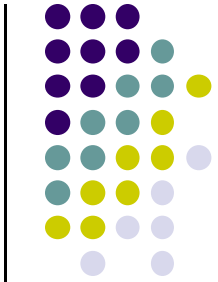
Introduction of OHMUGA Solvers



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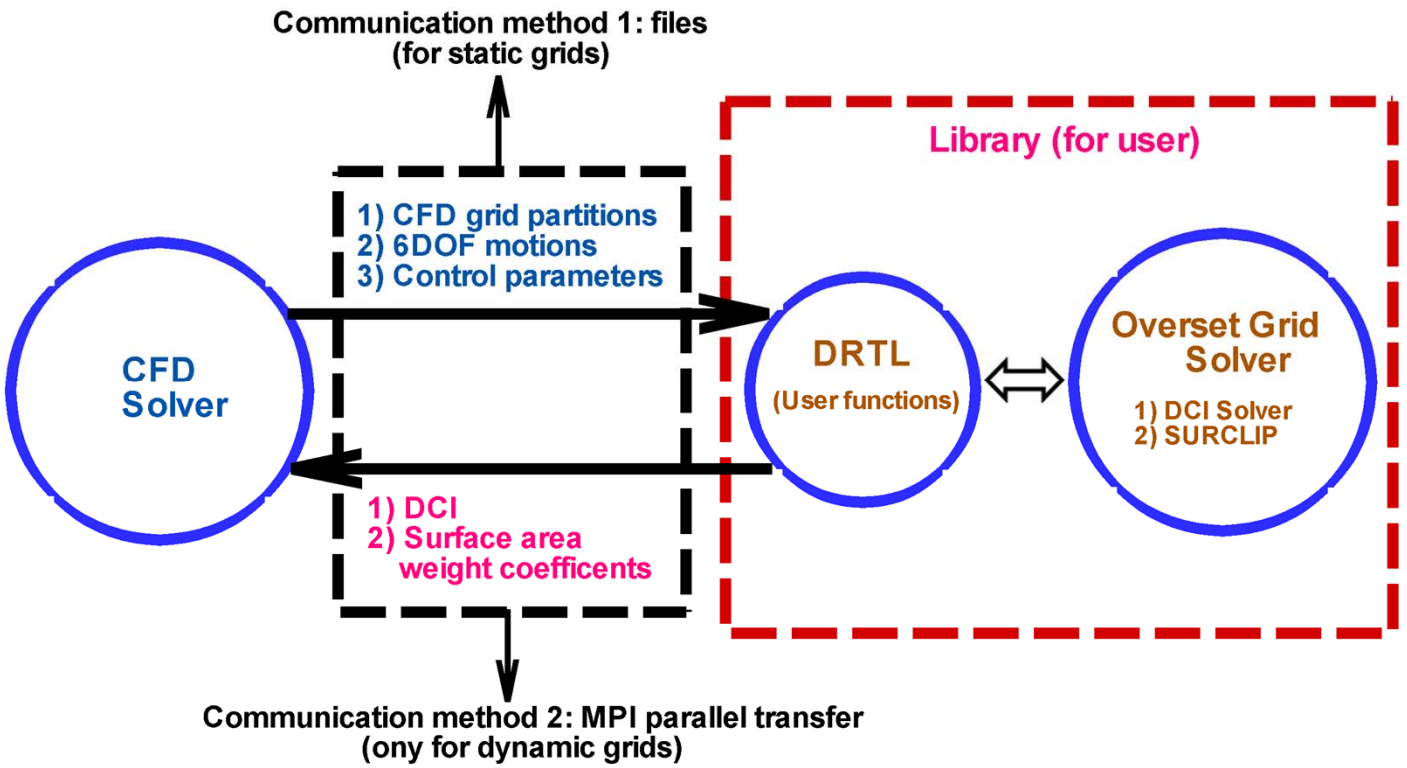
Contents:

CFD-OHMUGA Solver

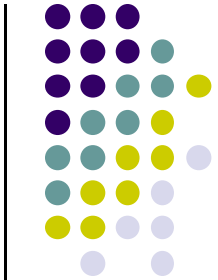
Overset-OHMUGA Solver

- CFD Solver (CFD-OHMUGA)
  - MPI parallel, unstructured grid, viscous flow solver for simulating multi-object (bodies), wave-body (or flow-body) interaction problems with prescribed or predicted 1-6DOF rigid body motions, and prescribed 1-3DOF appendages' (controllers) rotations to the bodies.
- Overset Grid Solver (Overset-OHMUGA ,Library)
  - Domain decomposition, MPI parallel, unstructured, dynamic overset grid solver for DCI (Domain Connectivity Information) and surface area weight coefficients serving for different CFD solvers (CFD-OHMUGA or others).
- Coupled solvers
  - CFD and overset solvers can work alone, or together but in independent and parallel way.
  - Simulating flow in whole domain by exchanging boundary information between overset grids.
  - Printing out and reading files from hard disk for static grids.
  - Communicating information through DRTL for dynamic grids in MPI parallel way.
  - Overset-OHMUGA also provides necessary DCI of previous time step (hole nodes move and change into active nodes).

Coupled CFD and Overset Grid Solver



CFD-OHMUGA Solver



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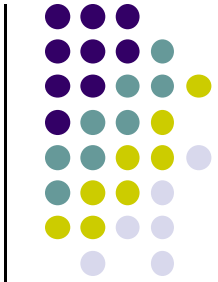
Outline

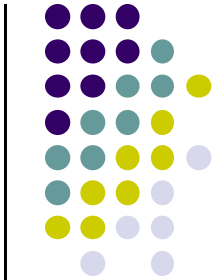
- Objectives and current function
- Mathematical model
- Numerical method
- Validations and computational examples

Objectives and Current Functions



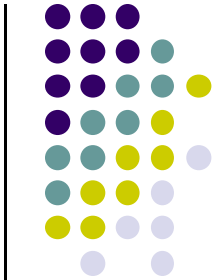
- Objectives
  - The copyrighted unstructured grid CFD code is addressing for computing marine hydrodynamics in the objects with very complicated geometries and motions (ships, underwater vehicles, offshore structures, rotators, etc).
  - Fast, robust and accurate computation.
- Current functions
  - MPI parallel simulation for marine hydrodynamics, for example, resistance and propulsion (autopilot), maneuvering (e.g. zigzag using propeller and rudder controllers), seakeeping (e.g. pitch-heave, course-keeping in waves), etc. for single or group of ships.
  - Coupled parallel computation for viscous fluid flow, free surface (waves), body forces, moments, and 6dof motions and active controllers, for fluid-body (or wave-body) interaction problems of multi-bodies (floating or submerged multi-bodies) with independent 6dof motions, and their multi-controllers with independent motions (3dof rotations relative to their corresponding parent bodies).
  - Overset-OHMUGA solver is coupled with CFD solver: parallel dynamic unstructured overset grids (multi-block structured grids can be read and translated) solver.
  - Motions: prescribed or predicted 1-6dof, captive or free-body motions. (for active controller: 1-3dof controller rotations relative to the body).
  - Active controller actuators: 1) appendages (real propeller, rudders), 2) models (model propeller, others). Controller types: 1) open-loop, 2) feed-back.
  - Others: rigid body dynamics, linear regular and irregular incoming waves, linear mooring model, RANS or DES turbulence models,Projection coupling, HPC, TVD scheme, etc.

Mathematical models

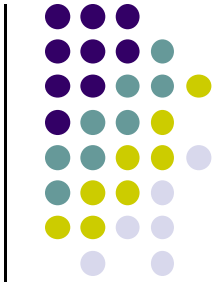


- Inertia or non-inertia coordinate systems: earth system or body-fixed system.
- Single-phase incompressible viscous flow.
- Free surface model including level set transport and reinitialization models.
- RANS (BSL, SST) and DES turbulence models.
- Multi-body (1-6DOF motions) and multi-appendage (1-3DOF rotations) rigid body dynamic models.
- Dynamic overset grids with ALE (Arbitrary Lagrangian Eulerian method).
- Incident linear regular or irregular waves.
- Body force propeller model.
- Linear mooring model.
- Active controllers for: autopilot, heading control, etc.

Numerical methods



- Publishing: Huang 2013, Vol.3, pp. 1011-1018, ISOPE.
- Dynamic unstructured overset grids constructed by either multi-block, body-fitted, non-orthogonal curvilinear structured grids (automatically transformed to unstructured grid formation), or normal unstructured grids with 4 different kinds of hybrid elements (tetrahedral, hexahedral, prismatic and pyramidal elements).
- Collocated grid (all variables are set at nodes based on element vertexes).
- Finite Volume (median-dual scheme).
- Projection or PISO method for velocity and pressure coupling.
- 2nd-order Implicit method for temporal and spatial discretization for momentum and level set governing equations to apply big time step.
- Upwind edge-conformed method, or line-extension method of shape function interpolation for fiction node in a tetrahedral element (constructed by tagged node and its edge-connected neighbor nodes) for convection term discretization.
- Limiter functions for convection term discretization (venkatakrishnan or barth jesperson limiter, or TVD method of Roe's minmod, Roe's superbee, van Albada, Van Leer, etc.)
- An option of variable gradient calculation based on local fiction orthogonal coordinates.
- Shape function (iso-parameter) interpolation method is used for discretization for the poison equation (either for pressure equation or diffusion terms of other equations).
- Far distance water fiction points and fiction elements method for accurately calculating pressure gradient near free surface.

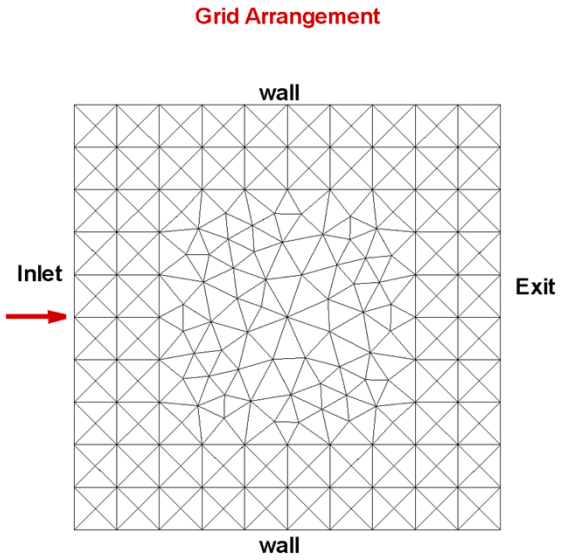


- Narrow Band and Geometry method for level set equations (to keep fast calculation and accuracy in skewed grids).
- KD-Tree fast search and geometry method for calculating distance of close points for level set reinitialization.
- Efficient and compact stencil numerical treatments for pressure equation for hexahedral elements.
- Multi-body (object) 6-DOF motions
  - Earth coordinate and body-fixed coordinate switch; ALE for grid motion; Multi-body forces, moments and motions are computed independently; multi-layer refinement overset grids can be set flexibly to follow all or part of body motions. Mixed predictor (explicit) and corrector (implicit) method for time evolution for predicting 6-DOF motions.
- Multi-appendages (controllers)
  - Euler angle methods for 1-3DOF appendage rotations which is independent from body motions.
  - Calculate motions in earth system by Compositing the appendage 1-3DOF motions with their parents' 1-6DOF body motions.
- All above are MPI parallel calculations.
  - Automatic load-balancing domain partition.
  - Arbitrary number of layers of fiction nodes for inter-processor communication.
  - Dynamic memory allocation.
  - Gauss-Seidel iteration solver for control equations.
  - PETSc toolkit (Copyrighted by UChicago Argonne, 2-clause BSD license, permission is perpetual, world-wide, and provided on a royalty-free basis) is used for solving pressure poison equation:
    - KSP options : Generalized Minimal Residual (GMRES), BiConjugate Gradient, BiCGSTAB,etc.
    - Preconditioner options : Block Jacobi, Incomplete LU, Incomplete Cholesky, SOR, Multi-Grid, etc.

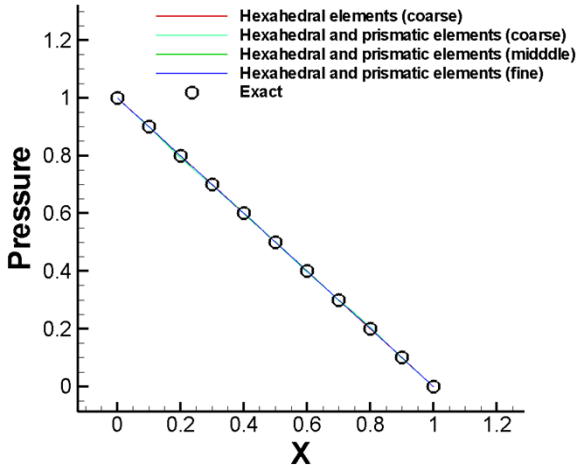
Validations and Computational Examples

- 2D laminar flow in a channel
  - Computational conditions: channel has width of 1.0 and length of 1.0, Reynolds number is equal to 1.0

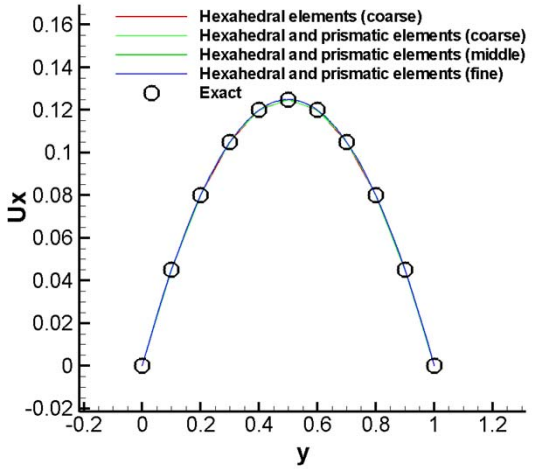
Analytical solution $p = 1 - x$ $U_x = \dfrac{y(1-y)}{2}$



Grid arrangement (mixed grid)

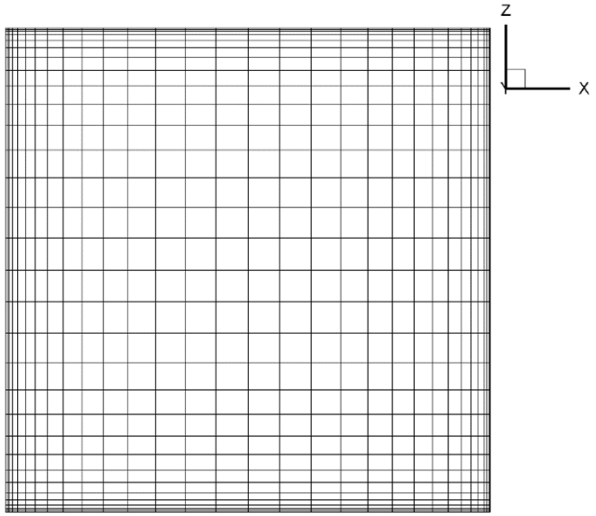


pressure distribution

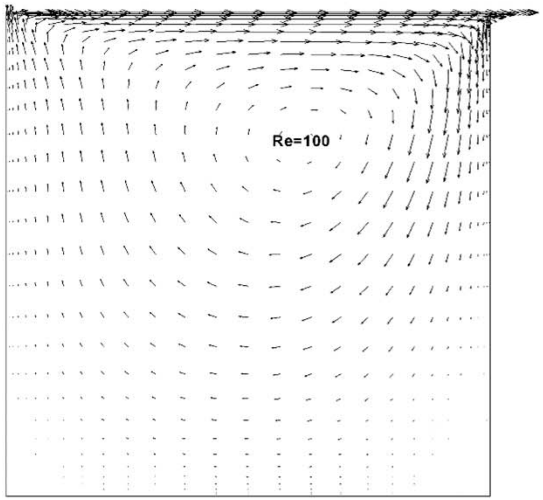


velocity (Ux) distribution

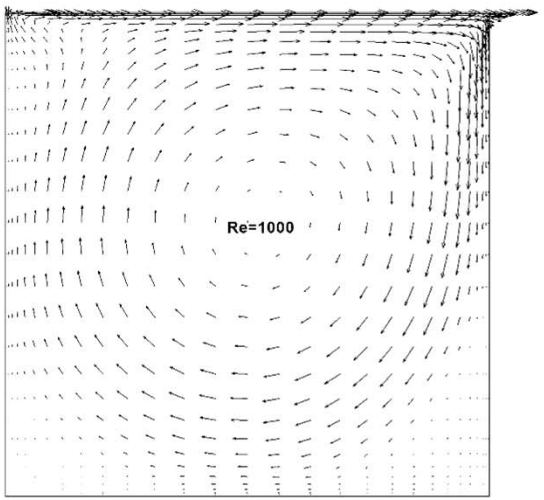
- 2D cavity flow
  - Laminar flow with Re=100 and Re=1000
  - 30×2×30 hexahedral cells



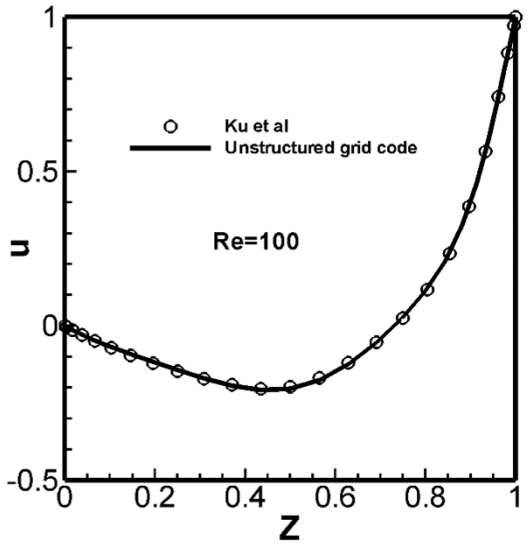
Grid arrangement



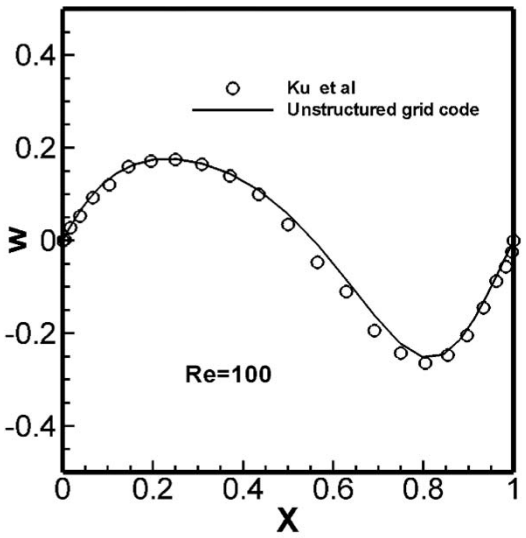
Velocity distribution
(Re=100)



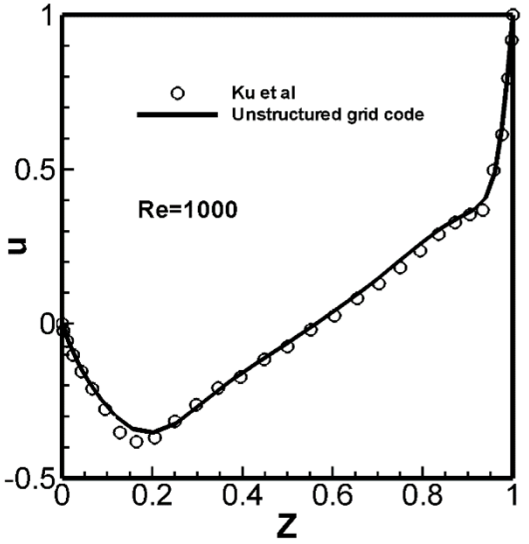
Velocity distribution
(Re=1000)



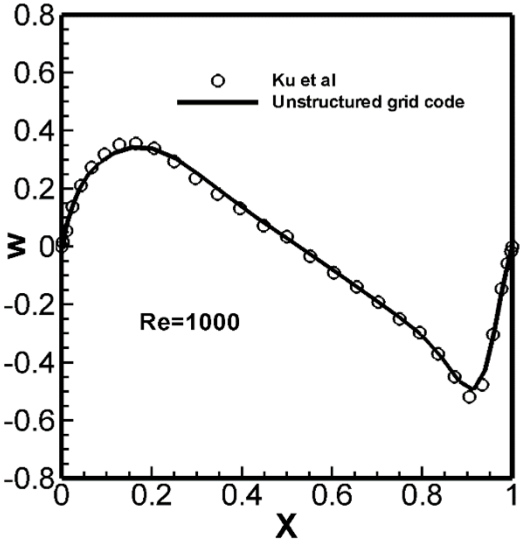
u velocity distribution (Re=100)



w velocity distribution (Re=100)



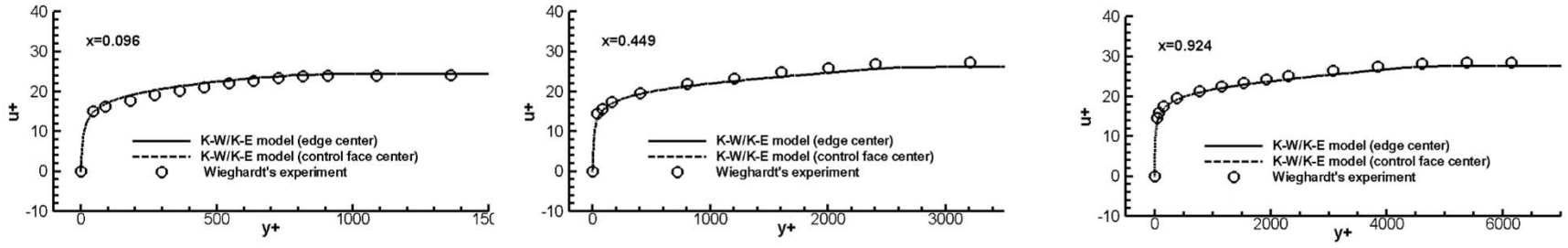
u velocity distribution (Re=1000)



w velocity distribution (Re=1000)

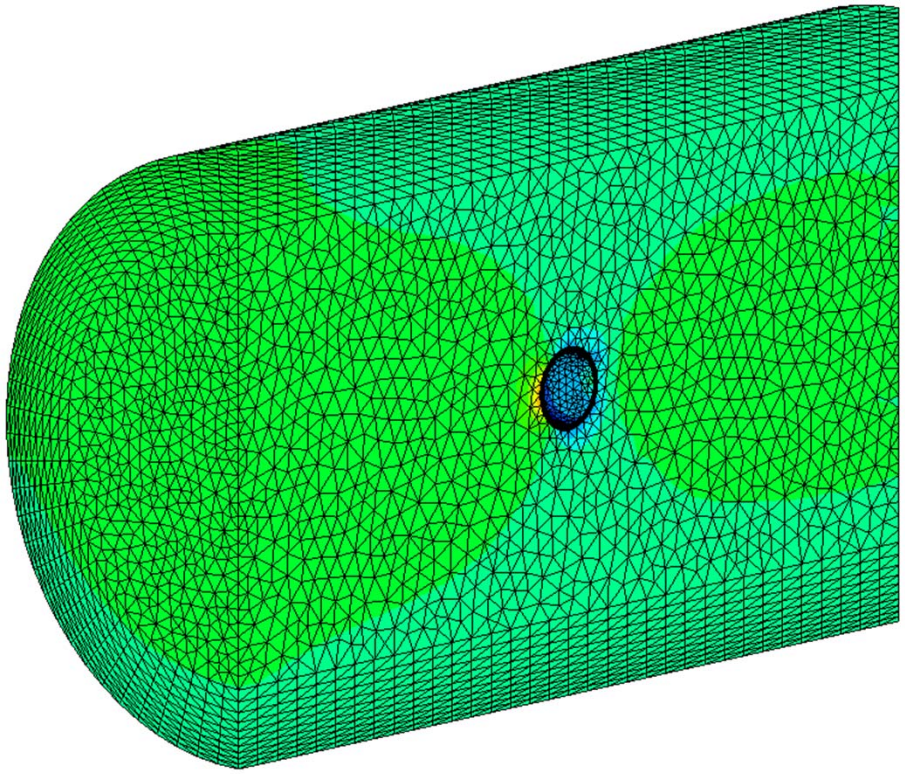
- Turbulence flow over a flat plane
  - The streamwise length and height of domain is 1 and 0.5 respectively
  - Reynolds number based on the benchmark of plane length is 1.03E+07.
  - 200×2×80 hexahedral cells

Grid arrangement Pressure W velocity

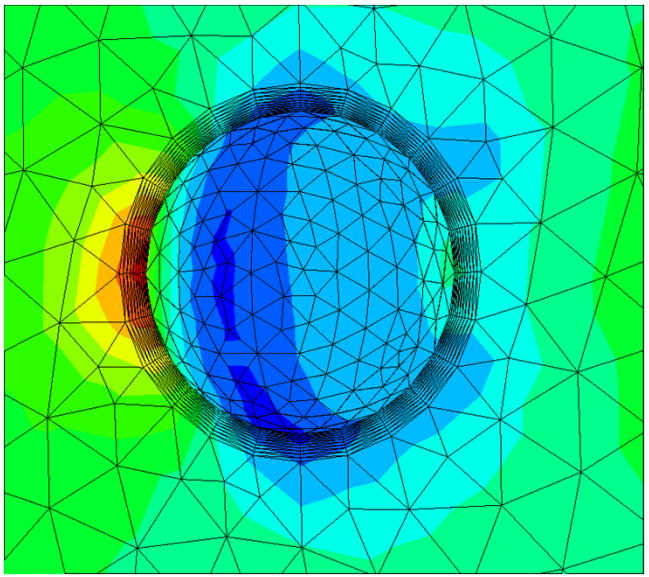


Comparisons of the profiles of u+ vs y+ between CFD (K-Omega/K-Epsilon model) and EFD results (Wieghardt's results) in different sections along streamwise direction.

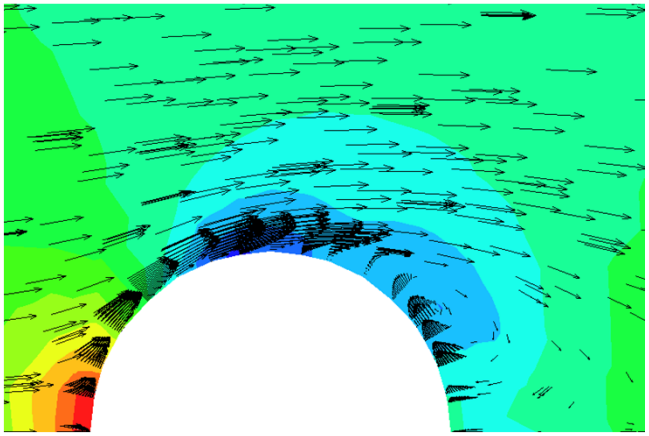
- Flow around a spherical ball (only for demonstration)
  - Reynolds number is 1.0×10^4 .
  - 4 kinds of hybrid elements (Hexahedral, tetrahedral, prismatic, and pyramid)



Grid arrangement

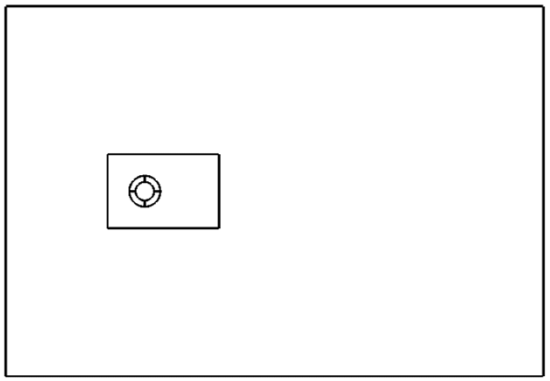


Pressure on boundaries (near the section of y=0)

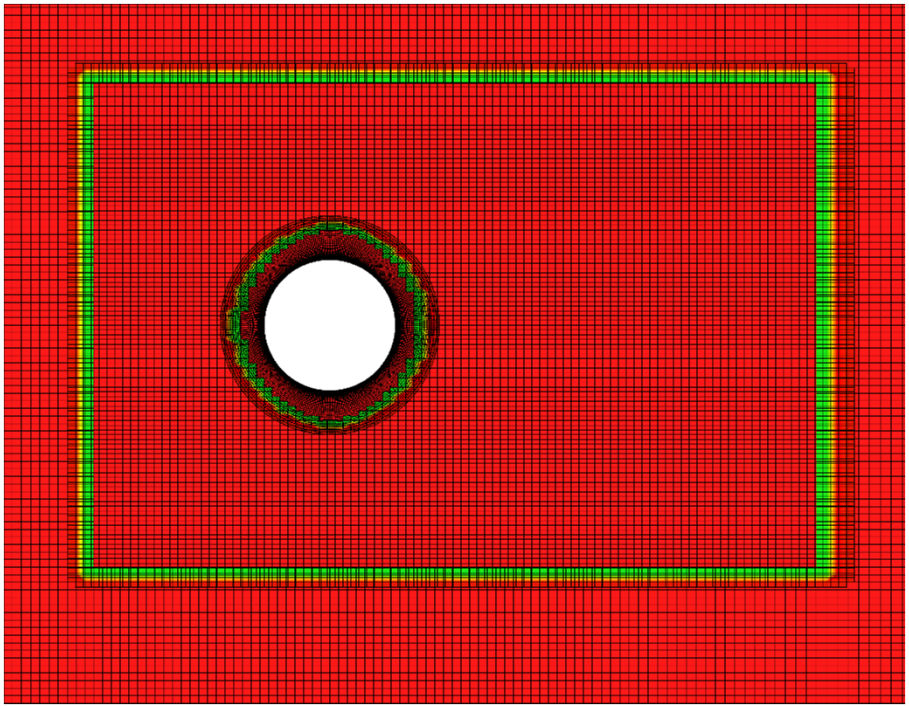


Pressure and velocity (section of z=0)

- VIV(Vortex Induced Vibrations)
  - Re=9.3E+4. URANS model (blended k-w/k-E, SST model)
  - D=0.206 m
  - Three static overset grids, eight processors for MPI parallel computation.



