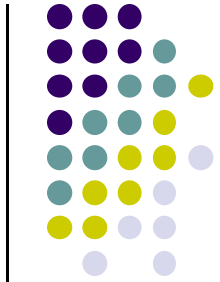
Overset-OHMUGA : A Dynamic Structured and Unstructured Overset Grid Solver for CFD



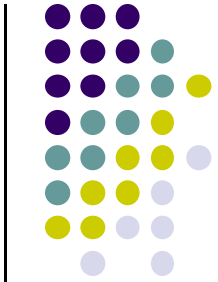
Juntao Huang

OHMUGA Fluid Dynamics Inc., St. John's, NL, Canada

Outline

- Background
- Objectives and Current Situation
- Examples (Overset and CFD Solvers)

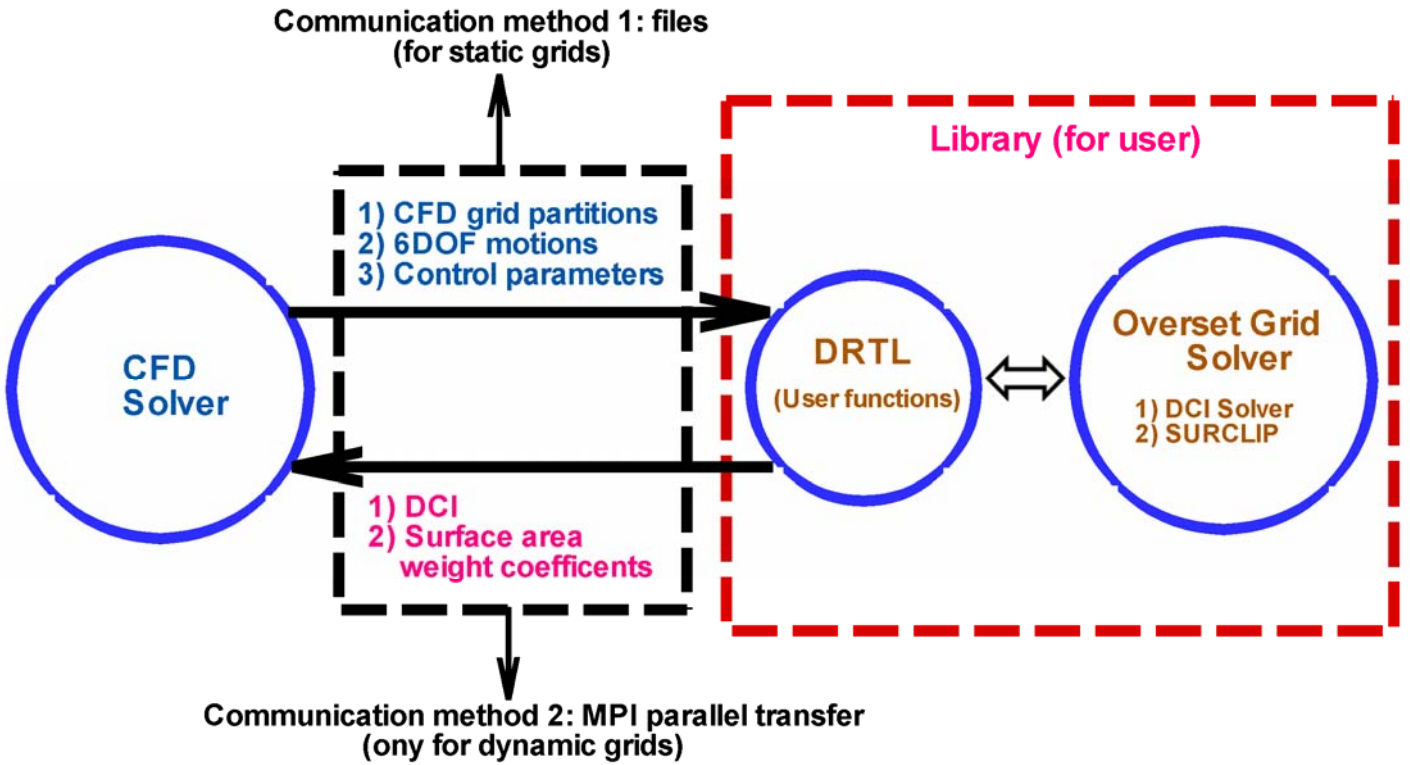
Background

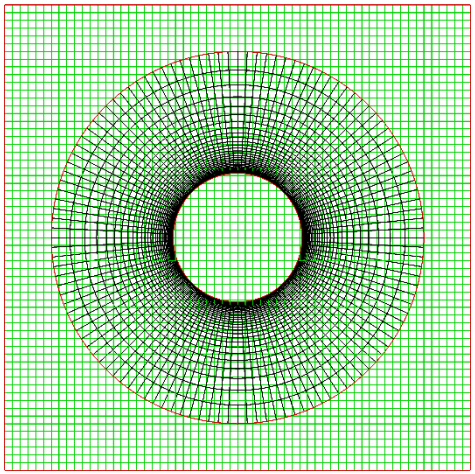


- Broad problems of grid refinement, relative motion, very complicated geometries, etc.
- Grid refinement.
  - Shock wave, free surface, wave breaking, complicated vortex structure.
- Relative motions.
  - Large amplitude ship motion, multi-ship interaction (multi rigid bodies with different motions), ship automatically cruising in waves under operations of propeller and rudder. Hydrodynamics of Underwater vehicle with 6DOF motion. Other marine floating body and wave interaction.
  - Aircraft cruising with 6DOF motions.
  - Flow relating to rotor, propeller, fan, etc. Water turbine hydrodynamics and wind turbine aerodynamics.
  - Ice-ship interaction
  - FSI (Fluid Structured Interaction): non-conformal overset grids of fluid and body grids, considering rigid body deformation.
- Complicated geometries.
  - Grids of fin, empennage, wing, etc. which are appended on the corresponding base grids.

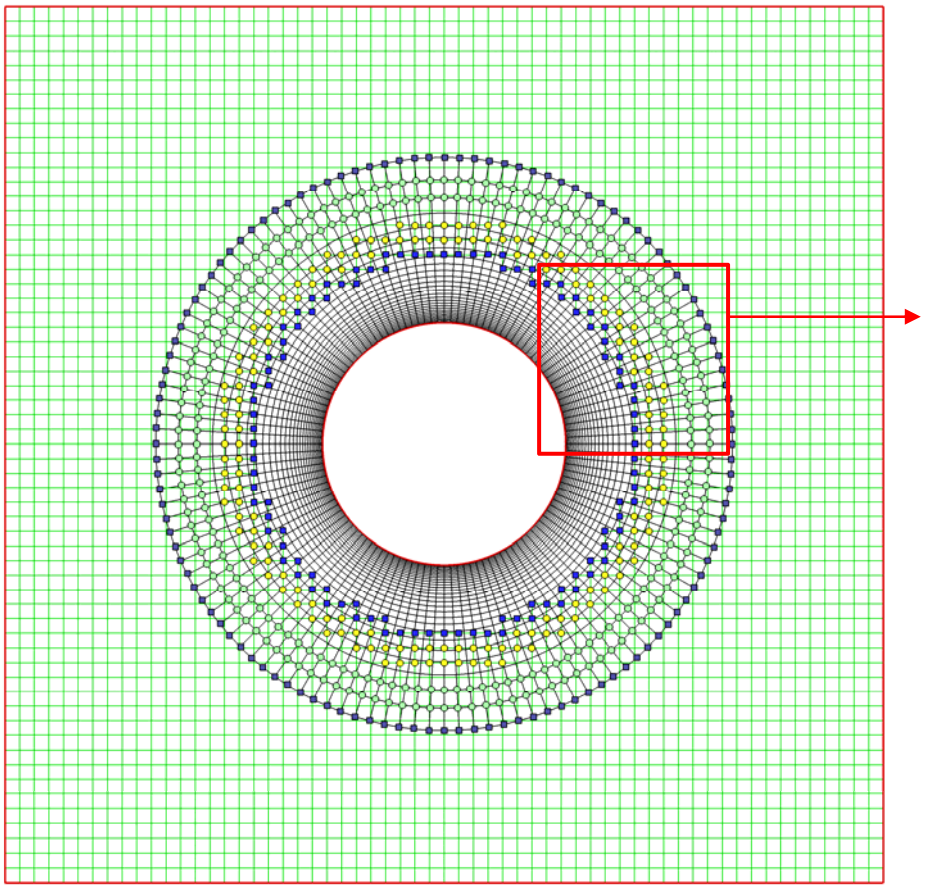
Objectives and Current Situation

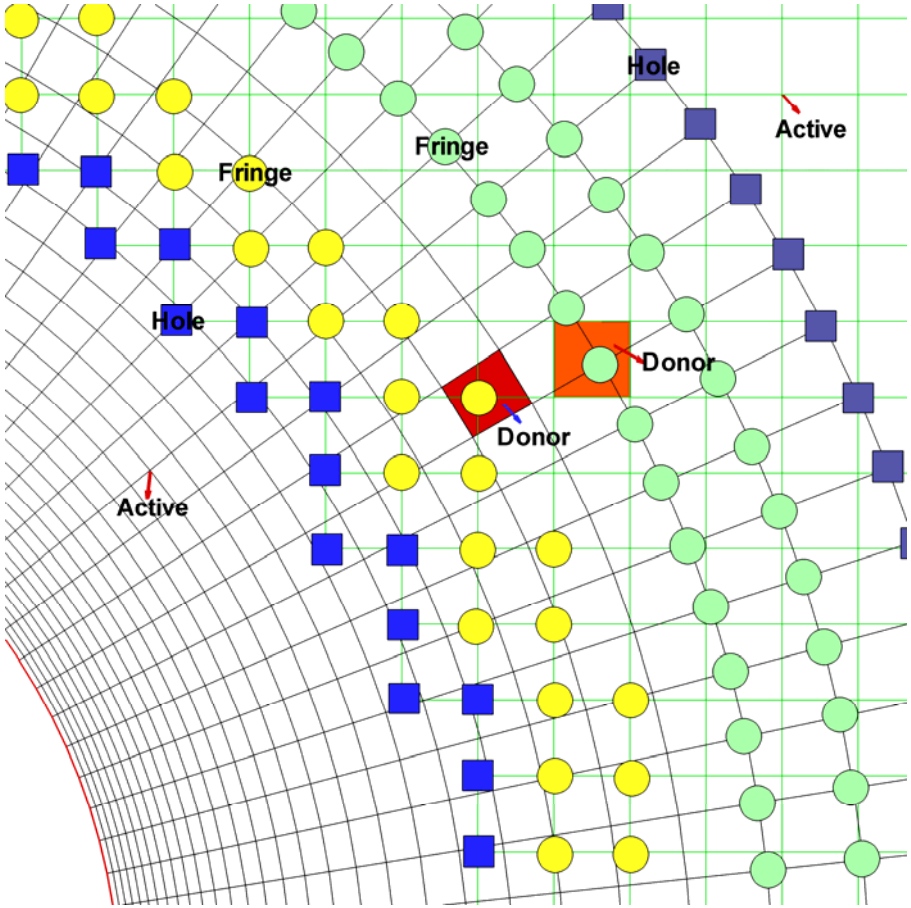
- Objectives
  - Overset-OHMUGA provides an efficient tool for CFD solvers for simulating problems of relative body motions, grid refinements, and complicated geometries.
  - Efficient, robust, and accurate calculations for DCI (Domain Connectivity Information) and surface area weight coefficients (for predicting forces and moments).
- Current Architecture



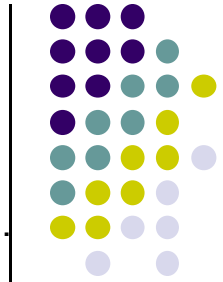


- Basic knowledge of overset grid method
  - One composited grid generated from some separated overset grids by the way of boundary interpolation.
  - Active (computed), fringe (interpolated), hole (cut off), orphan nodes (avoided).
  - Key process: hole cutting for nodes out of domain of interest.





Current Situation



- Developed DCI solver, SURCLIP, and DRTL.
  - Structured (multi-block) or unstructured (four hybrid elements) overset grids.
  - Static or dynamic grid with 6DOF body motions and 3DOF rotations of their controllers.
  - Multi-bodies and multi-appendages (controller) with independent motions.
  - Efficient calculation: domain decomposition method, MPI parallel treatments, data structure, etc.
  - Convenient to use: input file, grids and boundary conditions (e.g. Gridgen, FIELDVIEW Grids formation).
- DCI solver
  - Calculate DCI information for CFD
  - 1) Suggested a new efficient method named Iterative Band Algorithm for hole cutting. 2) Automatic process, watertight band, no grid hierarchies, no auxiliary geometries, no protected elements near boundaries. 3) Multi-level fringe nodes. 4) Multi-level appendages. 5) Efficient searching method. 5) Orphan nodes treatment by average method.
- SURCLIP
  - Efficiently create unique outer surface enclosing tagged objects with overlapped surfaces.
  - Calculate surface area weight coefficients for predicting forces and moments.
- DRTL (Donor Receptor Transaction Library).
  - User functions for communicating information between CFD and overset solvers.
  - Static grid: printing out files.
  - Dynamic grid: 1) MPI parallel transfer, 2) different grid partitions and parallel treatments are permitted for overset and CFD solvers for flexible operations .
- Examples of overset grid solver, or combined CFD and overset solvers are demonstrated.
  - 2D or 3D cases with very complicated geometries, and relative motions.

DCI Solver

- Multi-block curvilinear structured grids and unstructured grids. (see in Huang J. Vol.3, pp.1011-1018 , ISOPE 2013)
- Dynamic grid with 1-6DOF body motions and 1-3DOF rotations of controllers (appendages attached on body with independent motions).
- Iterative Band Algorithm (IBA) for Hole cutting outside the domain of interest (see in Huang J. Vol.3, pp. 368-375, ISOPE 2016).
- Finest grid method for donor search inside the domain of interest.
- Multi-level of fringe nodes (level number can be set arbitrarily if the grids are overlapped enough) for high precision CFD.
- Multi-level appendages (fixed, not controller) for very complicated geometries.
  - For example: ship superstructure, skeg, bilge keel, fin, empennage, wing, etc.
- Efficient methods.
  - Oriented bounding box, vision space bin , and ADT and KD-Tree data structures not rebuilt each time step.
- Domain decomposition method and MPI Parallel treatments.
- Shape function method used for interpolation coefficients.
- Orphan nodes treatments for grid not overlapped enough, or under geometry tolerance.
- Previous time solver.

SURCLIP

- A solver incorporated in DCI solver.
  - Unique Surface Integration.
  - Calculating surface area weight coefficients for predicting forces and moments in CFD. (OHMUGA report: Huang J. Introduction of SURCLIP: A Parallel Code for Predicting CFD Forces and Moments Using Dynamic Overset Grids. 2016.)
- Structured (multi-block) or unstructured overset grids.
- Efficient search method of ADT data structure and fitting oriented bounding box.
- Directed Acyclic Graph (DAG) for ranking original grids.
  - Directed graph.
  - Strongly connected components (SCC).
  - Closest connection break and sources and sinks methods for ranking cyclic SCC.
- Polygon Boolean difference operator
  - Clip a tagged polygon by other higher-ranked and overlapped polygons.
  - Only sublets with no hole-vertex are considered.
  - GPC Library (contact website: http://www.cs.man.ac.uk/~toby/gpc/#Licensing, if for commercial usage. For example: it is free for research work).
- Area weight coefficients.
  - Clipped area divided by original area of a surface sublet.
- MPI parallel treatments.
- Communicate information to CFD by DRTL.
- SURCLIP is copyrighted (GPC is an option to choose). For commercial usage, users should contact University of Manchester before use GPC library.

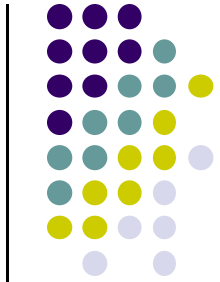
DRTL (Donor Receptor Transaction Library)

- Tools designed for providing DCI and surface area weight coefficients for CFD.
- Static grid: files for CFD (input CFD grid partition information if parallel)
- Dynamic grid: Medium library that simplifies the addition of an overset capability to a flow solver. (call functions or subroutines through memory and MPI)

Overset solver	DRTL	CFD solver
• Triggered whenever CFD solver requires. • Run independently and parallel from CFD, and different grid index, grid partition, parallel method from CFD are permitted.	⇐	• Grid, boundary files • Grid partition information (if parallel) • 6DOF motions • Other operation parameters from an input file
• Provide DCI information for CFD: location and index of active, fringe and hole nodes, and donor elements. • Provide interpolation coefficients, (CFD solver can also calculate it for their special cases.) • Provide area weight coefficients.	⇒	• Discretize governing equations in term of DCI data. • Assemble linear system in term of DCI data. • Calculate forces, moments, flux, etc. • Update 6DOF motions and send them to overset solver in each iteration or time step.

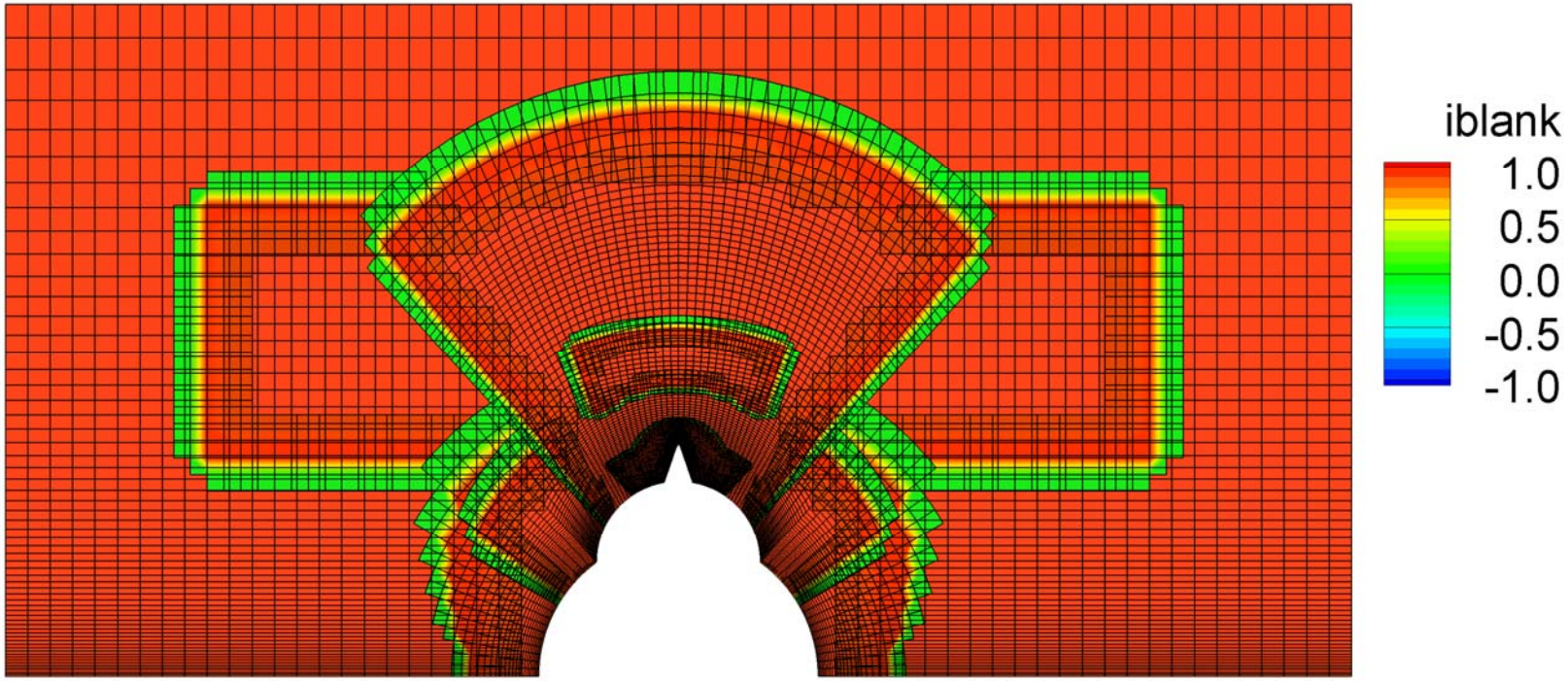
- More general and compatible services scheduled for CFD solver
  - Other special treatments possibly required by users: for examples, cell centered grids, staggered grids, fully-coupled equation solvers, etc.

- Operation Method
  - Create an input file with basic parameters, such as 2D or 3D mode, time steps, separated grid names, features (structured or unstructured) and partition numbers, 1-6DOF masks for prescribed or predicted body motions, output file name, etc.
  - Provide overset grids (each separated grid could be a hybrid grid of tetrahedral, hexahedral (also looked as structured grid), prismatic and pyramidal elements).
  - Mask structured grids or unstructured grids
  - Mask physical domain boundaries and overset grid outer boundaries.
  - Create Files predicting the 6dof motion histories for separated grids masked.

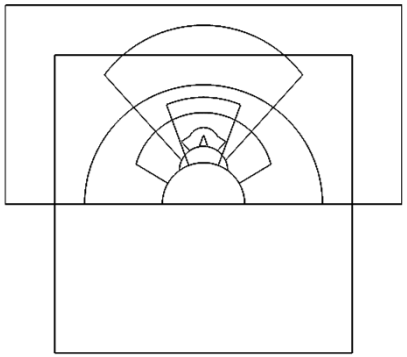


Examples

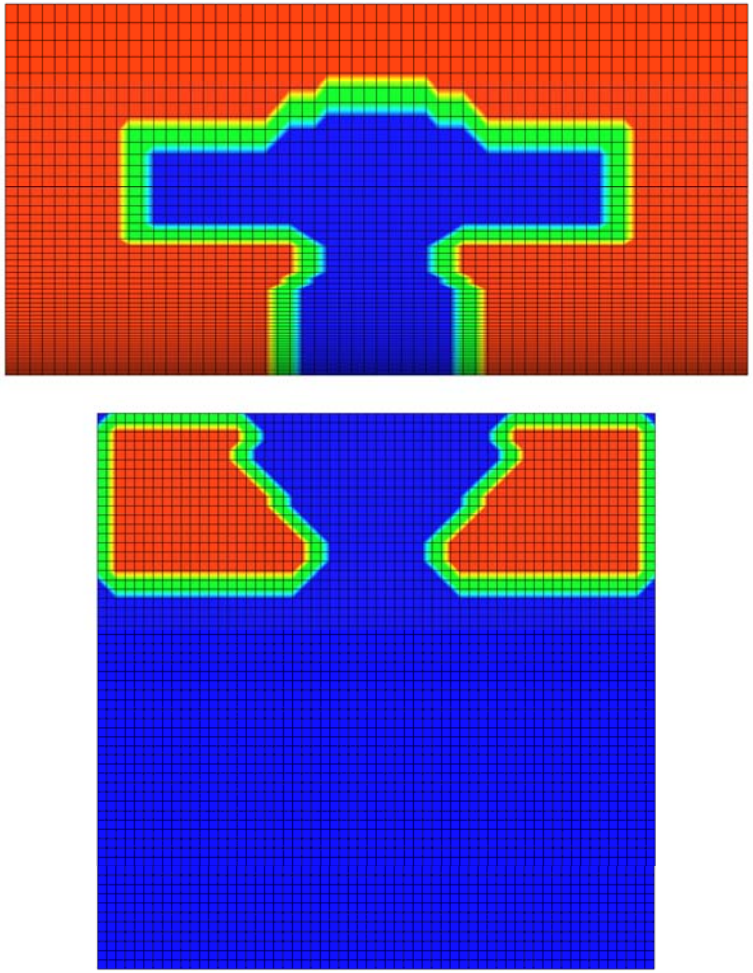
- Example 1 (Appendages and Sharp Geometry)
  - Conditions:
    - 7 grids with 16 processors arranged for parallel DCI (3 for each background grid, 2 for each other grid).
    - 2 elements into the paper (3D method calculate 2D problems).
    - Physical boundary conditions for domain are set in background grids, cylinder wall and its appendages.
  - Functions of solving problems :
    - Multi-layers and different grid sizes.
    - Multi-inlay appendages (iteration number for IBA is M+1, M=3 inlay here).
    - Sharp geometries.

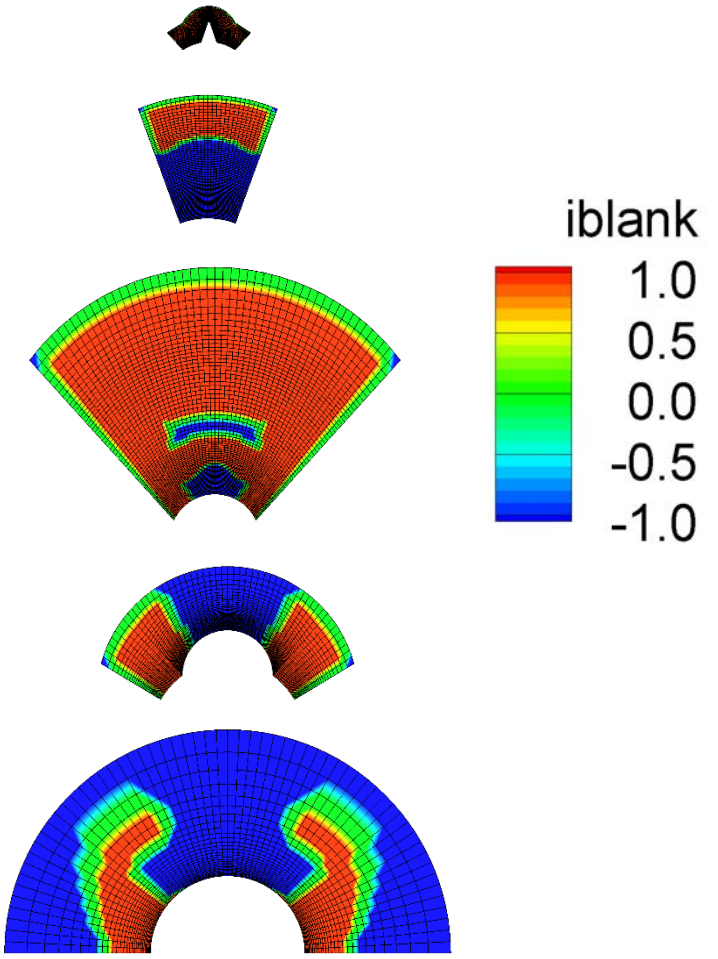


Distributions of active and fringe nodes after hole cutting

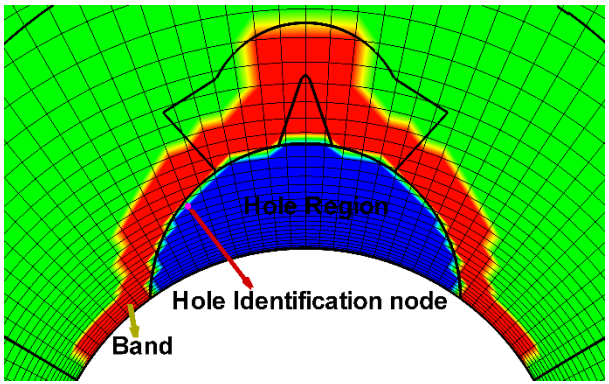


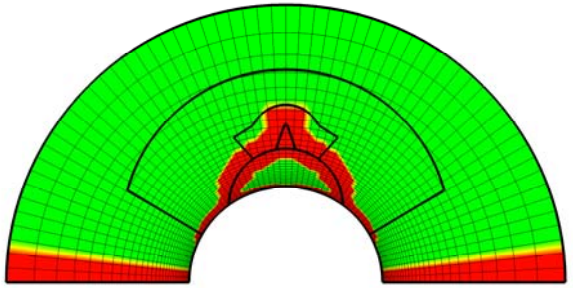
Distributions of active, fringe and hole nodes in seven overset grids

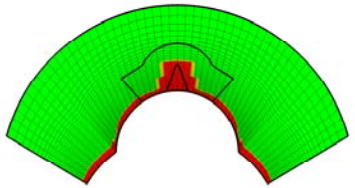




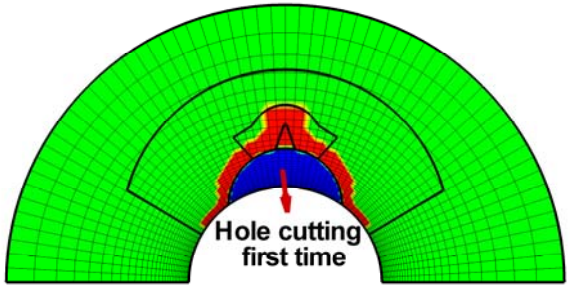
Demonstration for Hole-Cutting and Bands Update Process

