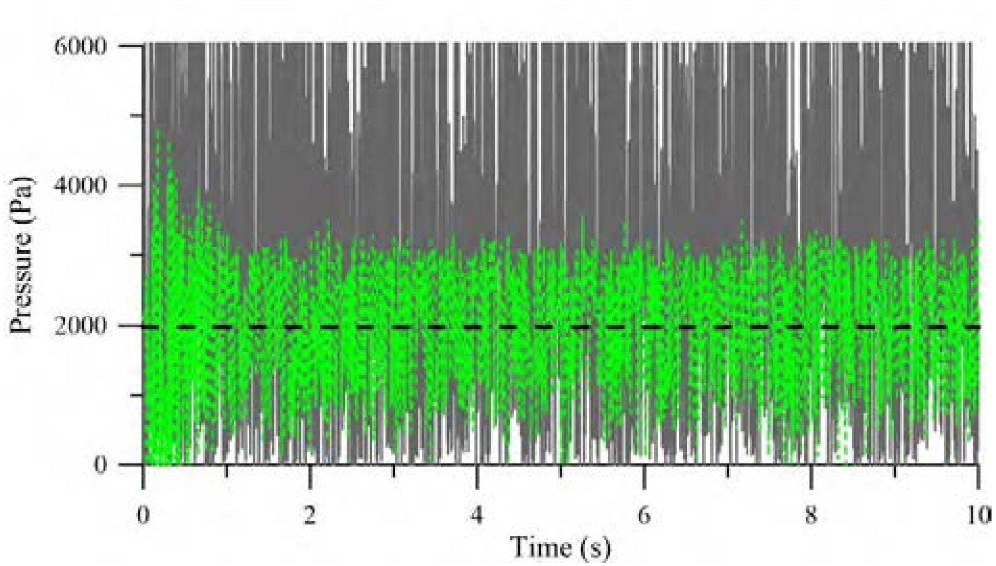
对压力梯度的测试

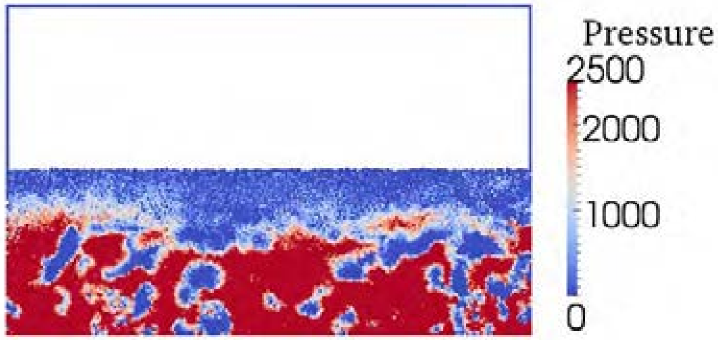
静水问题

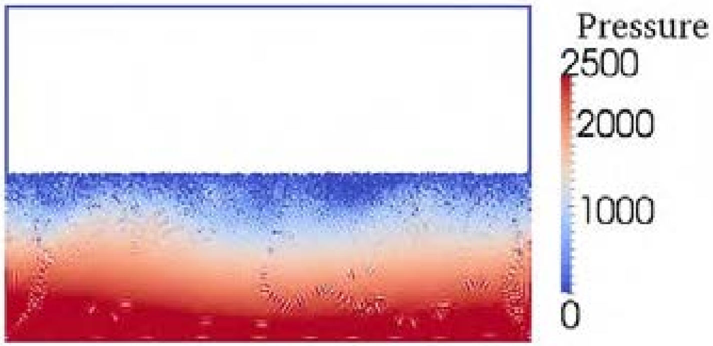


液舱几何模型（单位： mm）

- - - - 理论值　　—— 原始MPS方法