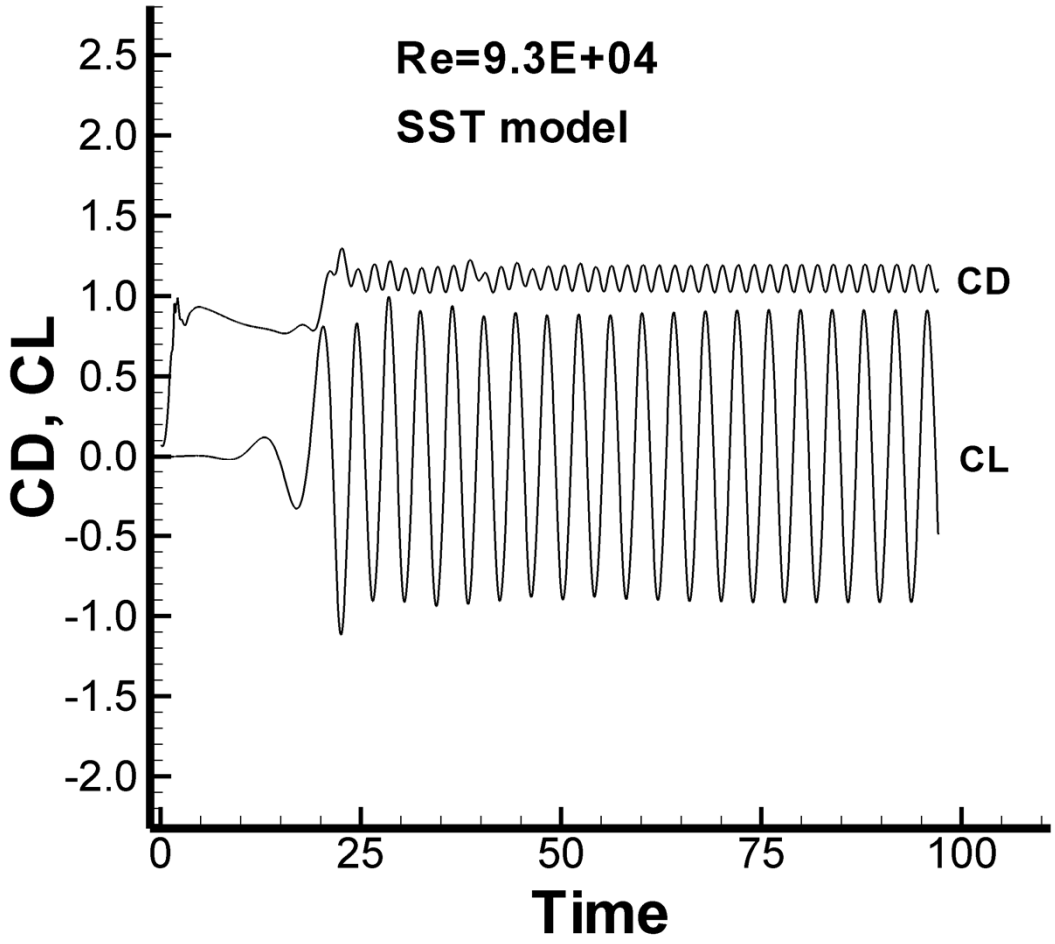
Grid outline



Active and fringe nodes in overset region

Three overset grids: 1) 4-block cylinder curvilinear grids,
2) refinement grid, 3) background grid)

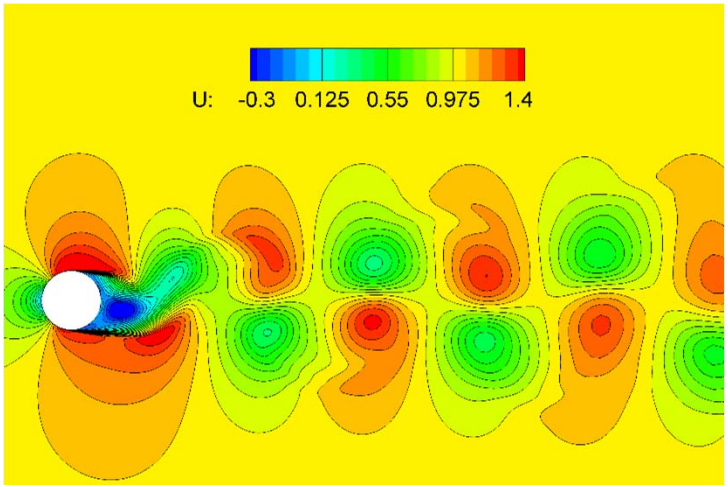
- Average Drag coefficient (CD(cfd)=1.11, CD(experiment)=1.2)
  (CD(cfd)-CD(experiment))/CD(experiment)= -7.5%
- Largest Lift coefficient (CL(cfd)=0.913)

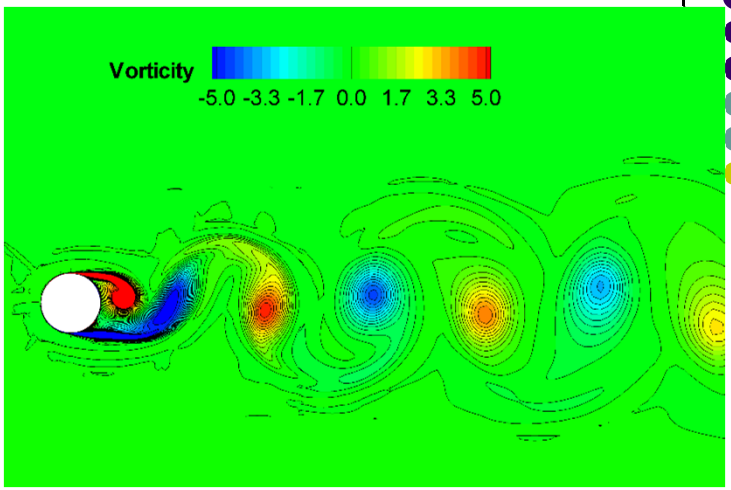


Drag and Lift coefficients

Karman vortex street

T=83.97

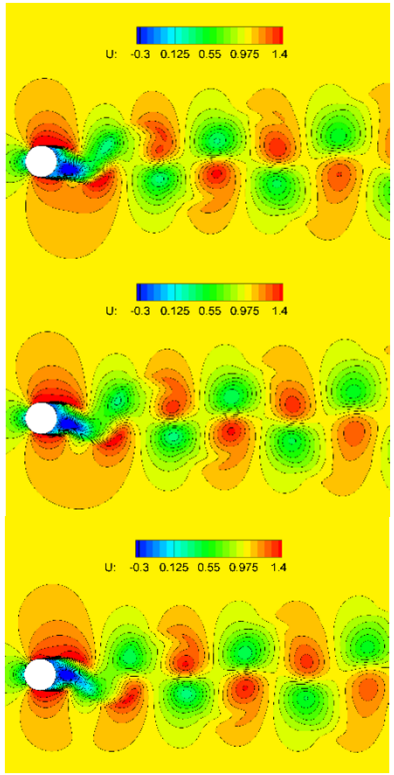




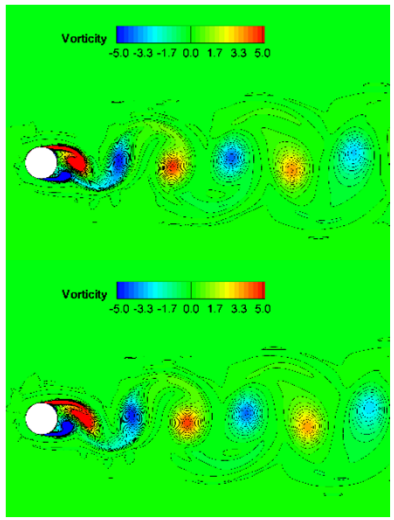
T=84.46

T=84.95

T=85.43



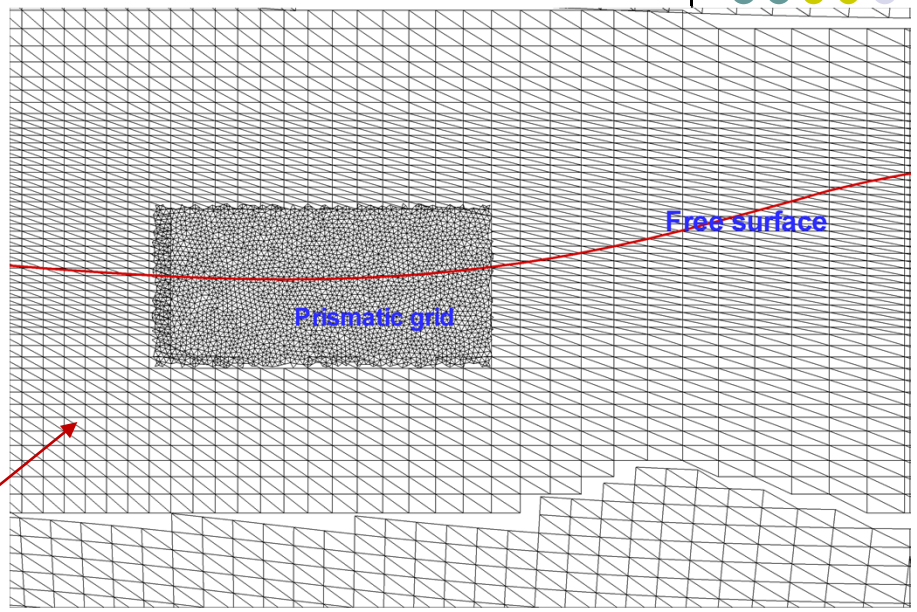
u velocity

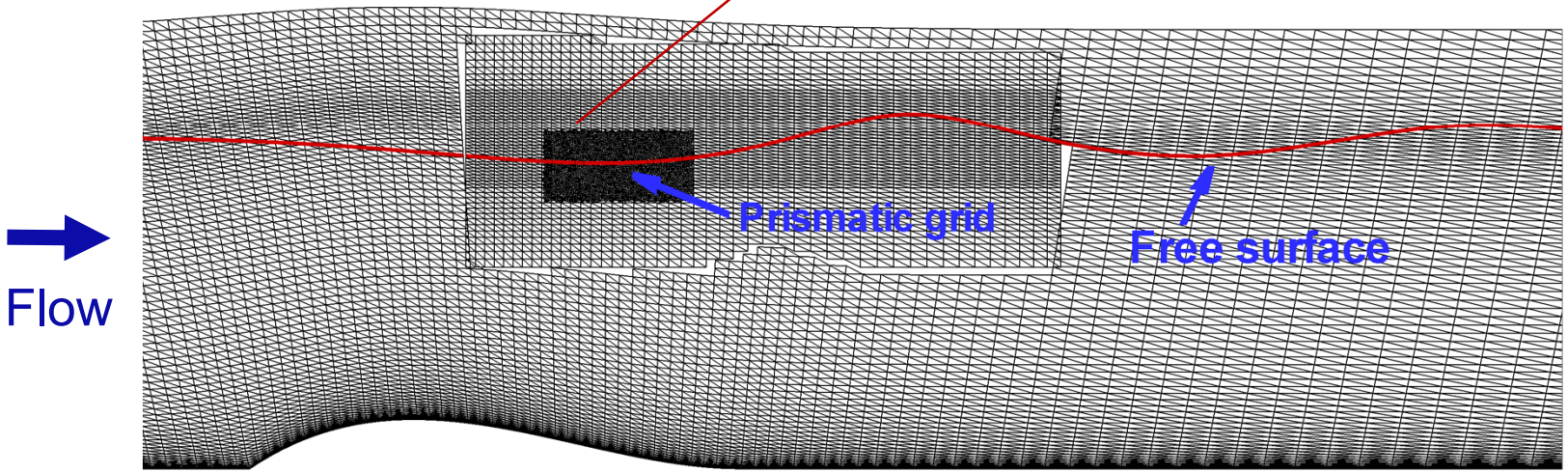


Vorticity

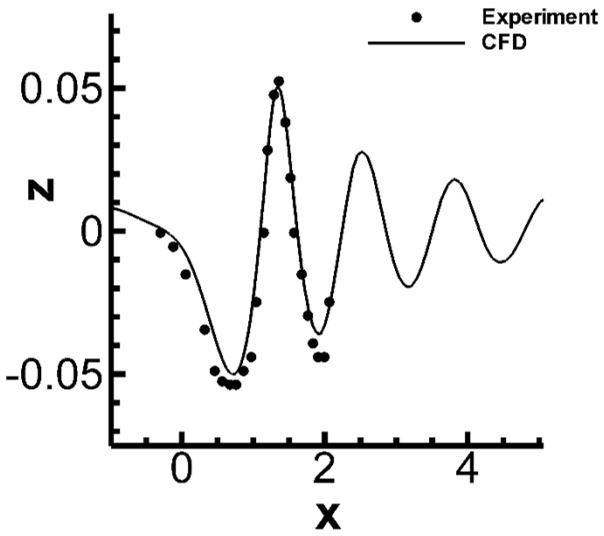
Free surface flow

- Flow over a submerged bump
  - Fr=0.426, Re=infinite.
  - EFD: Cahout (1984)
  - Three static overset grids: 1) fine prismatic grid, 2) Cartesian refinement grid, 3) curvilinear structured background grid.

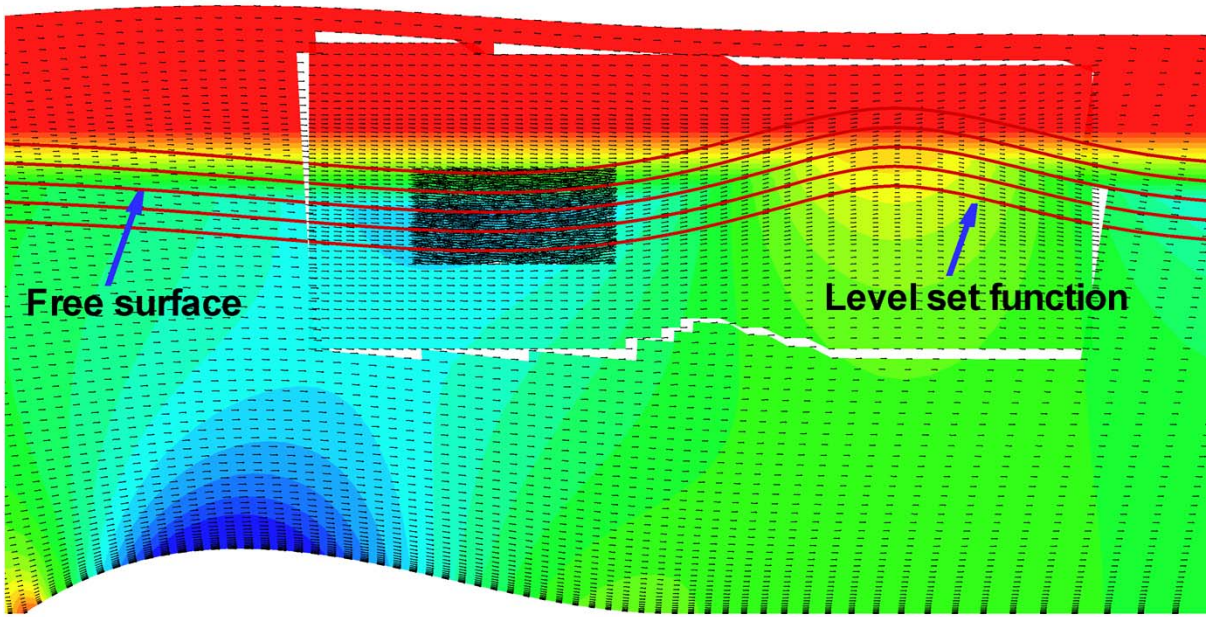




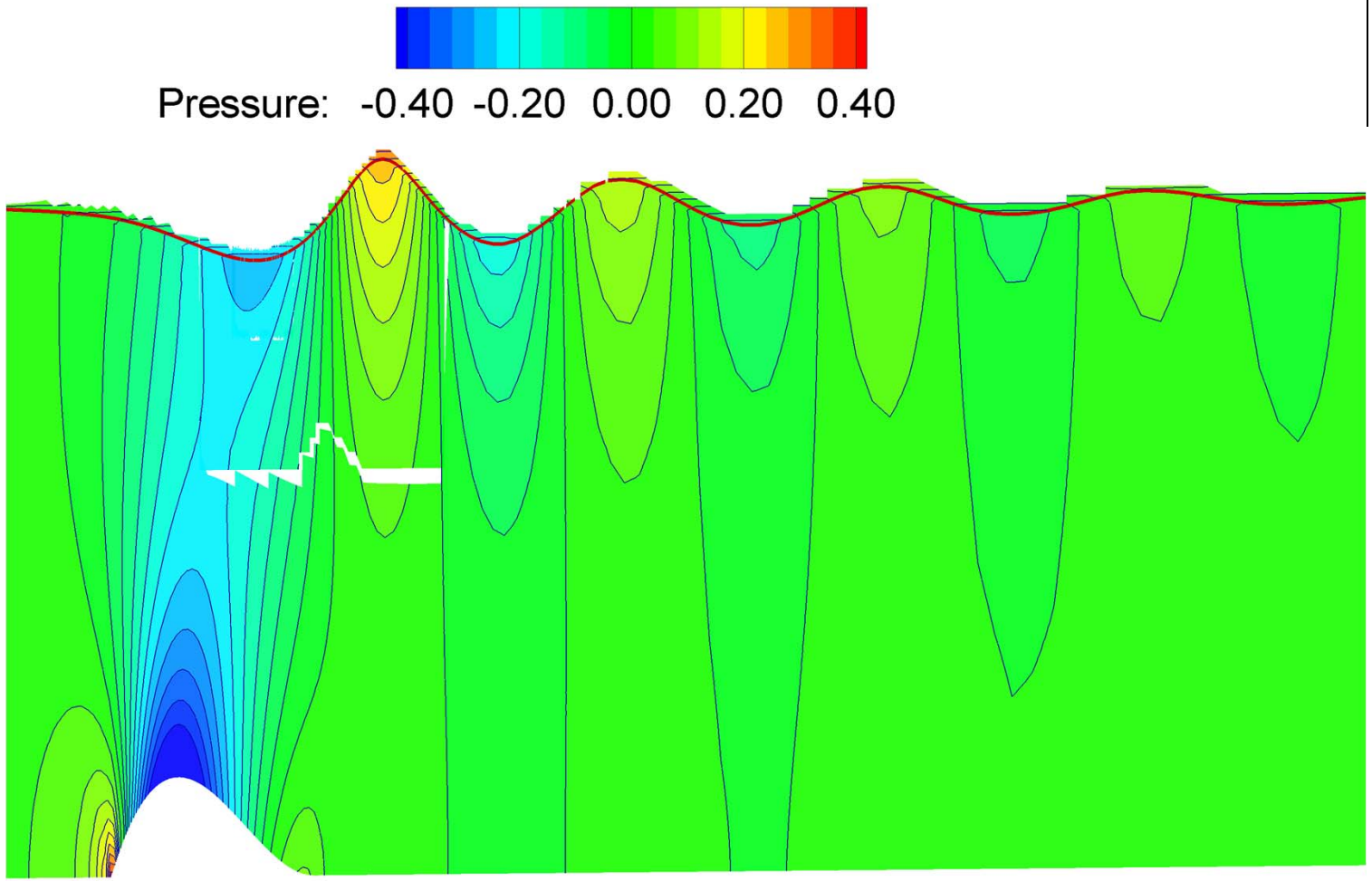
Three overset grids (active nodes) arrangement



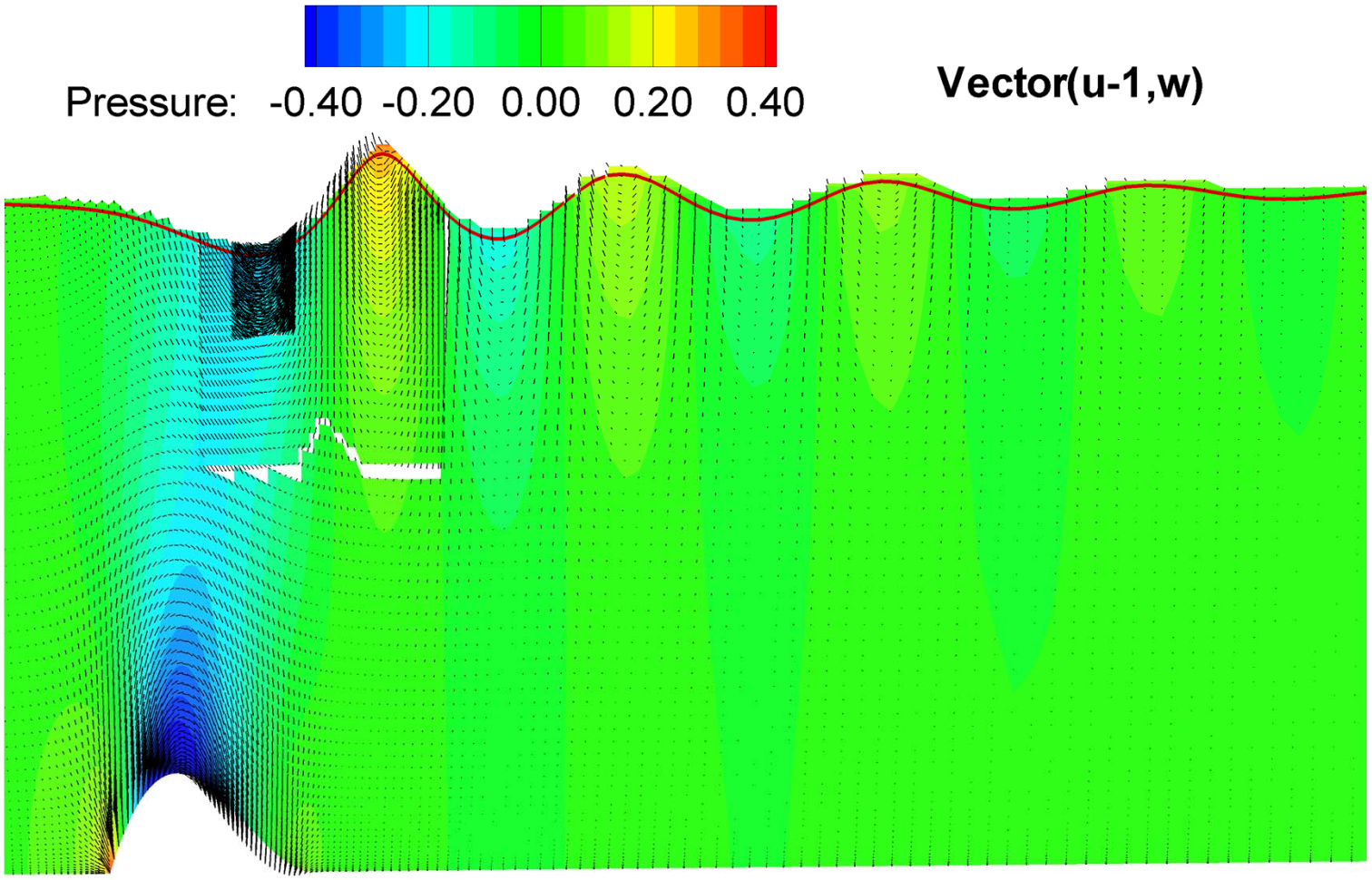
Wave elevation



Distribution of pressure, velocity and level set in the region near the first wave (only active nodes shown)



Distribution of pressure (z enlarged 5 times, active nodes shown)

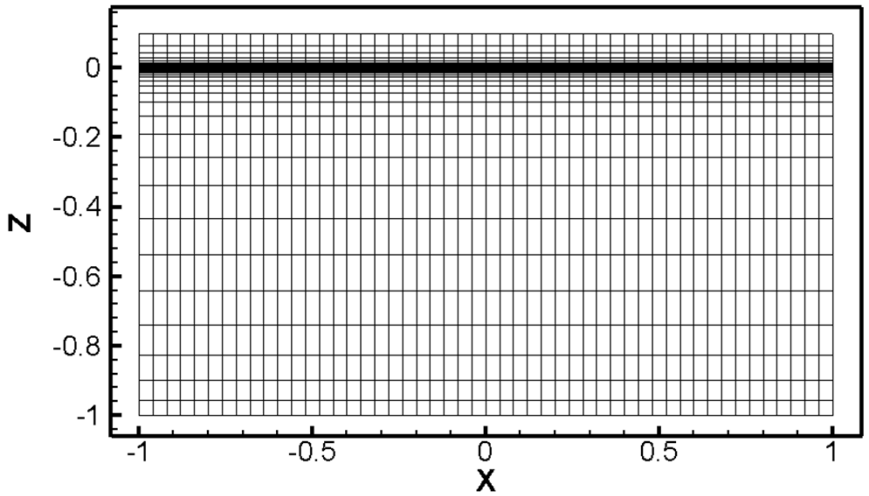


Distribution of pressure and velocity

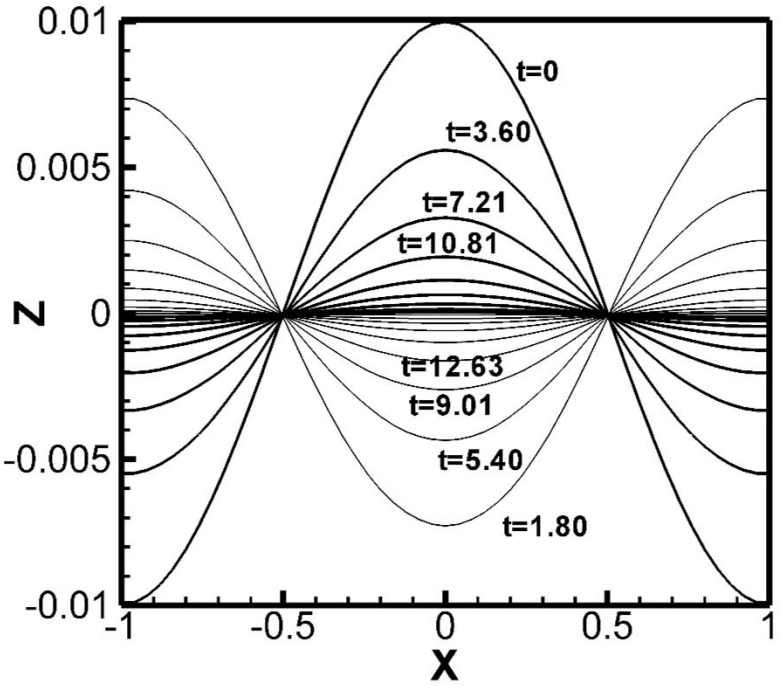
(z enlarged 5 times, only active nodes shown)

- Sloshing in a 2D fixed rectangular tank
  - Fr=1, Re=100 or 2000.
  - 50×2×37 hexahedral cells in the domain of x(-1,1) and z(-1, 0.1)
  - Analytical solution : Wu et al. (2001)
  - Initial free surface profile (*A*=0.01, *d*=1):