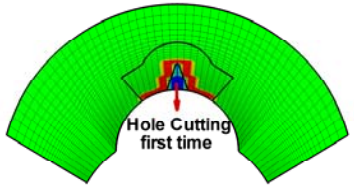




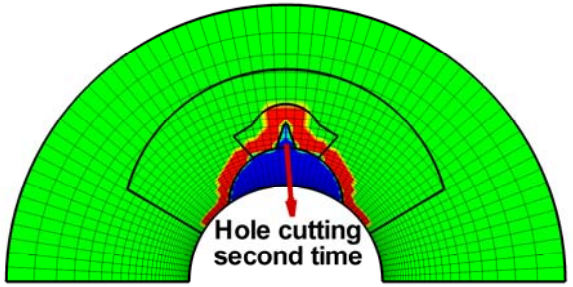


(a) Initial setting



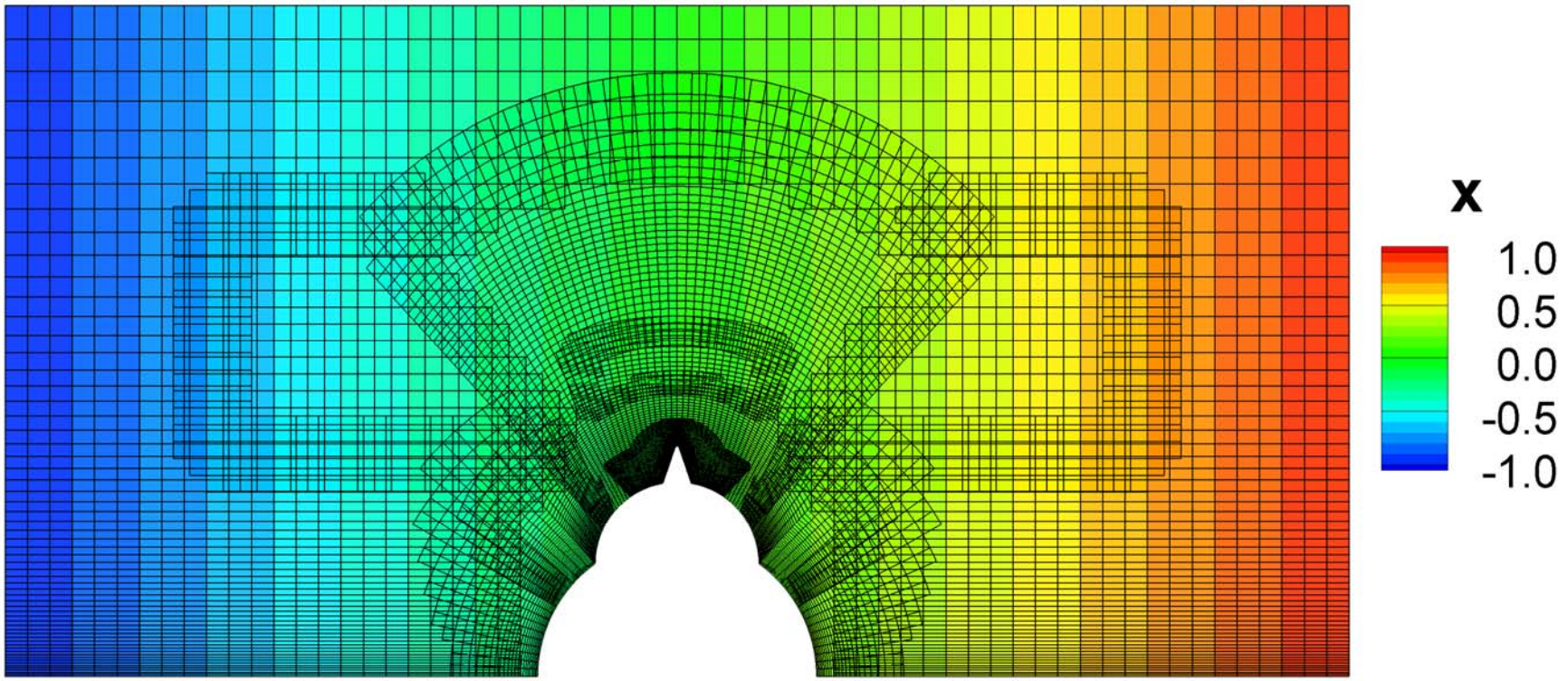


(b) First iteration

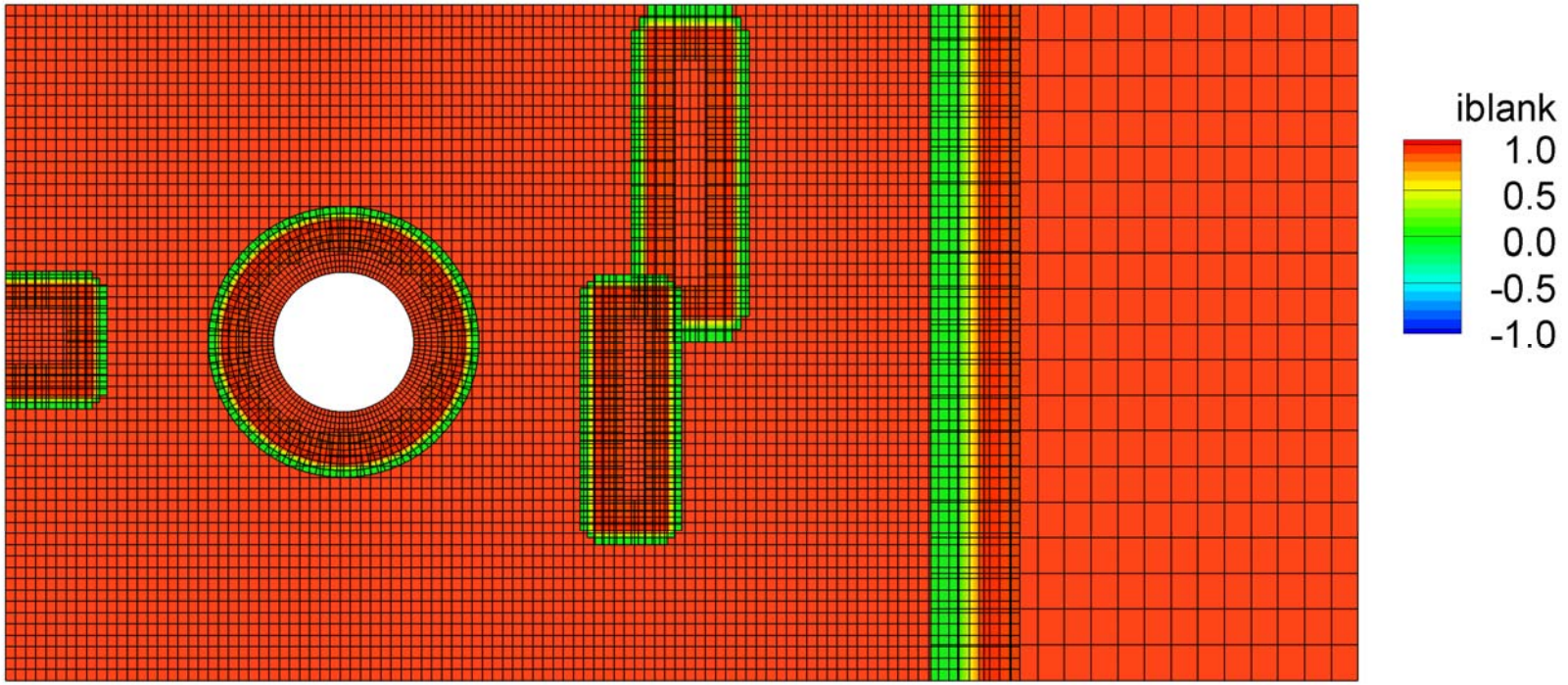


(c) Second iteration

Distributions of x coordinate value using donor element interpolations for fringe nodes

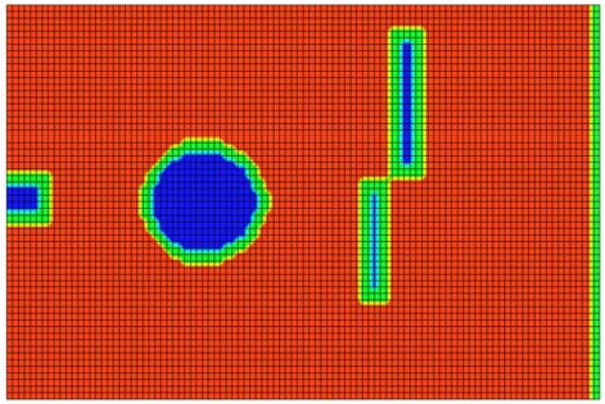


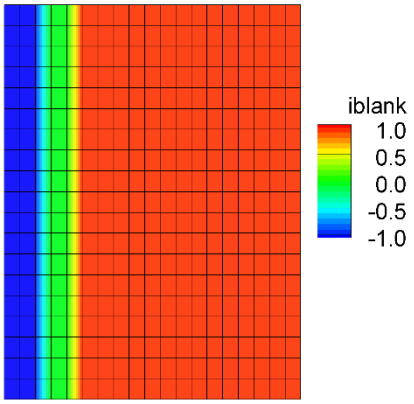
- Example 2 (Cylinder and Boxes)
  - Conditions:
    - 13 grids with 26 processors arranged for parallel DCI (2 for each grid).
    - Physical boundary conditions for domain are set in background grids, cylinder wall and one refinement grid (inlet).
  - Functions of solving problems :
    - Multi-layers and different grid sizes.
    - Exactly match, or fully outside or inside physical domain boundaries or holes.
    - Multi-block structured grids (the circle is composed by four different structured blocks originally).
    - Parallel treatments.

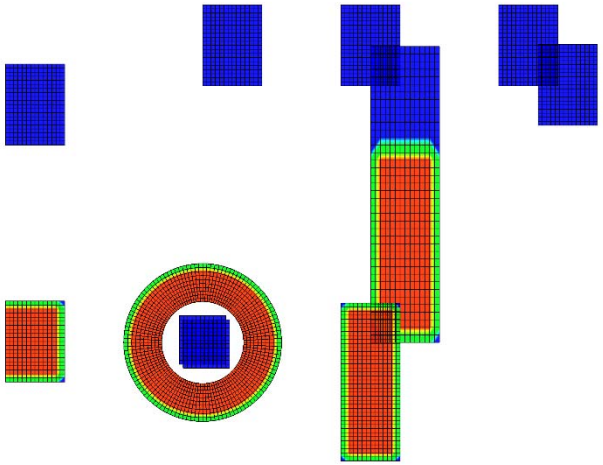


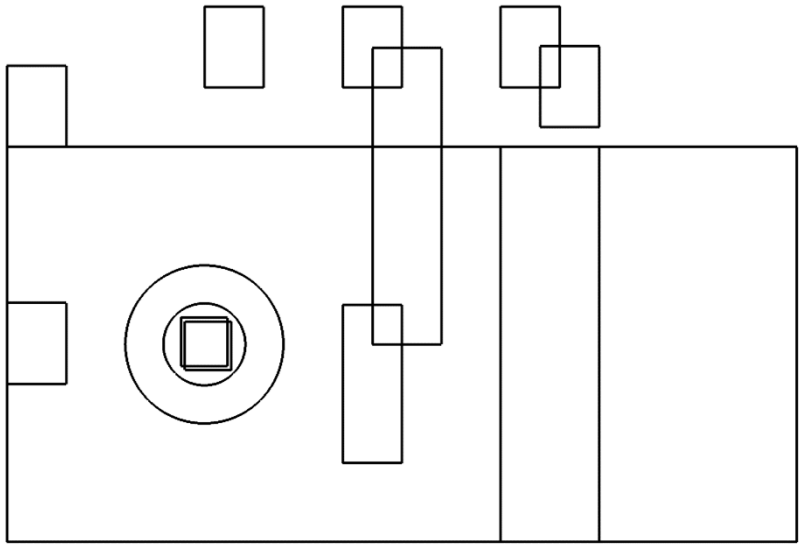
Distributions of active and fringe nodes after hole cutting

Distributions of active, fringe and hole nodes in 13 overset grids

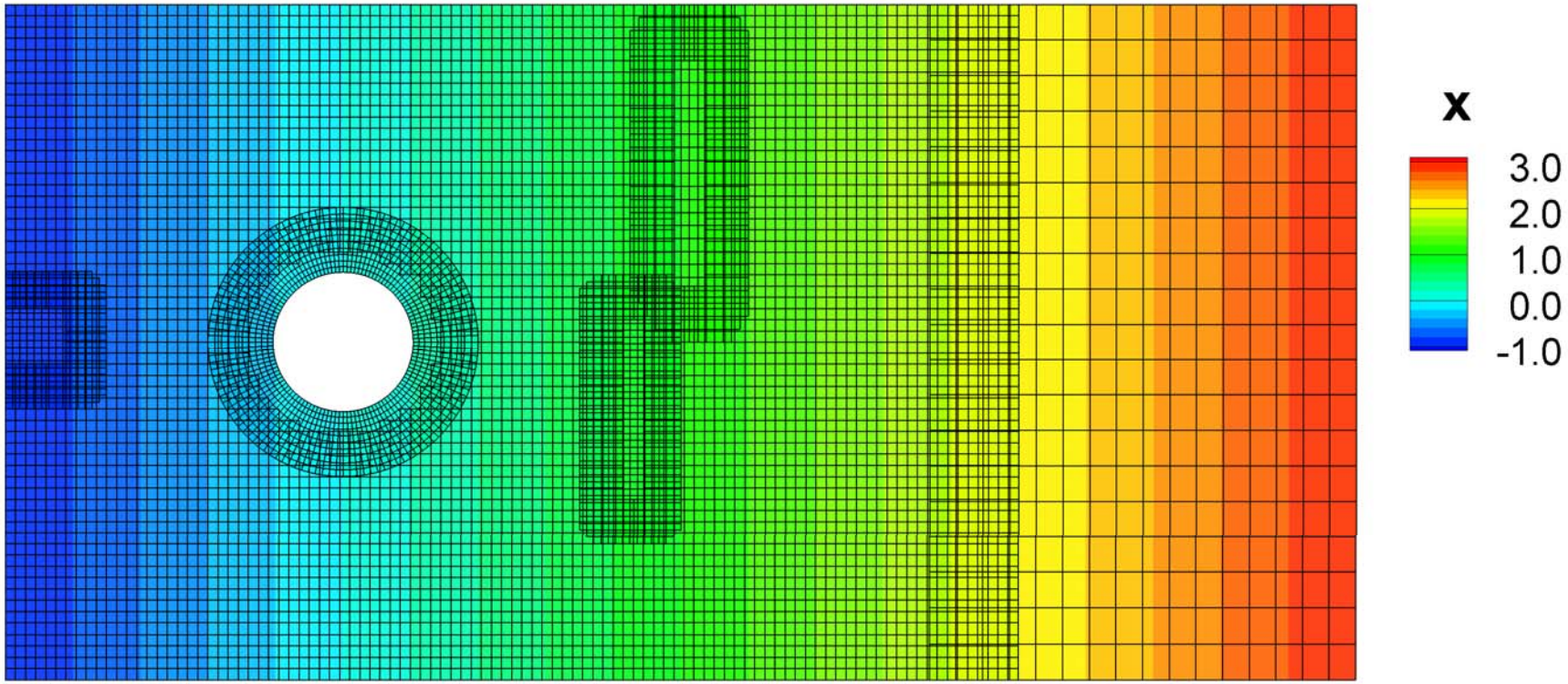






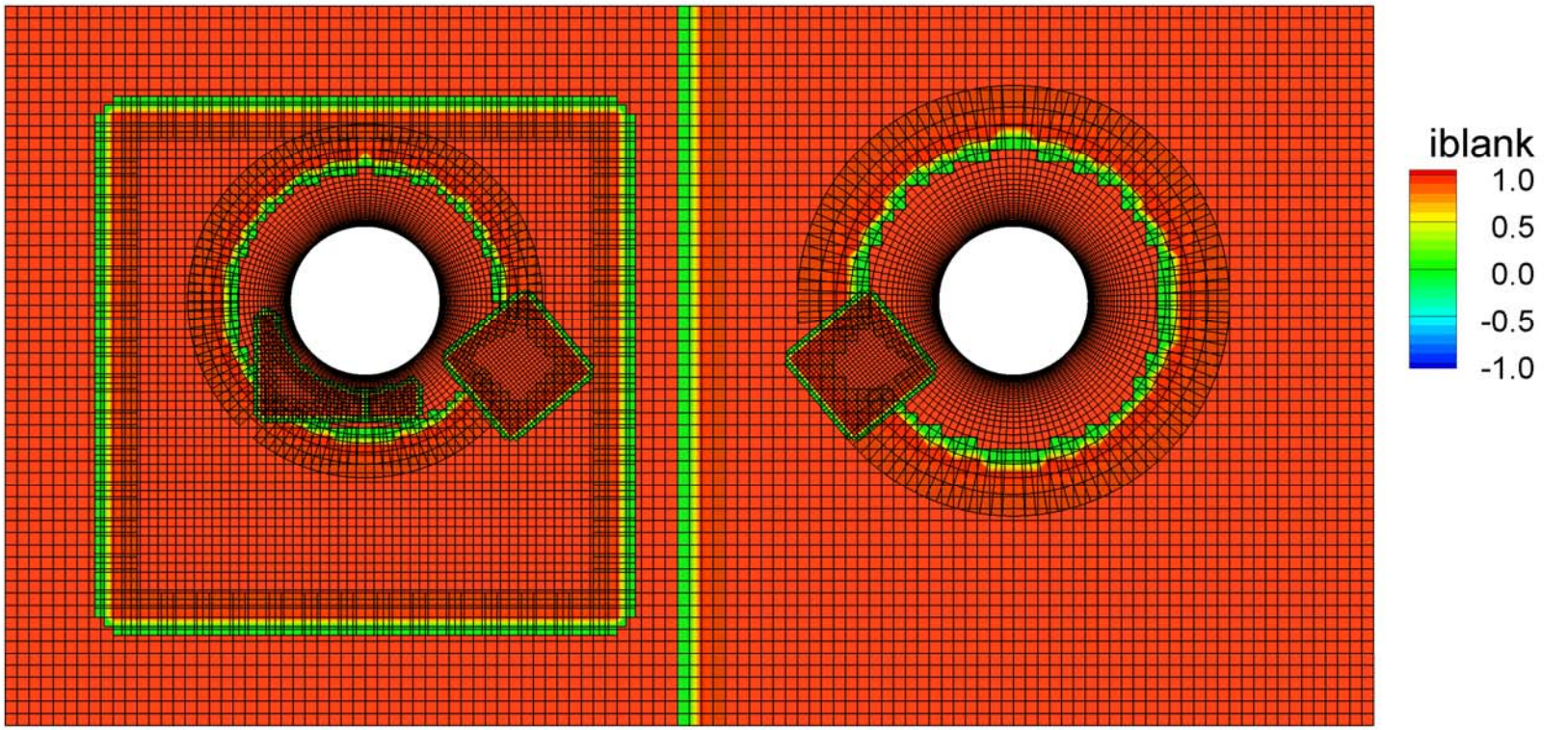


Distributions of x coordinate value using donor element interpolations for fringe nodes



- Example 3 (Dynamic Grids)
  - Conditions:
    - 9 grids with 20 processors arranged for parallel DCI (3 for each cylinder grid, 2 for each other grid).
    - Motions (prescribed): 2 cylinders (oscillate vertically), 2 side boxes (rotate with y axis and move horizontally).
    - Physical boundary conditions for domain are set in background grids and cylinder wall.
  - Functions of solving problems :
    - Rigid body 6DOF motion and dynamic grid.
    - Grids with arbitrary positions with physical domain.

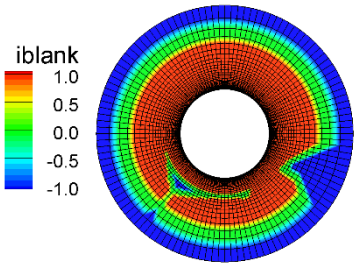
Movie

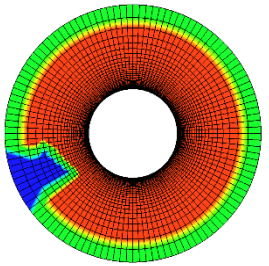


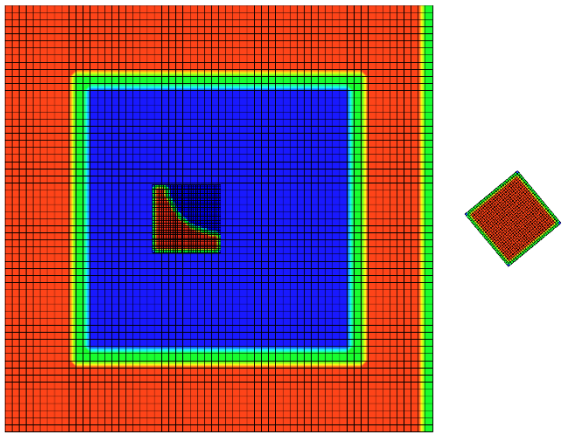
Time=0.64

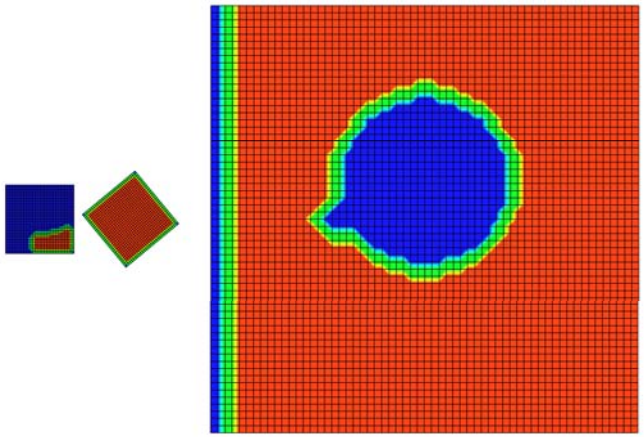
Distributions of active and fringe nodes after hole cutting

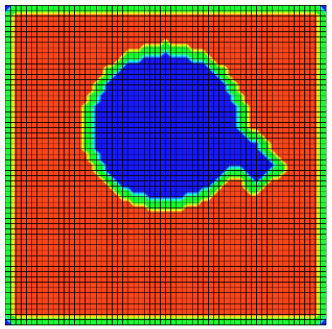
Distributions of active, fringe and hole nodes in nine overset grids

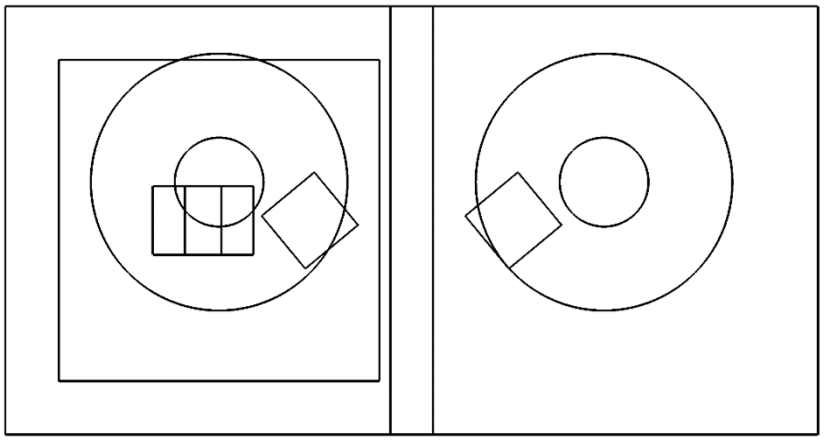




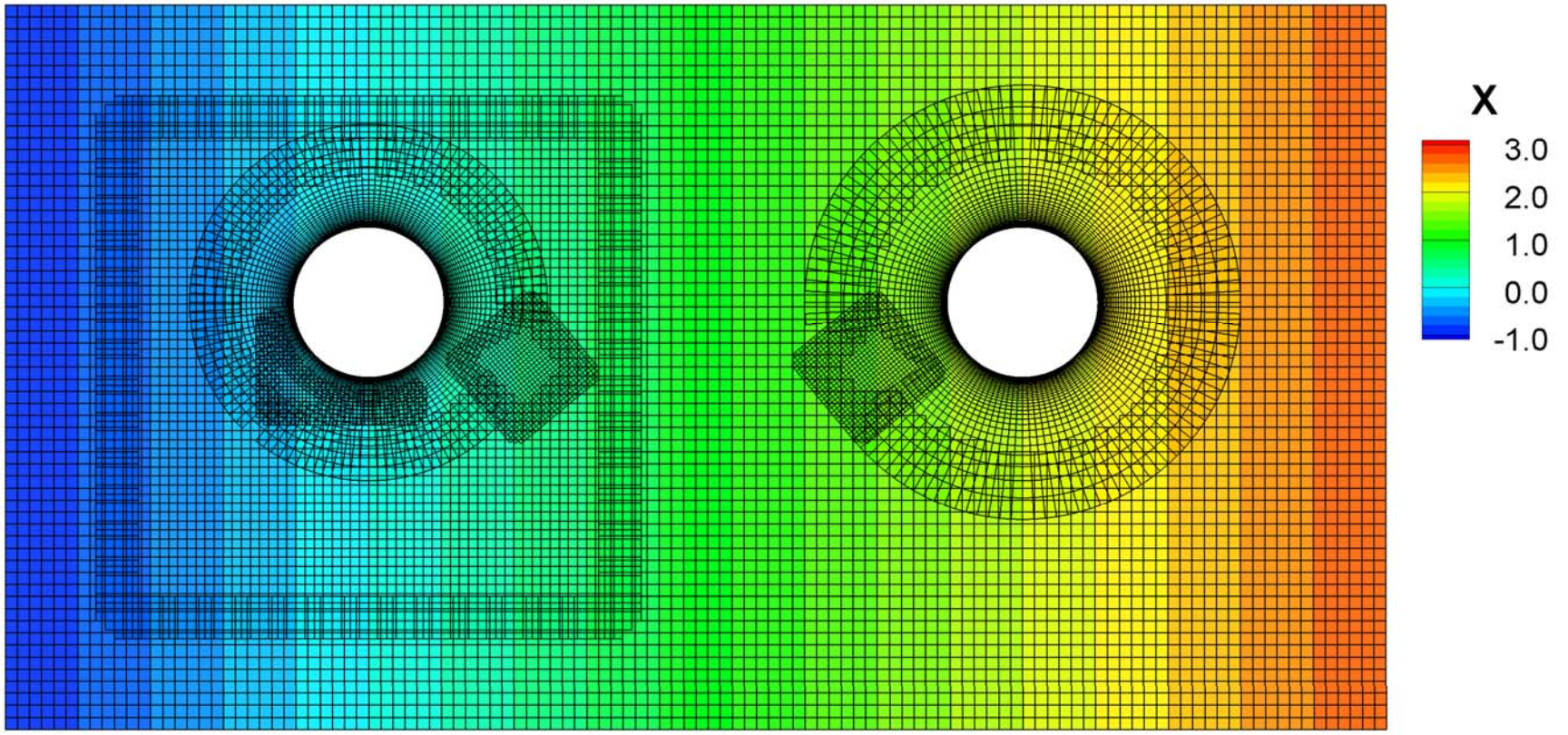




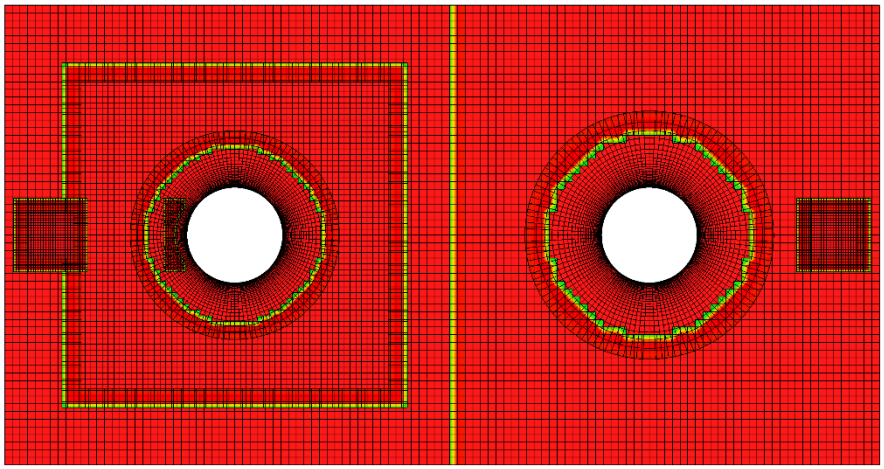




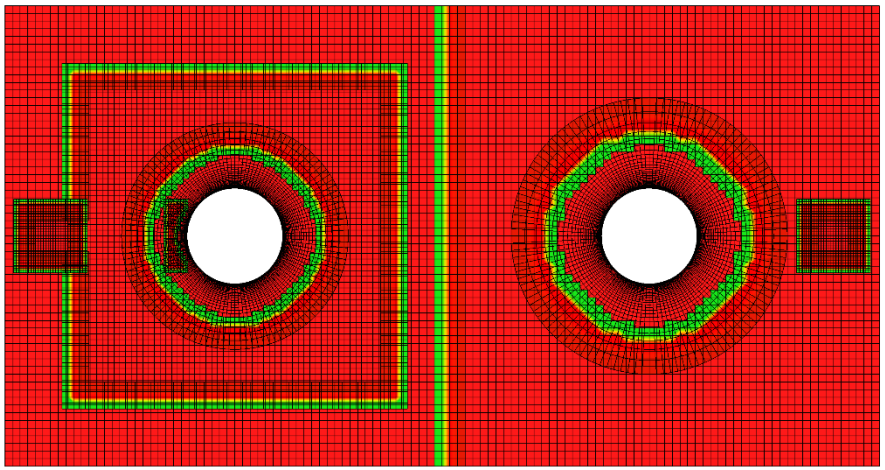
Distributions of x coordinate value using donor element interpolations for fringe nodes