- - - - 使用改进压力梯度







原始MPS方法　　使用改进压力梯度

压力Poisson方程源项

- 原始MPS方法

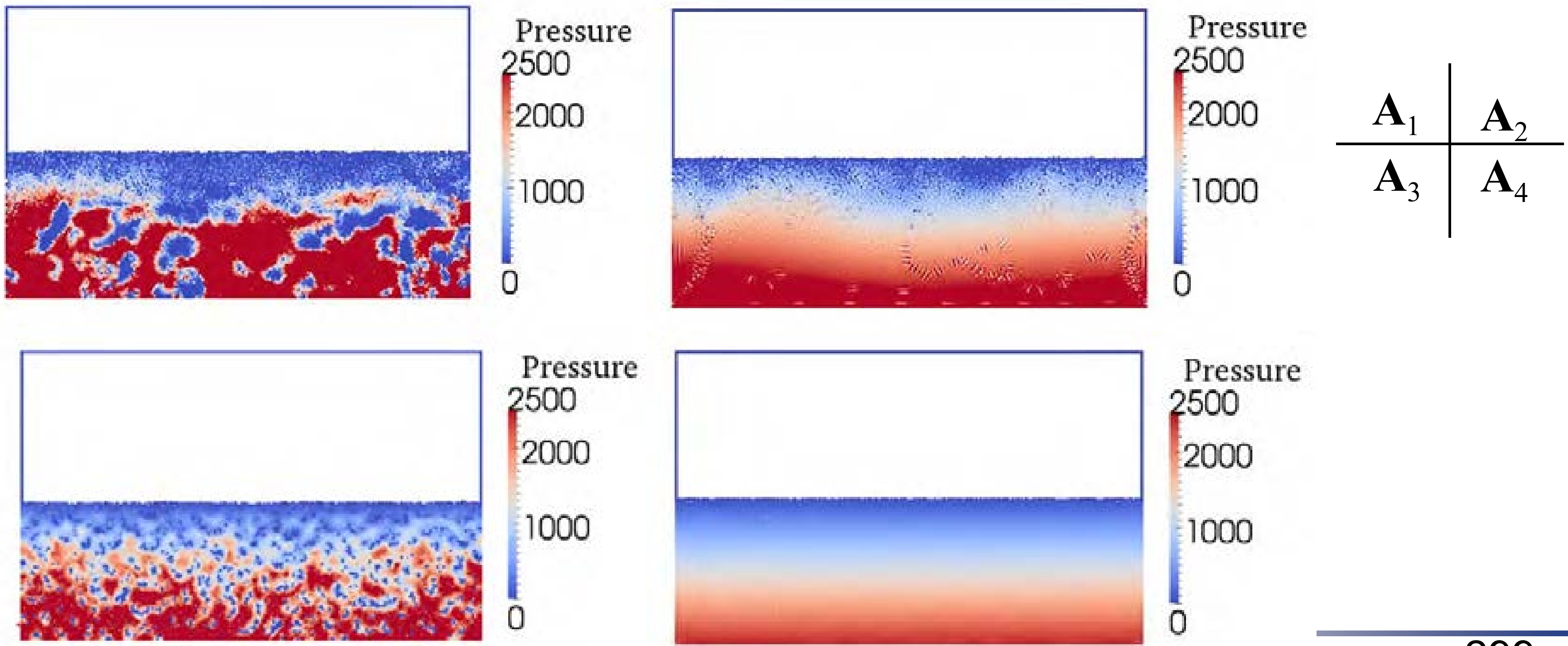
$$< \nabla^2 P^{k+1} >_i = -\frac{\rho}{\Delta t^2}\frac{< n^* >_i - n^0}{n^0}$$

