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Developing Spline Based Overset Grid Assembling Approach and Application to Unsteady Flow Around a Moving Body

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Abstract: Overset or Chimera grid approach is one of methods to cope with complex geometries. A spline based overset grid assembling system has been developed. The system is based on structured grid approach and covers comprehensive features for overset assembling, i.e., grid generation, grid modification, and computing Domain Connectivity Information (DCI) for overset interpolation. Ferguson spline curve is used to compute curves through grid points and cell centers for trimming grids and computing DCI robustly and accurately. Flow simulation around Kriso Container Ship (KCS) with jointed grids shows good continuity of flow field between the grids. The overset grid assembling is enhanced to unsteady problem as dynamic overset approach coupled with a solver which also has been developed in National Maritime Research Institute, Japan. Computed results for pitchup spheroid are compared with measured data and show good agreement in unsteady force acting on the spheroid. It is confirmed that the system has capability to simulate flow field around jointed grids and unsteady flow with dynamic overset assembling approach practically.

Key words: Overset Assembling, Dynamic Overset, Unsteady Flow

1. Introduction

CFD simulation becomes common tool to predict ship performance in design sites, and it's getting more important to compute flow field around complex geometries such as energy saving devices (ESDs) for vessels in order to evaluate ship performance more rapidly and precisely. Overset grid approach [1, 2] is one of methods to cope with complex geometries, simplifying grid generation and it provides flexibility to rearrange geometries. While, it is essential to compute weight values for interpolation accurately robustly to ensure continuity of flow field. Especially, treatment for junctures of solid boundaries critical for accuracy of solution close around ESDs. UP_GRID (User-oriented and Practical overset GRID system) [3, 4] is developed at NMRI (National Maritime Research Institute, Japan) as an overset grid assembling system. Enhancing the approach to unsteady problems, dynamic overset approach is effectual to large amplitude motion or multibody problems. In dynamic overset approach, DCI has to be updated at each time step and key issue of simulation are keeping no ill-interpolation (orphan cells or circular referencing), faster computation and accuracy of results. In the present paper, details of UP_GRID is described firstly, following application to the flow around a hull with a bulbous bow and a stern tube, and the flow around a rotating spheroid, compared with measured data

2. Procedure of Overset Assembling

Overset grid approach uses a set of grids that enclose the computational domain and overlap each

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other without requiring face-to-face matching between grids. Overset grid assembling is composed of three steps as follows.

(1) Generation of each grids

(2) Modification of each grids (translation, scaling, trimming, regridding or clustering grid points and so on)

(3) Computation of weight values for overset interpolation

An overset assembling system called UP_GRID is developed at NMRI. It is based on structured grid approach and is composed of three programs corresponds to above steps, which are UP_WING, UP_MOD and UP_OVS, respectively.

2.1 Grid Generation (UP_WING)

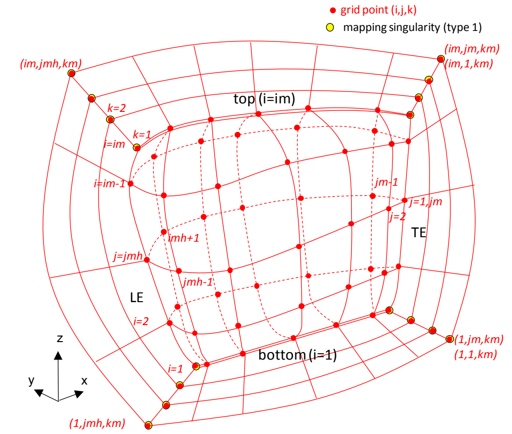
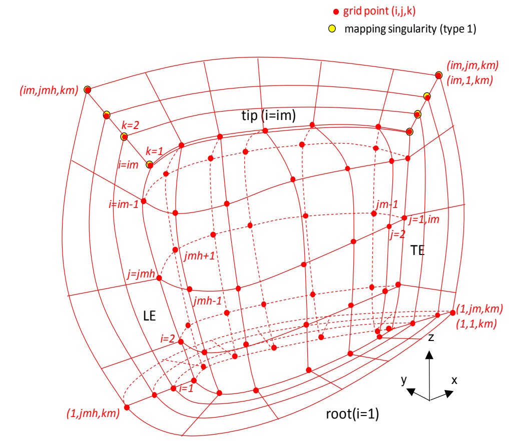
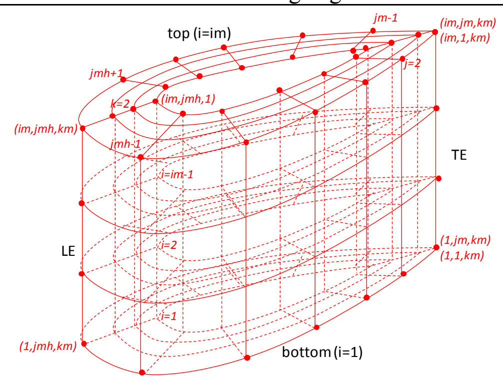
UP_WING generates a 3D structured grid around a solid body. It can deal with some kinds of topologies. Table 1 shows examples of topologies available in UP_WING. Coordinates ξ, η and ζ(or i, j and k) denote spanwise direction, chordwise direction and normal to solid surface respectively. In addition to topologies listed in Table 1, other topologies, called "duct" (faces at min(ξ) and max(ξ) abut each other of "strut" topology), "hull" (O-O topology) and "rect" (simple rectangular parallelepiped) are also available. Above topology names are used for descriptive purposes, and foldings of end surfaces and singularities determine topologies.