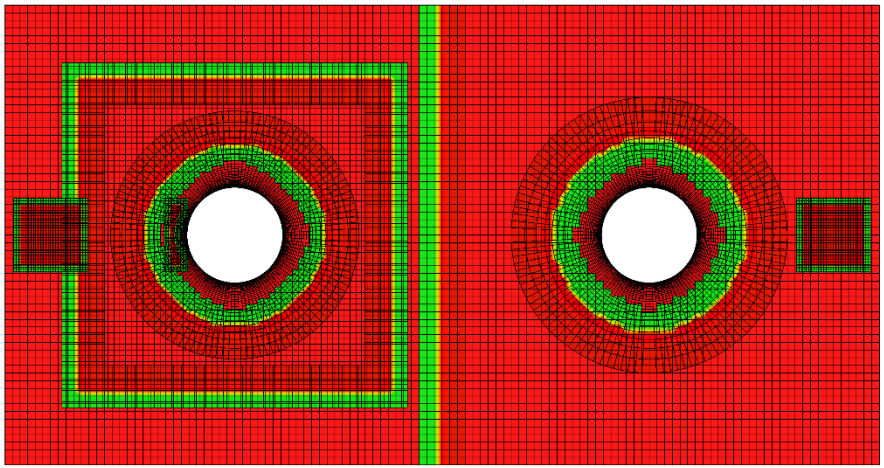
Multi-level fringe nodes (time=2.0)



one level

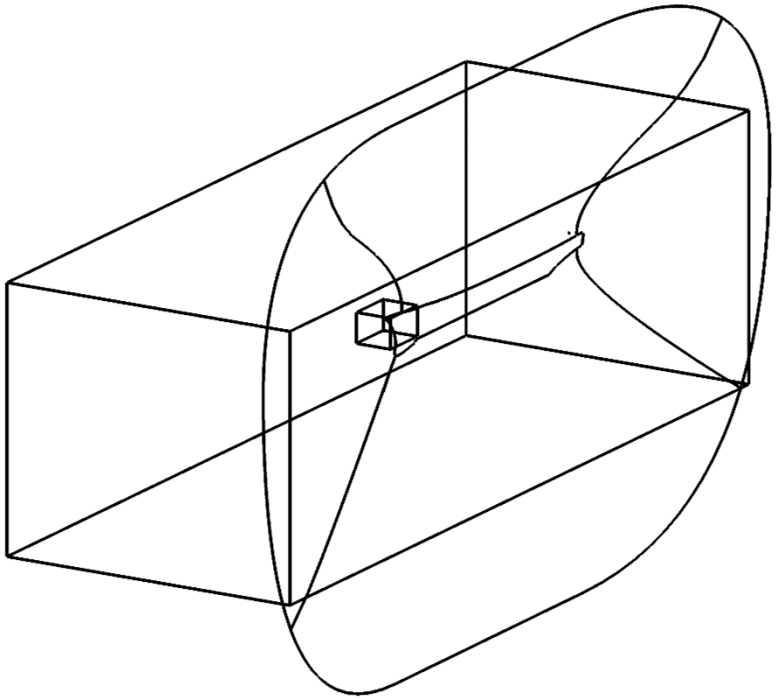


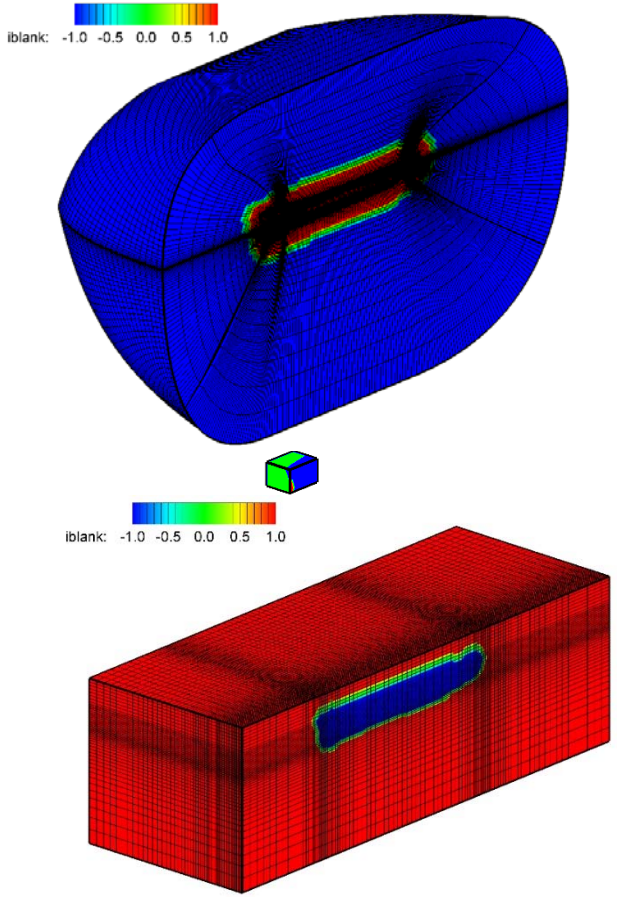
two levels



three levels

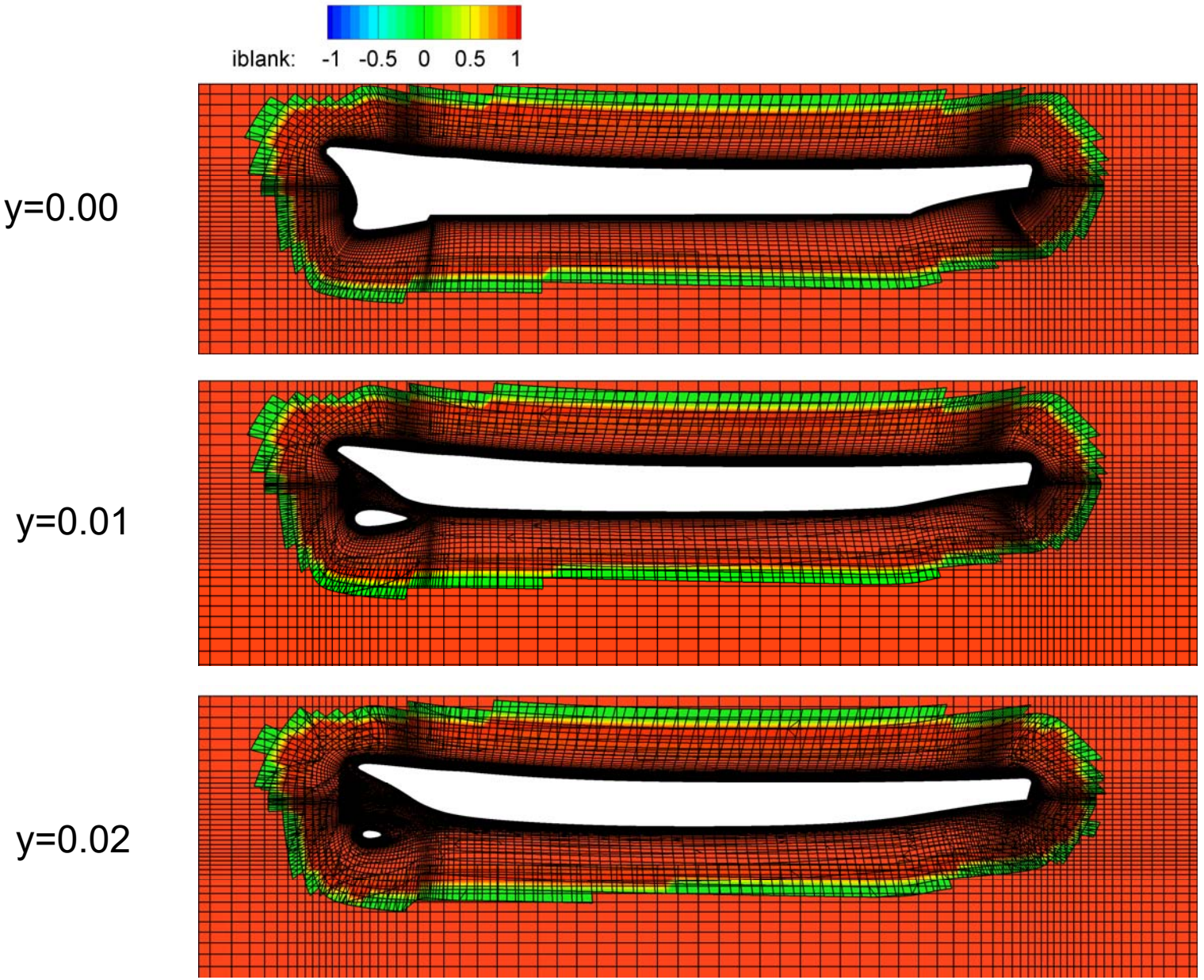
- Example 4 (DTMB 5415 Ship)
  - Conditions:
    - Half ship, Re=7.1E+06, first grid spacing satisfies y^+<1 to hull, maximum grid spacing ratio:1:10000.
    - 3 grids with 15 processors arranged for parallel DCI (5 for background , 5 for ship hull, 2 for refinement grid).
    - Physical boundary conditions for domain are set in box background grids and ship hull.
    - Both finest donor search and distance control (d=0.1 to ship hull) methods are used .
  - Functions of solving problems :
    - 3D complicated geometry of structured grids with large difference in grid sizes and qualities (e.g. grid space ratio is around 1: 10000 in flow boundary layer).
    - 3D Refinement grid in interested bow wave region.
    - The donor grid size near domain boundary is coarser than other overlapped grids.
    - Parallel treatments.



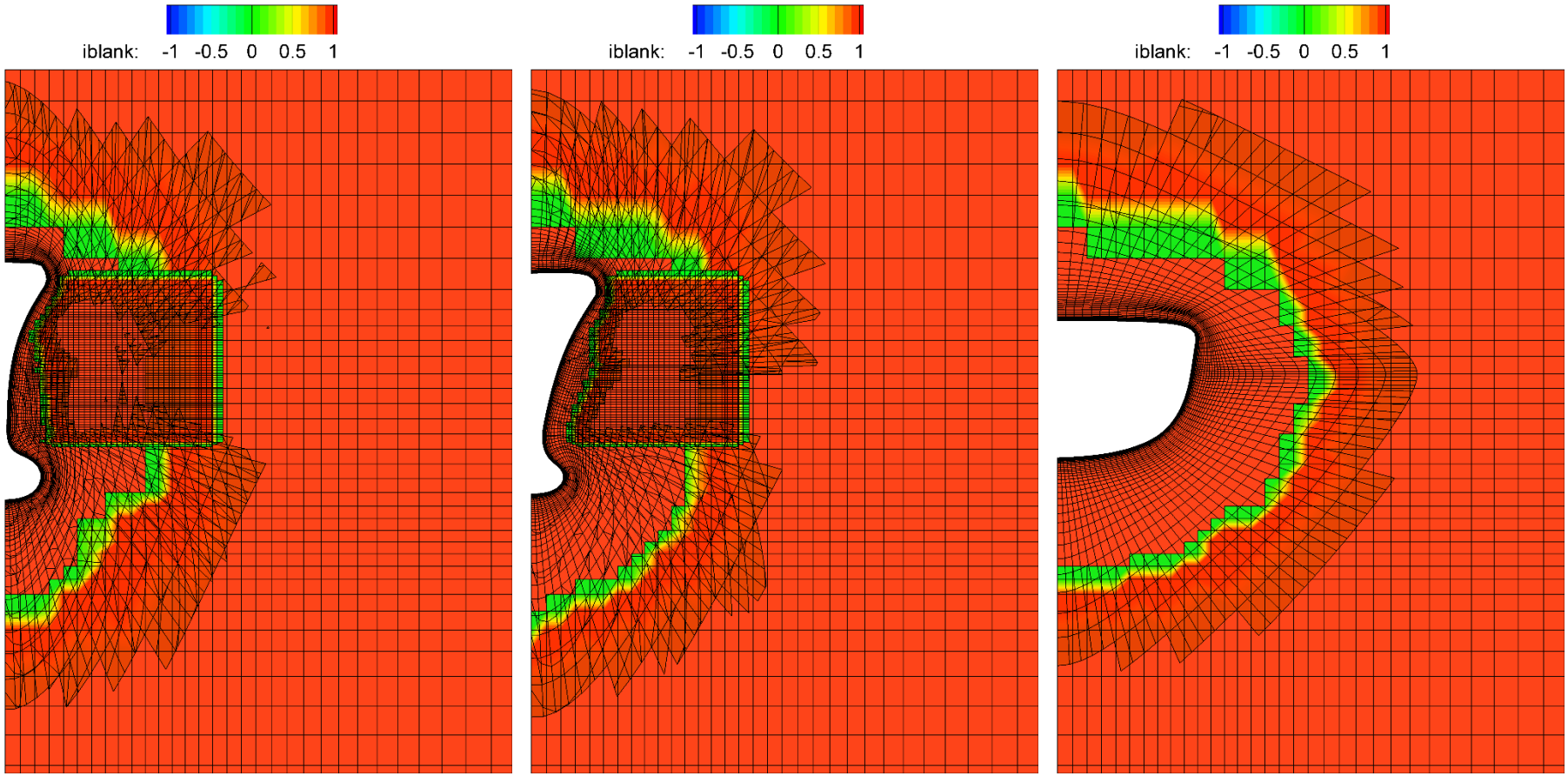


Distributions of active, fringe and hole nodes

Distributions of active and fringe nodes after hole cutting (y sections)



Distributions of active and fringe nodes after hole cutting (x sections)



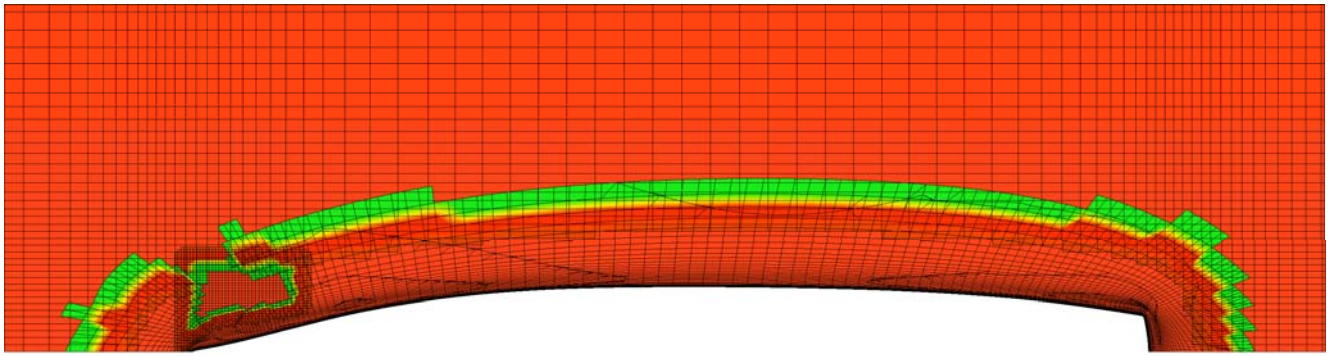
X=0.01

X=0.06

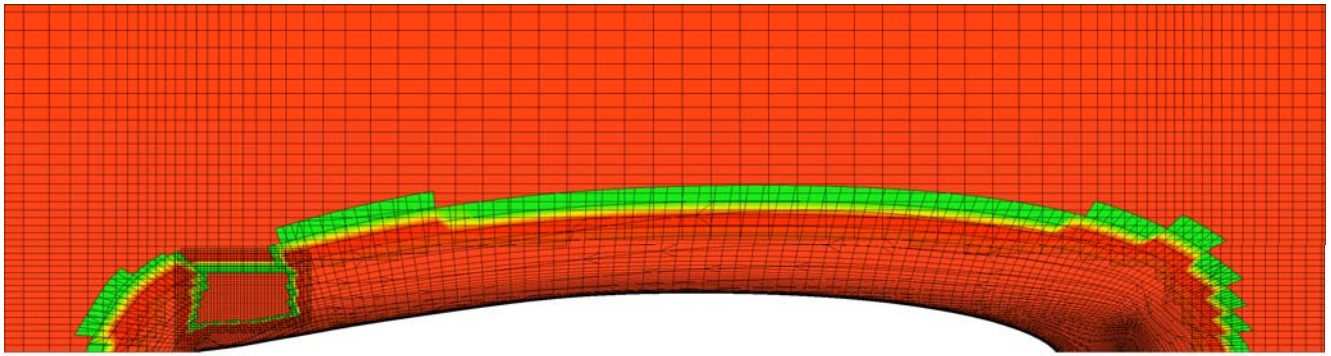
X=0.5

Distributions of active and fringe nodes after hole cutting (z sections)

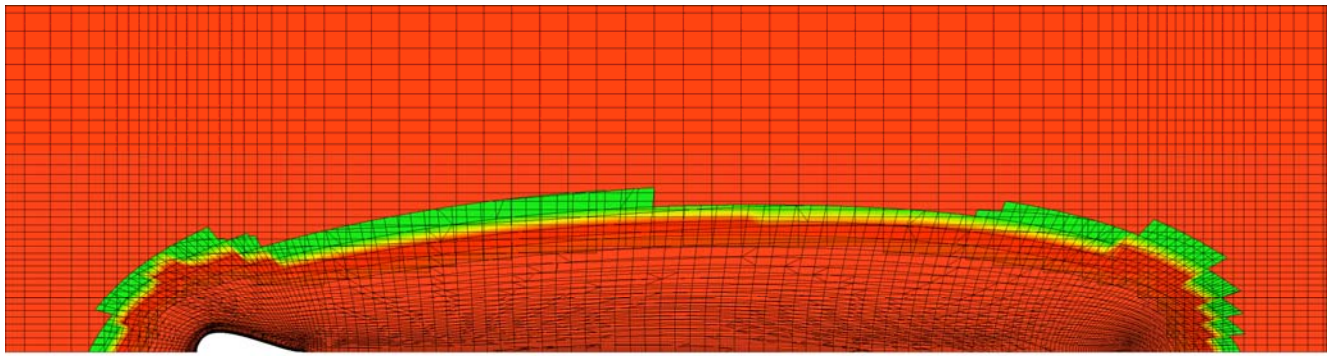
z=-0.00

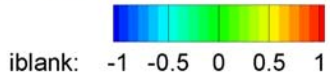


z=-0.02

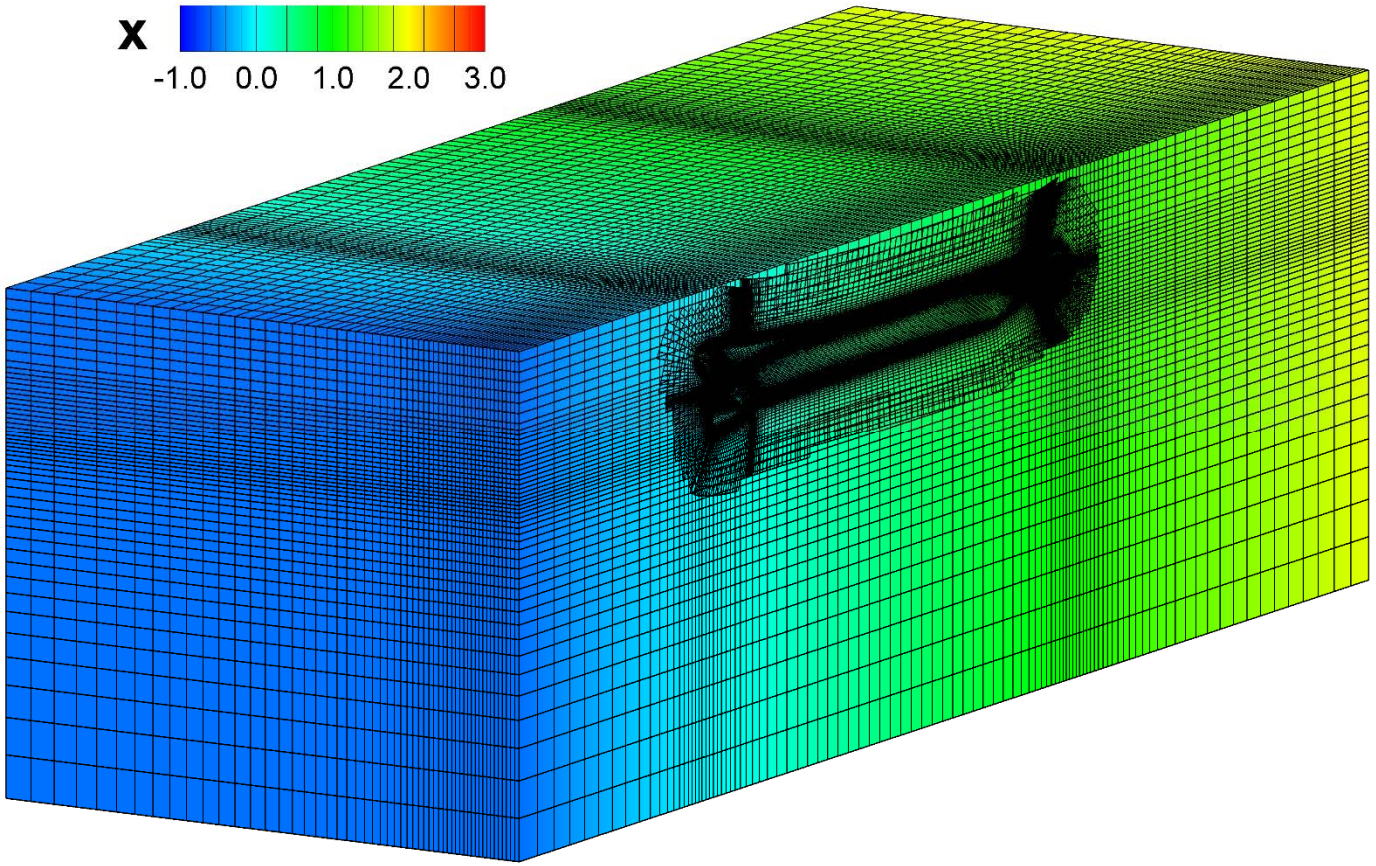


z=-0.05

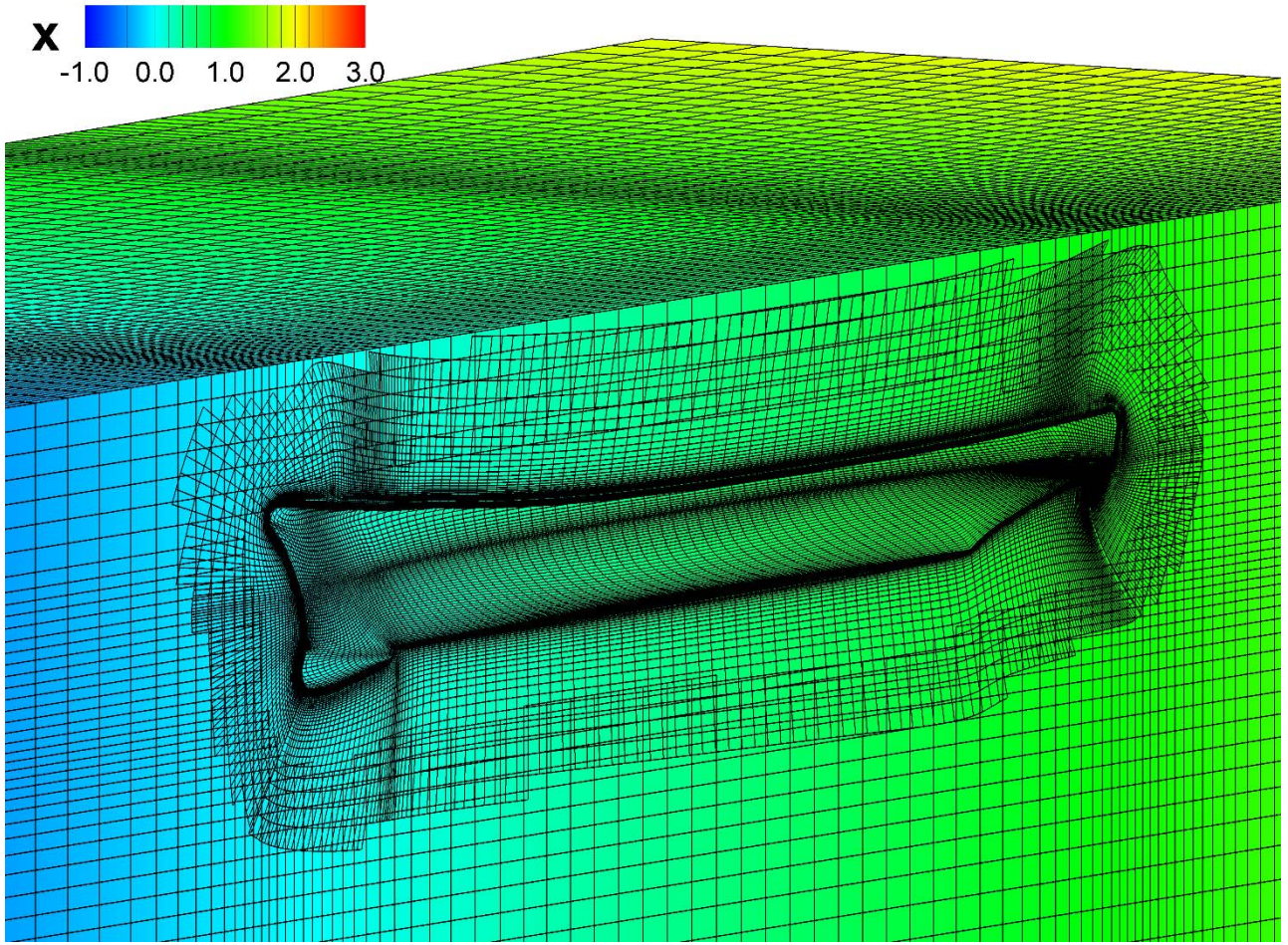




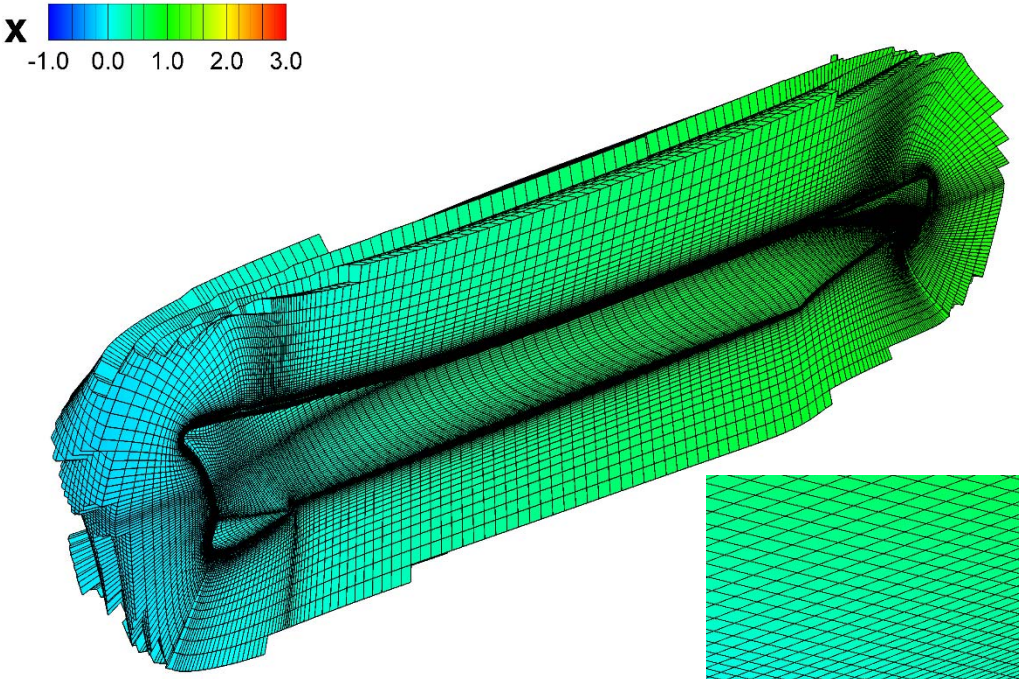
Distributions of x coordinate value using donor element interpolations for fringe nodes

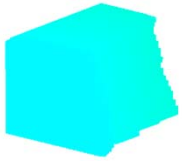


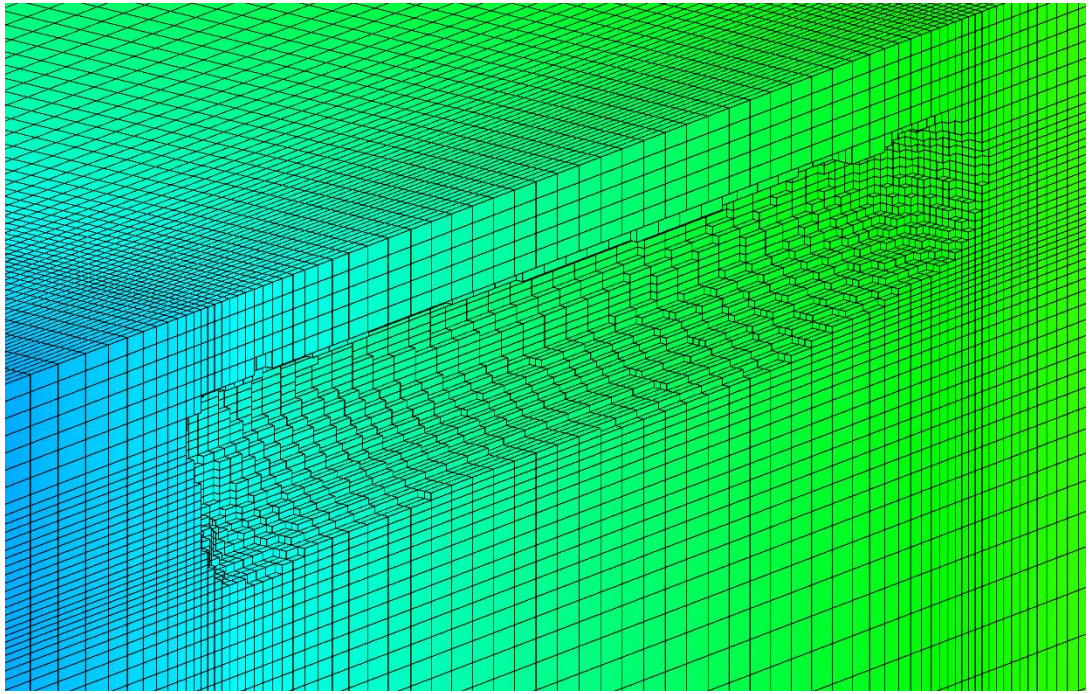
Distributions of x coordinate value using donor element interpolations for fringe nodes