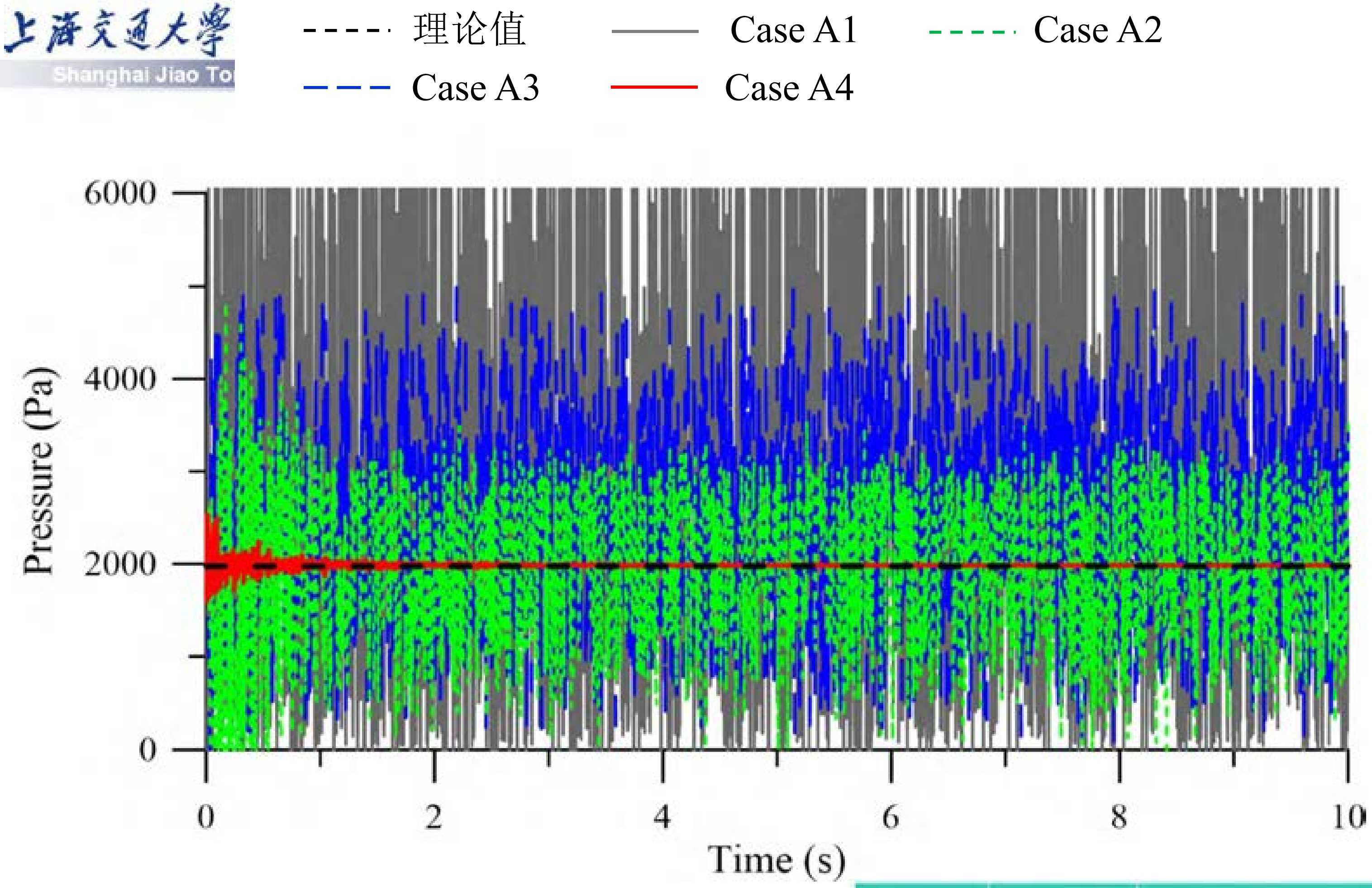
- 混合源项法：

$$< \nabla^2 P^{k+1} >_i = (1-\gamma)\frac{\rho}{\Delta t}\nabla \cdot V_i \; - \gamma\frac{\rho}{\Delta t^2}\frac{< n^* >_i - n^0}{n^0}$$

Tanaka et al. Journal of Computational Physics, 2010, 229(11): 4279-4290.

算例	压力梯度	压力Poisson方程源项	自由面判断
Case A1	原始方法	原始方法	原始方法
Case A2	改进方法	原始方法	原始方法
Case A3	原始方法	改进方法	原始方法
Case A4	改进方法	改进方法	原始方法





算例	压力梯度	压力Poisson方程源项	自由面判断
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