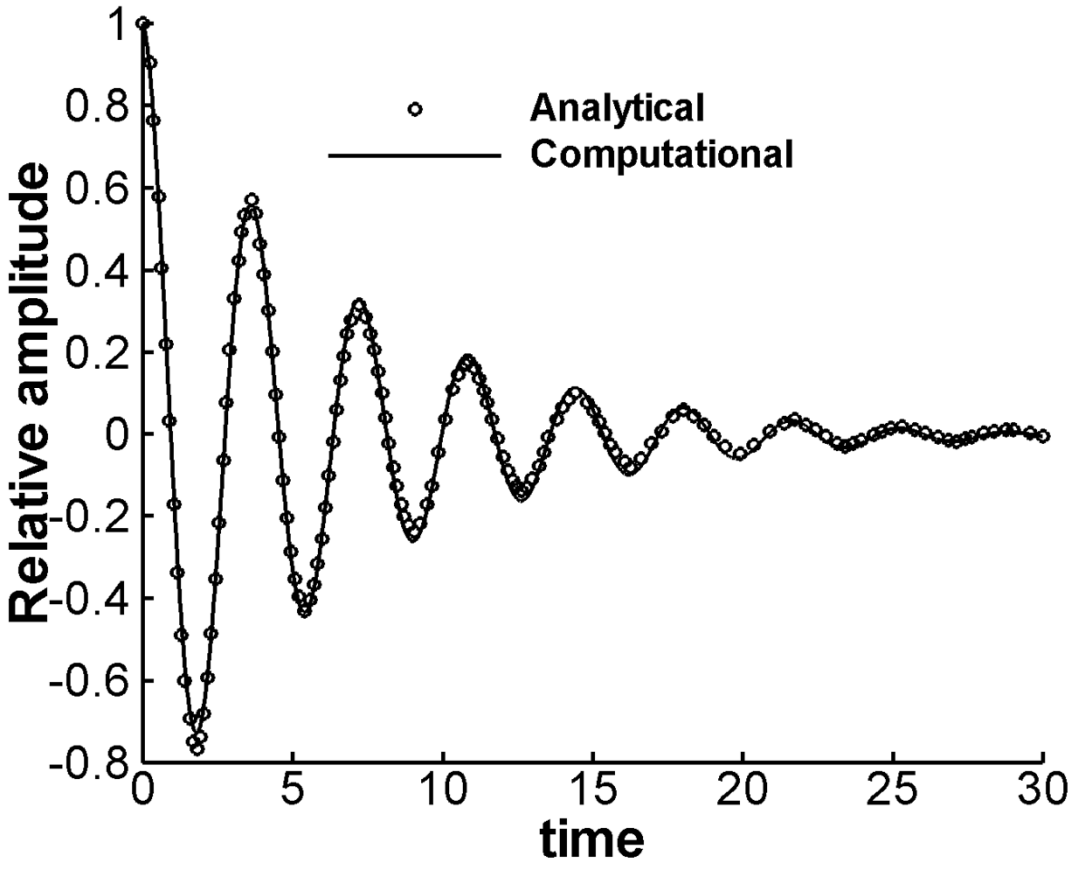
$$\zeta_0(x) = A\cos(\pi x/d)$$



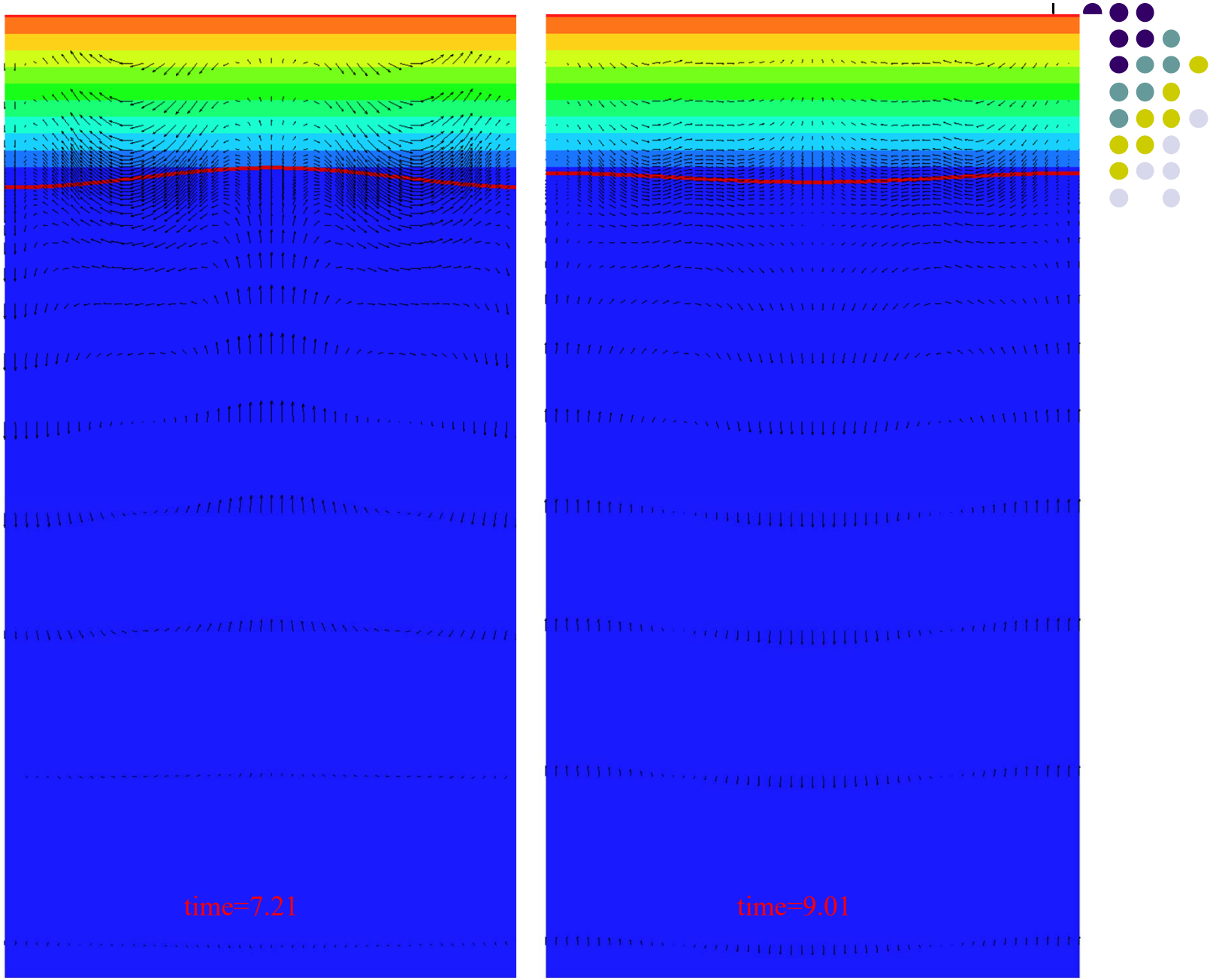
Grid arrangement



Free surface elevation evolution in a tank for different time (Re=100)



Wave amplitude evolution at the center of 2D tank (Re=100)



Typical velocity and pressure distribution (Re=100)

- Impulsive wave breaking

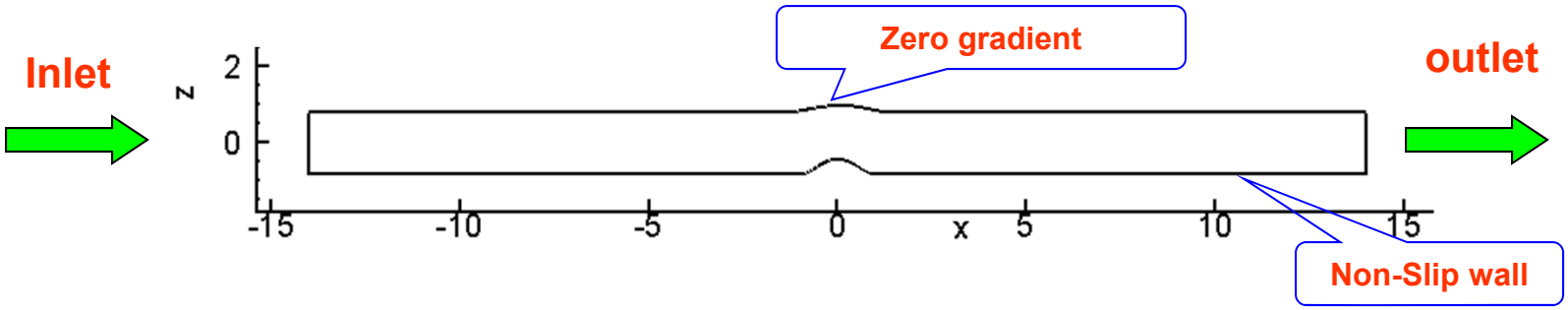
Table1 Bump data

	Bump length (2a)	Bump height (d)	Water depth	Free stream velocity	Fr (based on half bump length)	Re
Dimension	57.15 cm	11.43 cm	24.13 cm	53cm/s	-	-
Dimensionless	2.0	0.4	0.844	1.0	0.317	1.51E+05

Bump configure: $z = -0.844 + d(1 - 2\frac{x^2}{a^2} + \frac{x^4}{a^4})$ $x \in (-a, a)$

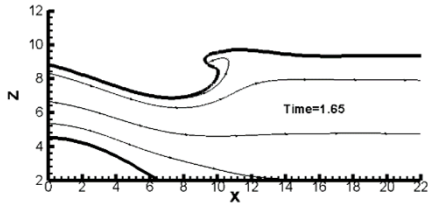
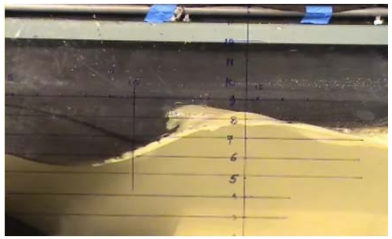
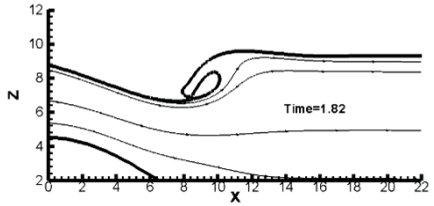
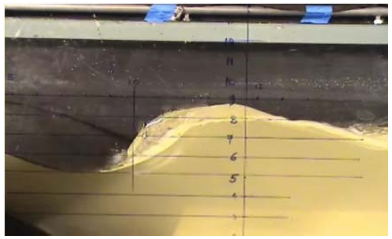
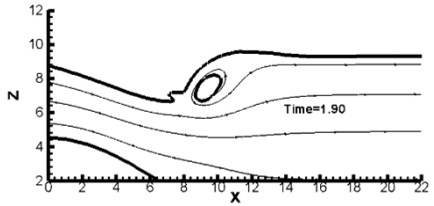
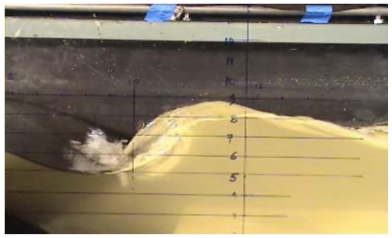
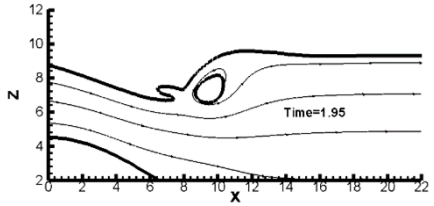
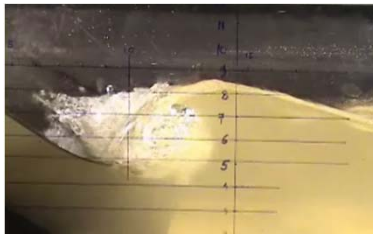
Initial condition: Sudden start from static state

(see Iafrati et al., 2001)



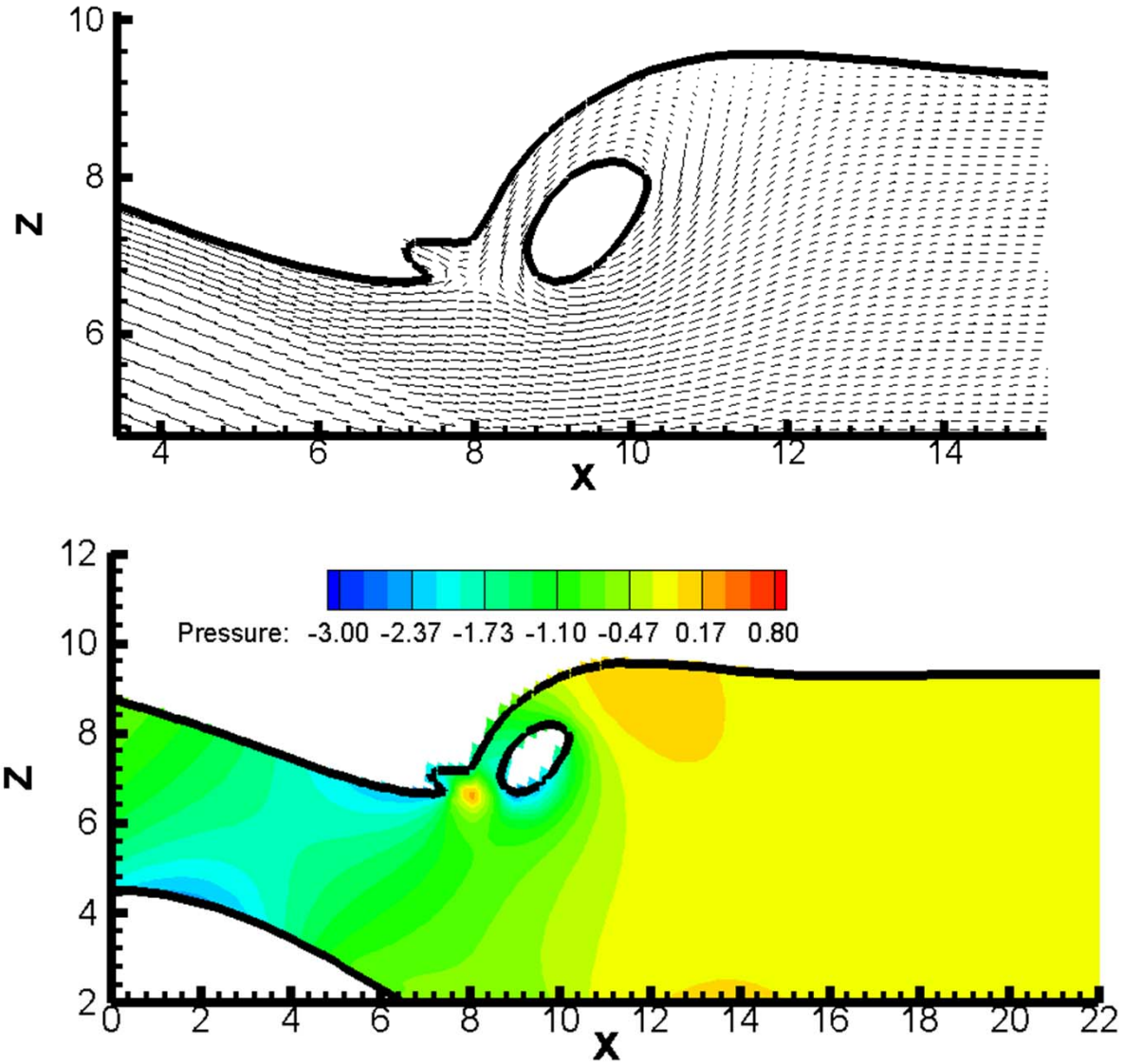
Domain and grid arrangement (461×3×132)

Movie

CFD	EFD
	
	
	
	

Experiment data (see Stern et al., 2006)

Comparison of CFD and EFD for an impulsive plunging wave



Velocity and piezometric pressure at time=1.9 (first splash)

- Free surface steady flow around a surface combatant (3-D DTMB 5512 ship with deck)

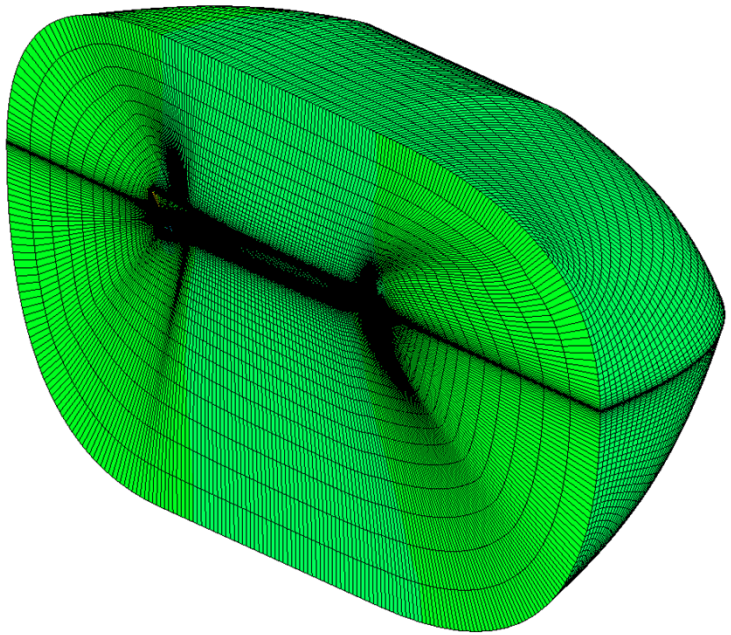
$$Fr = U_0 / \sqrt{gL} \qquad \mathrm{Re} = \rho_l U_0 L / \mu_l$$

	Model scale	Grid	Fr (based on ship length)	Re
Case 1	1:46.6	613,465 nodes	0.28	4.85E+06
Case 2		615,000 nodes	0.41	7.10E+06

Maximum time step: 0.02

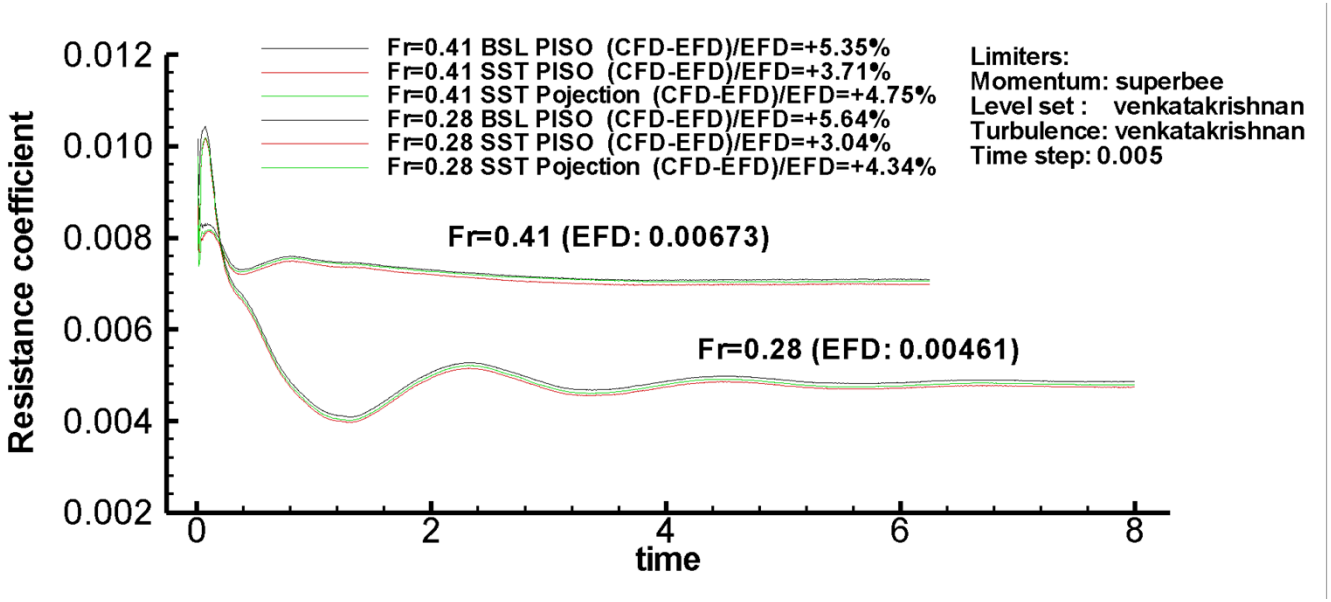
Maximum grid spacing ratio:

1:10000



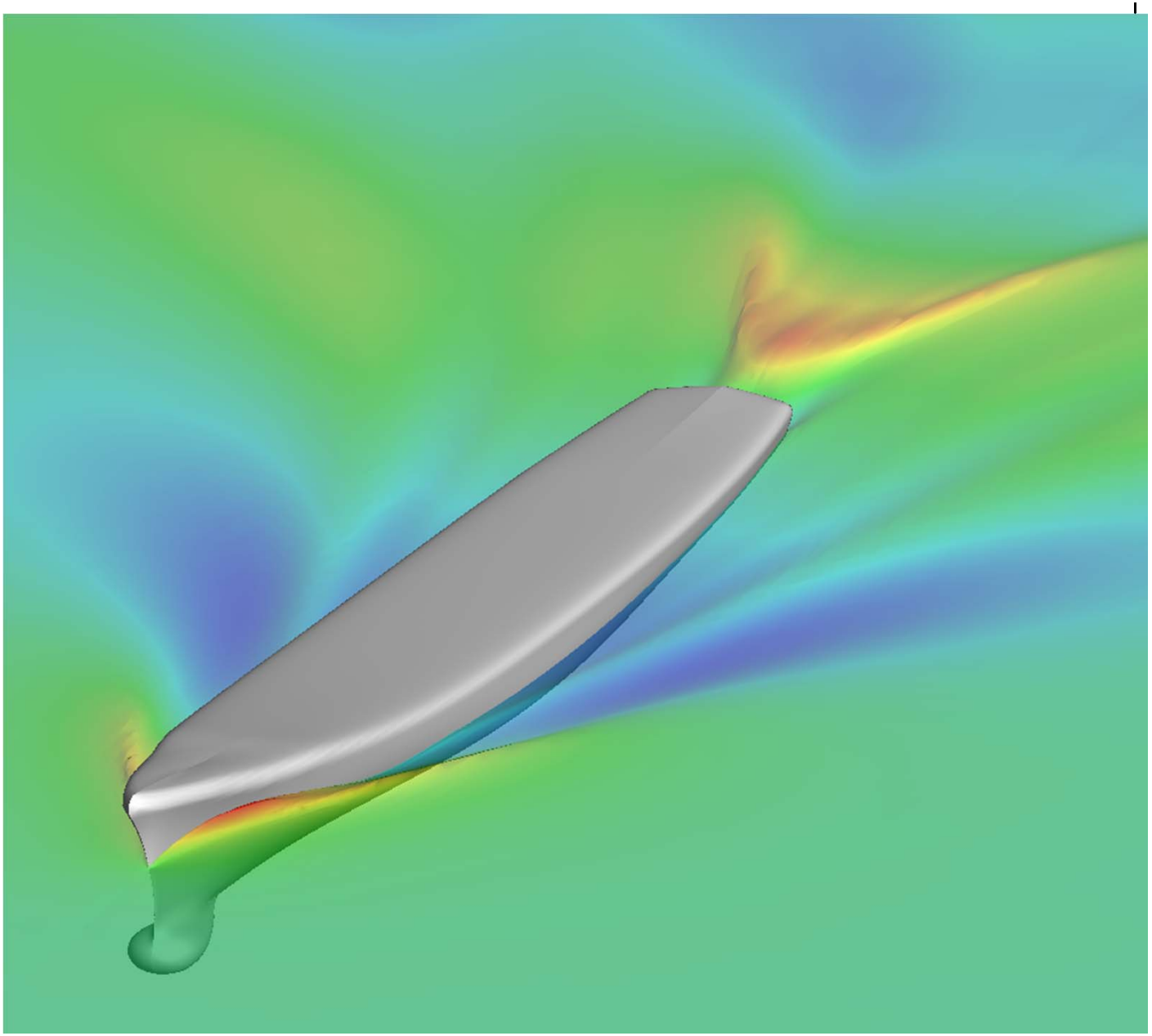
Grid arrangement (case of Fr=0.41: all hexahedral elements for,

Case of Fr=0.28 : Mixed elements with some tetrahedral elements in bow region)

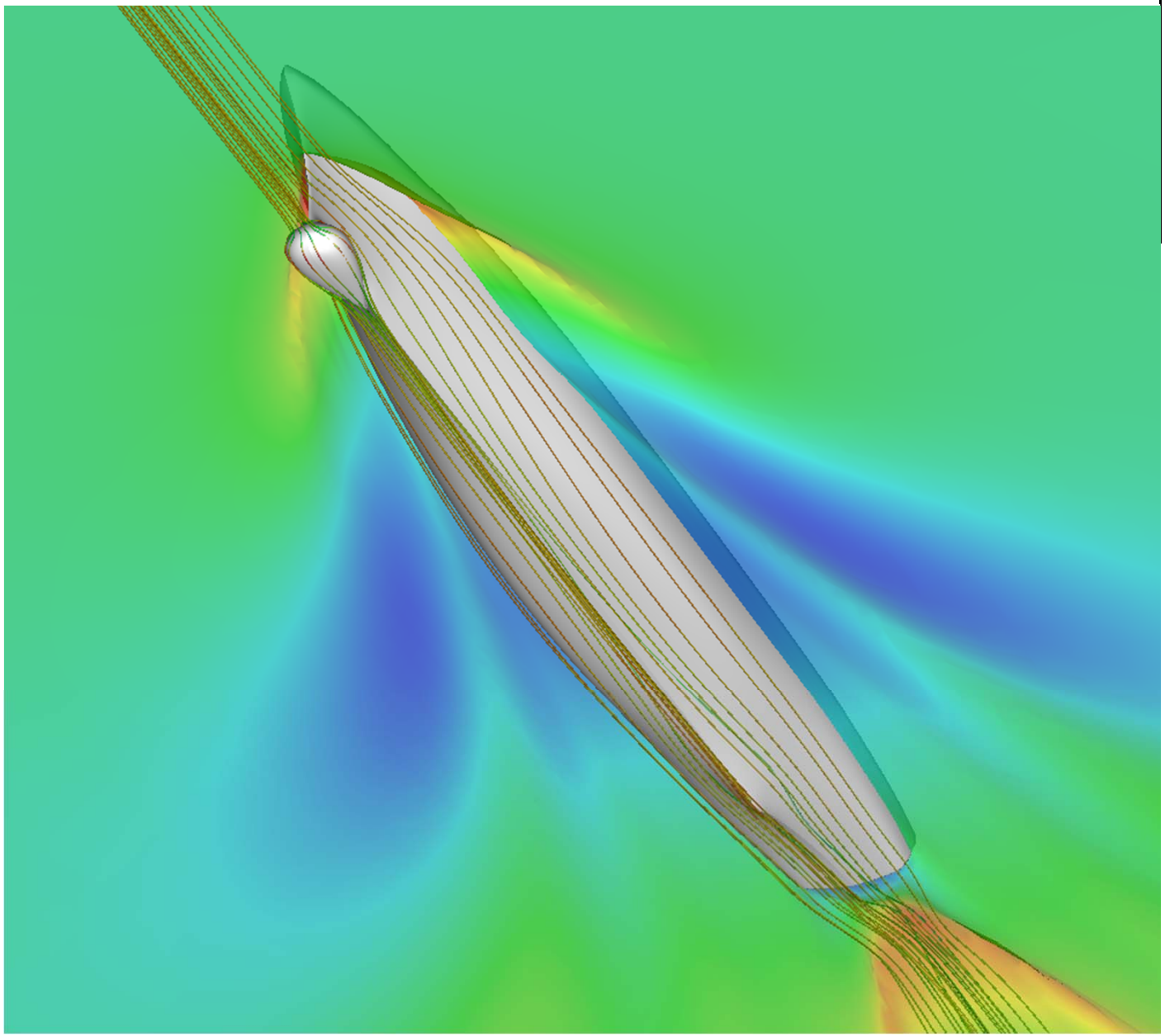


Froude Number	CFD, (CFD-EFD)/EFD			EFD
	PISO		Projection	
	BSL	SST	SST	
Fr=0.28	0.00487 (+5.64%)	0.00474 (+3.04%)	0.00481 (+4.34%)	0.00461
Fr=0.41	0.00709 (+5.35%)	0.00699 (+3.71%)	0.00705 (+4.75%)	0.00673