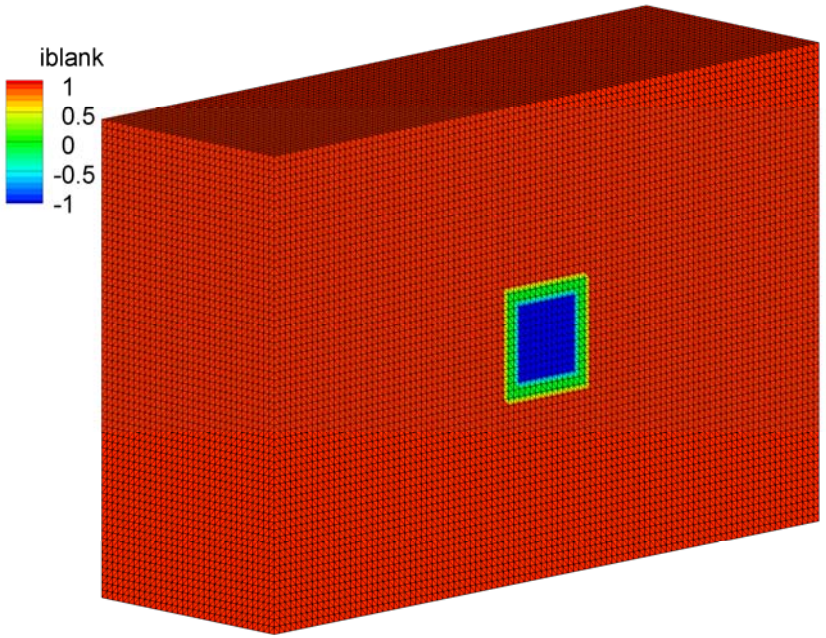
Distributions of x coordinate value of no-hole region of three domains using donor element interpolations for fringe nodes

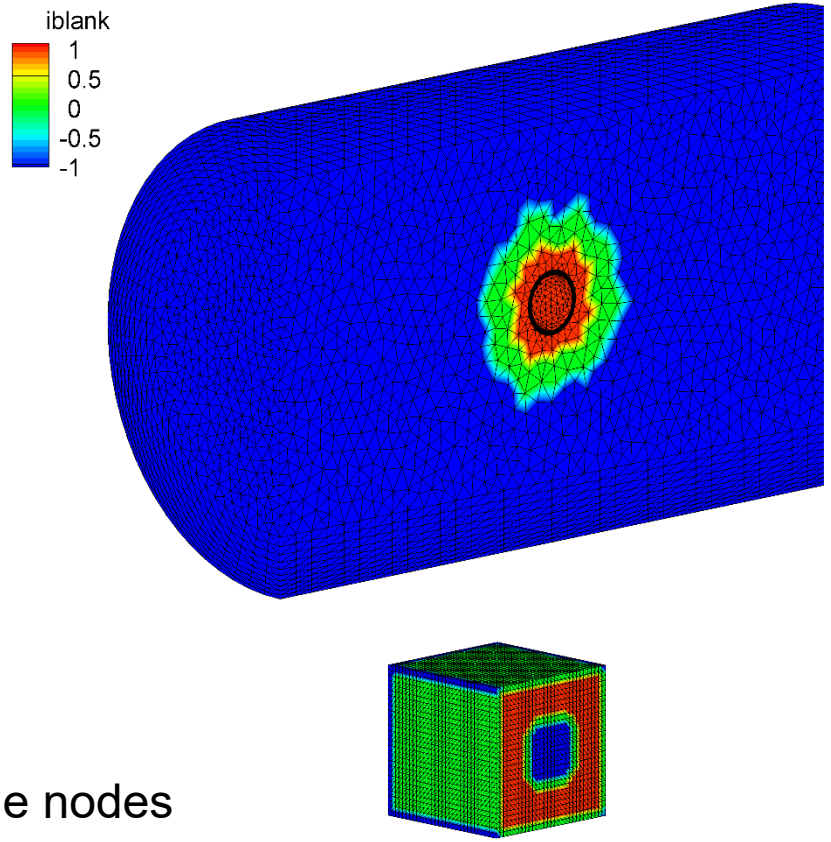






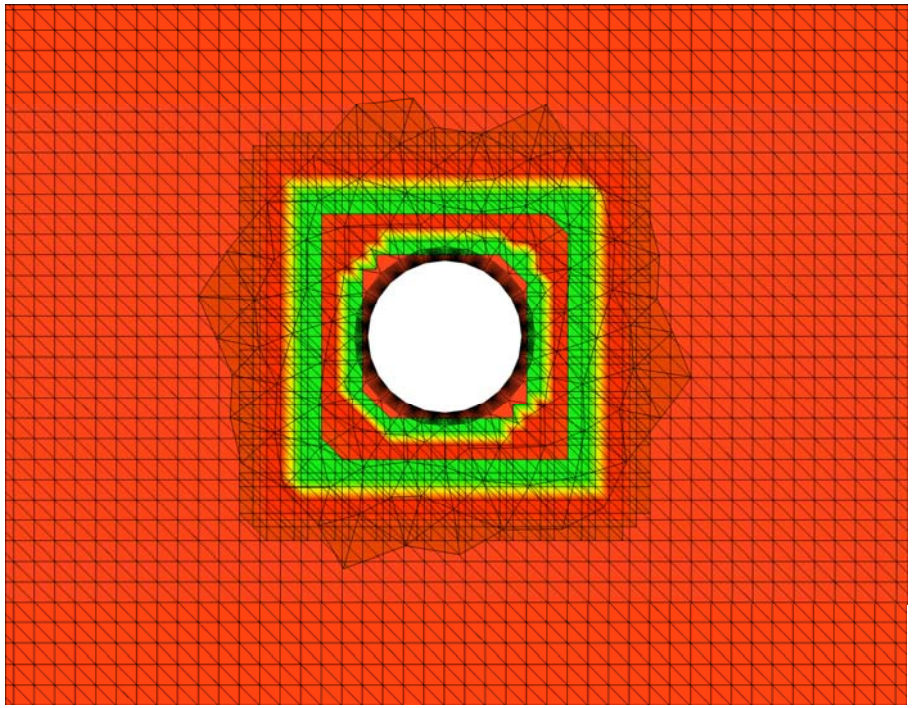
- Example 5 (hybrid unstructured grid)
  - Conditions:
    - 3 grids with 15 processors arranged for parallel DCI (7 for background,3 for small box,5 for hybrid grid).
    - Physical boundary conditions for domain are set in box background grids and wall of spherical ball.
    - Both finest donor search and distance control (d=0.12 to the wall) methods are used.
  - Functions of solving problems :
    - 3D unstructured grids with four different kinds of hybrid elements of tetrahedral, hexahedral, prismatic and pyramidal elements.
    - Parallel treatments.



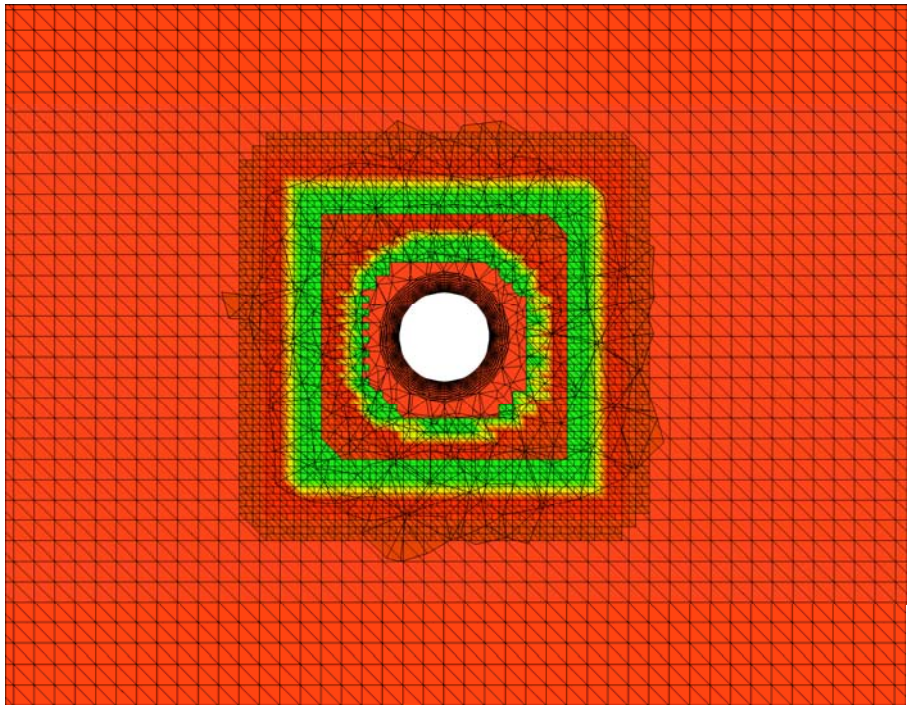


Distributions of active, fringe and hole nodes

Distributions of active and fringe nodes after hole cutting (y sections)

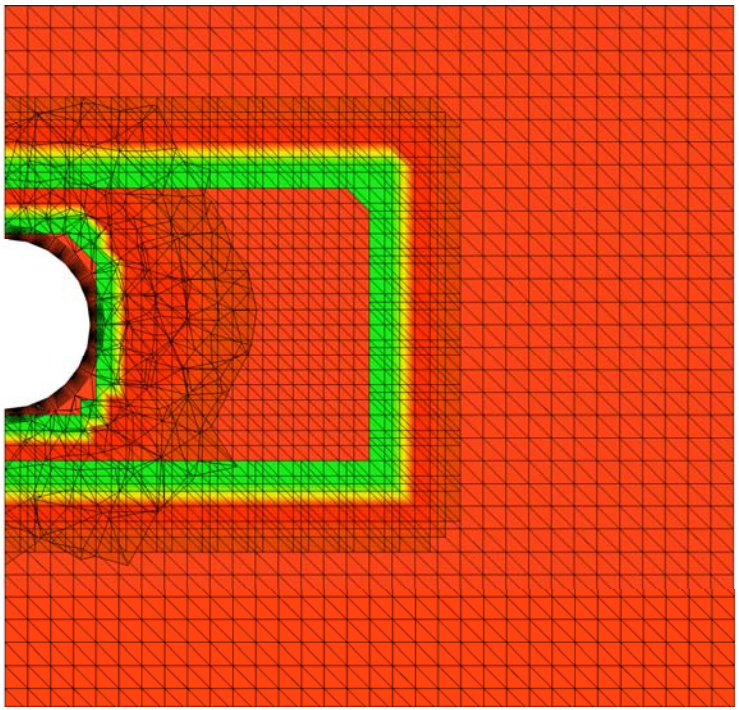


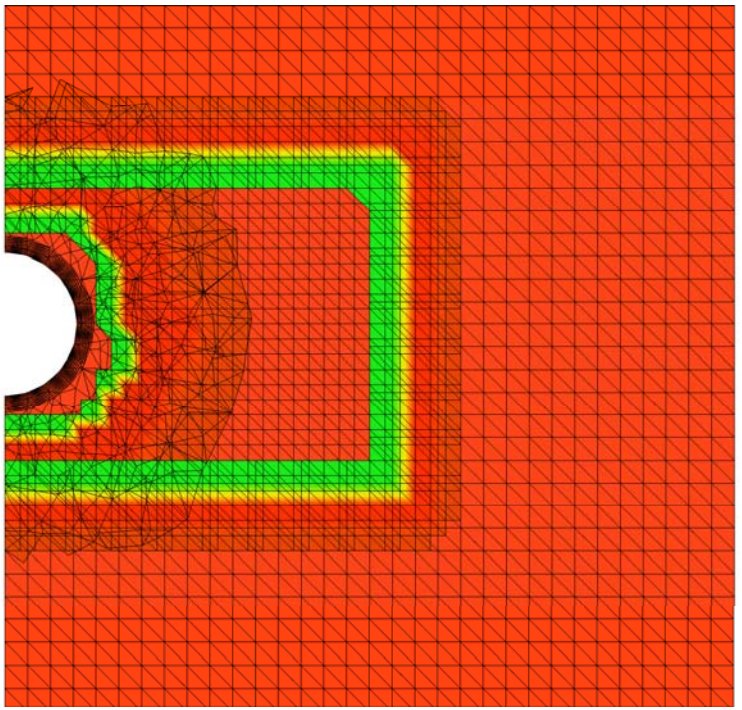
y=0



y=0.06

Distributions of active and fringe nodes after hole cutting (x sections)

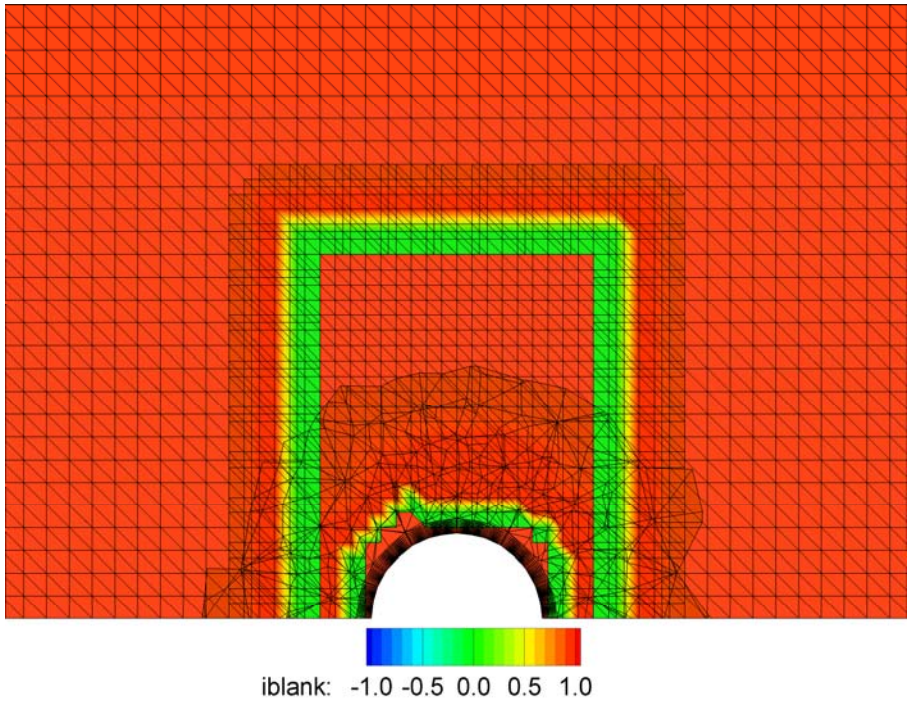




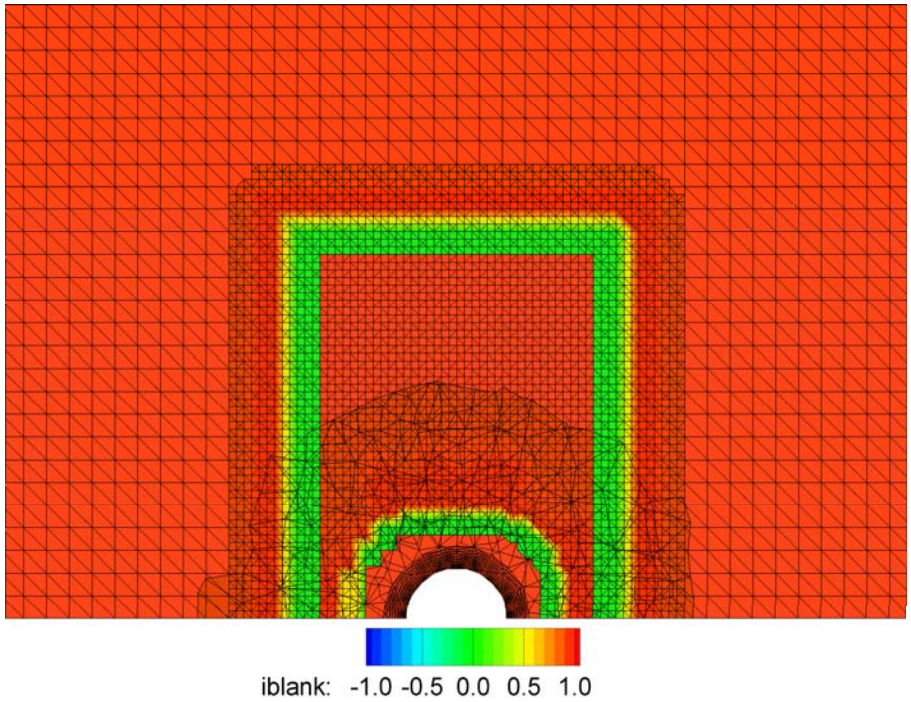
x=1

x=1.04

Distributions of active and fringe nodes after hole cutting (z sections)

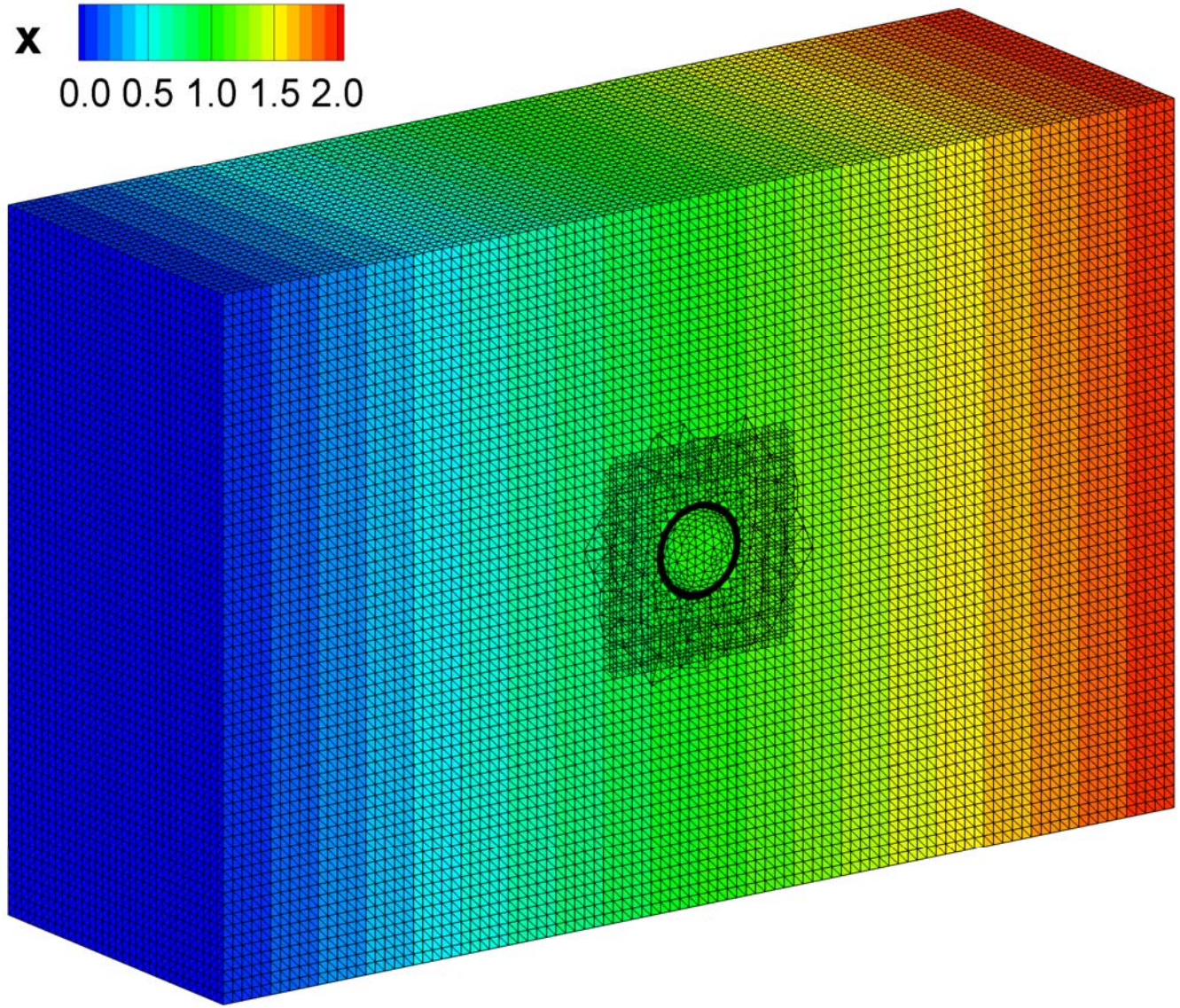


z=0.64

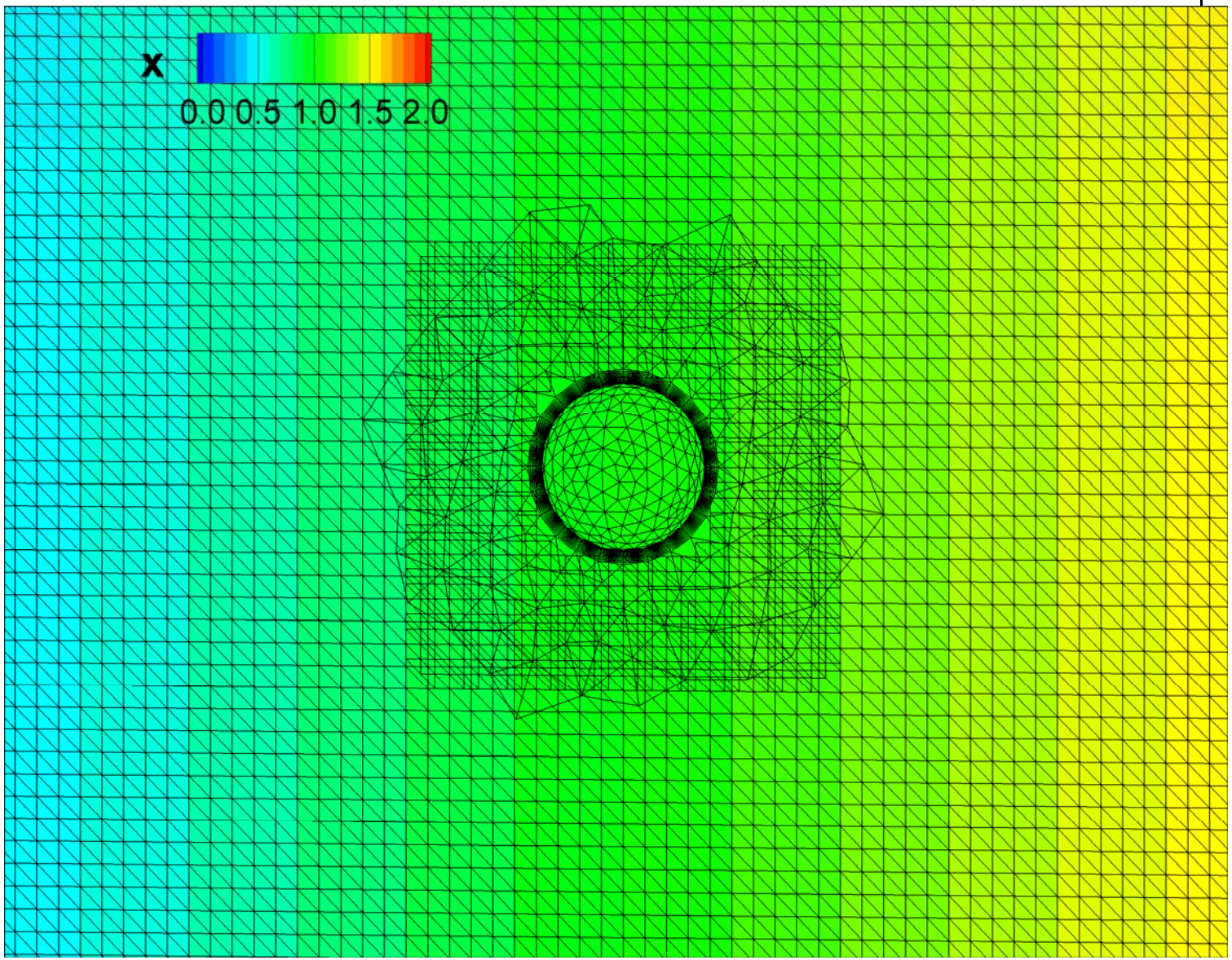


z=0.70

Distributions of x coordinate value of no-hole region of three grids using donor element interpolations for fringe nodes

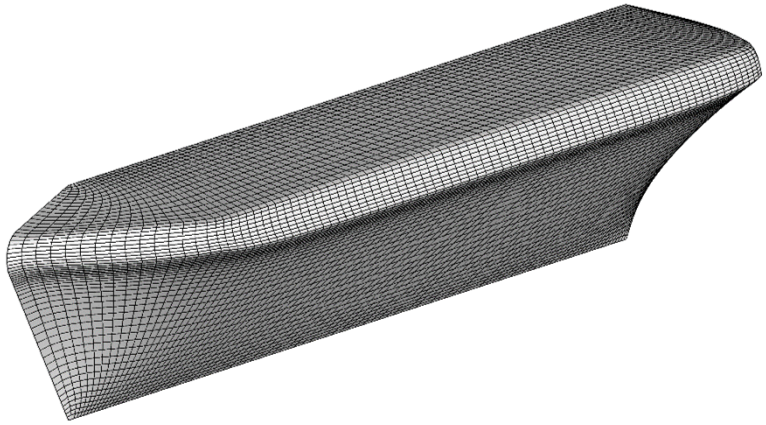


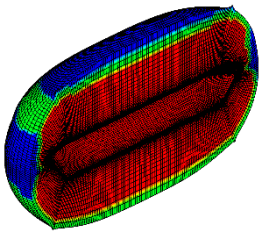
Distributions of x coordinate value of no-hole region of three grids (zoom in)

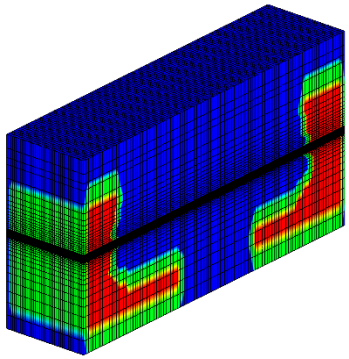


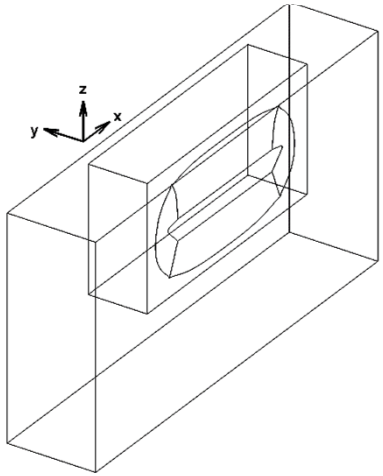
- Example 6 (3D dynamic grid)
  - Conditions:
    - 3 overset grids: ship hull, background grid, and refinement grid
    - Motions (prescribed): ship hull (pitch and heave), refinement grid (heave).
    - Physical boundary conditions for domain are set in background grids and ship hull.
  - Functions of solving problems :
    - 3D dynamic grid and rigid body 6DOF motions.