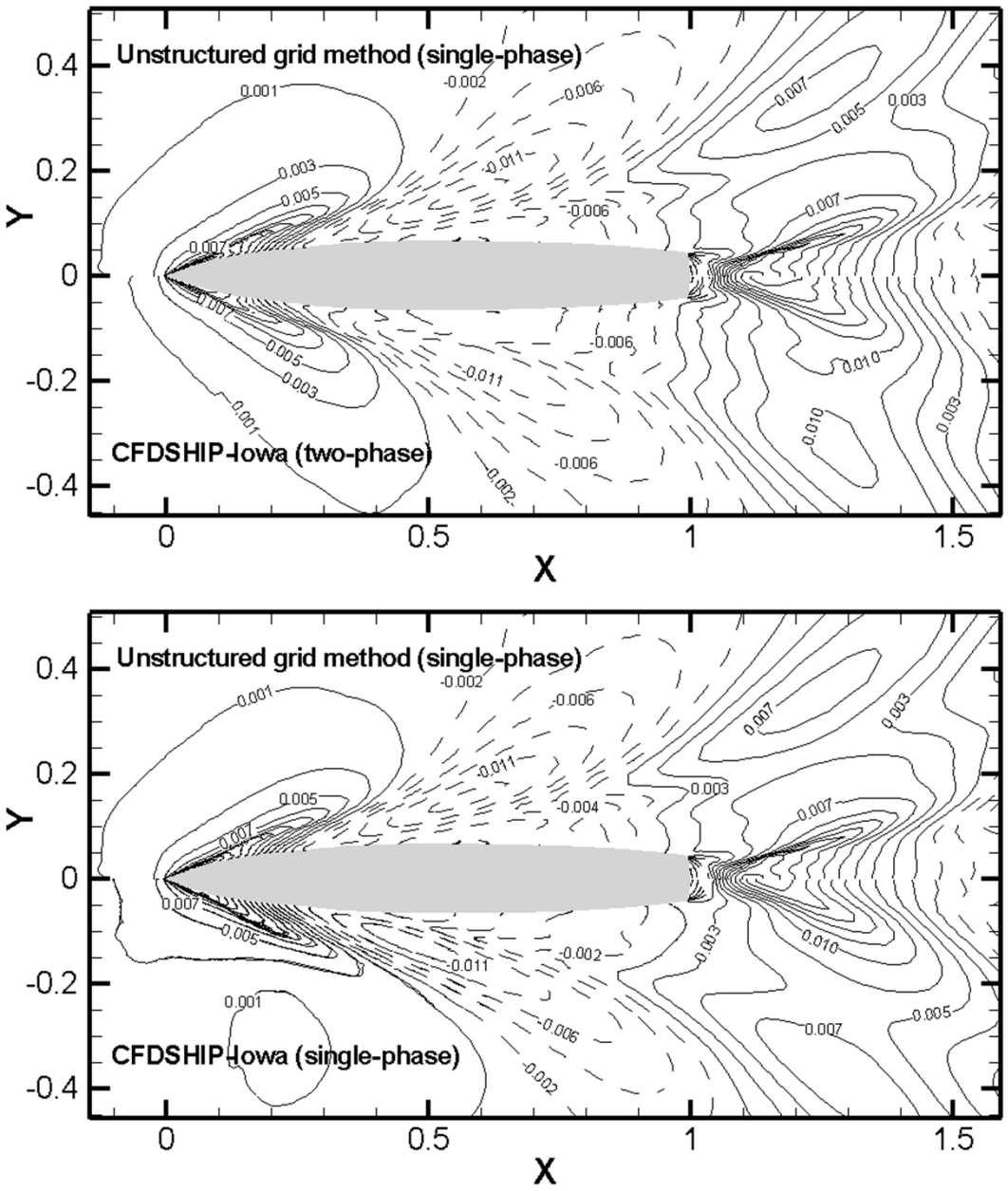
Resistance Coefficients for DTMB 5512 ship



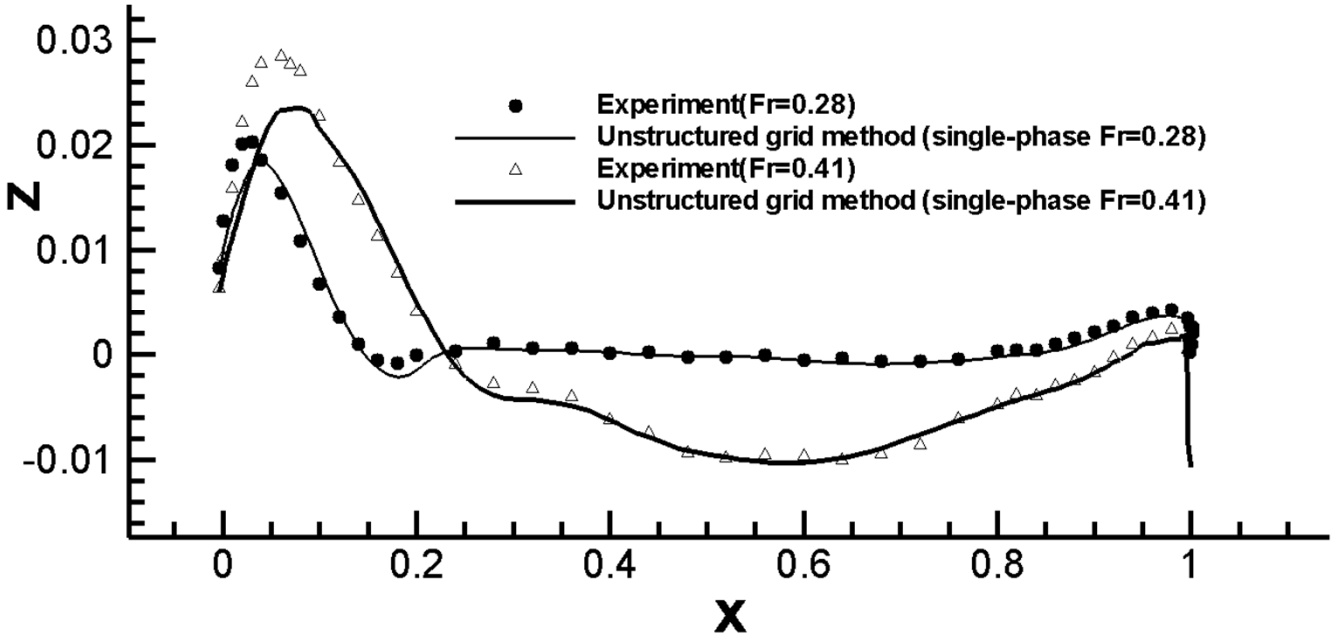
Top view of free surface for Fr=0.41



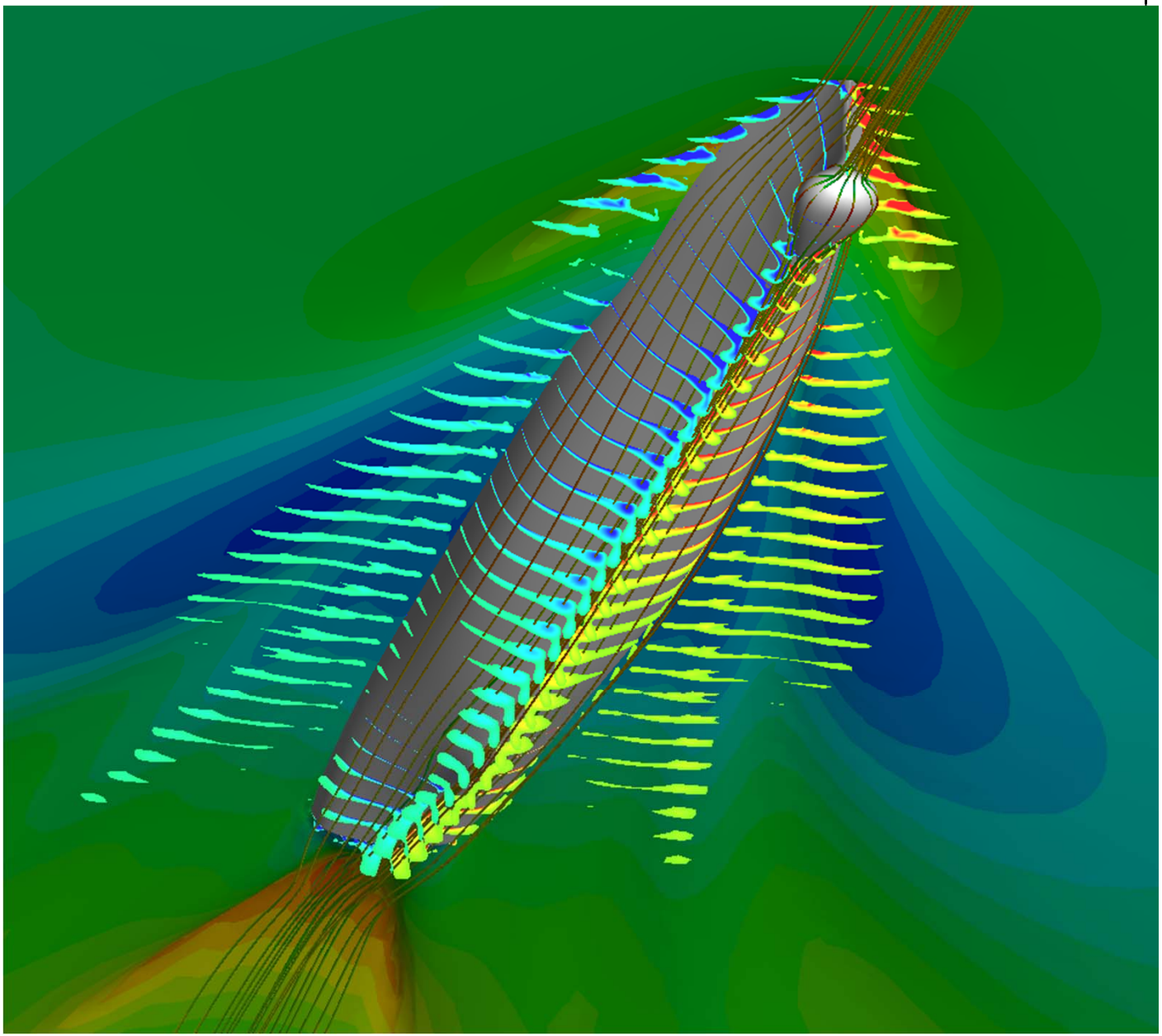
Below view of free surface and streamline for Fr=0.41



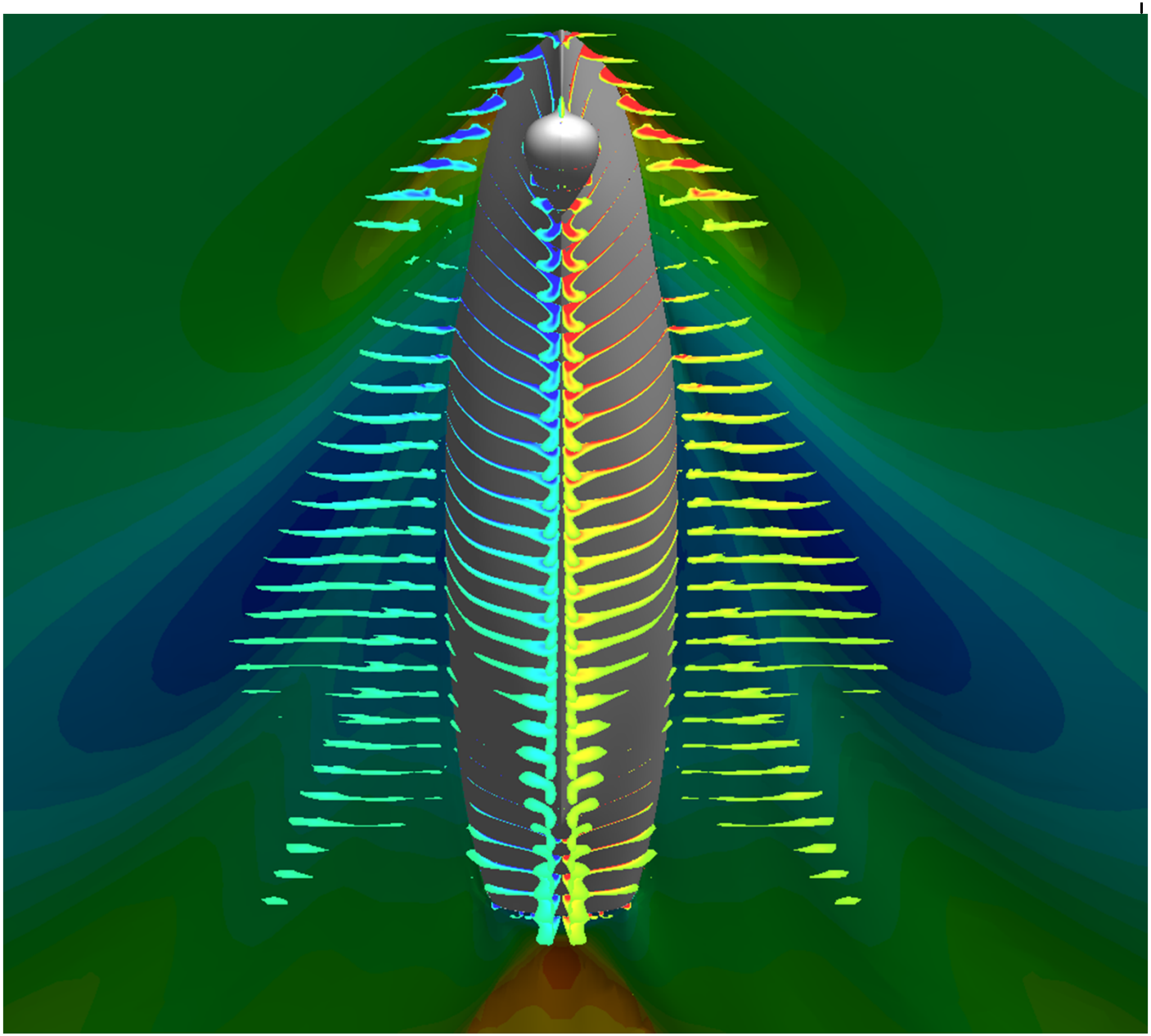
Comparison of wave elevation with CFDSHIP-Iowa (Fr=0.41)



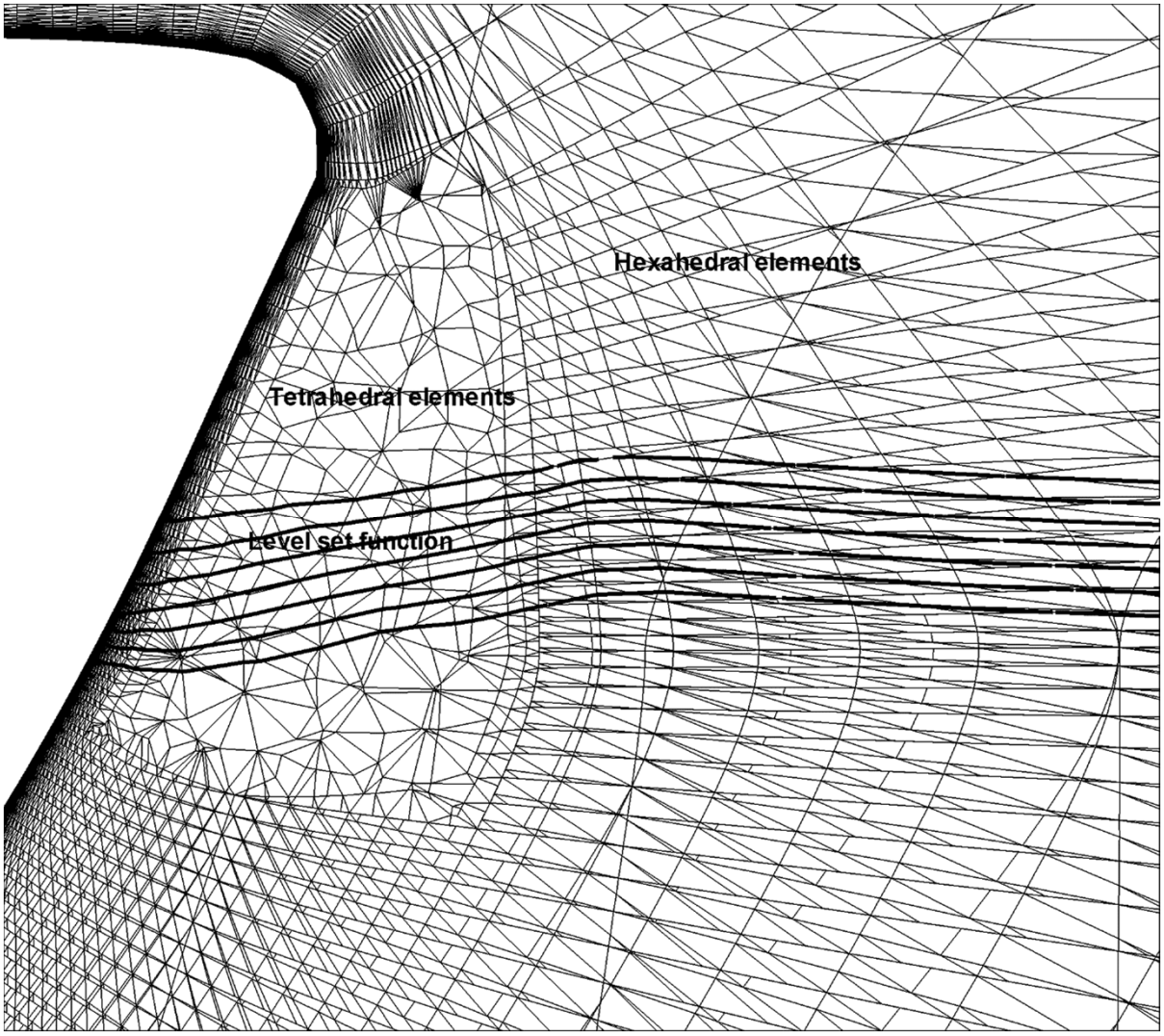
Wave profiles at the hull



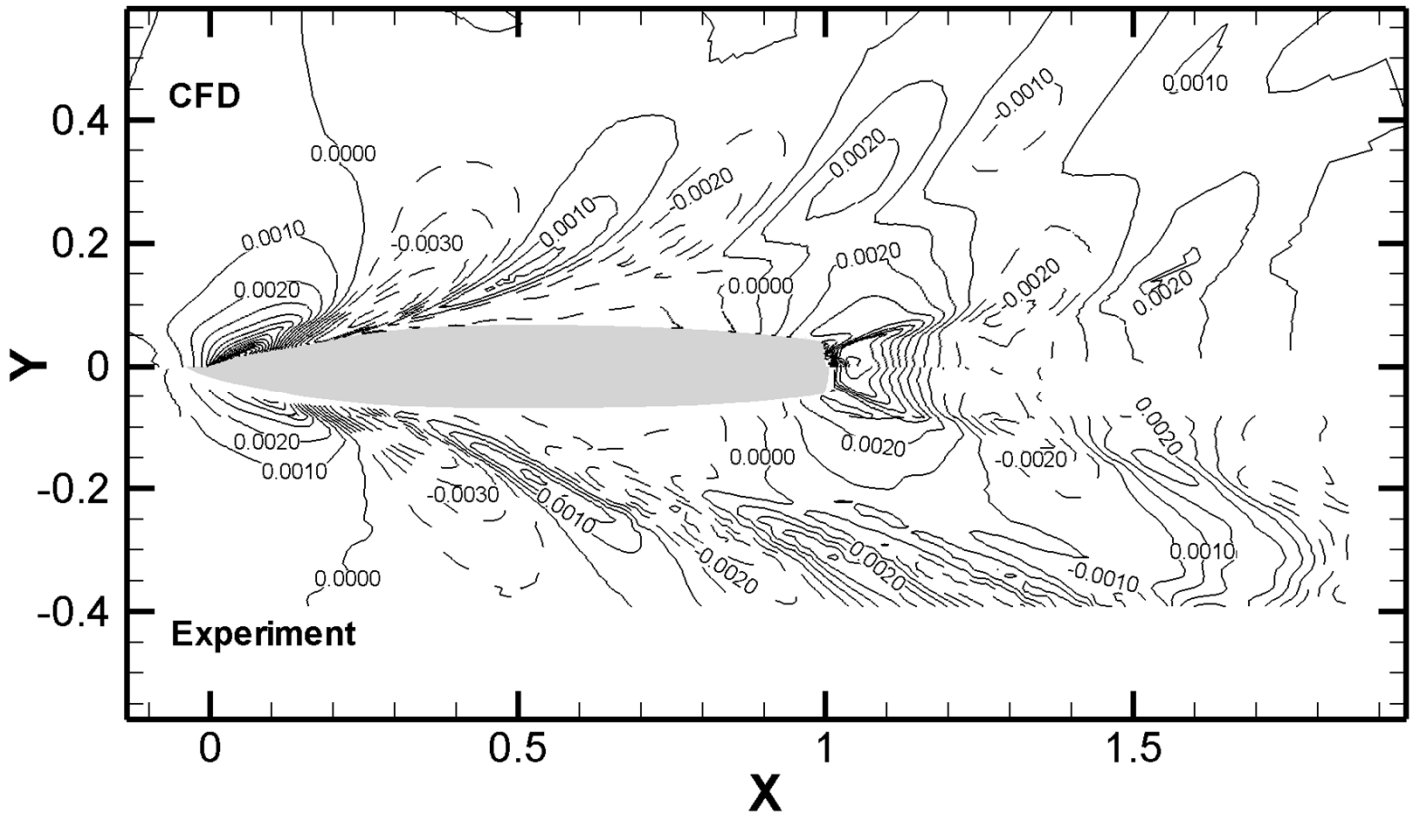
Distribution of streamline near the ship hull and axial vorticity for Fr=0.41



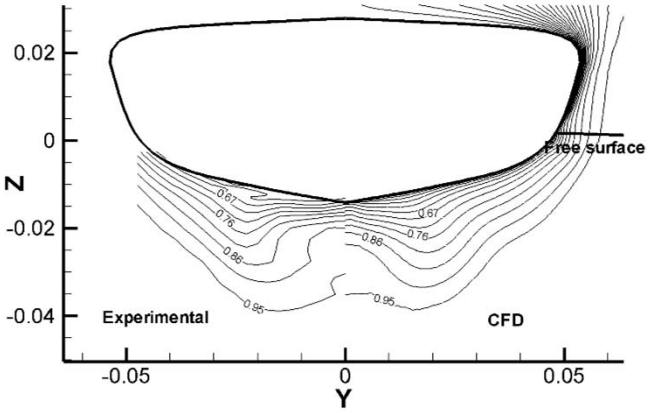
Distribution of axial vorticity for Fr=0.41



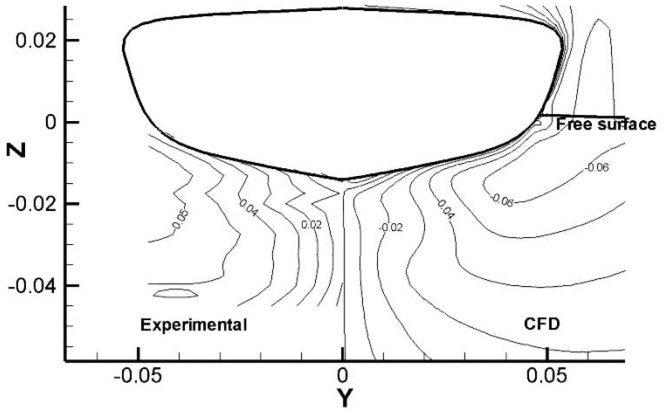
Distribution of level set function in the region of mixed elements (Fr=0.28)



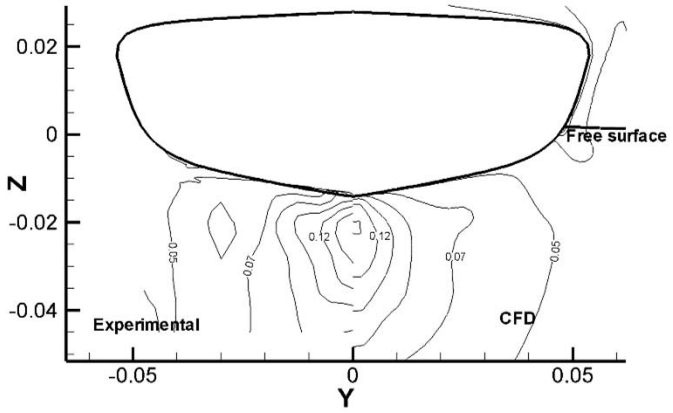
Comparison of wave elevation with Experimental data (Fr=0.28)



u velocity



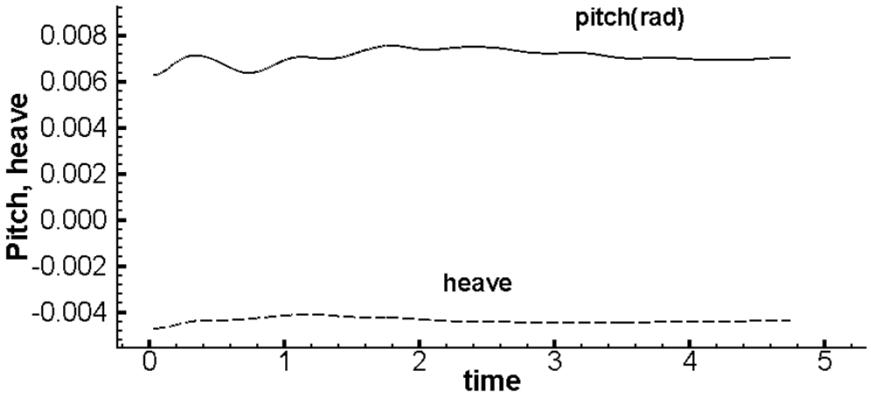
v velocity



w velocity

velocity contour at the nominal wake plane (Fr=0.28)

- Sinkage and Trim (DTMB 5415 ship)
  - Ship predicted motion of 2DOF: heave and pitch
  - Fr=0.41, Re= 1.35E+07 (ship length=5.72m)
  - Dimensionless inputs: radius of gyration r_{g_y}=0.25, weight coefficient =0.237, static area=0.074， gravity center (0.5054,0,-0.0097). Note: weight coefficient, mass, static area, and x_{CG} are calculated from static computation if float body shape and waterline are given.
  - Grid nodes: 615,000 .
  - Routine: 1) Restarting from the steady solution with fixed trim and sinkage of EFD of 5512 ship for saving computational time, 2) Artificial damp is used and coefficient=0.1.