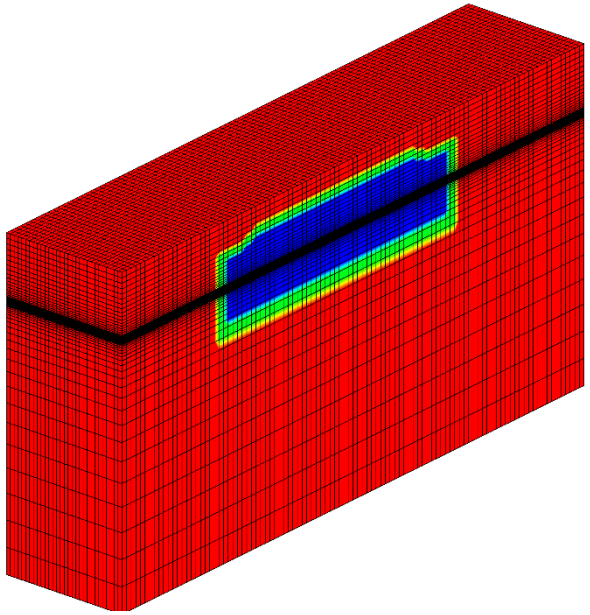
Movie





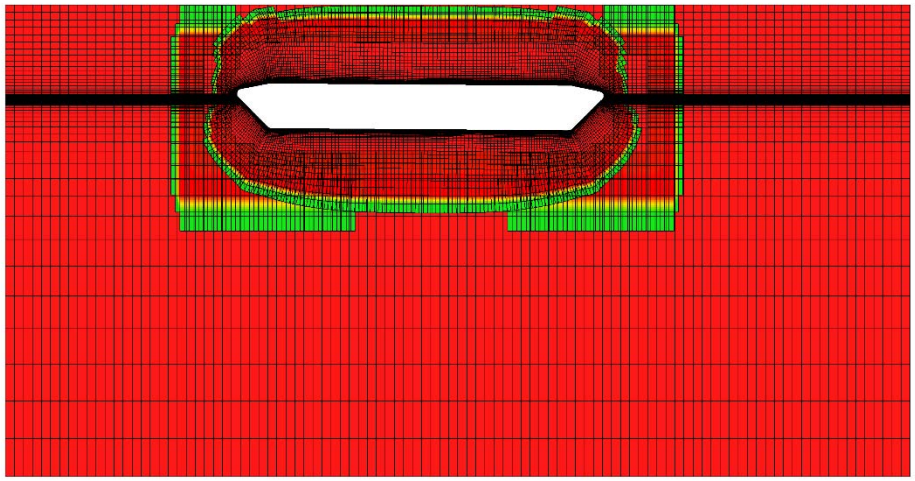




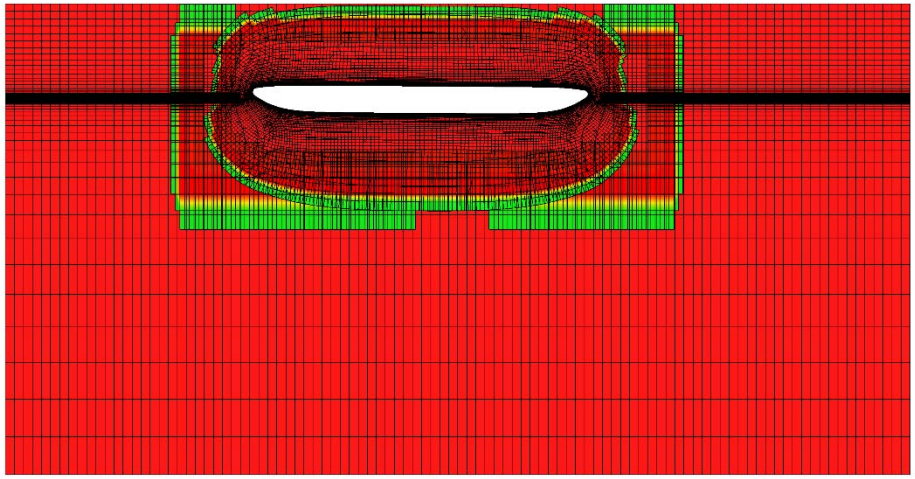


Distributions of active, fringe and hole nodes

Distributions of active and fringe nodes after hole cutting (time=0)

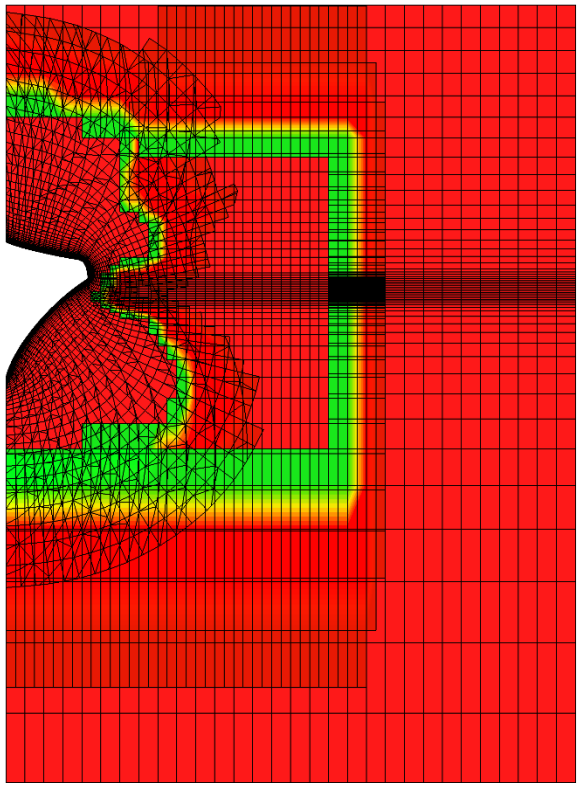


y=0

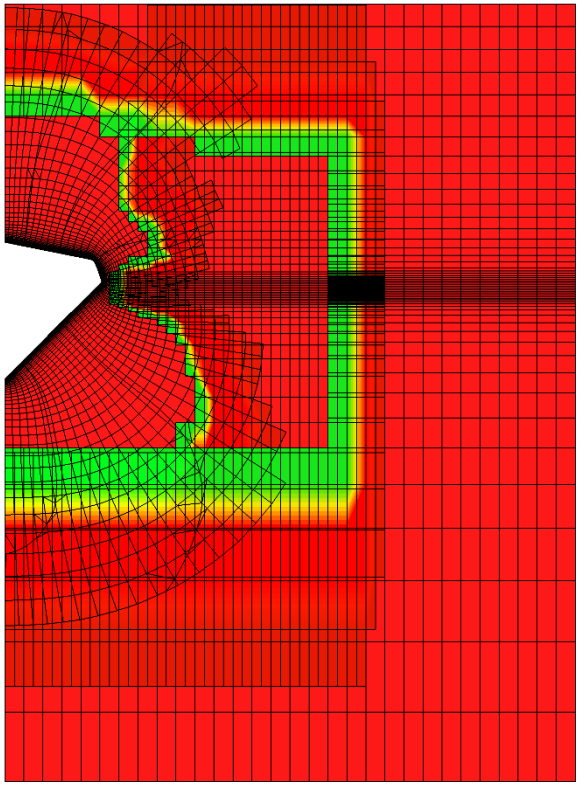


y=0.06

Distributions of active and fringe nodes after hole cutting

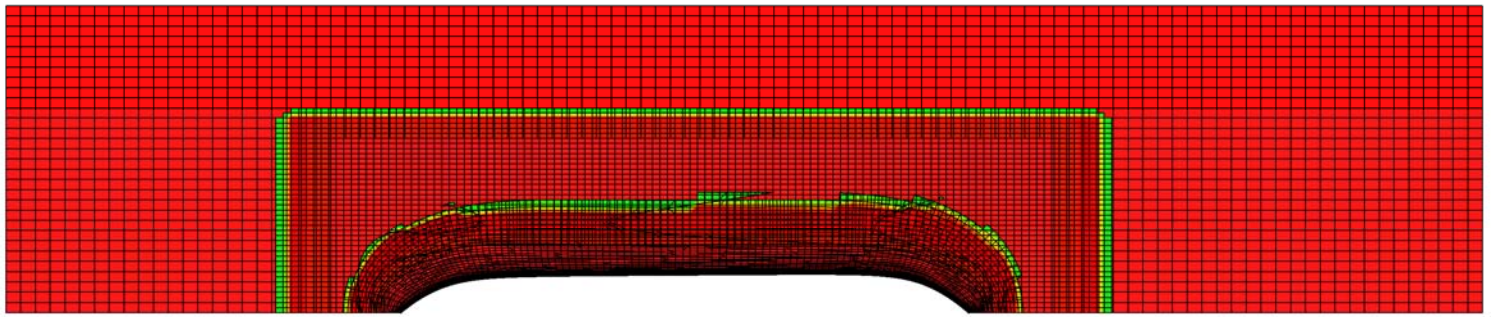


X=0.1

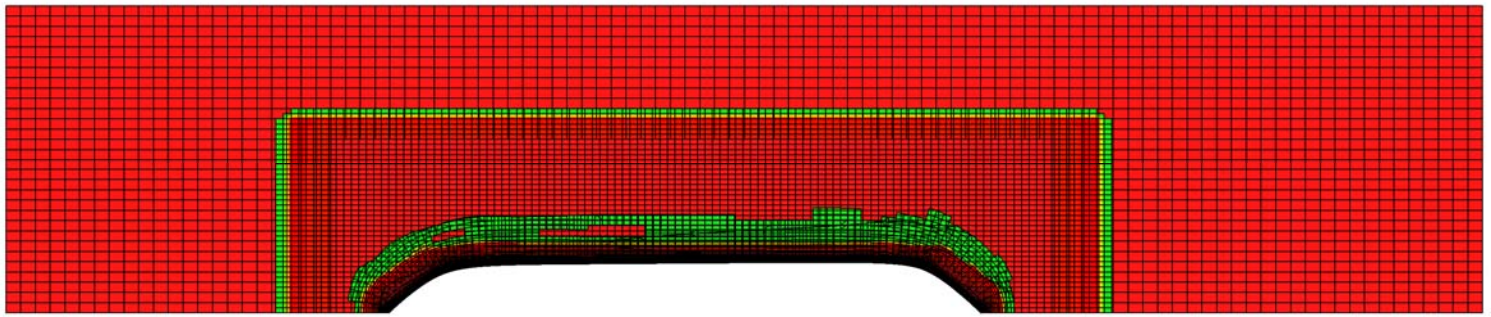


X=0.3

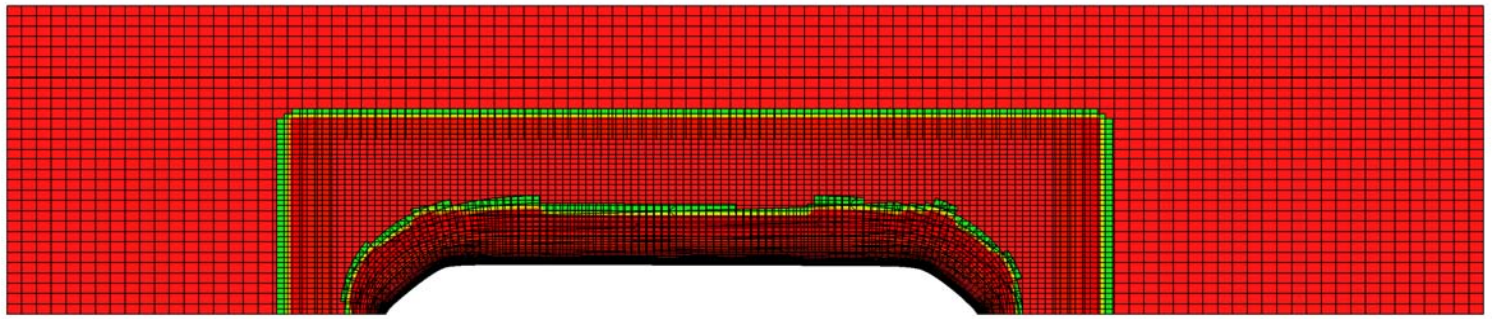
Distributions of active and fringe nodes after hole cutting



z=-0.02

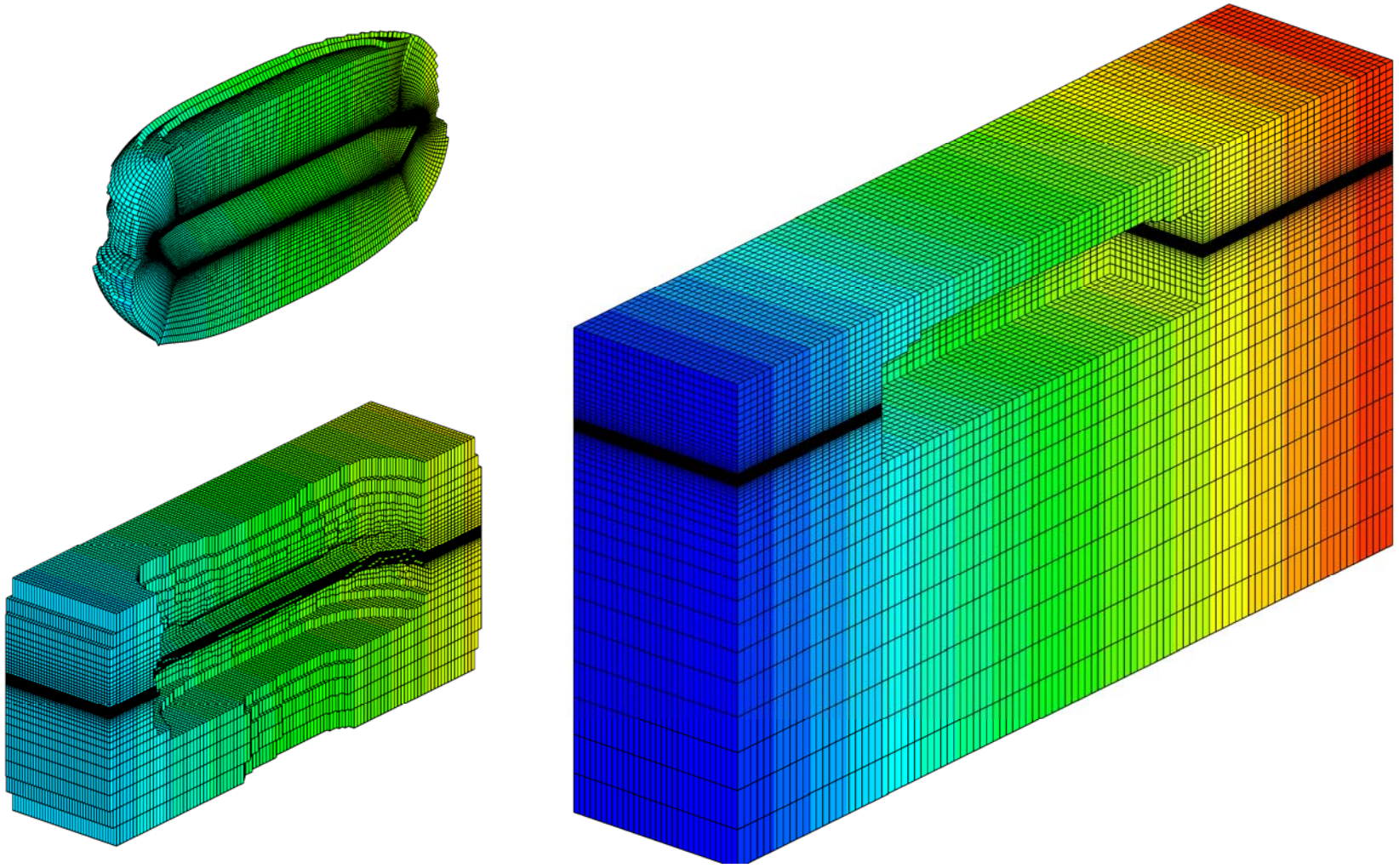


z=0

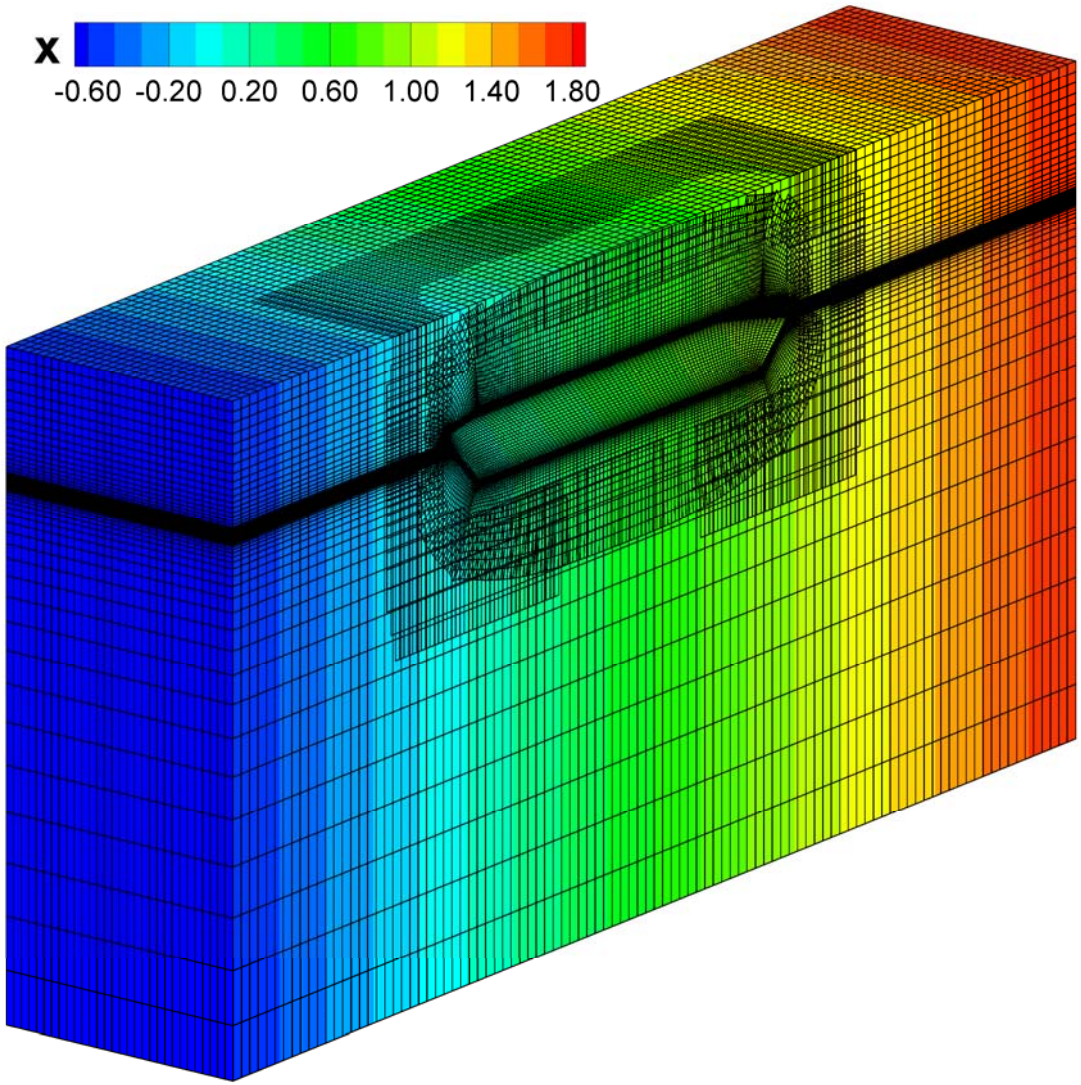


z=0.02

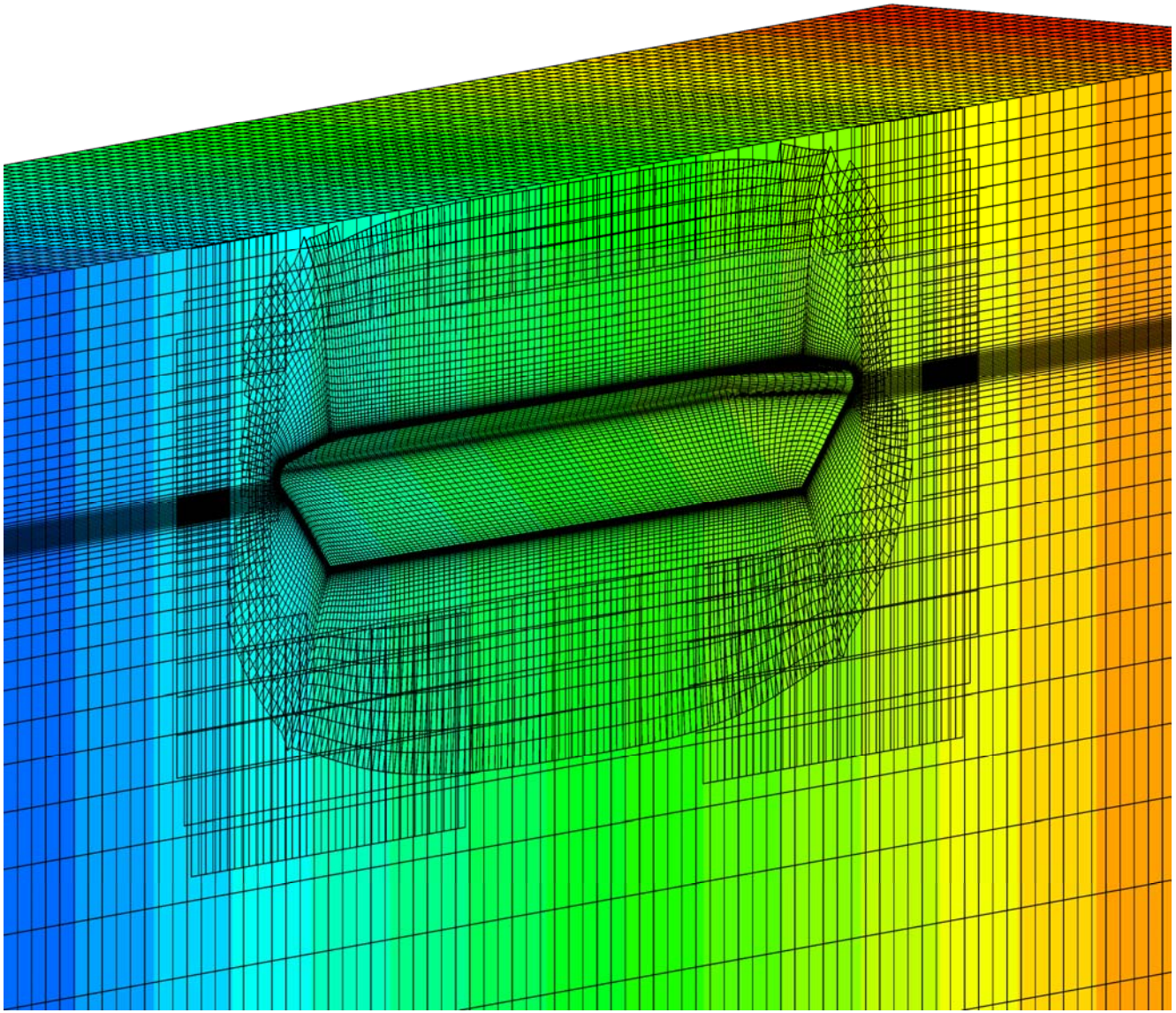
Distributions of x coordinate value of no-hole region of three domains using donor element interpolations for fringe nodes



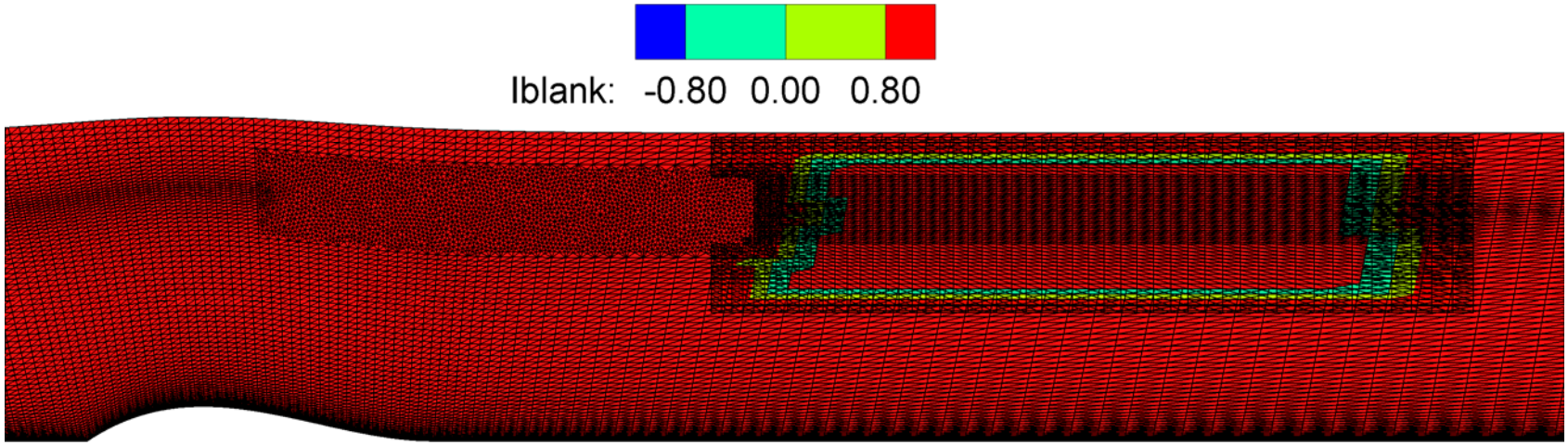
Distributions of x coordinate value of no-hole region of three domains using donor element interpolations for fringe nodes



Distributions of x coordinate value of no-hole region of three domains using donor element interpolations for fringe nodes



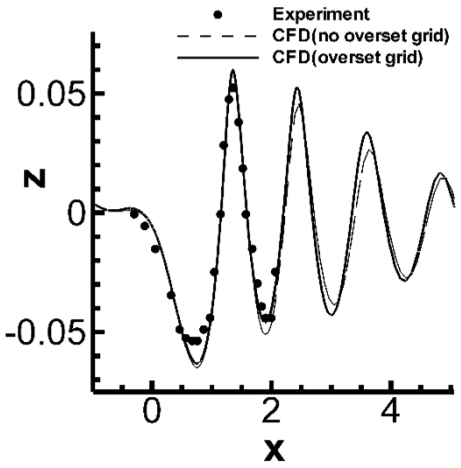
- Example 7 (2D free surface flow over a submerged bump)
  - Conditions:
    - All the CFD simulations in this presentation are performed by CFD-OHMUGA
    - Fr=0.426, Re=infinite.
    - EFD: Cahout (1984).
    - DRTL print out DCI file of static overset grids for CFD.
    - Overset solver: 2 overset grids with 4 processors.
    - CFD solver: 2 overset grids with 8 processors.
    - 2 elements into the paper (3D method calculate 2D problems).



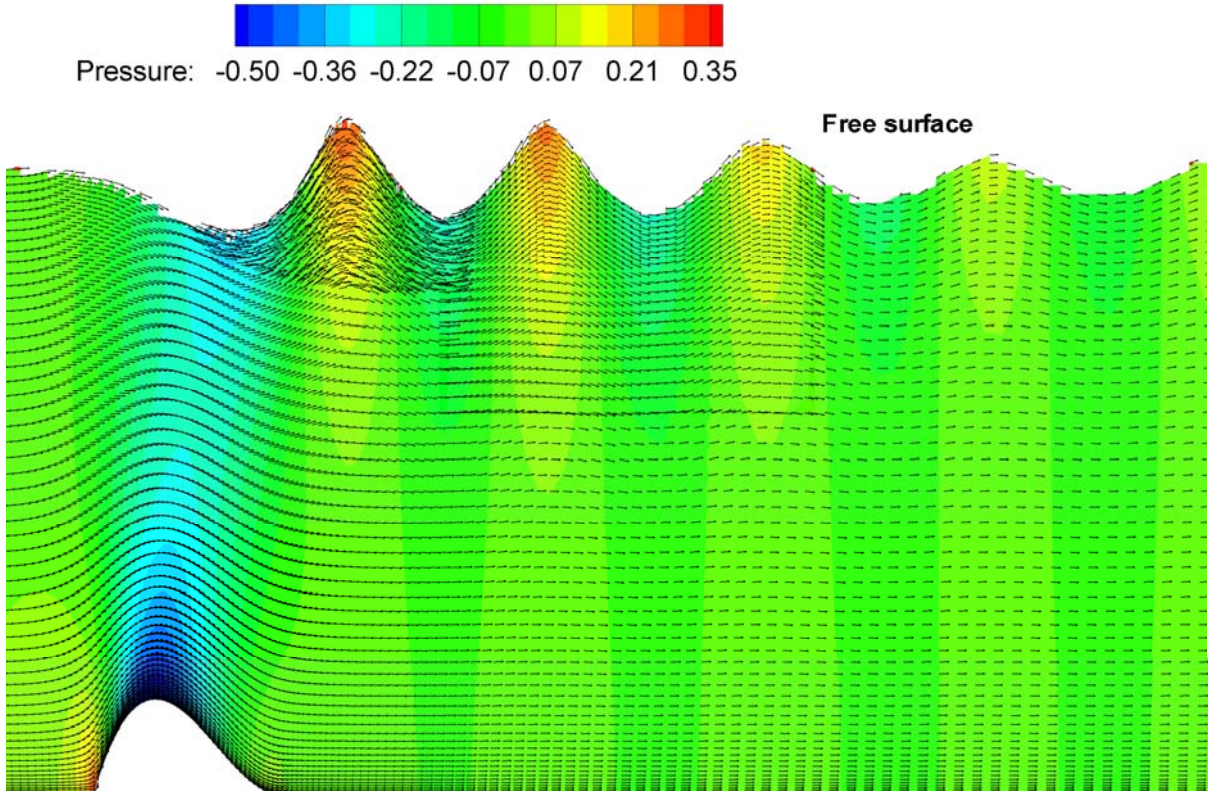
Grids arrangements (partly displayed), and active and fringe nodes

Overset Grid 1: mixture of hexahedral and prismatic elements.