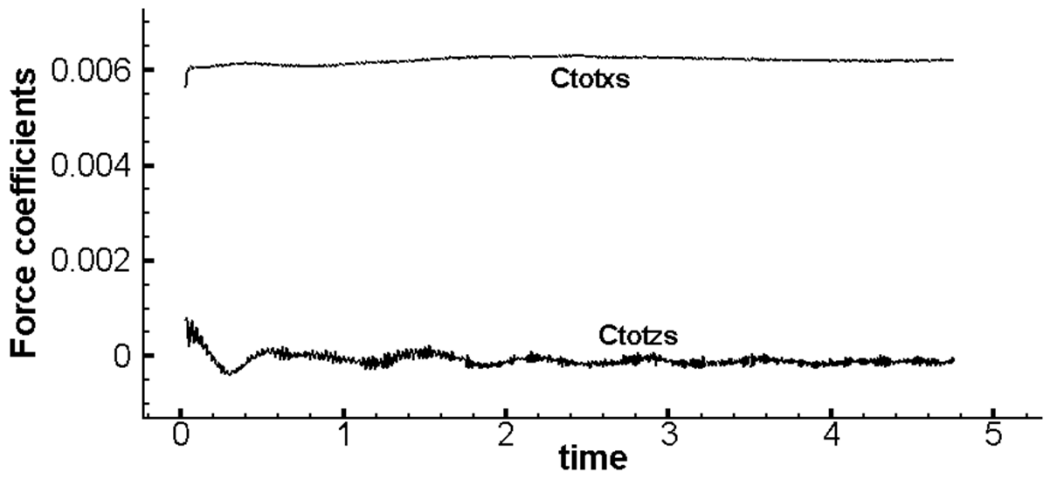


Heave and pitch history

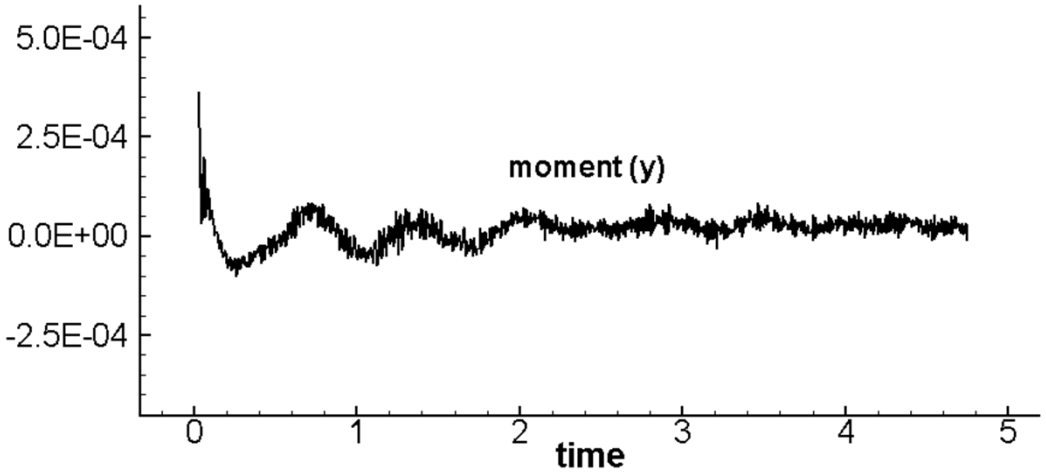
	STAR-CCM+	Experiment
Lift (N)	5385*	5385**
Drag (N)	152.17*	153.04
Sinkage (m)	0.0315	0.0263
Trim (°)	0.23	0.36

Example results of star-ccm+ workshop (dimensional results)

	Experiment	CFD	(CFD-EFD)/EFD%
Trim (°)	0.36	0.40	+11.11
Sinkage	-0.0046	-0.00438	+4.78
Drag(x)	0.00641 (calculated from EFD in star-ccm+)	0.00621	-3.12

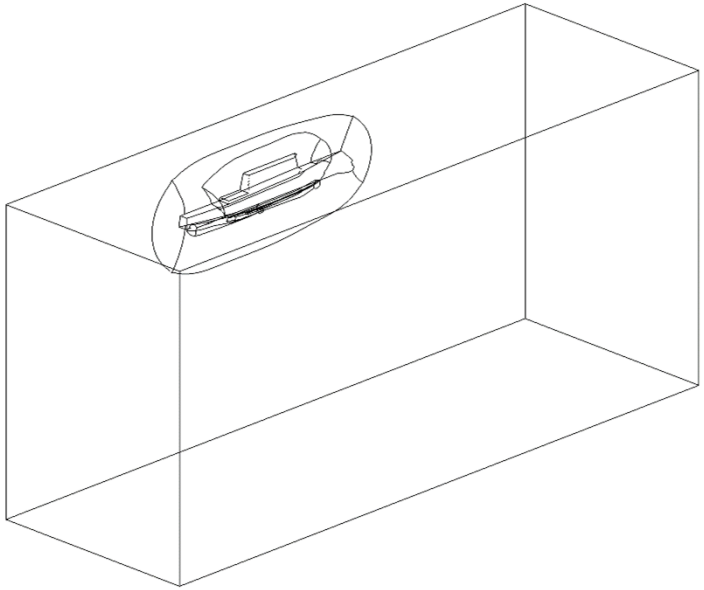


History of force coefficients (in ship system)

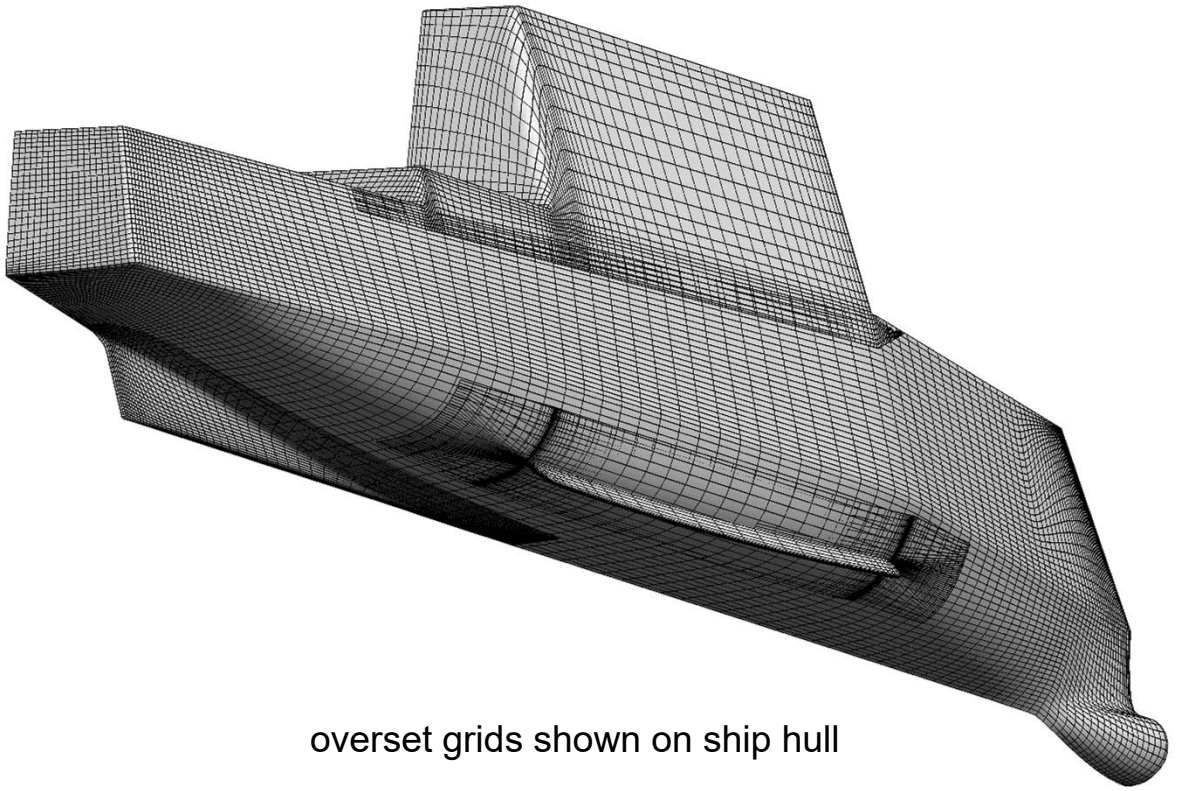


History of moment coefficient (y axis)

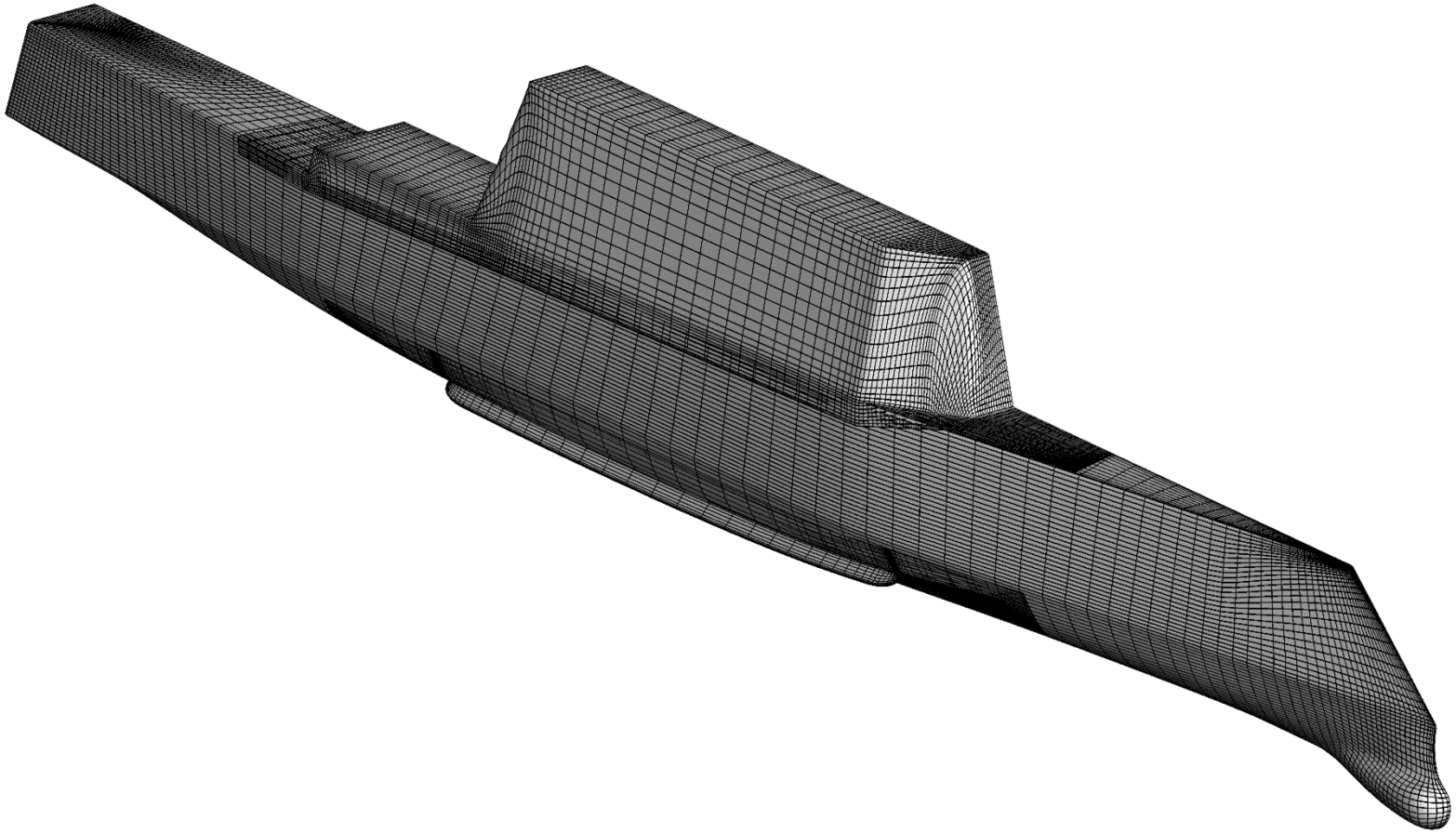
- Free surface flow around ship model DTMB 5613 with very complicated geometries
  - Conditions:
    - Five overset grids: ship hull, superstructure, bilge keel, skeg, and background grids.
    - Steady single water free surface flow, Reynolds number= 6.5E+6, Froude number=0.4.
    - Overset grid solver produces static overset grid files and transfer to CFD
    - The demonstration results are print out at time step =1000.



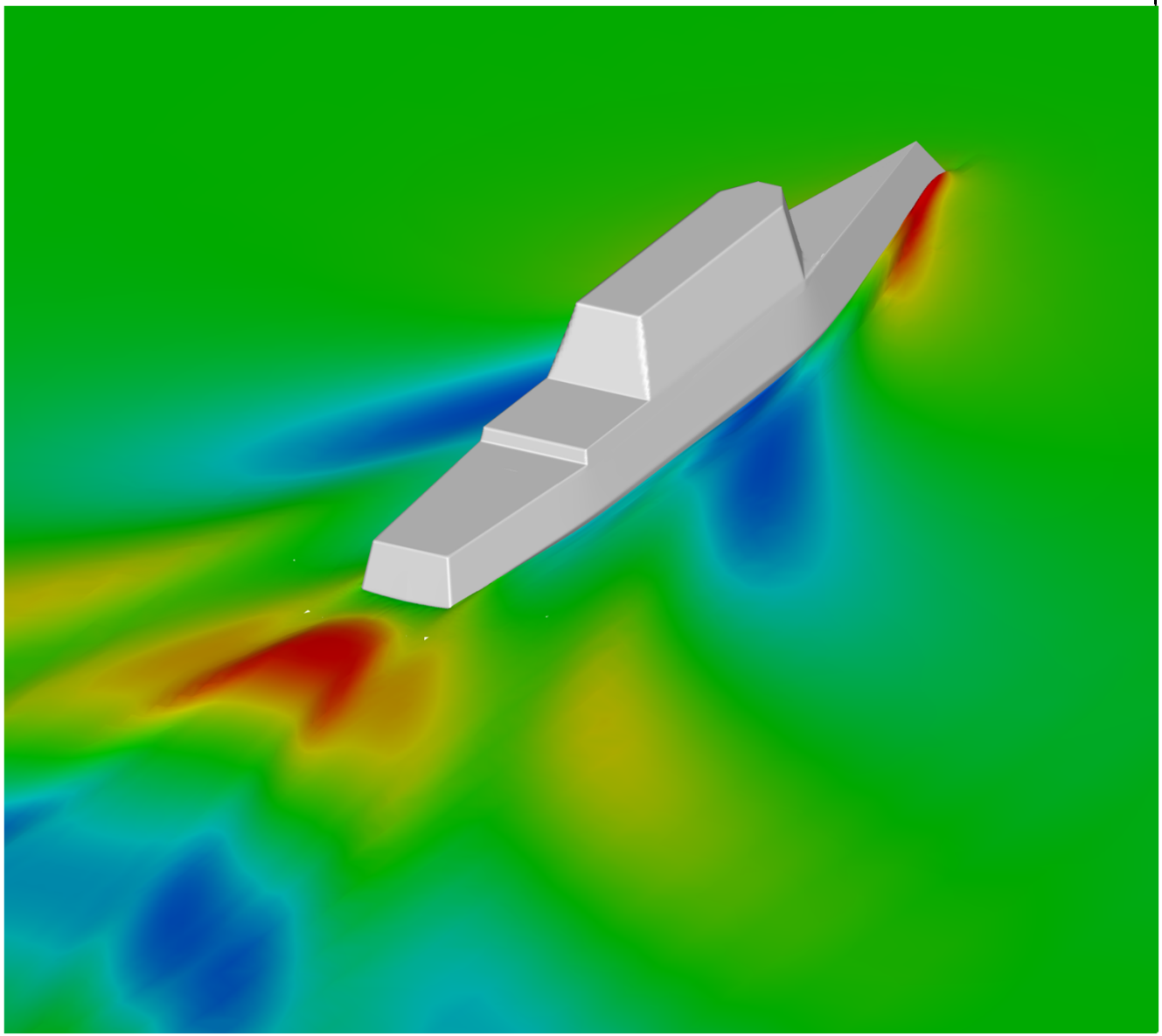
Frame of half ship grids



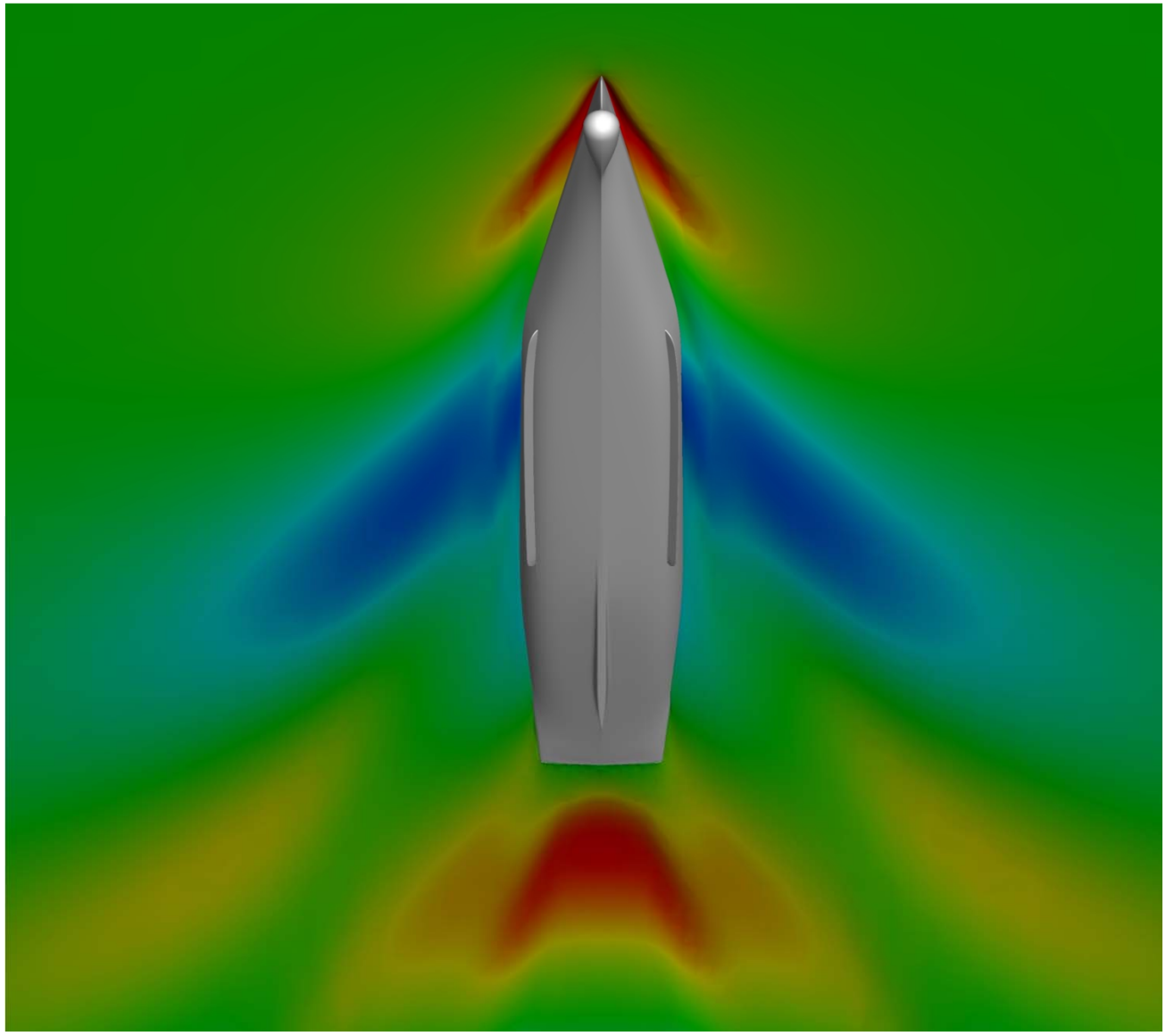
overset grids shown on ship hull



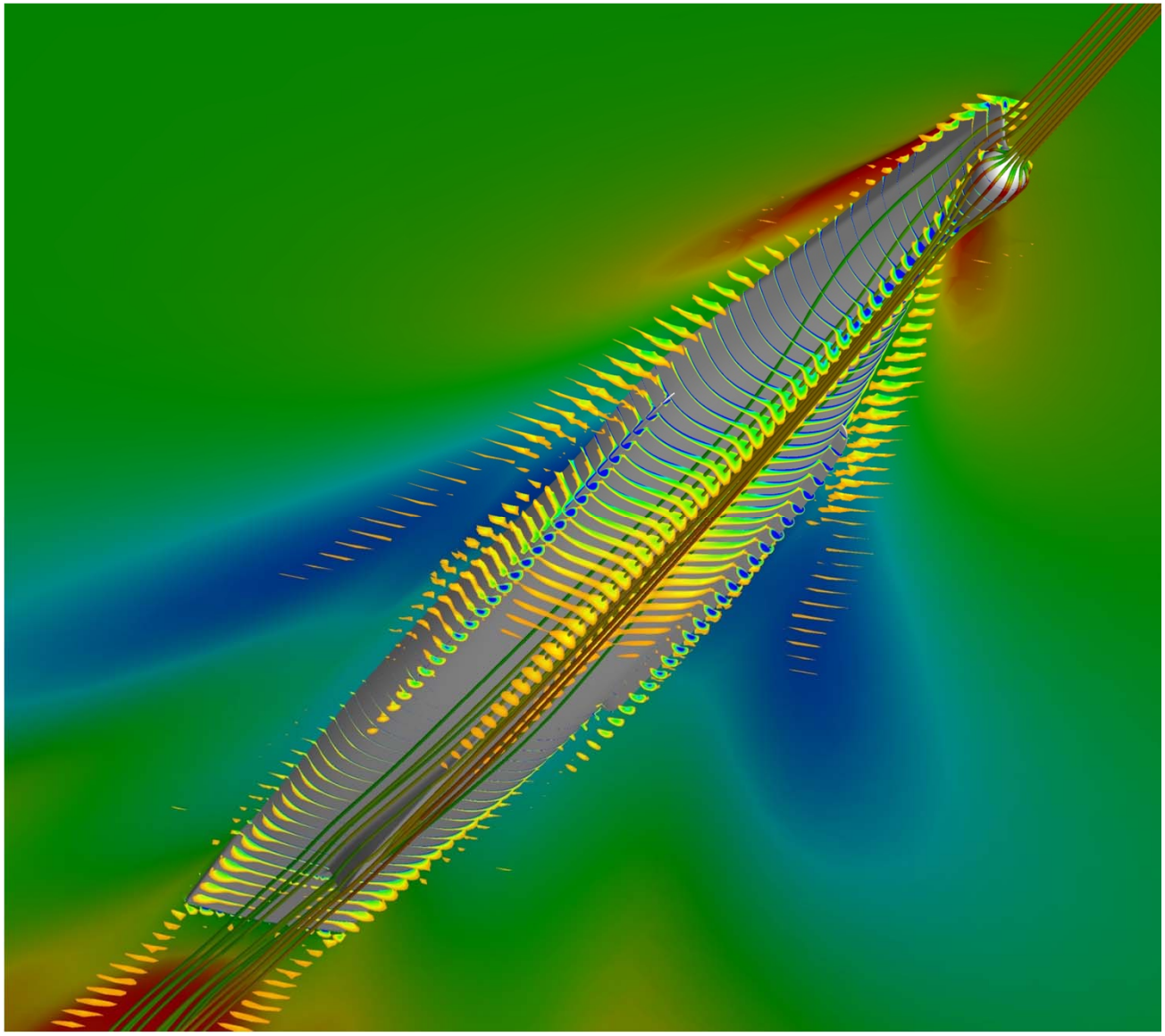
Front and side view of half ship hull



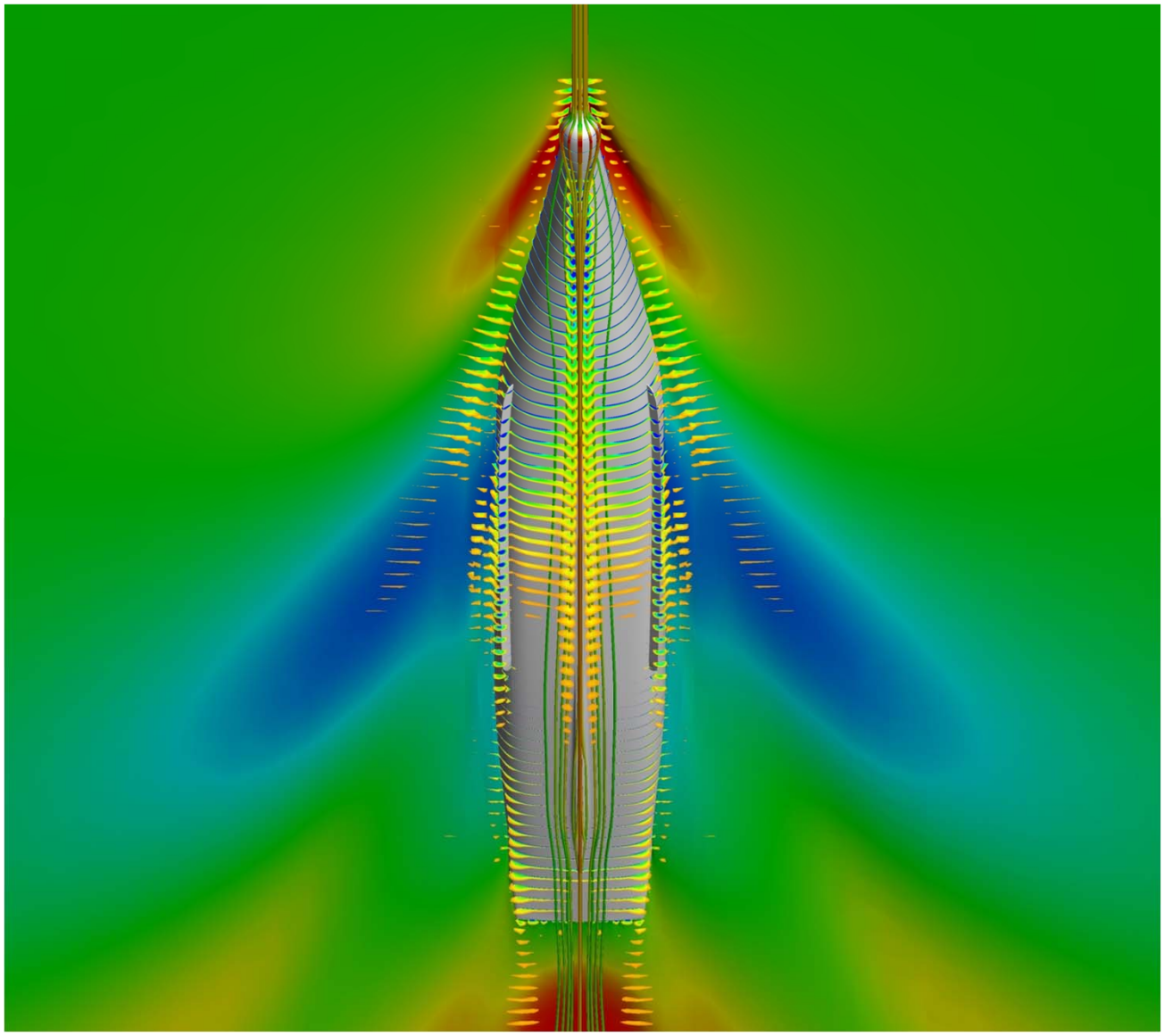
Free surface and ship hull (top view)



Free surface and ship hull(below view)

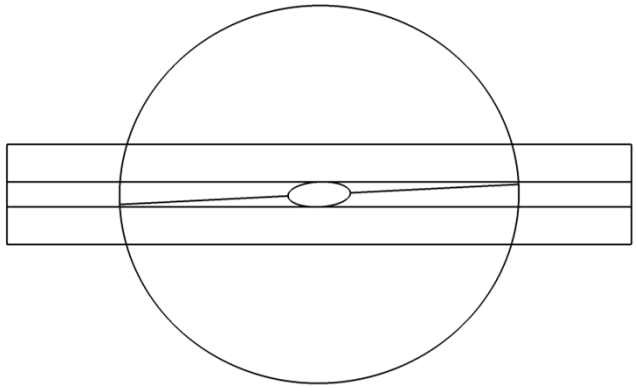


Vortex and streamline

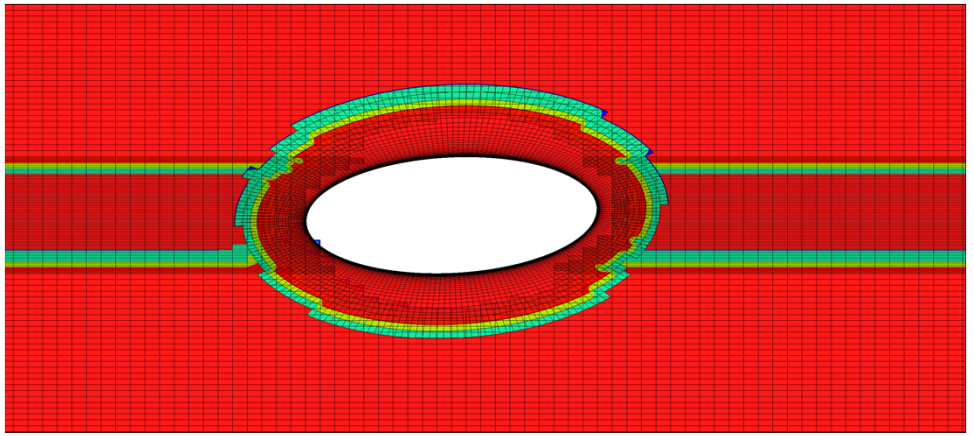


Vortex and streamline

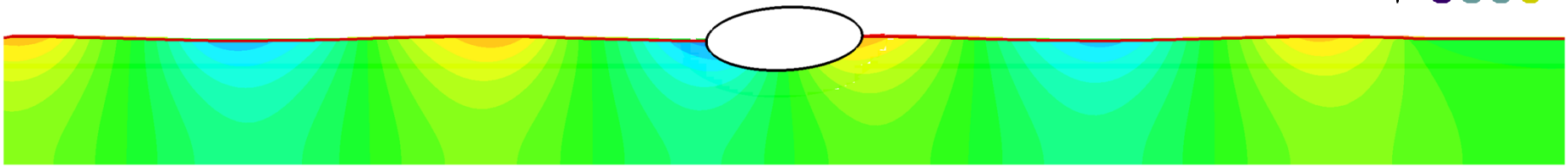
- Float Body in Waves in Shallow water
  - Linear regular waves. Amplitude: 0.005, length: 3.0, water depth: 0.8
  - Initial condition, body is static in waves
  - Re=5.E+5, Fr=0.4518, dt=0.01 (body length is used for non-dimensional benchmark)
  - Three dynamics overset grids of body, free surface and background



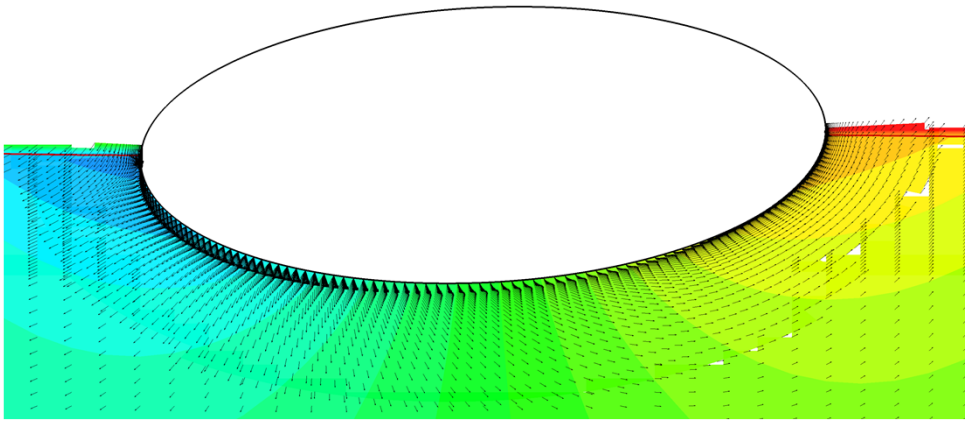
Overset grid outlines



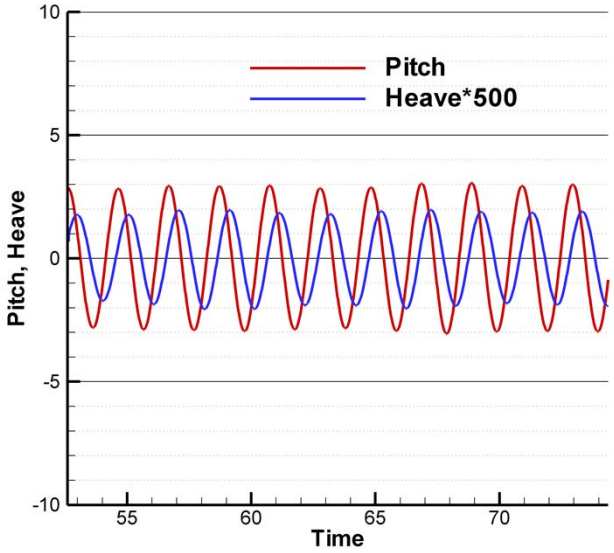
Distribution of active and fringe nodes
(time 8.0)



Waves and pressure(time=8)

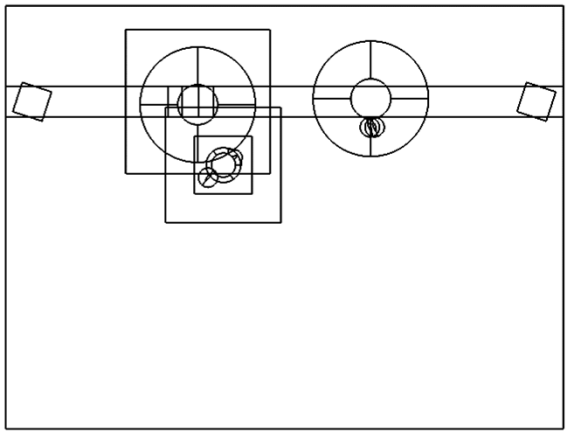


Pressure and velocity (time=8)

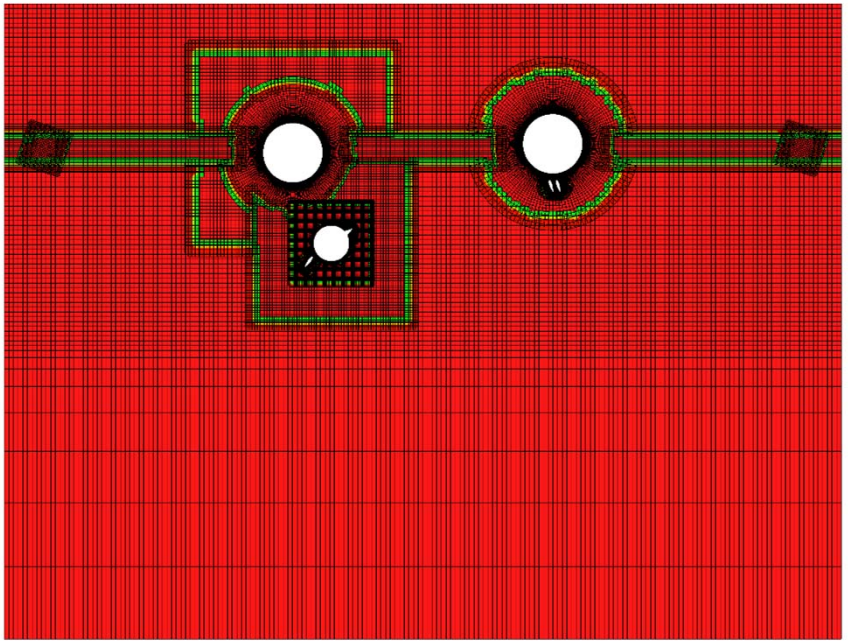


Body motions

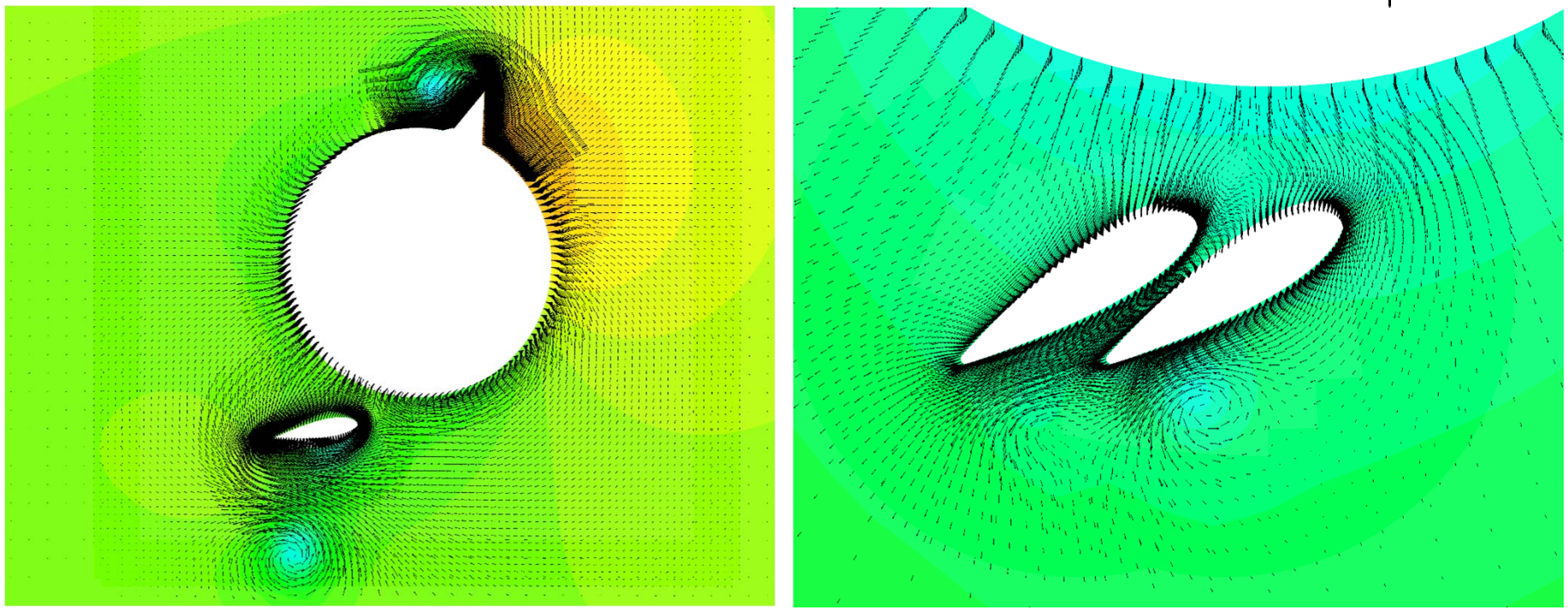
- Multi-body, multi-appendage (controller) prescribed motions, and interaction with free surface
  - Body motions: two cylinders oscillate up and down, one rotator moves along curve routine and rotates.
  - Two controllers (both are ‘prescribed’ ‘rudderangle’), first one (one foil)is assembled in rotator, 2nd one(constructed by two foils) is assembled for the second cylinder.
  - Controller (appendage) motions: rotate forth and back along fixed axis.
  - Re=1.E+4, Fr=1, dt=0.005
  - 16 overset grids, 50 processors (CFD: 26, Overset: 24) for parallel computation.



Overset grid outlines



Distribution of active and fringe nodes
(time step 110)



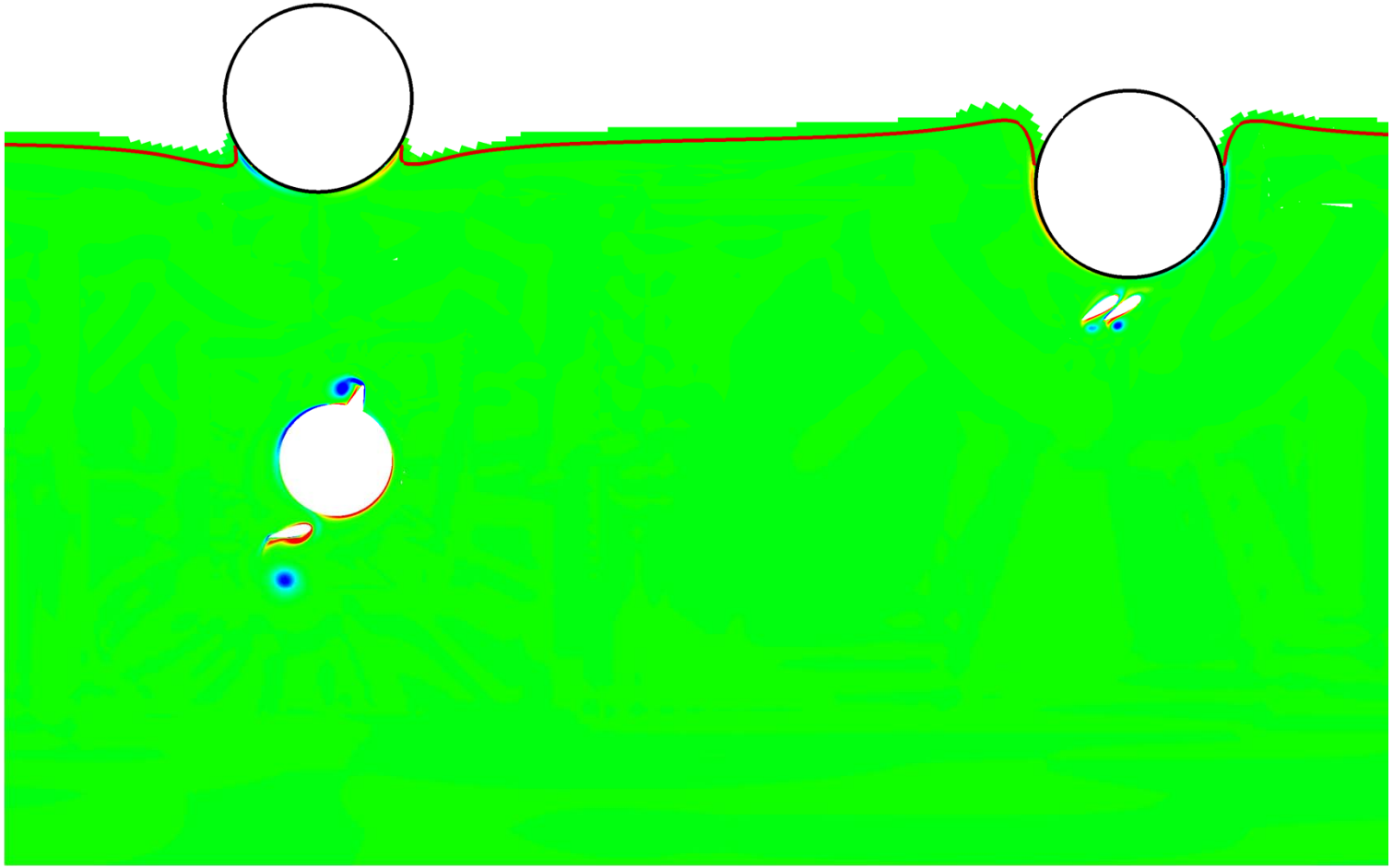
Velocity vector and pressure distributions near rotator and foils
(time step 40)

Movie1 (fast)
(vorticity evolution)

Movie2
(grid motions)

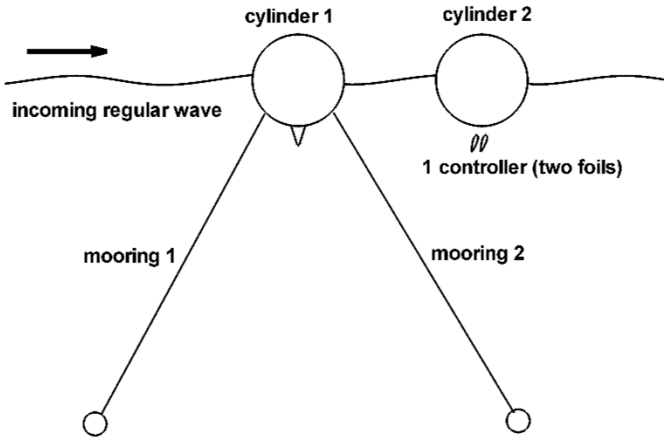
Movie3
(zoom in grid motions)

Movie4 (fast)
(active nodes)

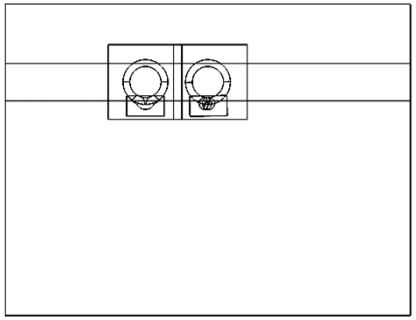


Vorticity and free surface distribution
(time step 40)

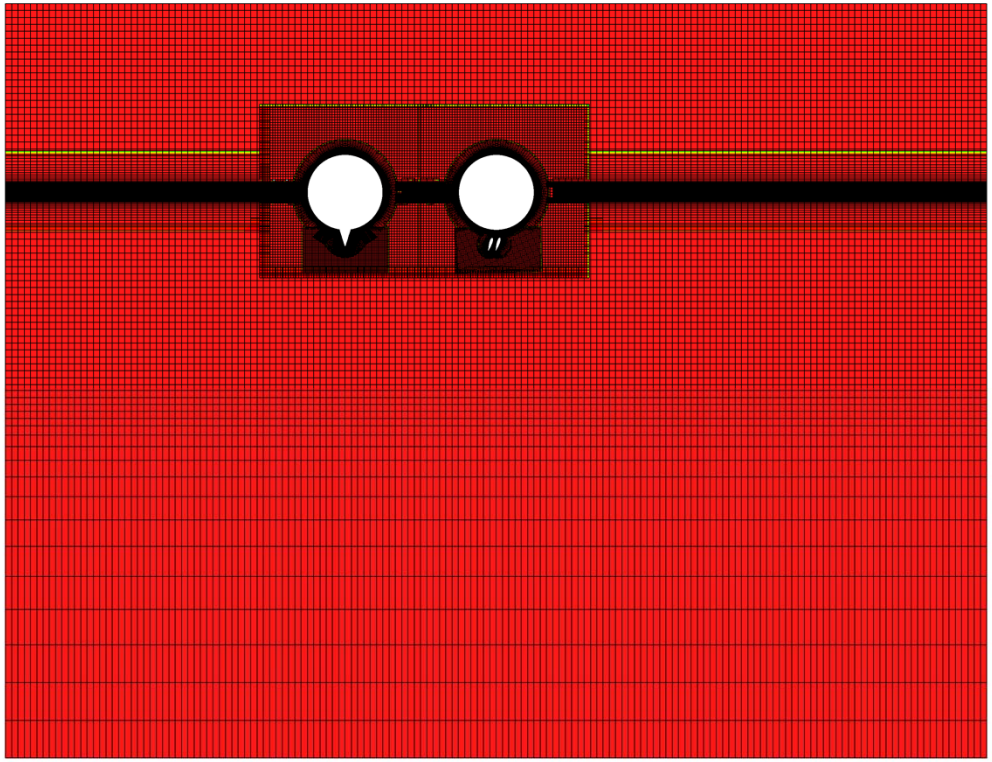
- Multi-body, multi-appendage (controller) predicted motions, (two cylinders with mooring or controller in waves)
  - Left cylinder: two moorings, right cylinder: a controller rotating along axis
  - Predicted body motions of 3DOF: surge, heave and pitch (prescribed foil motions).
  - Regular incoming wave: wave length 2, amplitude 0.05.
  - Fr=1.0 (based on reference speed), Re=9.3E+04.
  - 11 overset grids. 46 processors (CFD: 24, Overset: 22) for parallel computation.



Schematic view of conditions

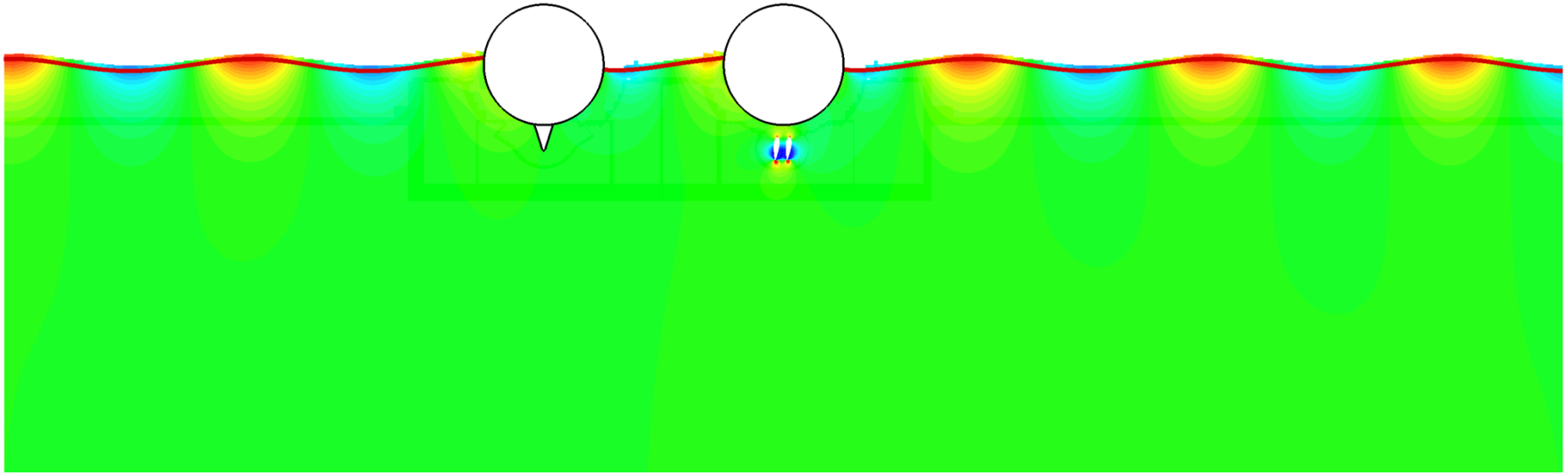


Overset grid outlines

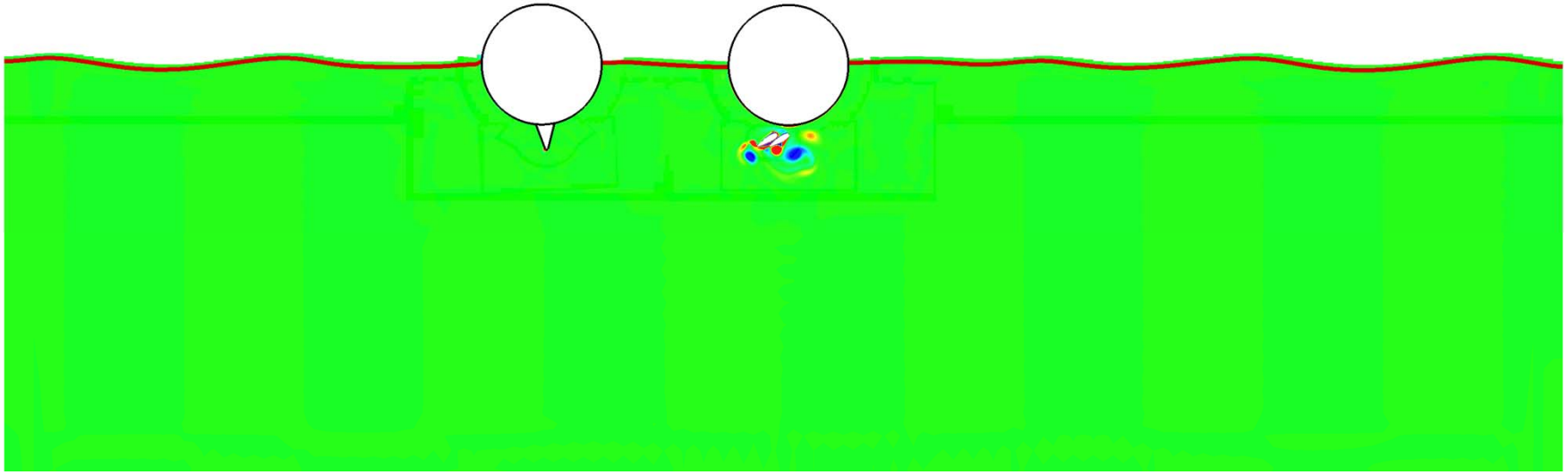


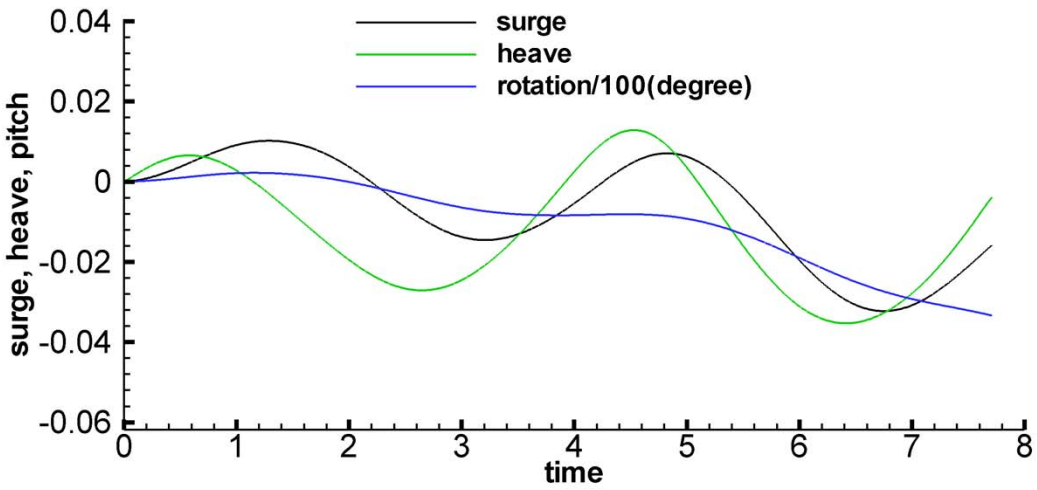
Active and fringe nodes of overset grids

U movie

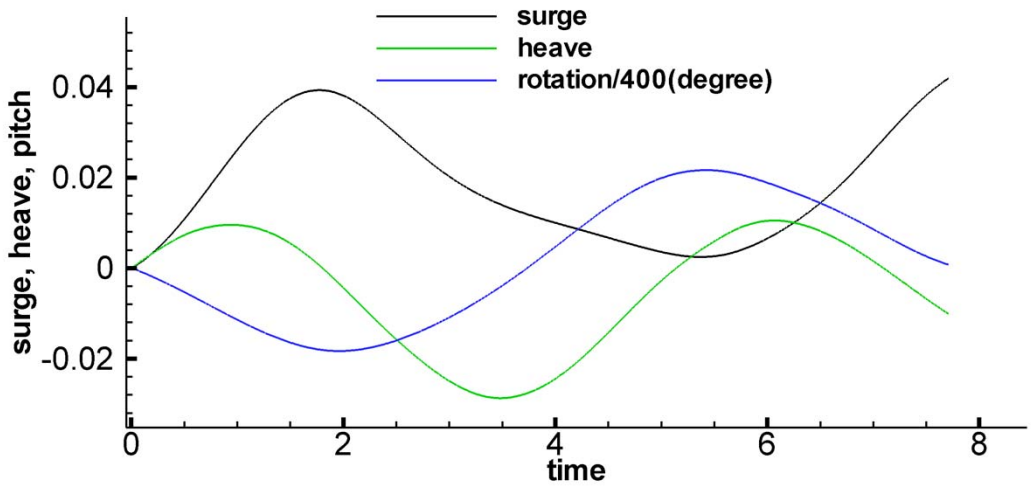


Vorticity movie



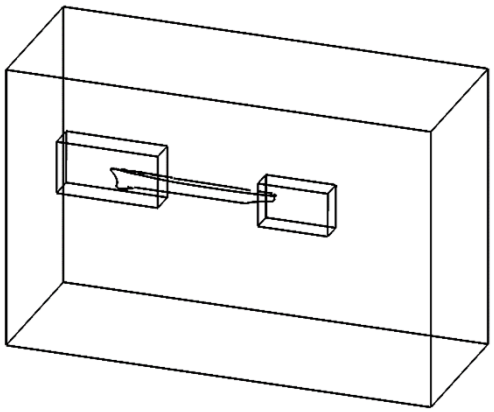


Cylinder 1: Surge heave, pitch, and rotation history

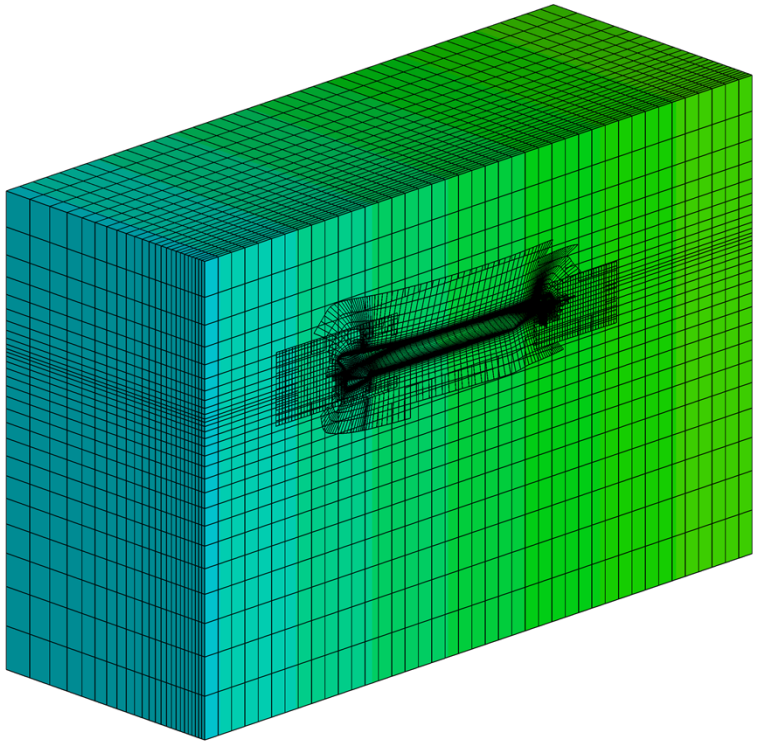


Cylinder 2: Surge heave, pitch, and rotation history

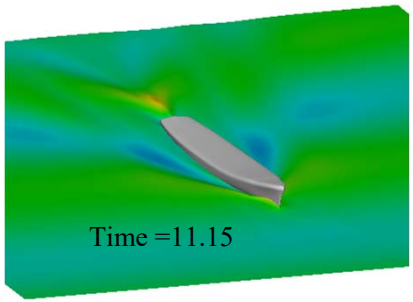
- Pitch and Heave(DTMB 5415 model ship, Fr=0.41)
  - 5512 ship (1:46.6 of DTMB 5415), Fr=0.41,Re=7.1E+6.
  - Incoming linear regular wave, wave length:1.5, wave slop: ak=0.025.
  - Radius of gyration rg_2 =0.25, weight coefficient = 0.237, static area= 0.074, gravity center (0.5059,0, 0.00984).
  - Pitch and heave motions are predicted, others are captive.
  - Half ship grids are used due to symmetry to longitudinal section.
  - Test the computation in extremely coarse overset grids (close to limit condition) or coarse grids: Four coarse overset grids (only background grid is fixed, others follow ship motions).
  - Verification and validation using three levels of coarse grids: 0.15, 0.25,0.40 million grids.