Overset Grid 2: Cartesian grid for local wave refinement

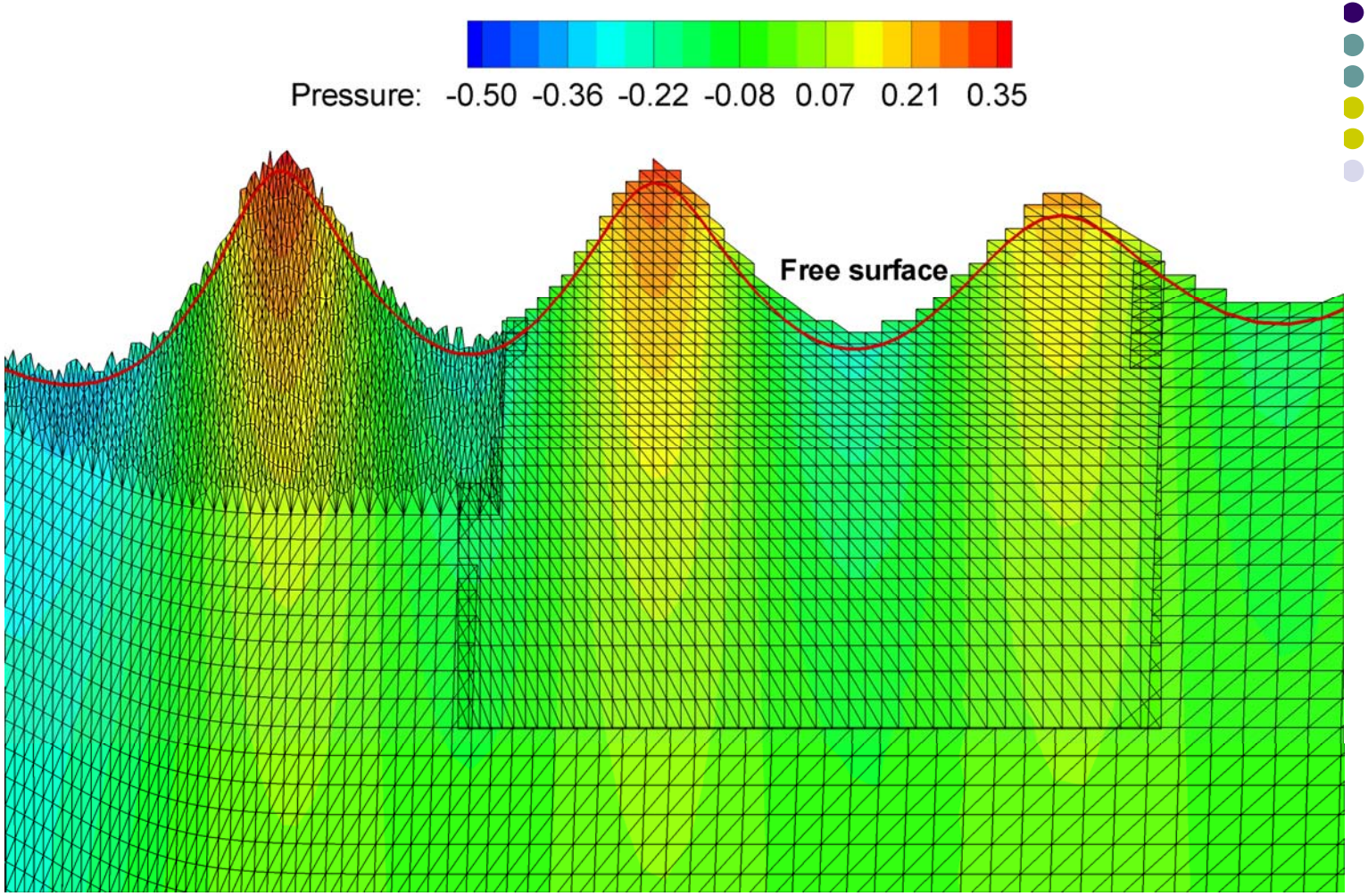


Wave elevation



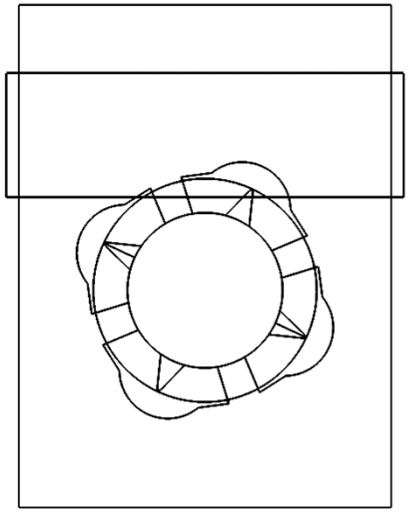
Distribution of Free surface, pressure and velocity

(displayed height coordinate is 5 time of the original one actually used)



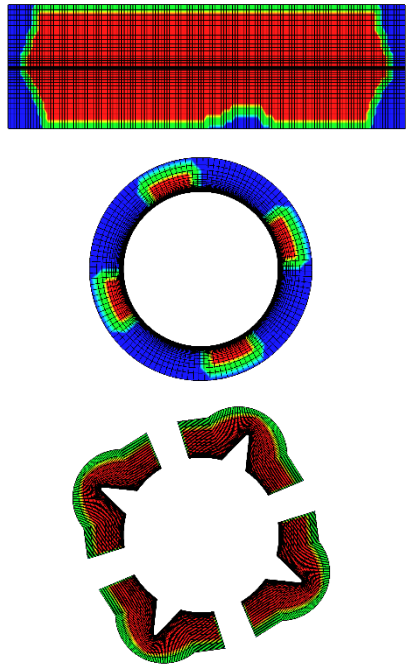
Distribution of free surface and pressure across different overset grids

- Example 8 (2D unsteady free surface rotating flow in a tank)
  - Conditions:
    - Reynolds number=1.0E+4, Fr=1.0, tank wall and rotator surface is non-slip, water free surface is upon the rotator.
    - 7 original dynamic overset grids (note: ring grid is a grid of multi-block (2 blocks) structured grid).
    - CFD solver partition: 18 processors, overset solver partition: 14 processors (same grid with CFD, but allow different partition methods). Totally 32 processors for one simulation.
    - CFD and overset solvers run in simultaneous, independent and parallel way.
    - CFD solver and overset solver dynamically and parallel communicate with each other by a library of DRTL, through which CFD provides its grid partition information, 6DOF motions, and control parameters to overset solver. Overset solver then provides DCI and surface area weight coefficients for CFD.

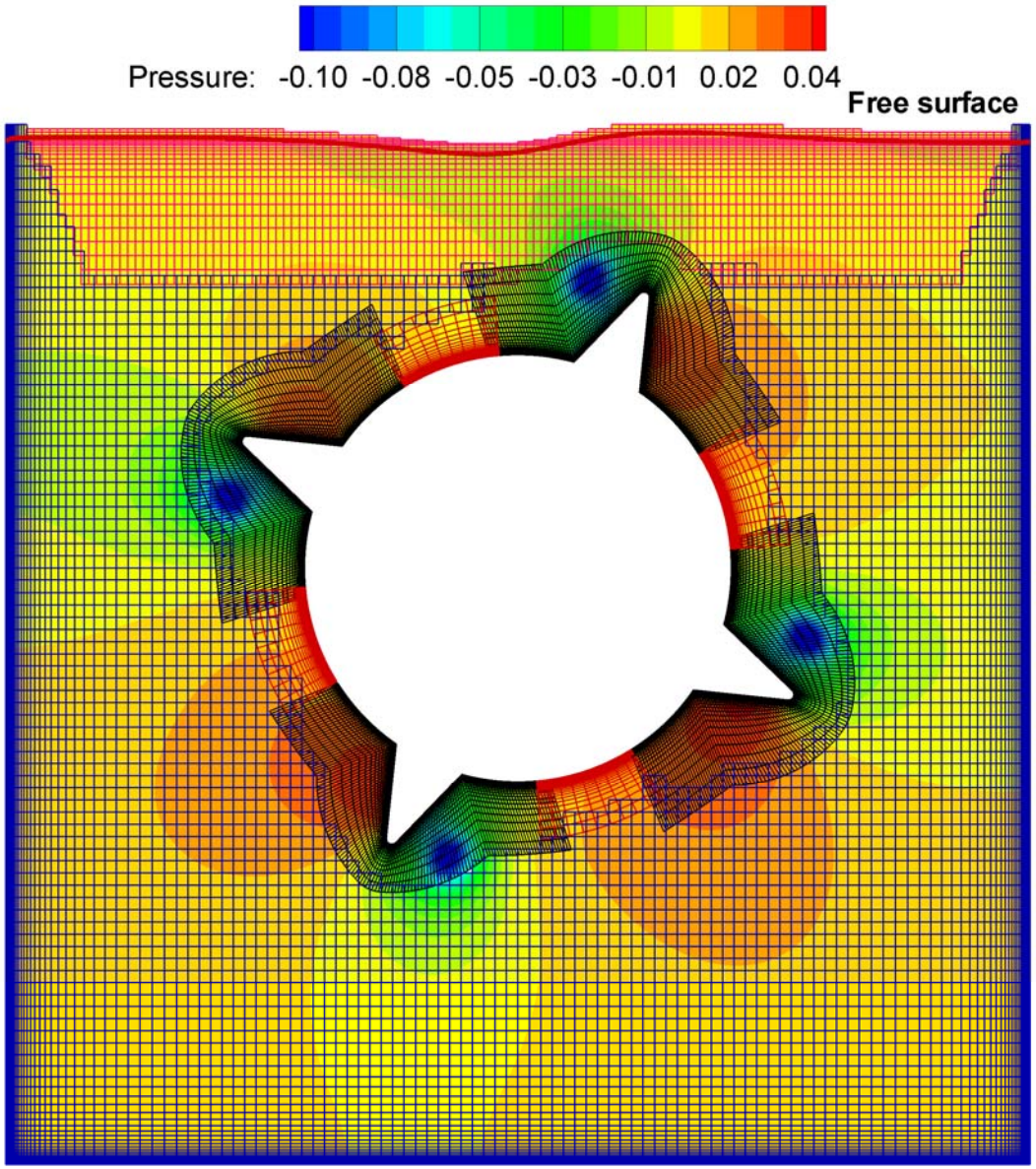


Grid frame

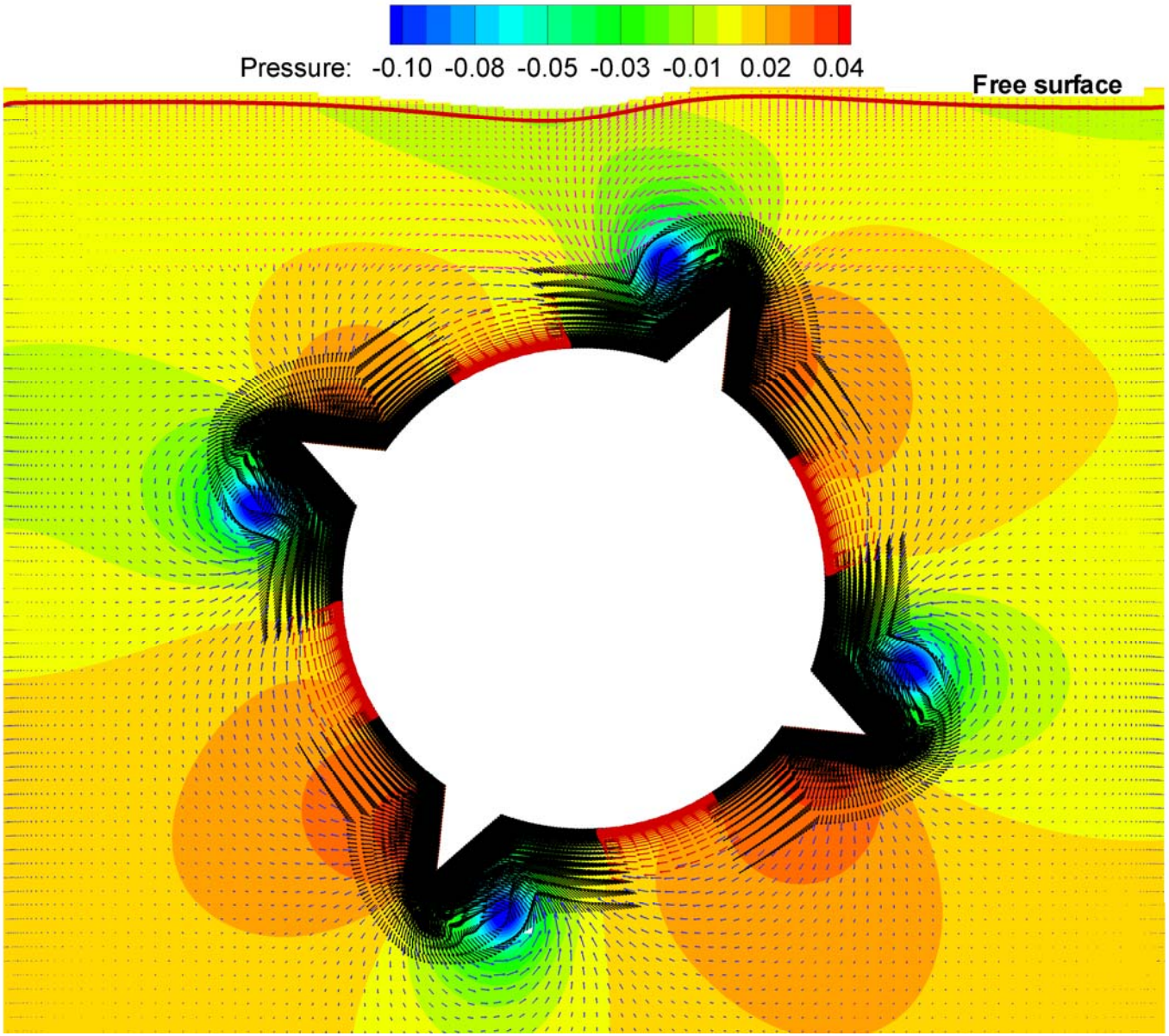
Active and fringe nodes in combined grids



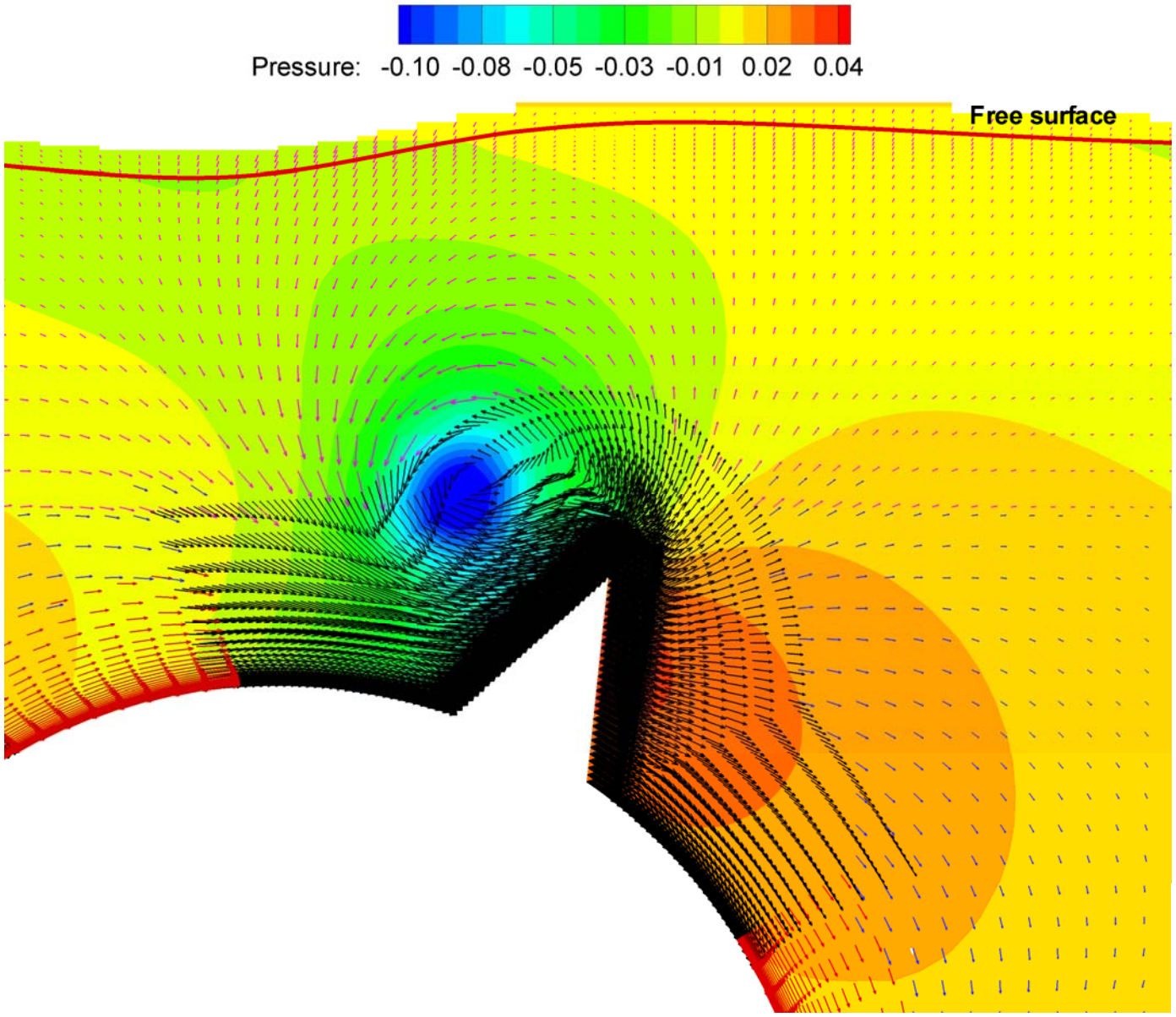
Active and fringe nodes in separated grids



Pressure distribution in different overset grids (with different colors, time step =50)

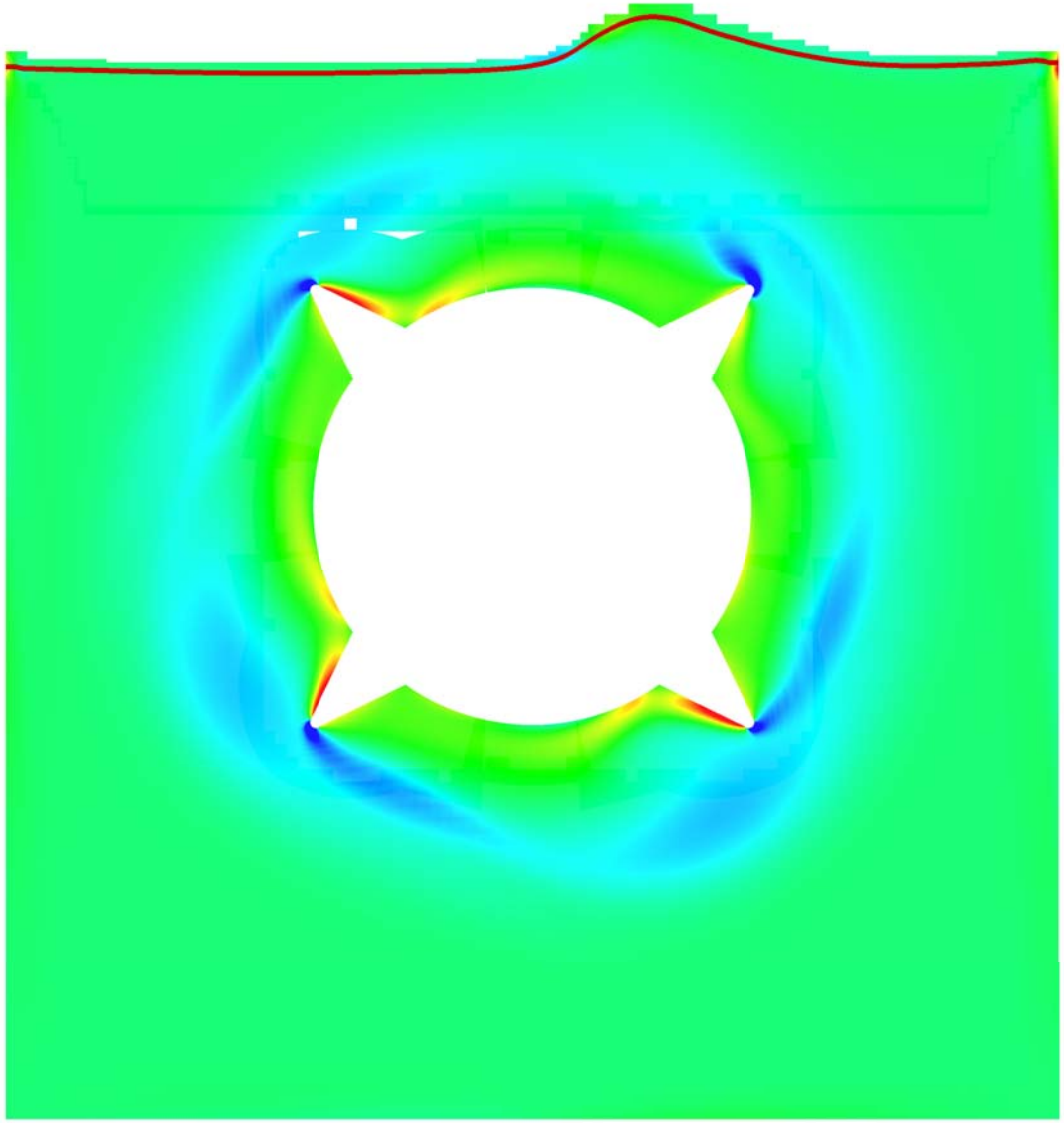


Velocity and pressure distribution in different overset grids (with different colors, time step=50)



Velocity and pressure distribution (zoom in)

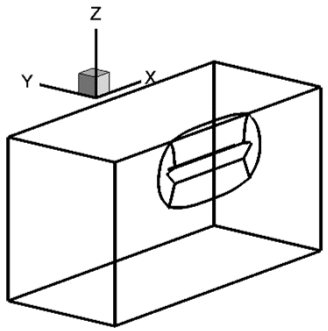
Movie (time step: 720-1440)



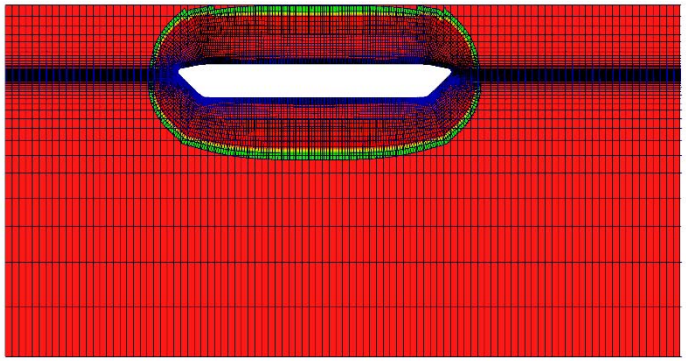
Vorticity distribution (time step=990)

- Validations for SURCLIP
  - SURCLIP is used to calculate surface area weight coefficients to predict forces, moments, fluxes, etc.
  - Current case (curvilinear surfaces)
    - The total area of the non-slip surfaces of rotator
      - Analytical solution: 0.22130
      - Overset Solver: 0.21983
      - CFD solver (using DRTL): 0.21983
    - Relative Errors
      - (Analytical-CFD)/ Analytical≈0.66%.
  - Other cases of overlapped surfaces in exact planes
    - Analytical solution –CFD solution=0 (under the condition of machine precision)

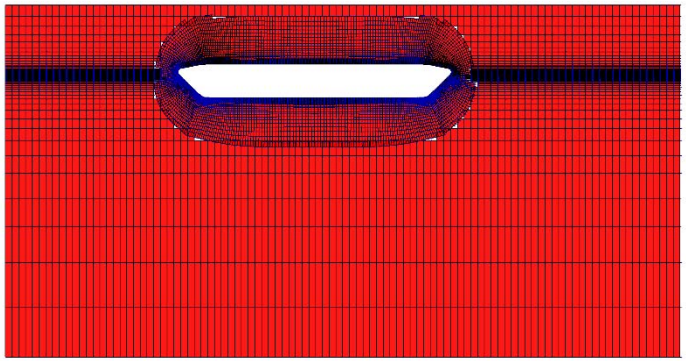
- Example 9 (3D free surface flow around a ship with coarse grids)
  - Conditions:
    - Steady single water free surface flow, Reynolds number=4.85E+6, Froude number=0.28, time=5
    - 2 static overset grids with big difference of grid scales: ship hull (363,600 nodes), background grid(306,434 nodes)
    - CFD solver partition: 6 processors (3 for each), overset solver partition: 4 processors (2 for each grid) .
    - CFD solver provides its node and cell partition information for overset solver, overset provides DCI file for CFD solver.
    - CFD solver computes the free surface flow according to DCI information, after read the corresponding DCI file by each processor.



Grid frame

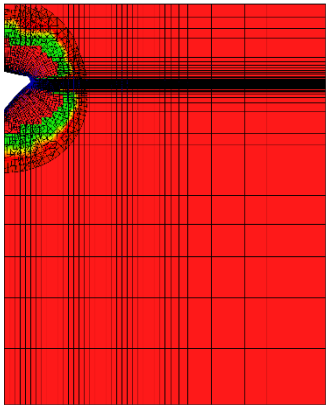


(a)

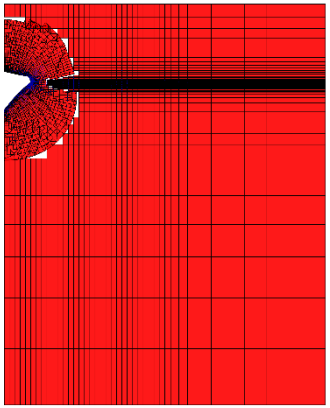


(b)

Section y=0 (half ship symmetry plane)
(a) Active and fringe nodes
(b) Active nodes

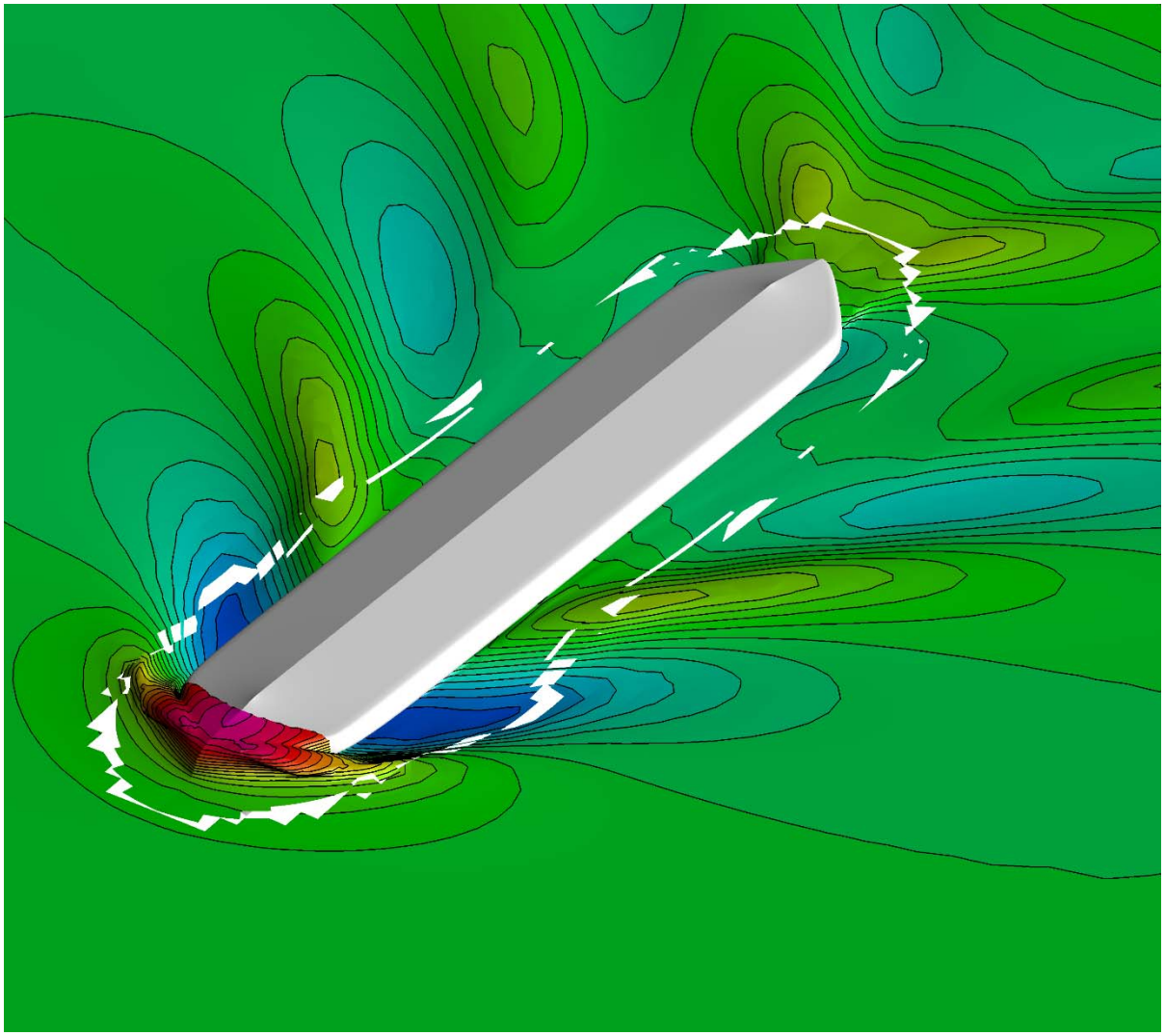


(a)