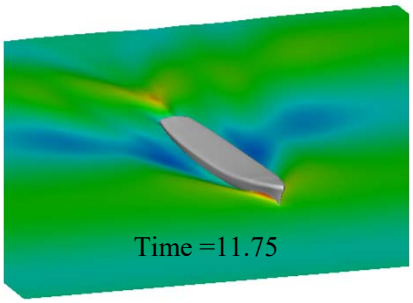


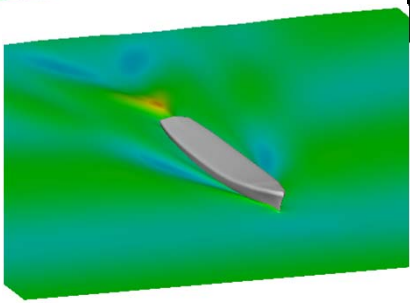
Overset grid outlines



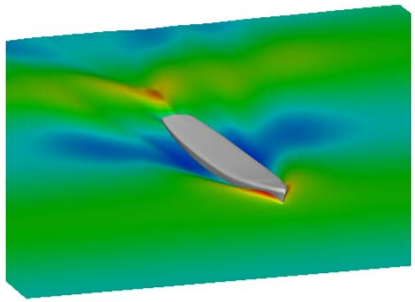
Overset grid arrangement

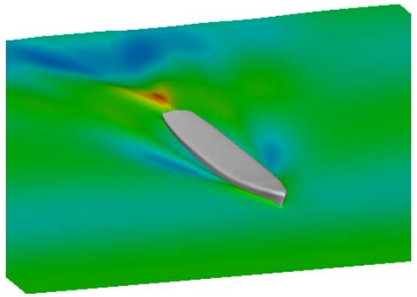


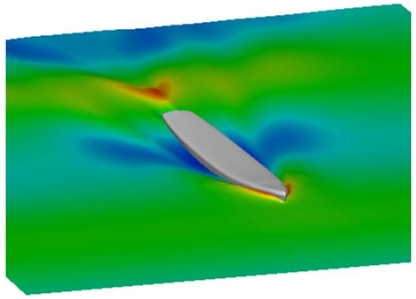


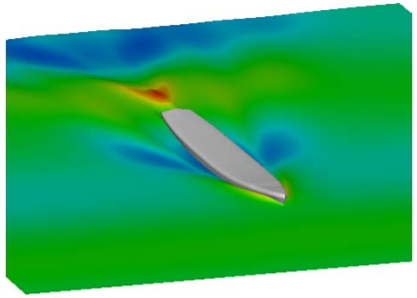


Ship motions
(one period)
(0.4 million grids)

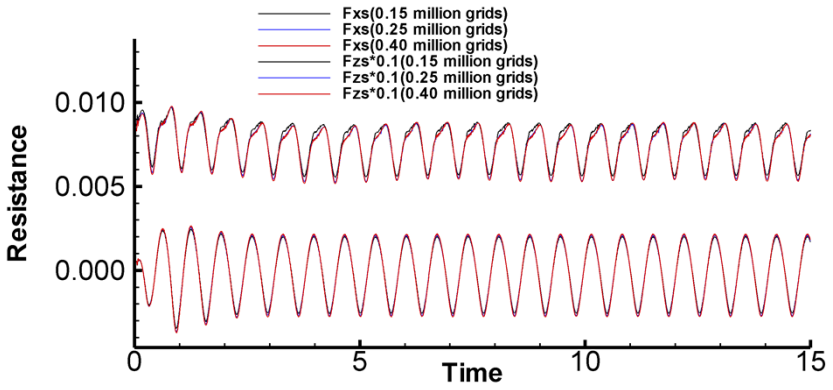


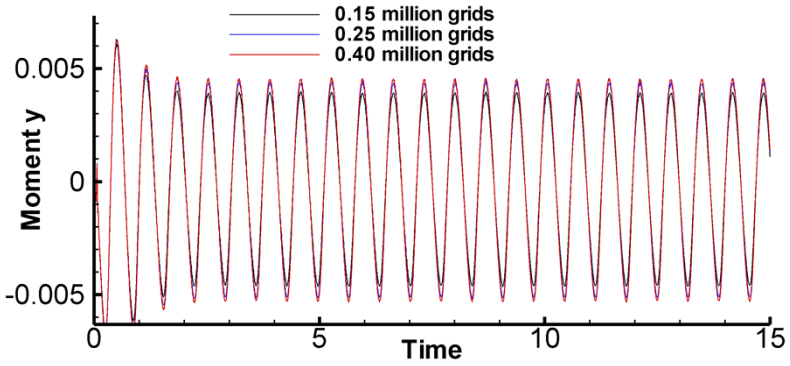


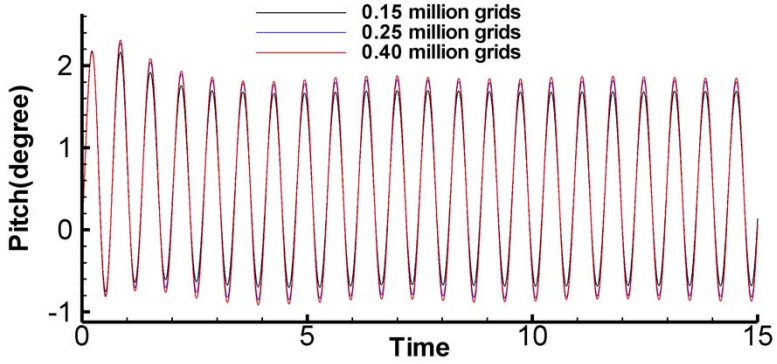


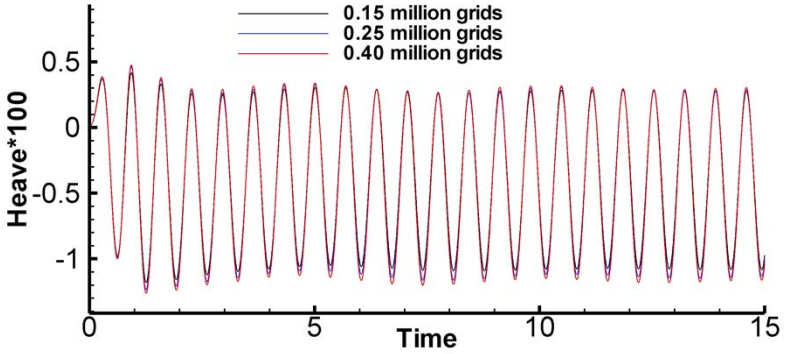


Evolution of forces, moments, and motions







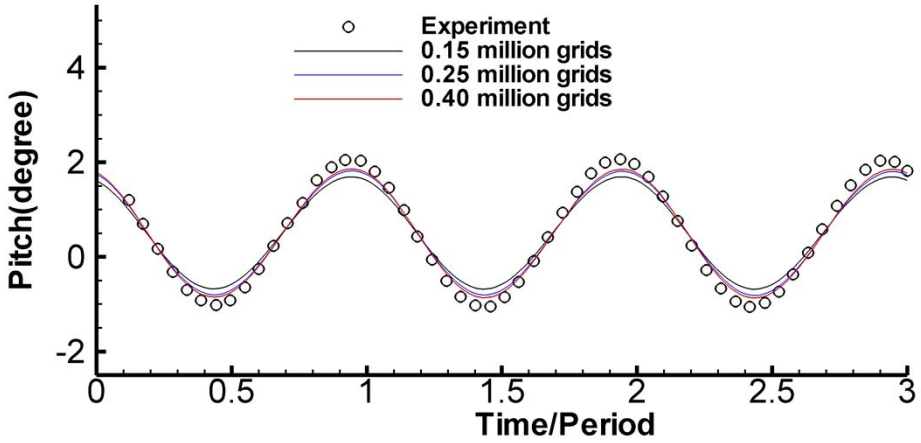


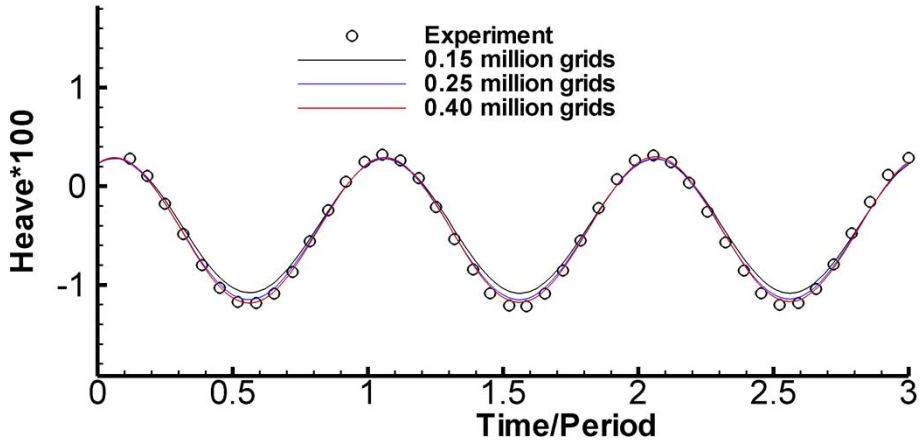
Convergence Study

Grids (million)	Force x (Amp.)	Force z (Amp.)	Moment y (Amp.)	Pitch (Amp.)	Heave (Amp.)
0.15	0.00156	0.0229	0.00426	1.1857	0.00680
0.25	0.00168	0.0241	0.00473	1.3109	0.00711
0.40	0.00172	0.0247	0.00494	1.3600	0.00735
Rate of convergence	6.51	3.95	4.75	5.40	1.55

Solution: monotonic convergence with grid spacing

Validations with EFD

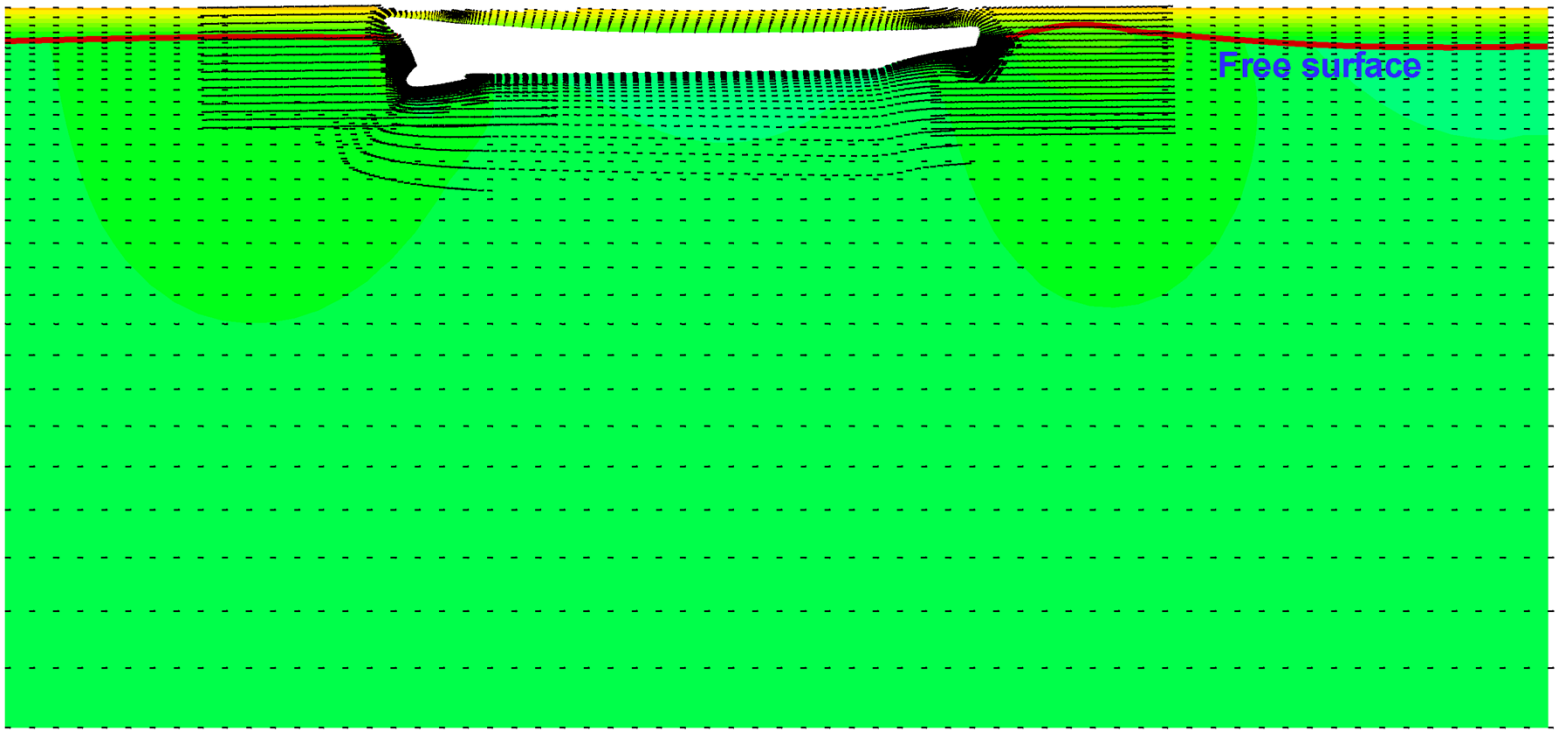




Note: 1) EFD (5512 ship, L=3.048): Irvine et al., Journal Ship Research, 2008, 52(2), pp.146-163

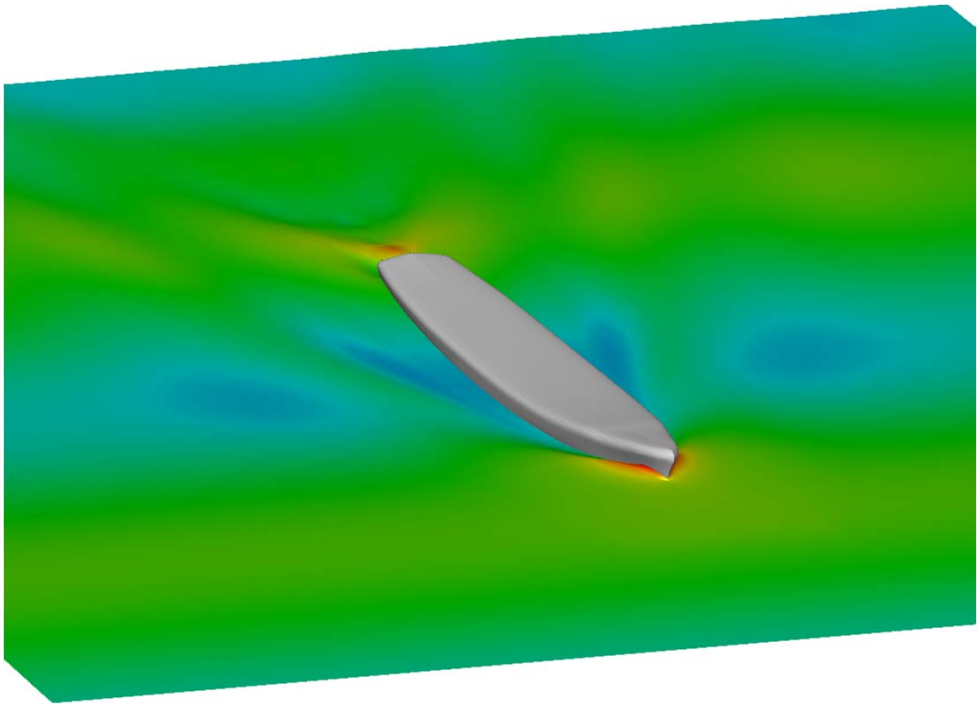
2) Results used from the time of long enough due to the sudden start condition

2) Period=1/f, f is encounter frequency, f=1.46



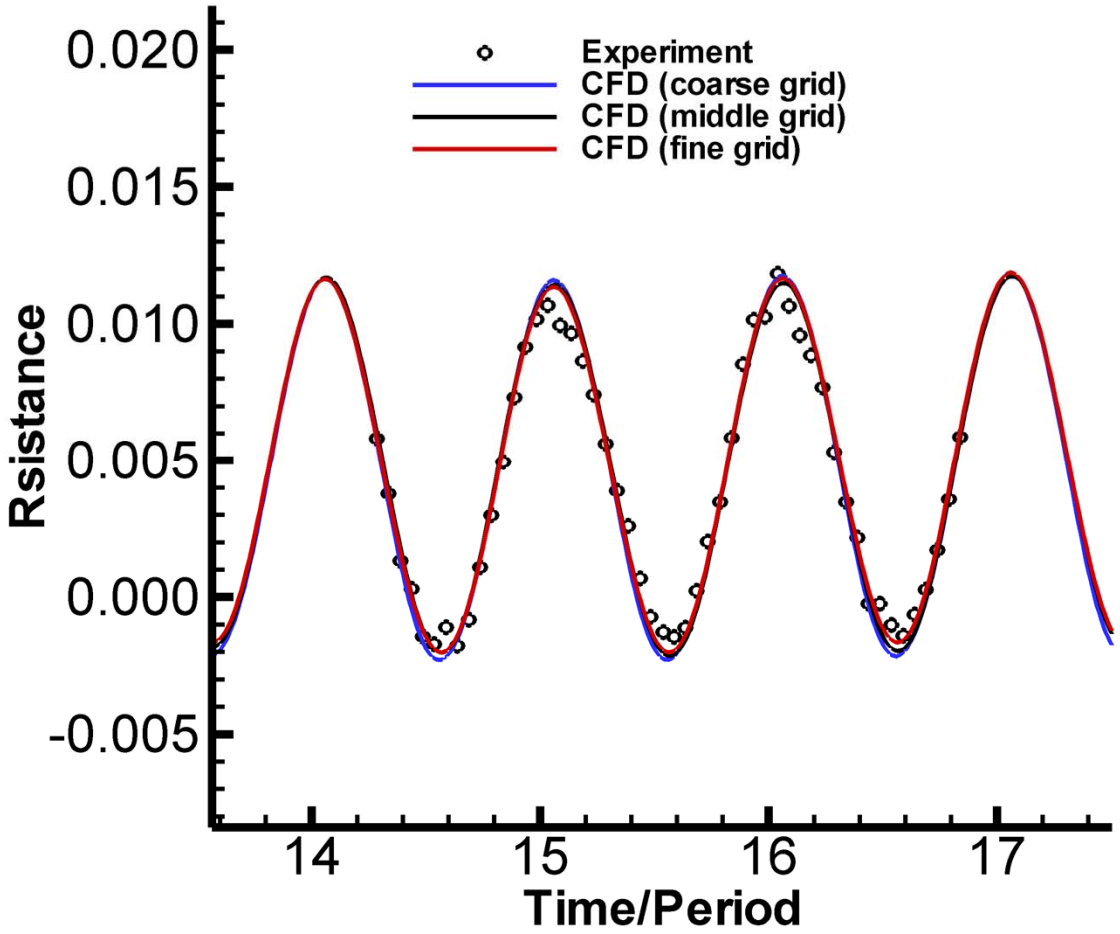
Pressure and velocity distribution (symmetry section, time=11.5)

- Pitch and Heave(DTMB 5415 model ship, Fr=0.28)
  - Incoming linear regular wave, wave length:1.5, wave slop: ak=0.025.
  - Pitch and heave motions are predicted, others are captive.
  - Half ship grids are used due to symmetry to longitudinal section.
  - 5512 ship (1:46.6 of DTMB 5415)
  - Three level grid of two overset grids with ratio $\sqrt{2}$ in each coordinate (fine grid of total 2.77 million, where hull:200×77×100, background 145×86×99)
  - Radius of gyration rg_2 =0.25, weight coefficient = , static area= 0.074, gravity center (0.5058,0, 0.00984).

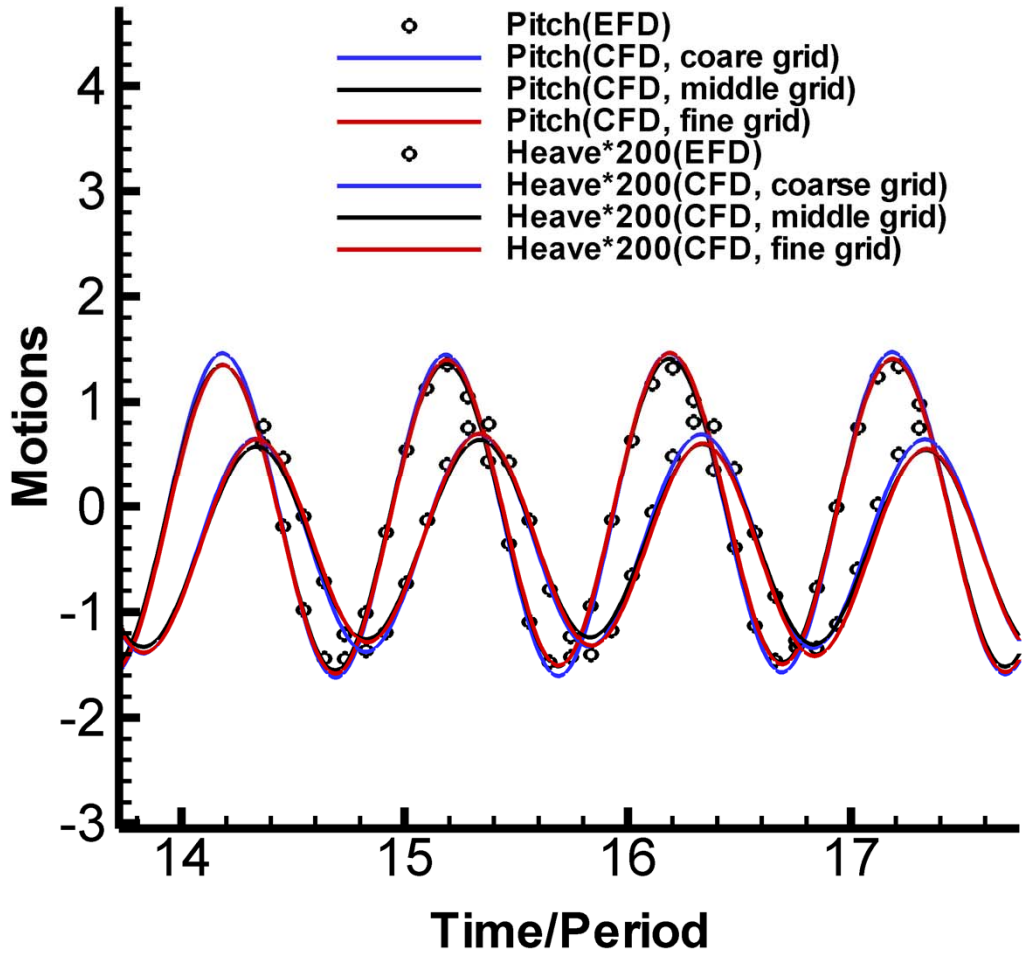


Free surface

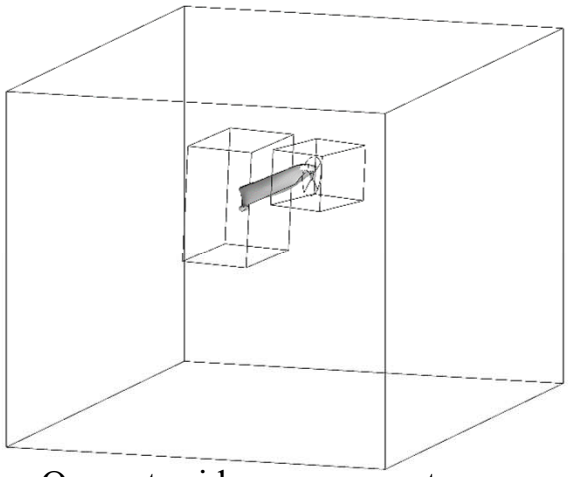
Resistance


Experiment
CFD (coarse grid)
CFD (middle grid)
CFD (fine grid)
0.020
0.015
0.010
0.005
0.000
-0.005
Rsistance
14
15
16
17
Time/Period

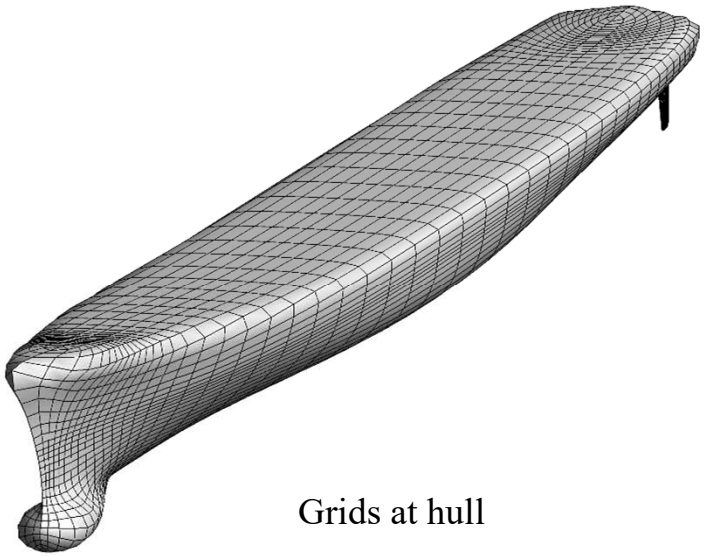
Motions


Pitch(EFD)
Pitch(CFD, coare grid)
Pitch(CFD, middle grid)
Pitch(CFD, fine grid)
Heave*200(EFD)
Heave*200(CFD, coarse grid)
Heave*200(CFD, middle grid)
Heave*200(CFD, fine grid)
Motions
4
3
2
1
0
-1
-2
-3
14
15
16
17
Time/Period

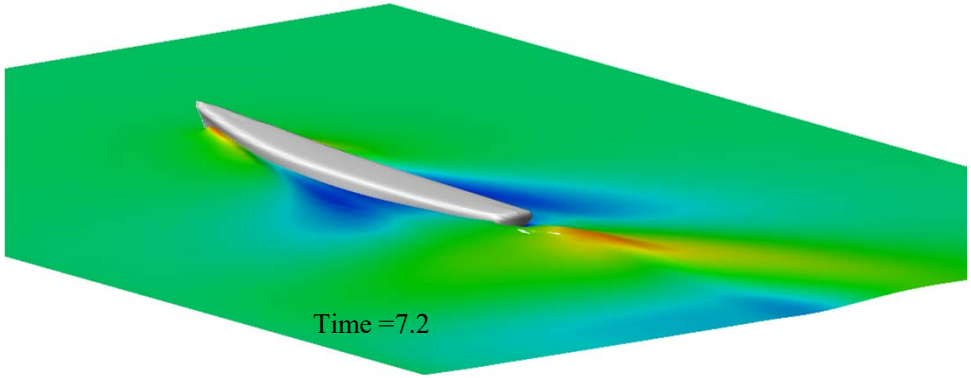
- Zigzag Maneuvering Demonstration
  - Fr=0.28, Re=4.85E-06 (benchmark of reference ship of 5512, 1:46.6 of DTMB 5415).
  - Current model ship (1:116.5 of DTMB 5415, small ship is to test functions of overset grid solver under conditions of very coarse grid close to limit usage).
  - Full ship grids are used, with about double grid node number of previous pitch and heave case (coarsest). The full rudder grid is also added here with total grid nodes of 41,000.
  - Standard 10/10 zigzag test.
  - Single model propeller (Hough and Ordway, 1964) and single real rudder (appendage with independent motions).
  - PD controller is used for controlling ship speed by adjusting value and rate of RPS (Revolution Per Second) of propeller: 1) autopilot from static state to target speed, 2) keep target speed.
  - Initial turning is triggered after the speed gets to a value close to target speed (time=3.0).

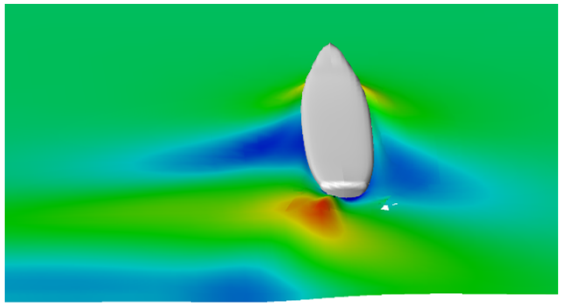


Overset grids arrangement

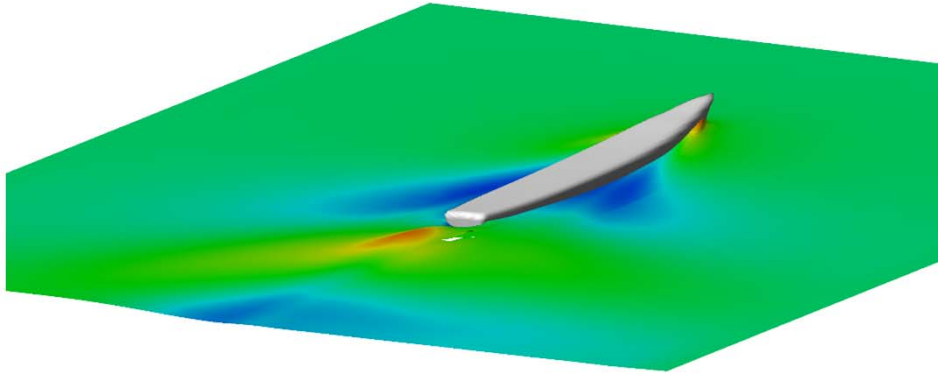


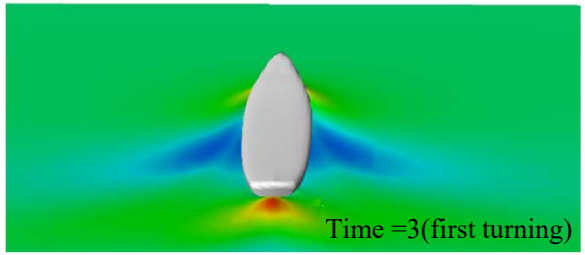
Grids at hull

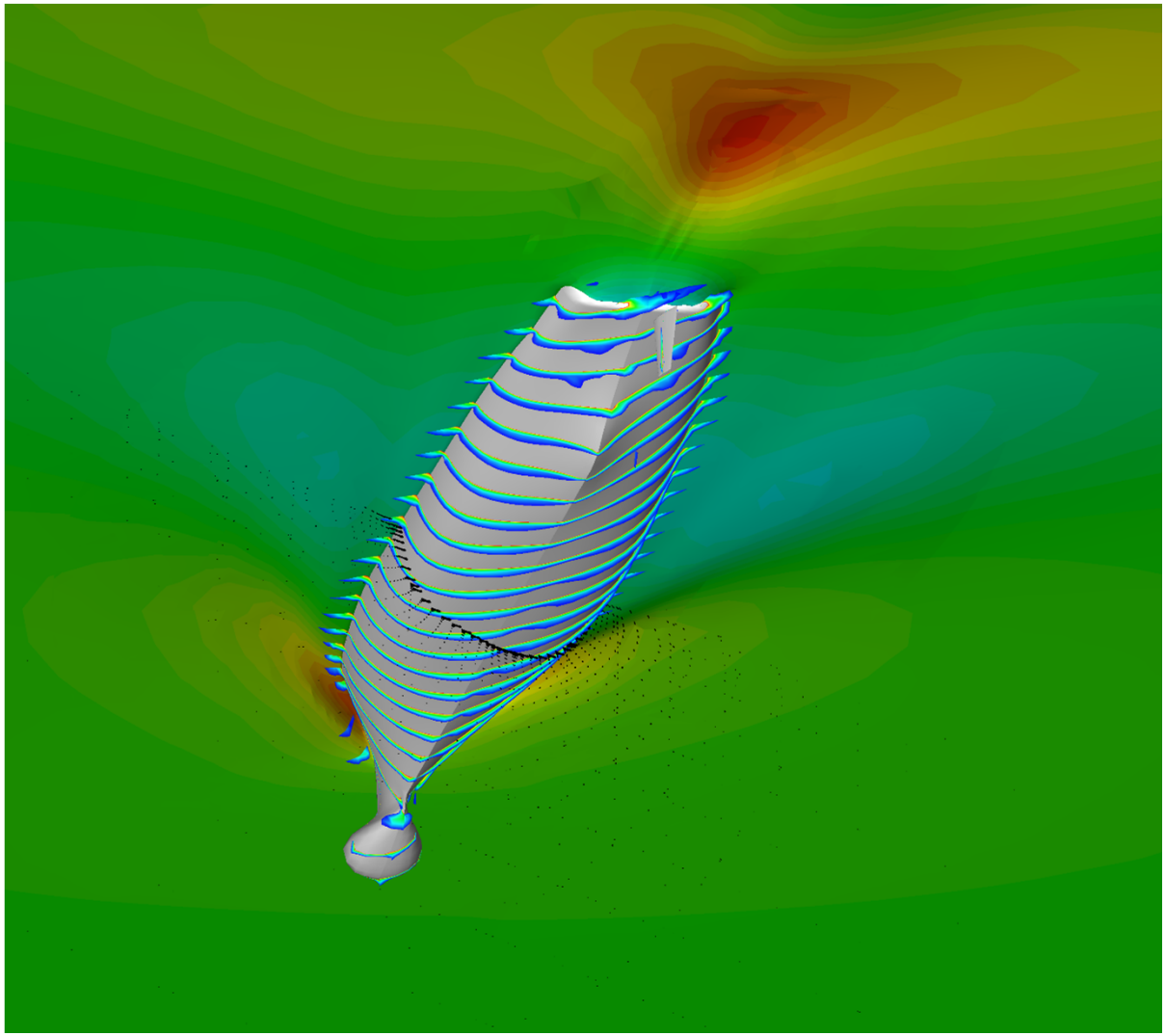




Ship motions of zigzag maneuvering

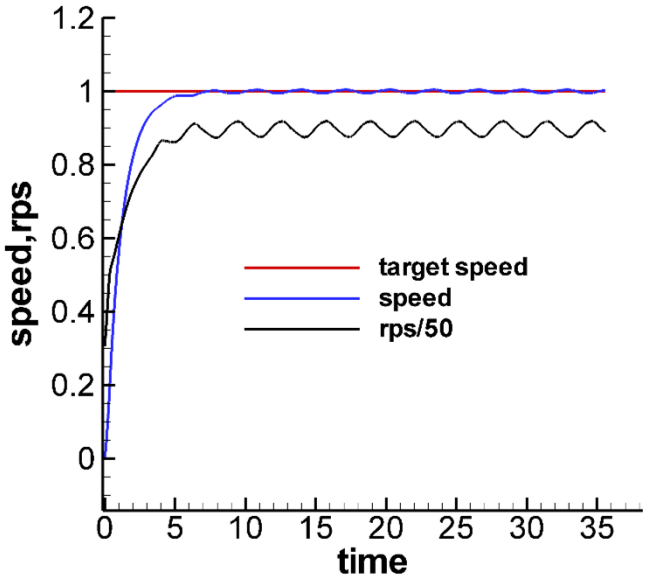




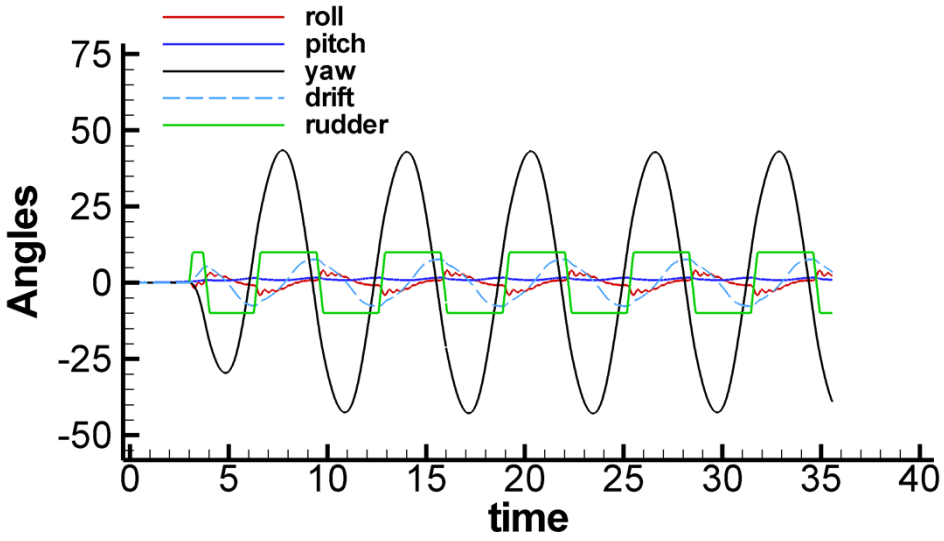


Free surface, vorticity (x component, value: 50-200),
and velocity vector (y section) distributions

(time=8)



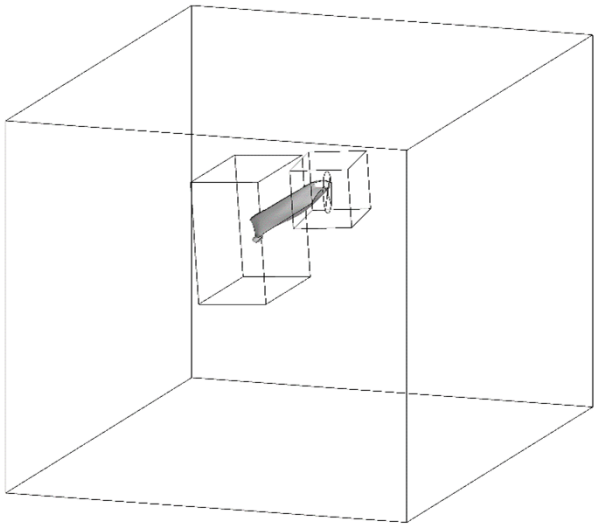
Ship speed and propeller RPS



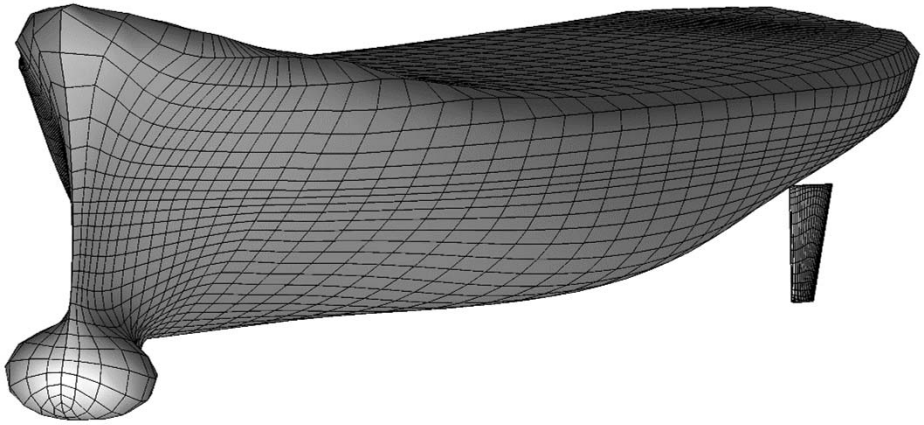
Rudder action, time history of rotations and drift

Seakeeping Demonstration (course keeping)

- Fr=0.28, Re=4.85E-06 (benchmark of reference ship of 5512 (this case is the first step to simulate future multi-ship case where a reference ship is usually required), 1:46.6 of DTMB 5415).
- Current model ship (1:116.5 of DTMB 5415, i.e. 1:2.5 of 5512), reason of using small ship is to test functions of overset grid solver under the conditions of very coarse grids close to limit usage.
- Full ship grids are used as the same as previous zigzag case (same rudder position).
- Irregular incoming wave (sea state is a little bit rough relative current model ship)
  - 1) Bretschneider spectrum, 2) multi-frequency (16 number is used here), 3) multi-directional (9 angle number is used here), 4) principal wave direction: 135 degree (southeastern: from starboard and following), 5) most probable wave length: 0.68 (dimensionless), 6) mean significant wave height: 0.01 (dimensionless), 7) potential flow solutions are used for initial and boundary conditions of free surface, pressure, velocities.
- Double model propellers (Hough and Ordway, 1964) and single real rudder (appendage with independent motions).
- PD controller is used for controlling ship speed by adjusting value and rate of RPS of propeller: 1) autopilot from static state to target speed, 2) keep target speed in waves.
- PD controller is used for controlling ship heading (0 degree, i.e. northing here) by adjusting value and rate of rudder angle.

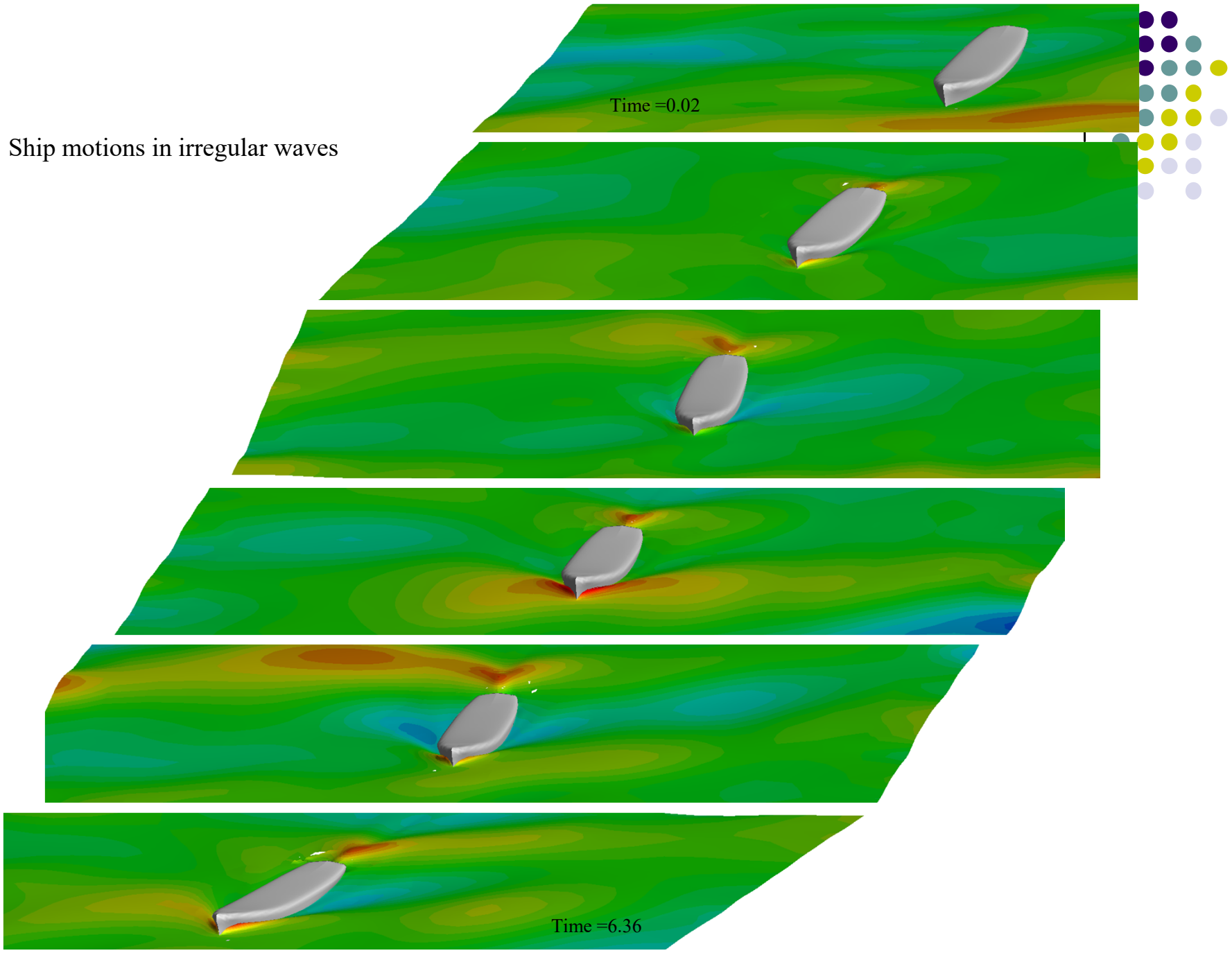


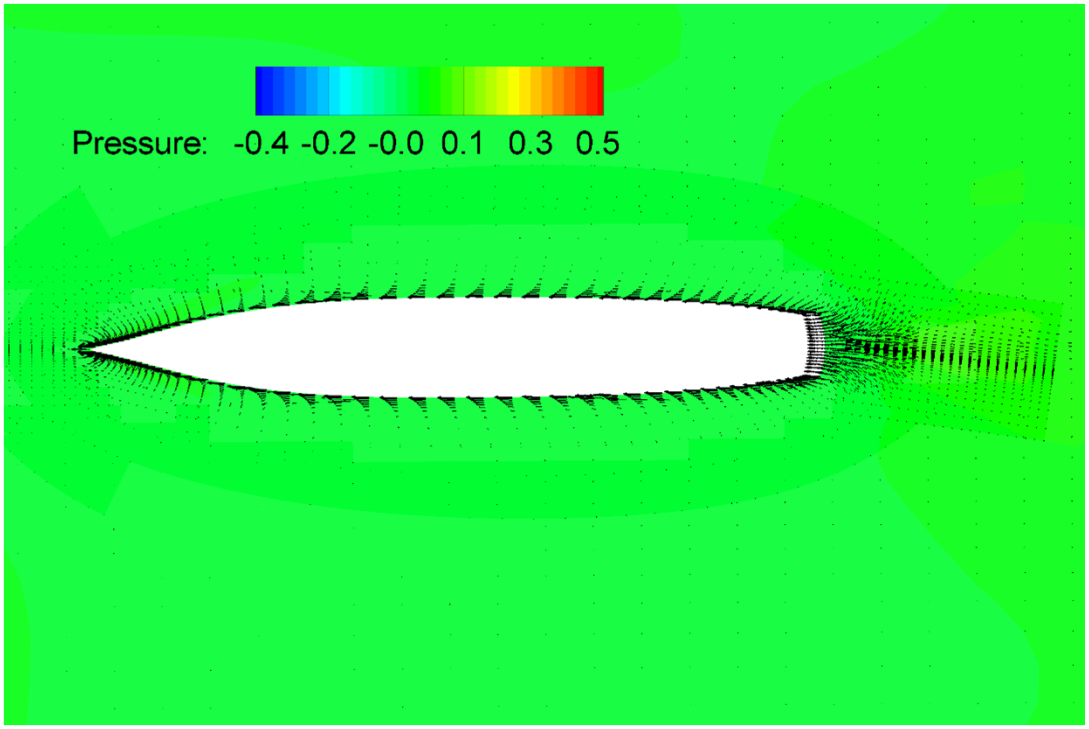
Overset grids arrangement



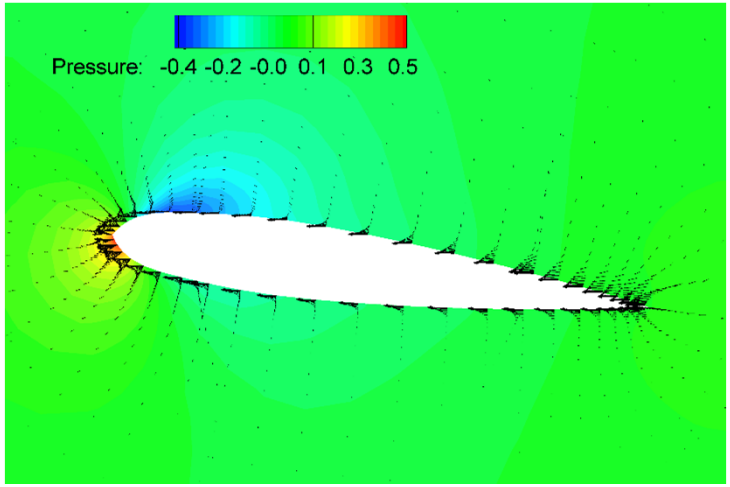
Grids at hull and rudder

Ship motions in irregular waves

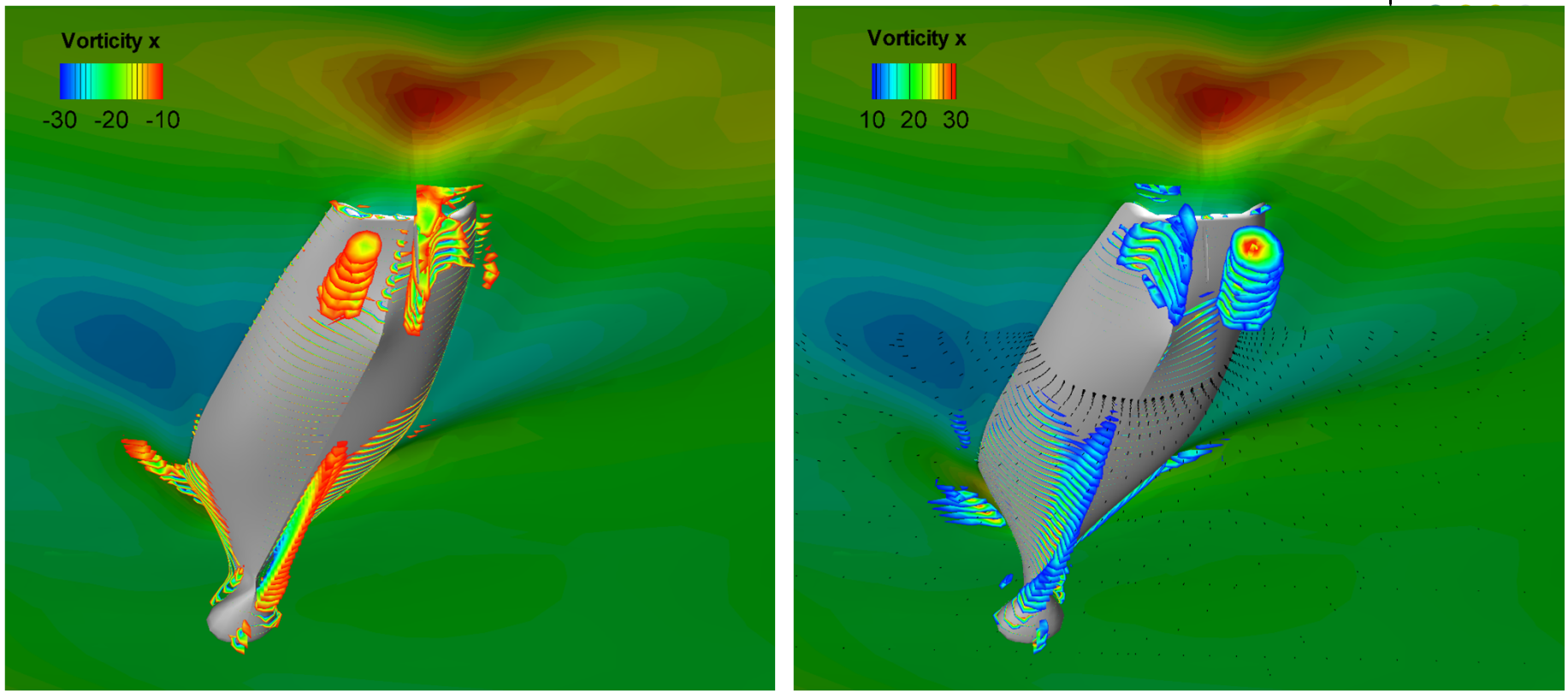




Pressure and velocity vector distributions around ship at section z=0 (note: velocity is extended in air region, time =4.5)

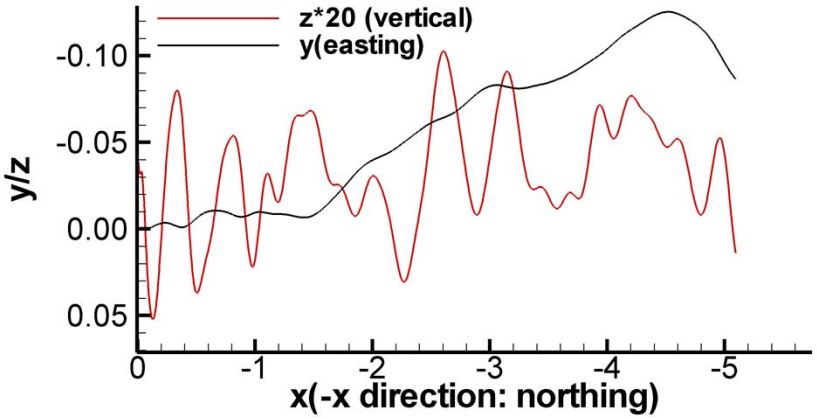


Pressure and velocity vector distributions around rudder at section z=-0.011 (time =4.5)

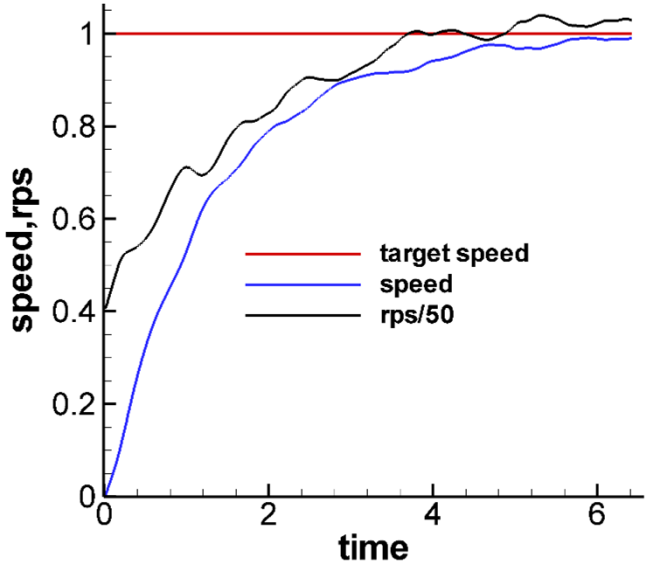


Free surface, vorticity, and velocity vector distributions at time=4.5

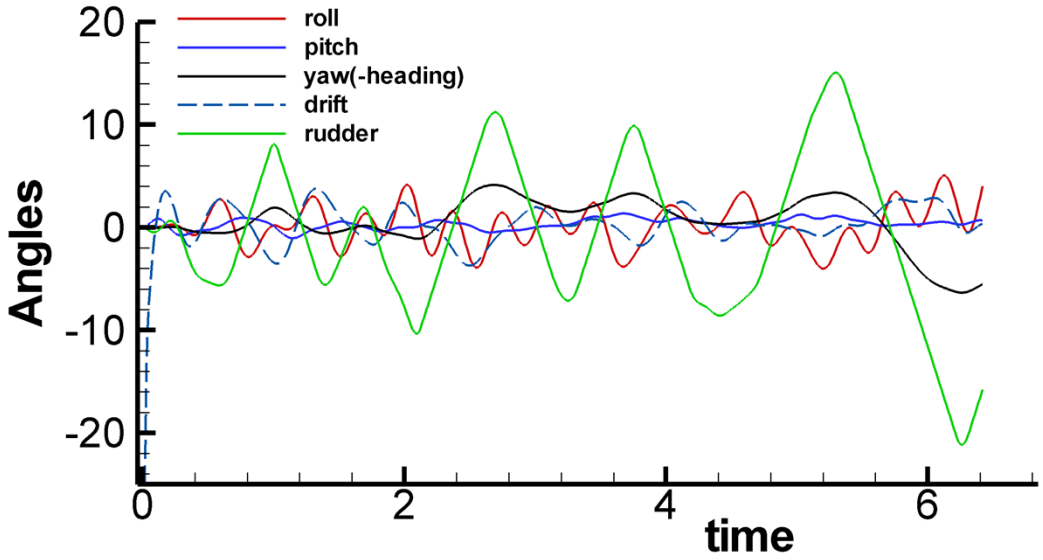
(left: negative vorticity value, right: positive vorticity value)



Ship trajectory



Ship speed and propeller RPS



Rudder action, time history of rotations and drift