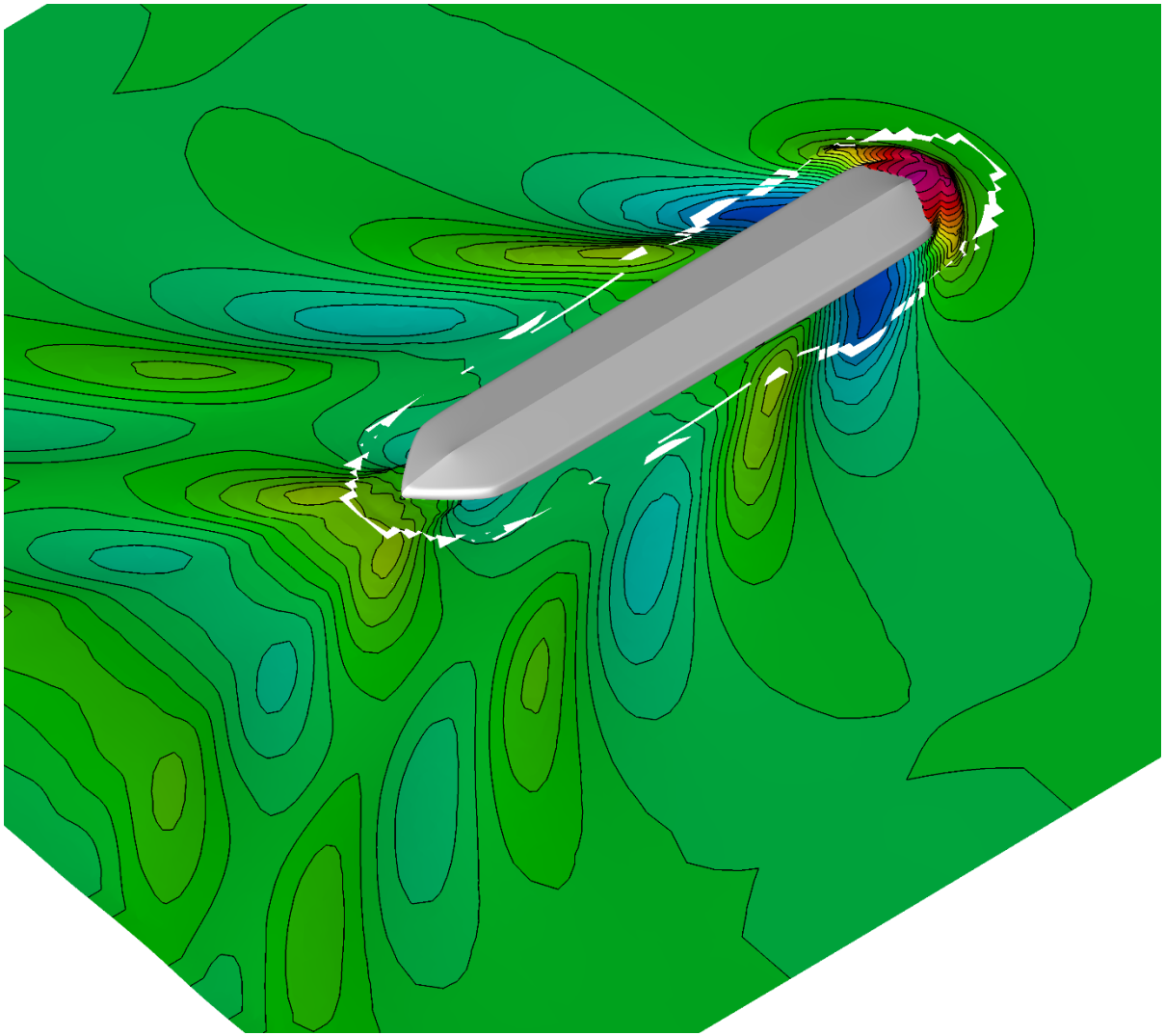


(b)

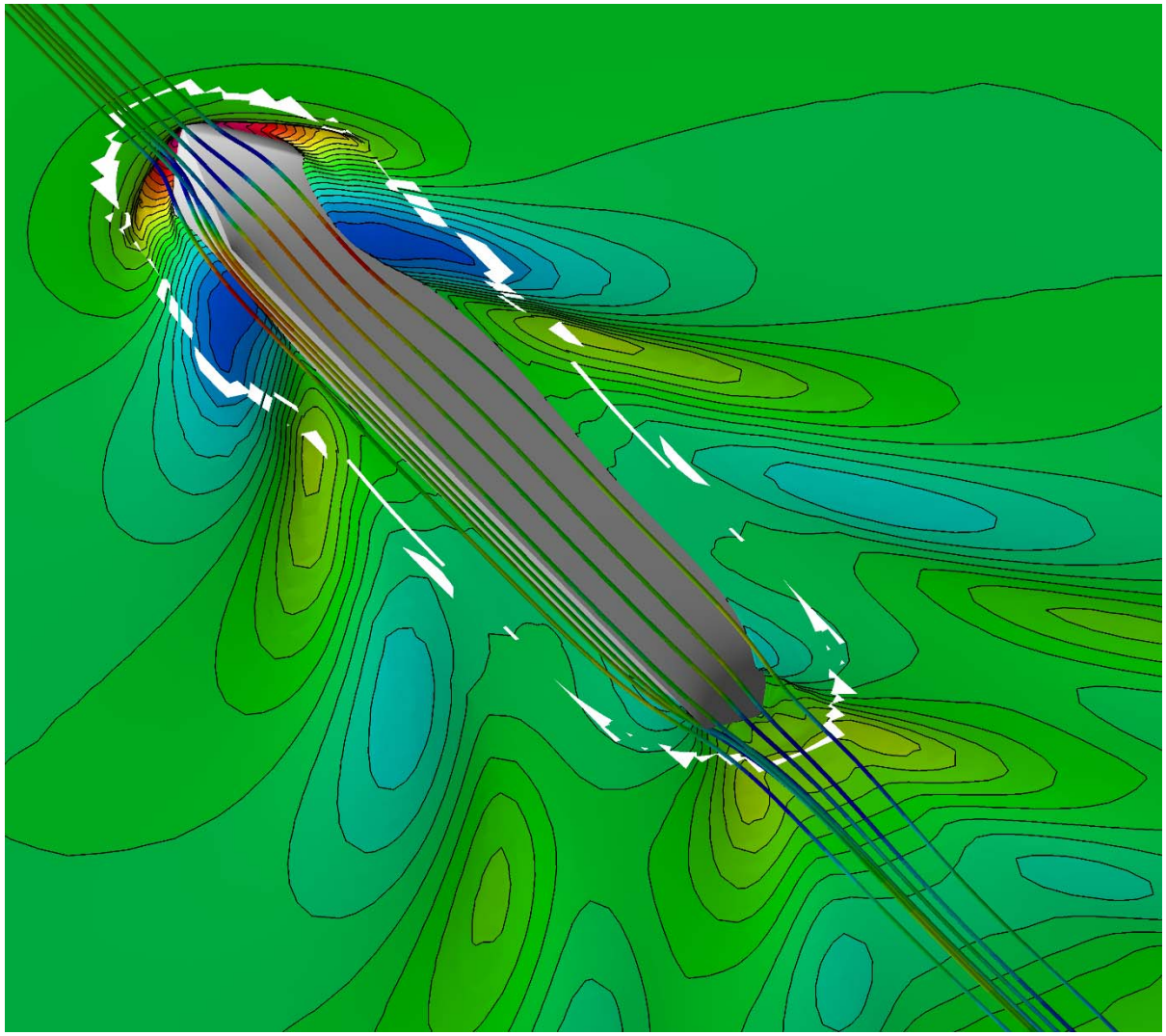
Section x=0.15 (near bow region)
(a) Active and fringe nodes
(b) Active nodes



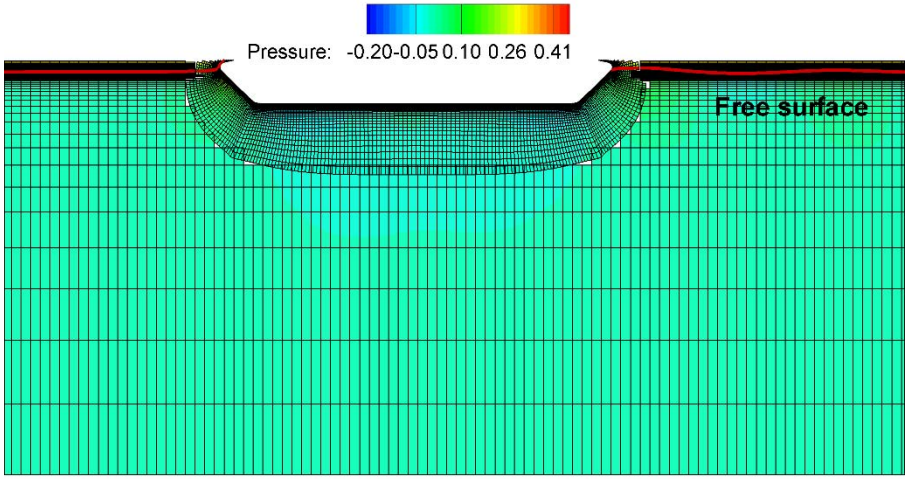
Front and top view for free surface
(only active nodes are shown)



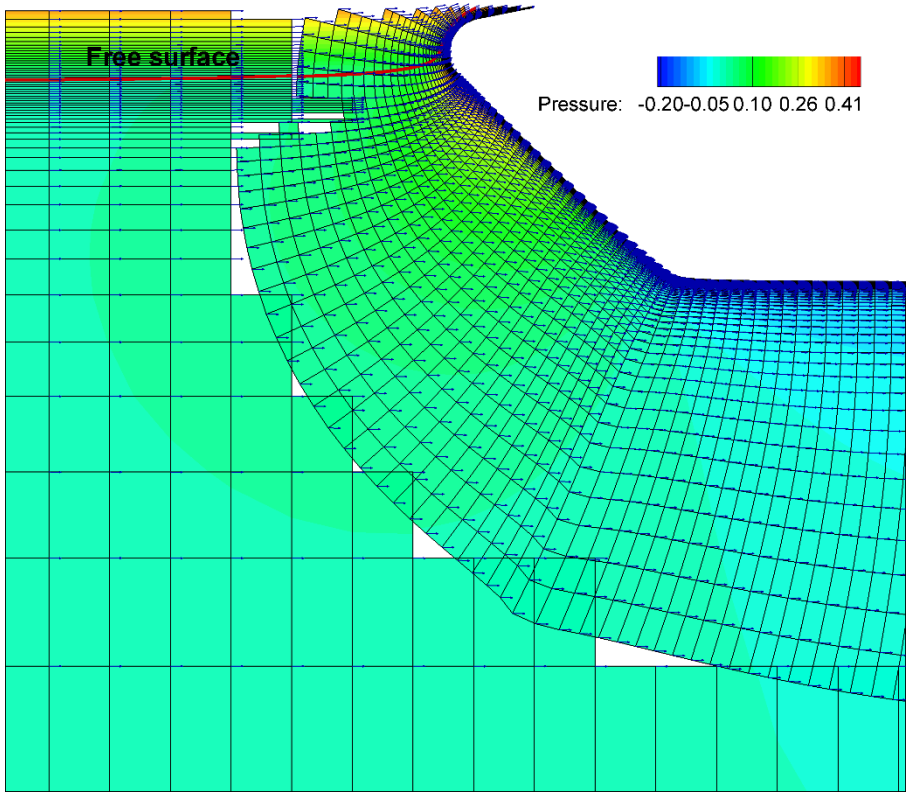
Top view



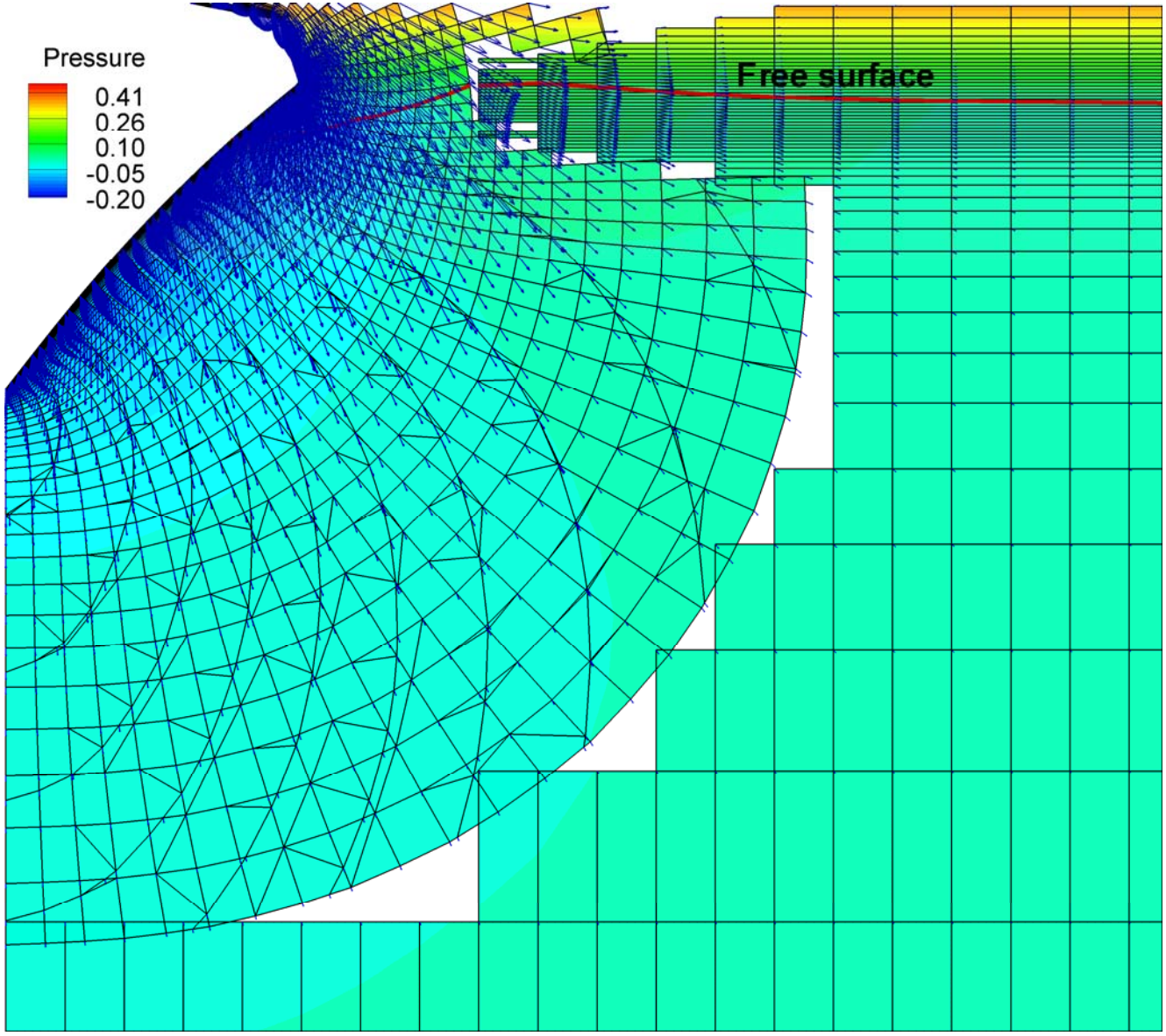
Below view
(free surface and streamline)



Grid allocation (active nodes), free surface, and pressure distribution in symmetry plane

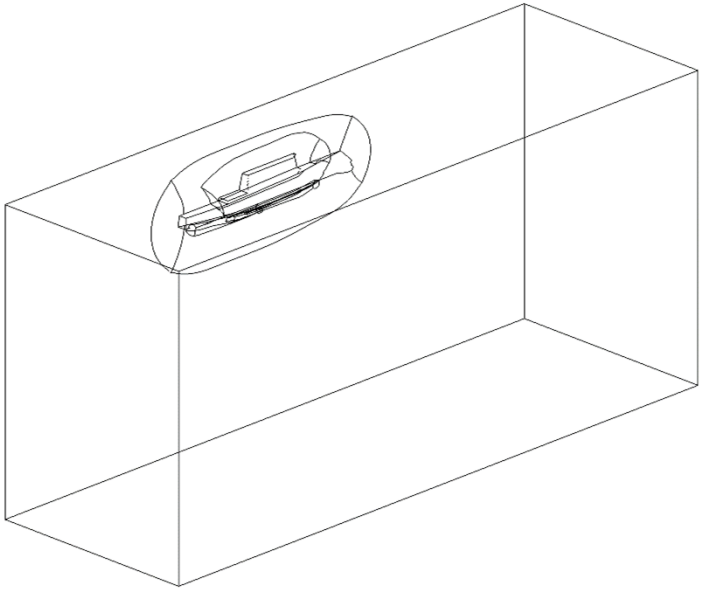


Grid allocation(active nodes), free surface, pressure, and velocity vectors distribution near bow region
in symmetry plane

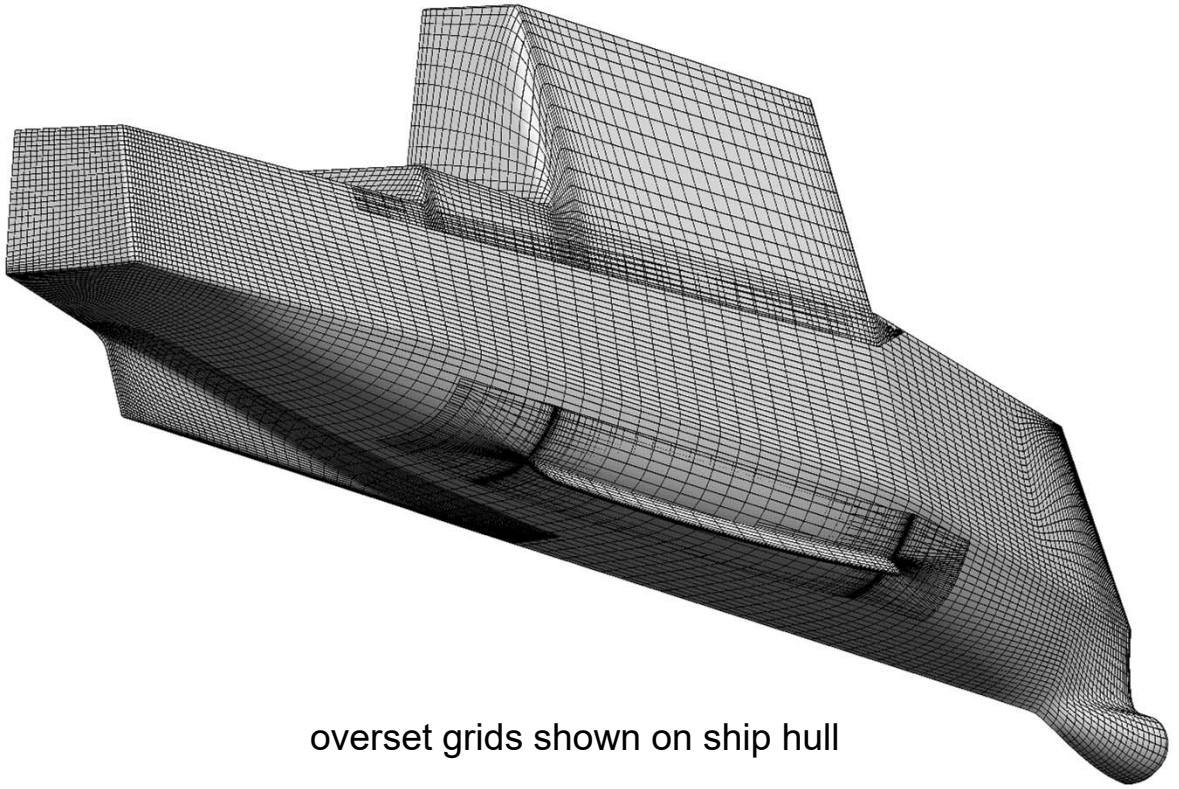


Grid allocation (active nodes), free surface, pressure, and velocity vectors distribution in the section x=0.15

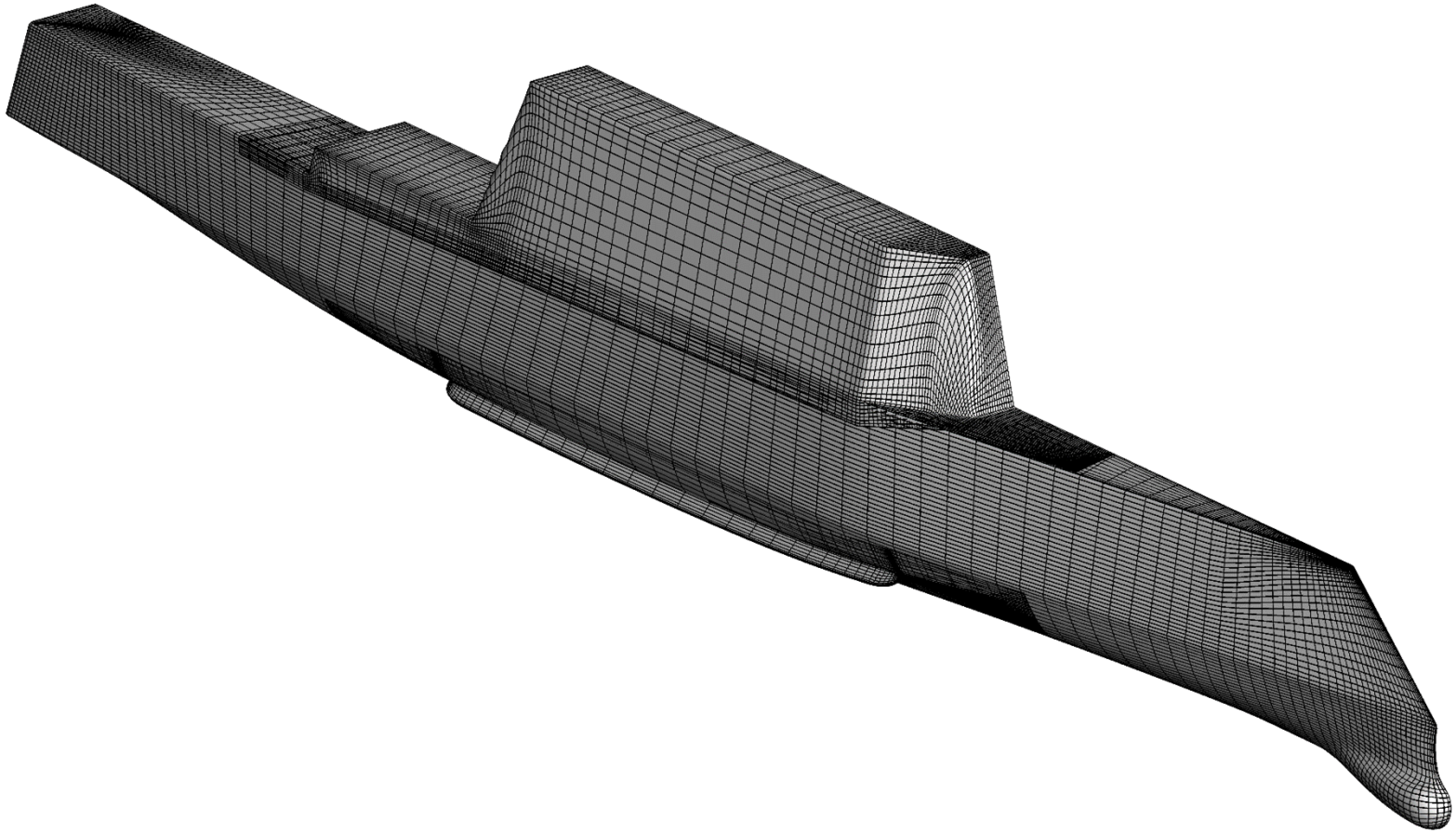
- Example10 (Free surface flow around ship model DTMB 5613 with very complicated geometries)
  - Conditions:
    - Five overset grids: ship hull, superstructure, bilge keel, skeg, and background grids.
    - Steady single water free surface flow, Reynolds number= 6.5E+6, Froude number=0.4.
    - Overset grid solver produces static overset grid files and transfer to CFD
    - The demonstration results are print out at time step =1000.



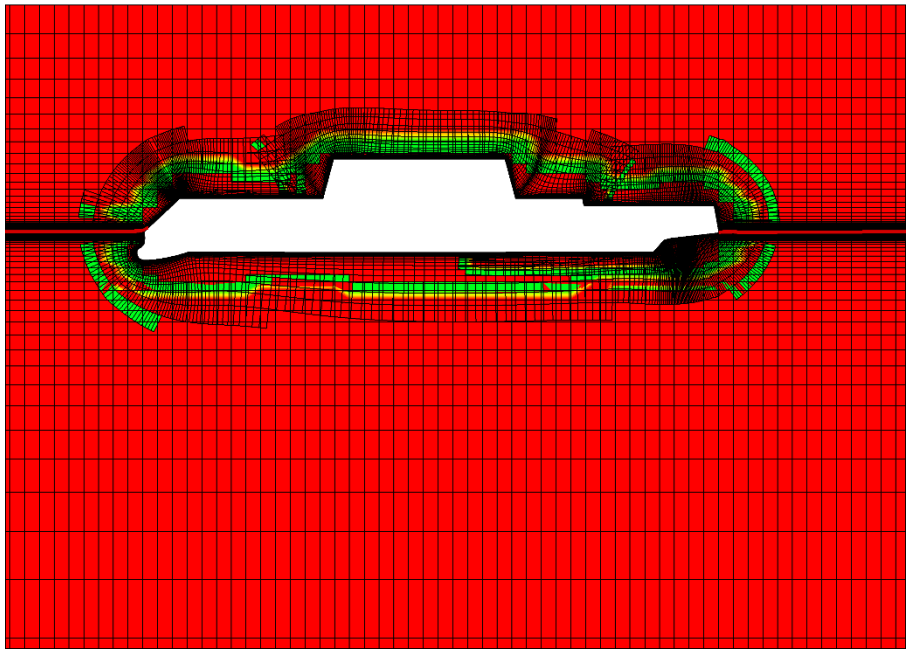
Frame of half ship grids



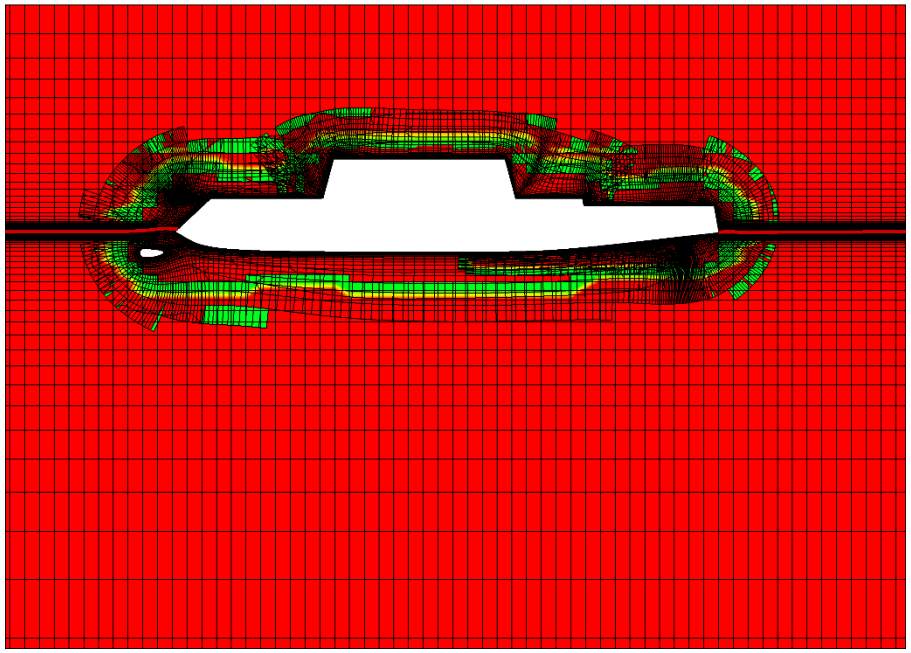
overset grids shown on ship hull



Front and side view of half ship hull

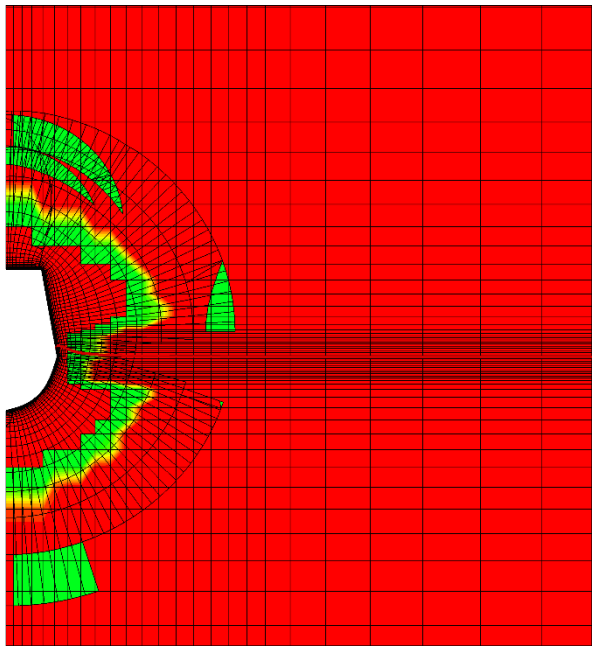


(y=0)

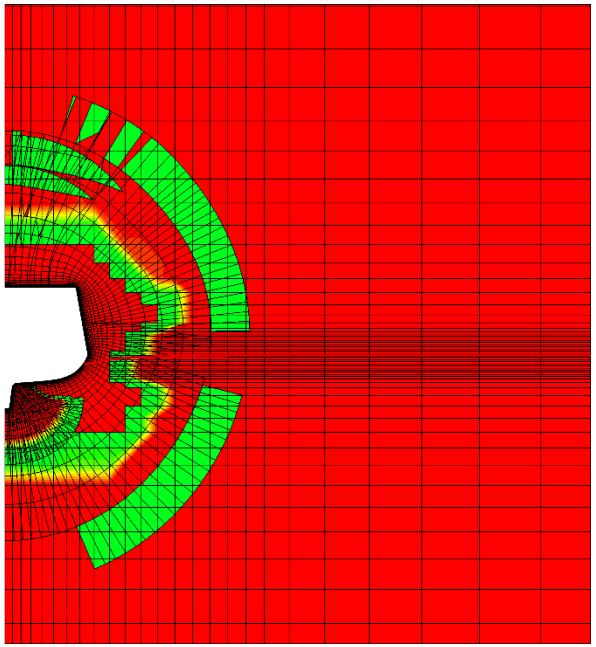


(y=0.1)

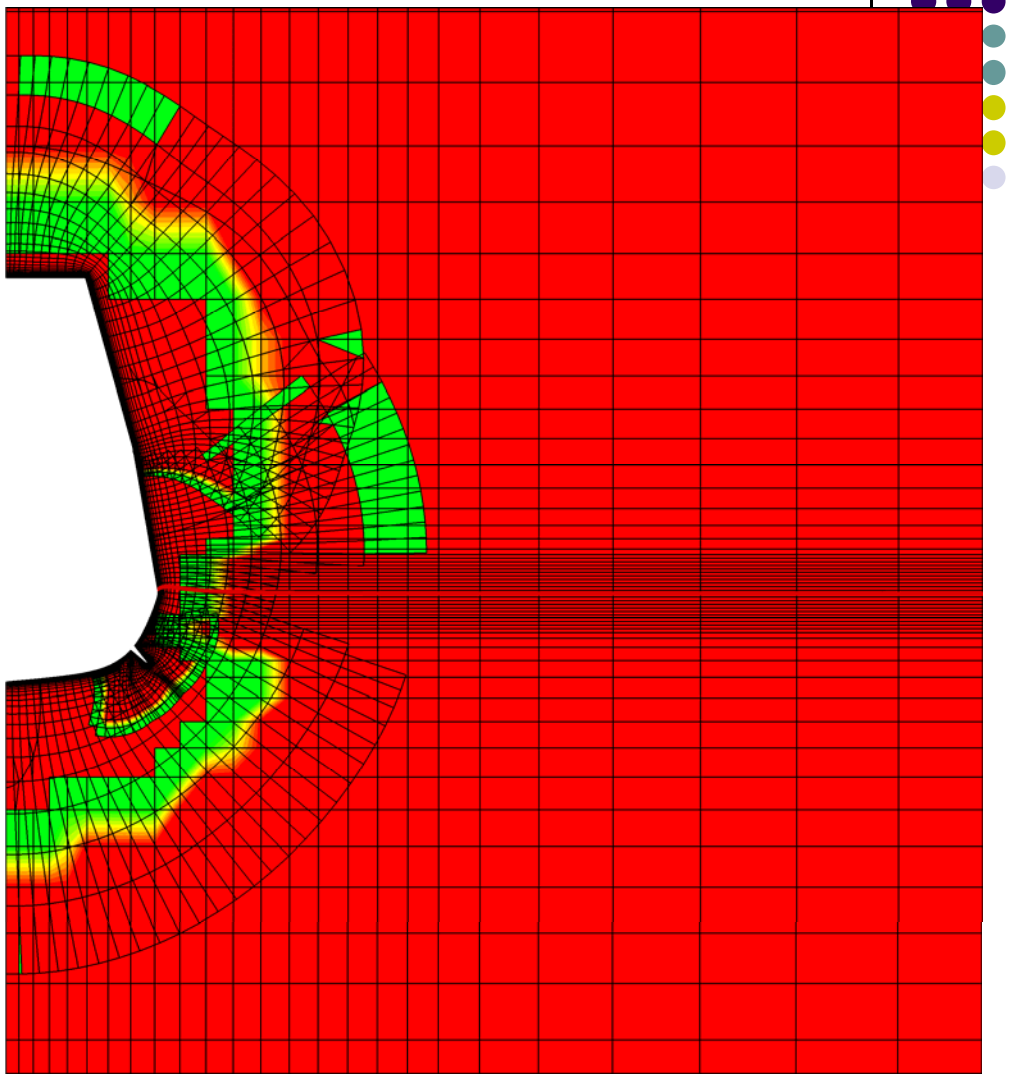
Distribution of active and fringe nodes



(x=0.2)

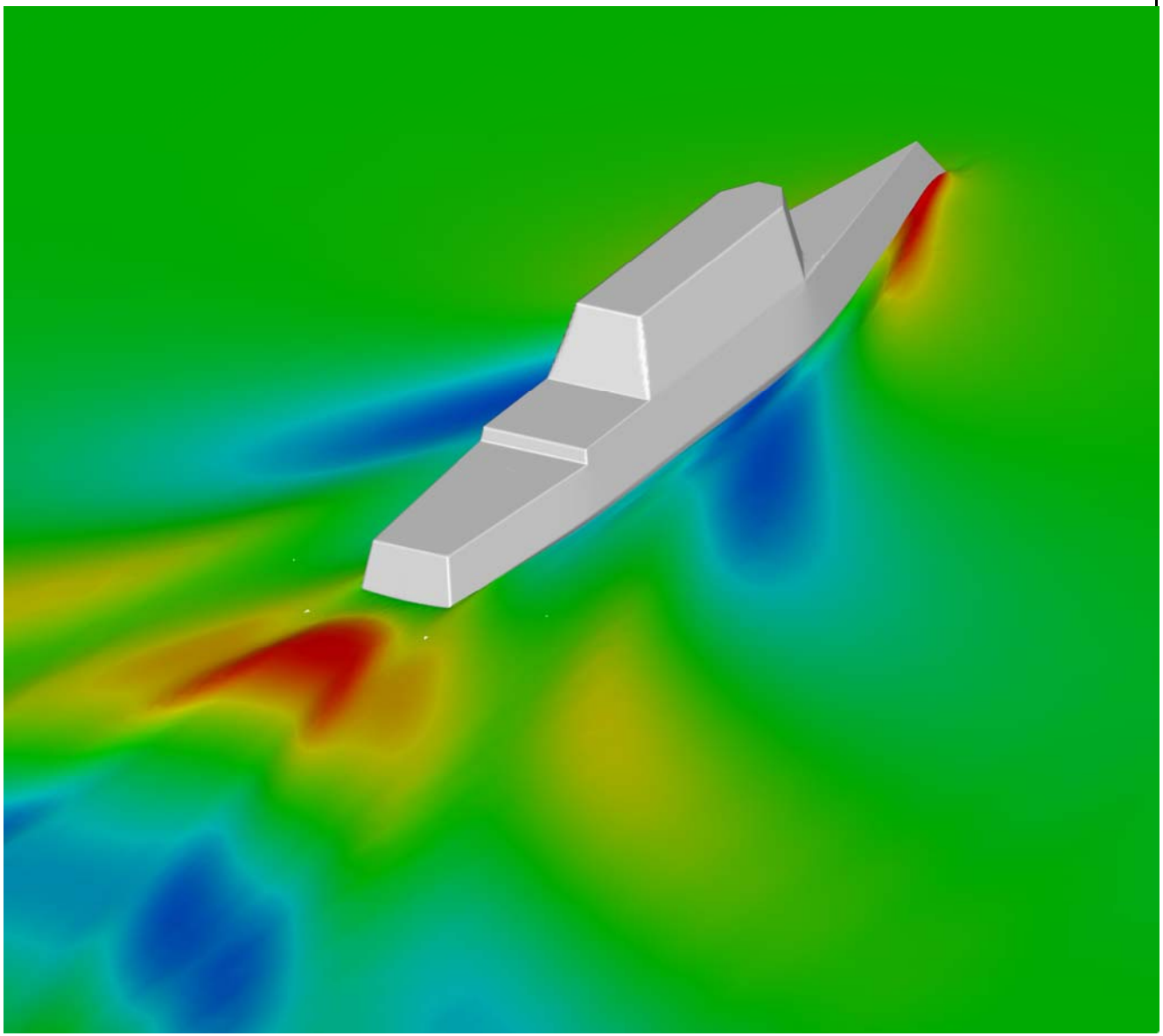


(x=0.85)

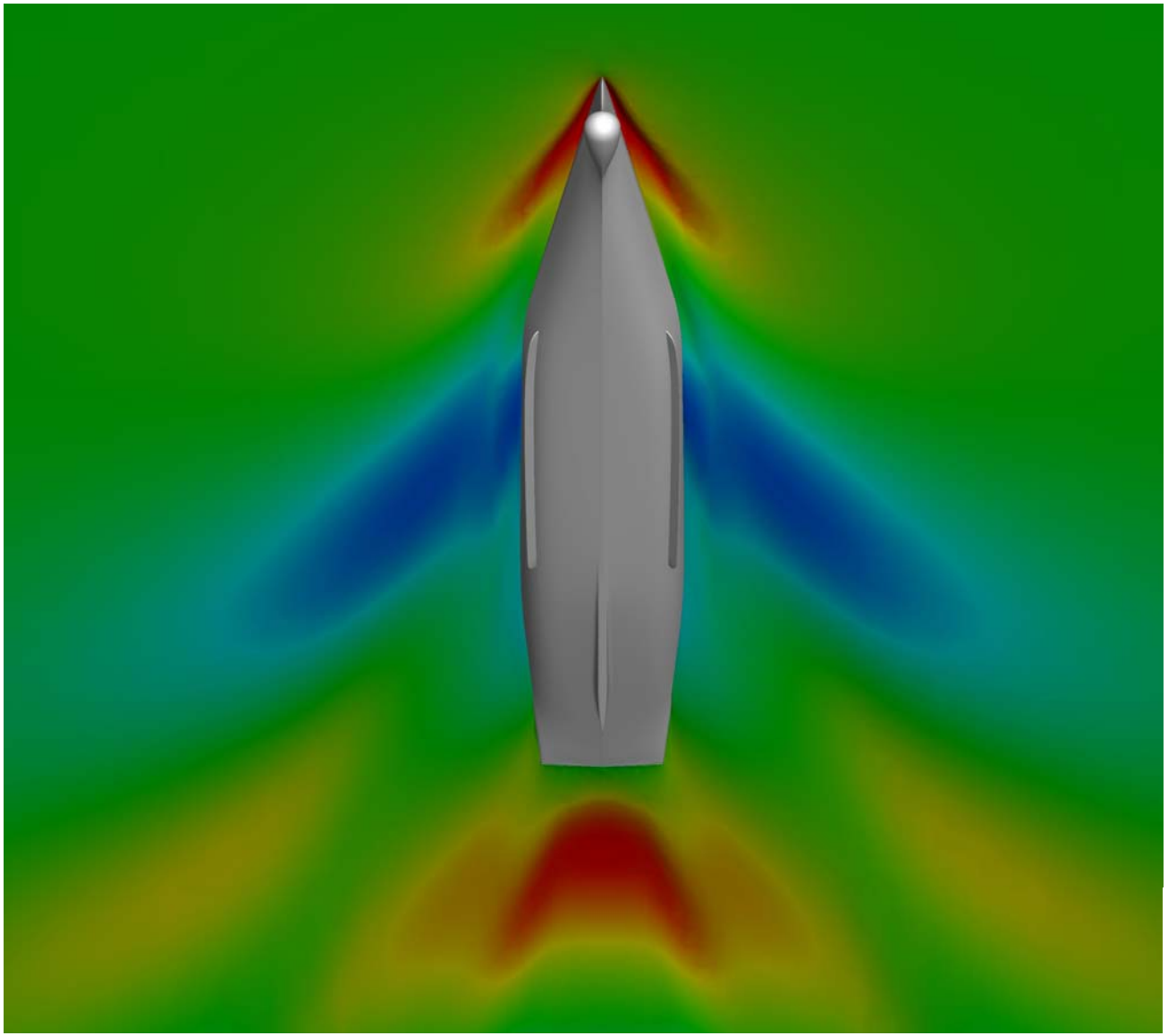


(x=0.4) (zoom in)

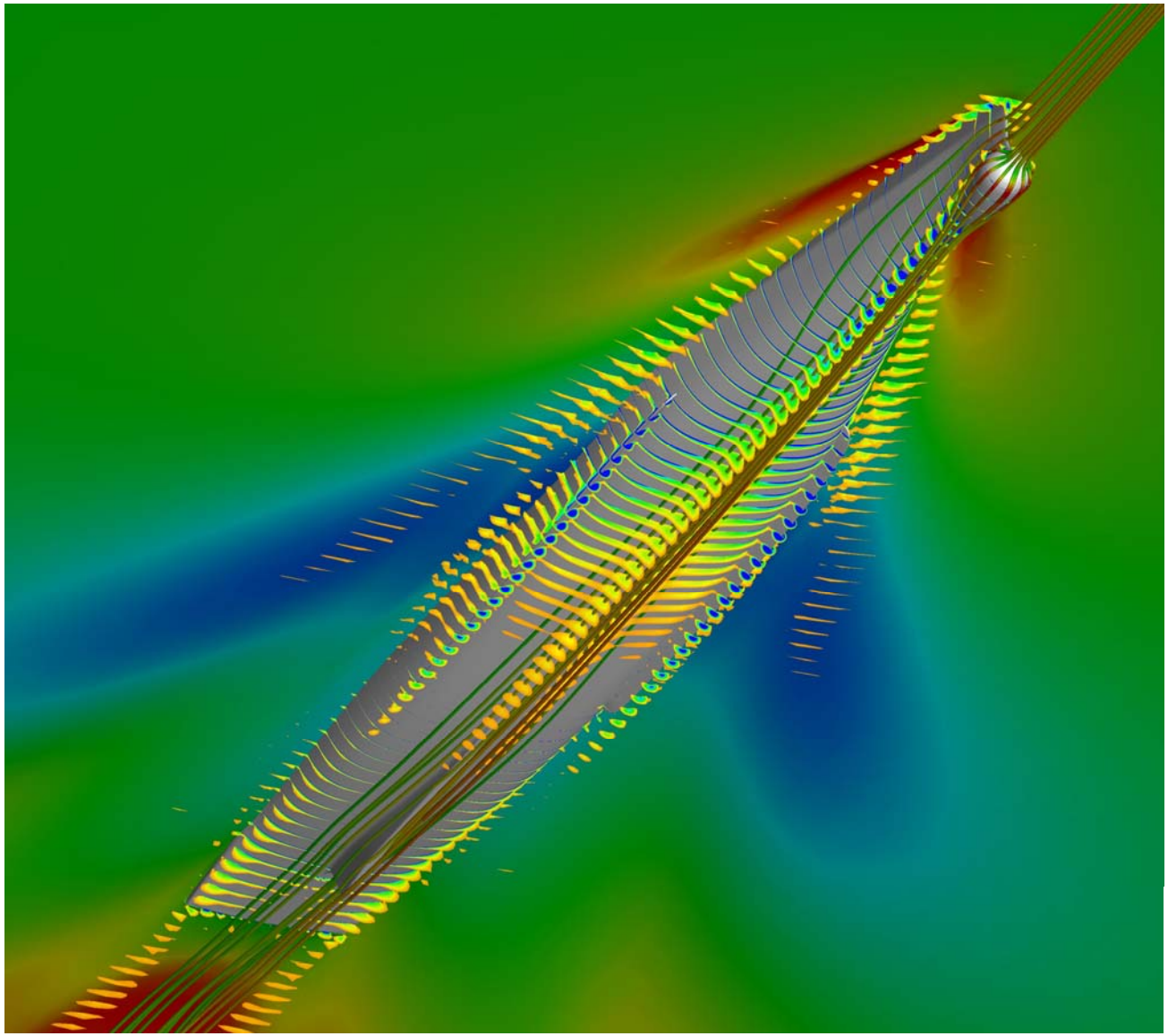
Distribution of active and fringe nodes



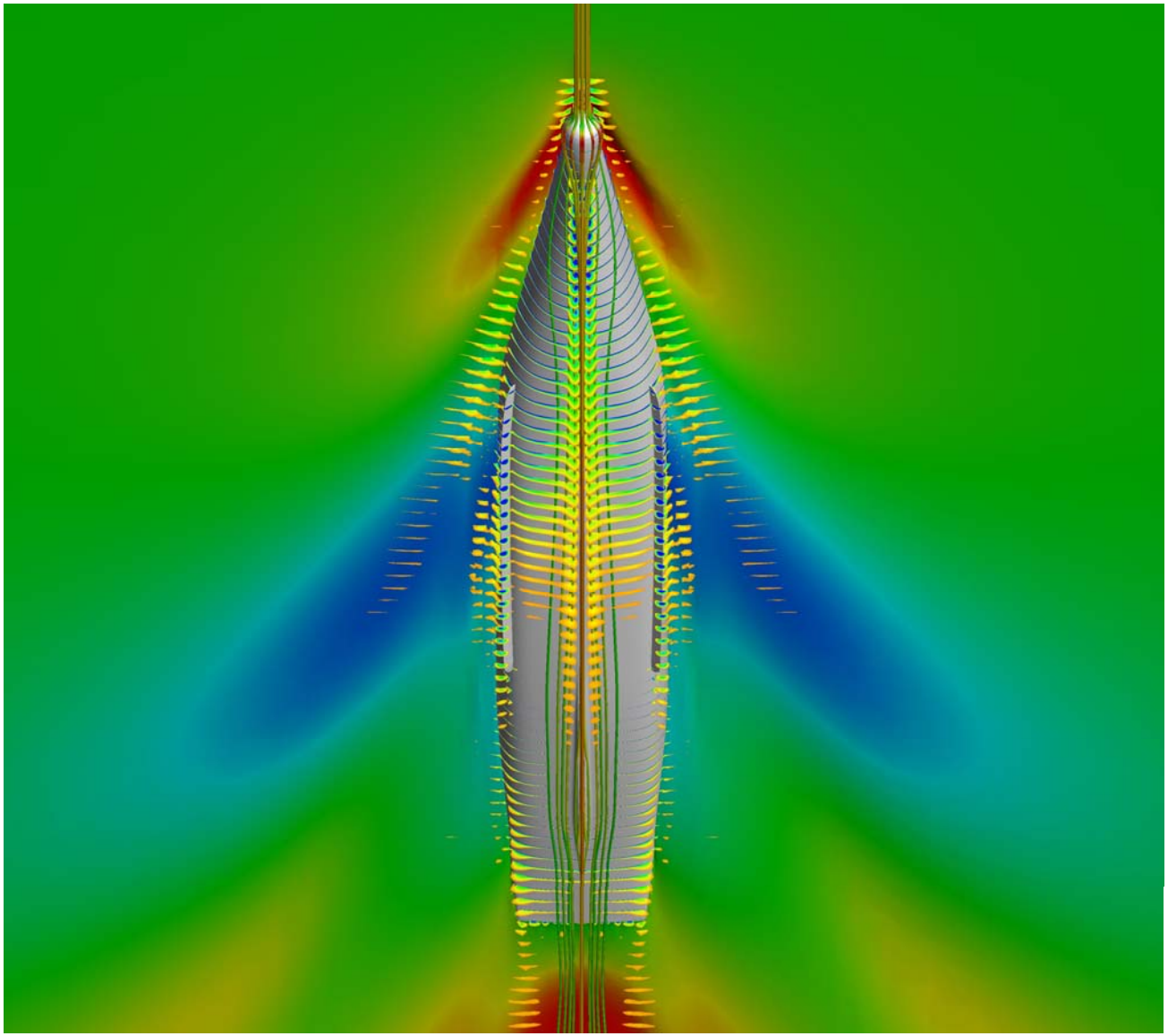
Free surface and ship hull (top view)



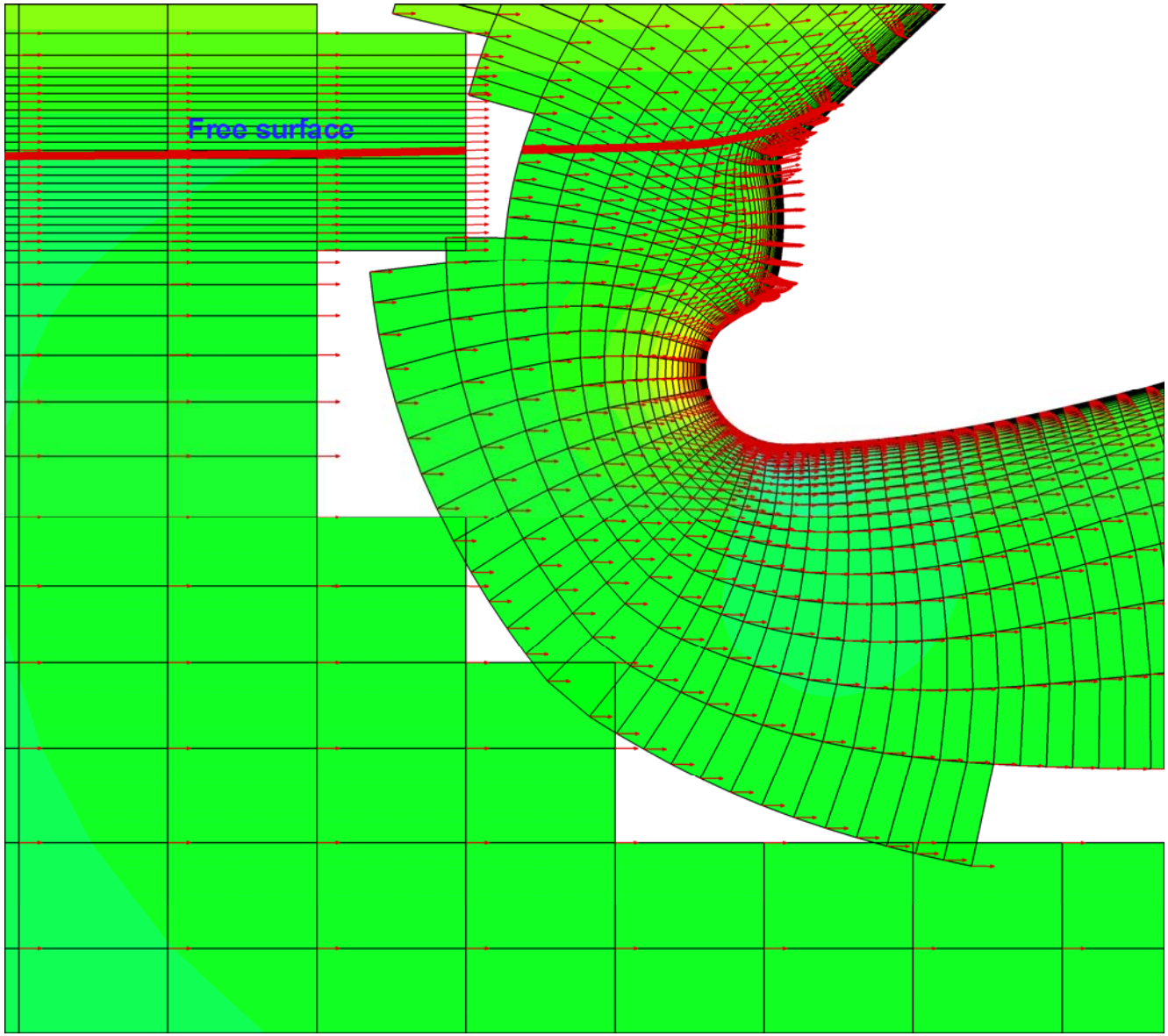
Free surface and ship hull(below view)



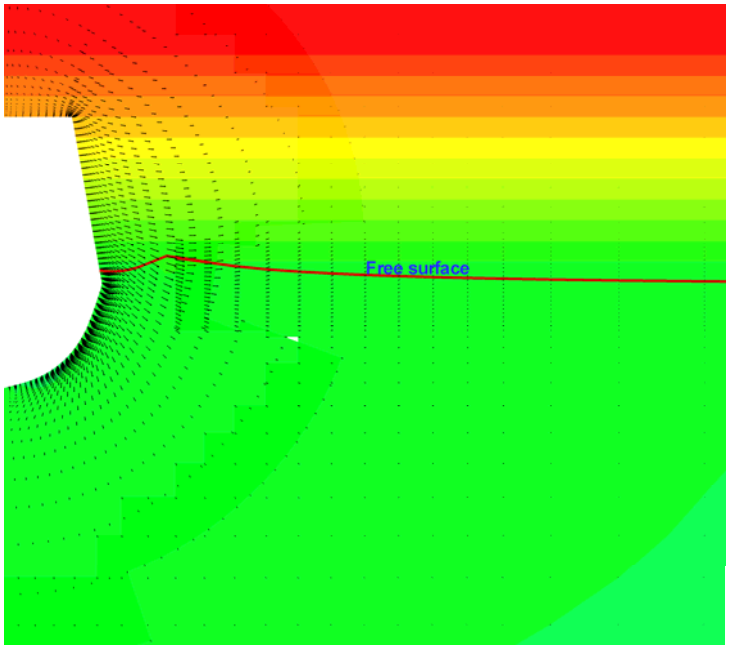
Vortex and streamline



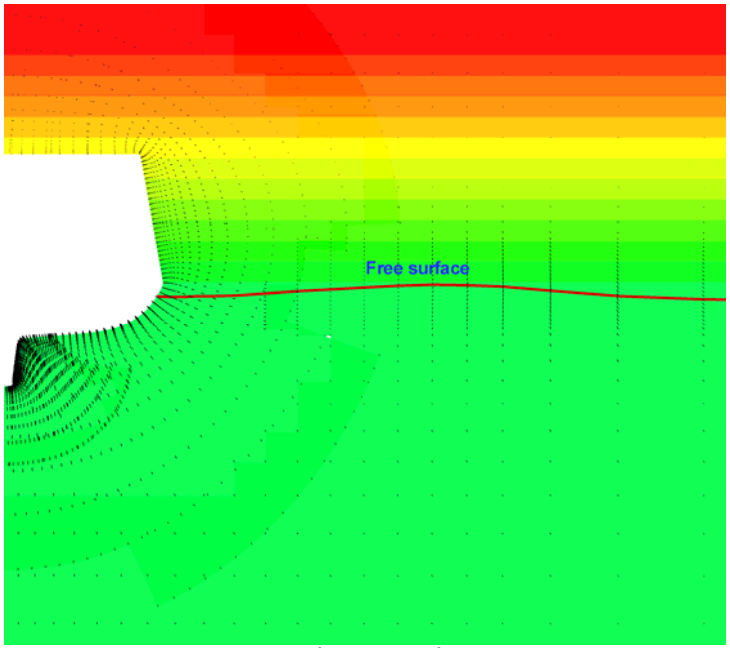
Vortex and streamline



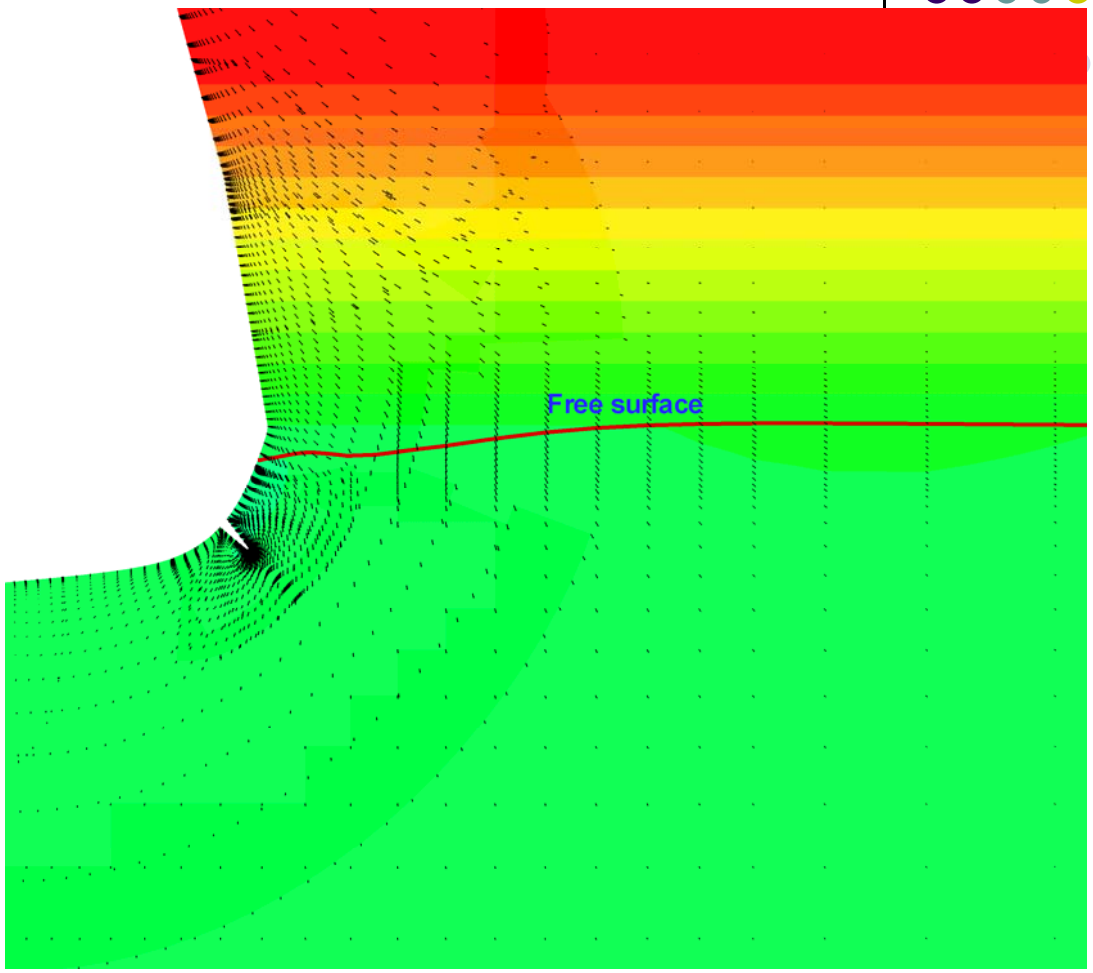
Distribution of free surface, pressure and velocity in the bow region (y=0)



(x=0.2)



(x=0.85)



(x=0.4) (zoom in)

Distribution of free surface, pressure and velocity