Shapes of a solid body and outer boundary should be provided by data of sections or a surface mesh. If data of sections is provided to represent a shape, UP_WING uses spline function [5] and TFI (Trans-Finite Interpolation)[6] to generate a surface mesh. Implicit Geometrical Method (IGM) [7] is used to generate three dimensional grid.

2.2 Grid Modification (UP_MOD)

It is an advantage of overset assembling approach to change position of solid bodies or deform them relatively easily than unstructured single block approach.

Table 1 Examples of topologies available in UP_GRID.

name	details
rudder	 folded at both ends in ξ direction. faces at min(η) and max(η) abut each other at trailing edge.
fin	 folded at one end and open(not folded) another end in ξ direction. faces at min(η) and max(η) abut each other at trailing edge.
strut	 open(not folded) at both ends in ξ direction. faces at min(η) and max(η) abut each other at trailing edge.

UP_MOD provides several features for modifying grids. Key features are:

- affine mapping (translation, scaling and rotation)
- regridding (partially refining or coarsening a grid)

- partial clustering (clustering grid points close to boundary layer)
- trimming (cutting and deleting inner portions of a grid at the intersection with another solid surface)
- generating Coons patches from NURBS data.
- fitting a surface mesh to another surface defined as a set of Coons patches

In all operations, grid lines are represented as spline curves so that grid points can be moved or added accurately. Figure 1 shows trimming and partial clustering schematically. An original grid of a fin is generated to pierce a surface of a larger body, in this case a hull surface, then trimmed by the hull surface with clustering grid points of the fin toward to the hull surface (solid wall). If there is a juncture of two bodies, this operation is necessary to compute flow field in boundary layer.

2.3 Computing Domain Connectivity Information (DCI) (UP_OVS)

UP_OVS computes weight values to interpolate flow variables between overlapped grids. Firstly, UP_OVS maps all discrete points of a grid to continuous function $x(\xi,\eta,\zeta)$ in a spline space by using Ferguson spline curve and TFI. This mapping is continuous and unique. Then, UP_OVS solves "Inverse Problem". This "Inverse Problem" means:

- selects a cell center $p_c(x,y,z)|_A$ of a grid (assuming "Grid A").
- solves coordinate values of $P_{target}(\xi,\eta,\zeta)|_B = p_c|_A$ in another grid(assuming "Grid B") in spline space. Figure 2 shows the procedure. P_{target} is a point of which the coordinate values (ξ,η,ζ) should be obtained. The coordinate values can be obtained by conversing a point $P_{iterative}$ to P_{target} iteratively from a certain initial point.
- carries above procedure for all cell centers of grid A.
- for all combinations of grid A and grid B, repeats the above process. (ex. If there are 10 grids, the number of combination is $10 \times 9 = 90$.)
- Then UP_OVS computes DCI. The steps of computation are described below with an example of 2D wing and a slat (Figure 3).

(1) prioritizes grids.

Generally, priority of a small grid is higher than a grid which covers it and the lowest priority grid has to cover whole computational domain. In the example, the priority is the slat → the wing.

(2) picks up in-wall cells.

UP_OVS identifies the cells in each grids that are outside the flow domain. "in-wall" cell is such a hole cell inside a body and should be extruded from flow computation. The cells colored pink in Figure 4 are in-wall cells.

(3) sets receptor_m cells.

receptor_m (mandatory receptor) cell is a cell to which flow variables have to be interpolated from donor cells (donor_m, mandatory donor cell) of other grid. Fringe cells adjacent outer boundary and in-wall cells are receptor_m. Number of fringe cells depends on the stencil of a flow solver. For third order discretization, two cells for each coordinates are necessary. The cells colored light green in Figure 5 are receptor_m cells.

(4) computes weight values for interpolation.

For each receptor_m, UP_OVS searches a cell of other grid (assuming "Donor Grid") which include the cell center of the receptor_m cell, by using the results of "Inverse Problem", then computes spline curves through cell centers of "Donor Grid" (dotted lines in Figure 6) and generates intermediate cells whose vertices are cell centers. By searching a intermediate cell which include the cell center of receptor_m, donor_m cells can be determined. Flow variable of receptor_m cell q_c is given as

$$q_c = \sum_{i,j,k} w_{i,j,k} q_{i,j,k}$$

where

$$0 \le w_{i,j,k} \le 1, \sum_{i,j,k} w_{i,j,k} = 1 \qquad (1)$$

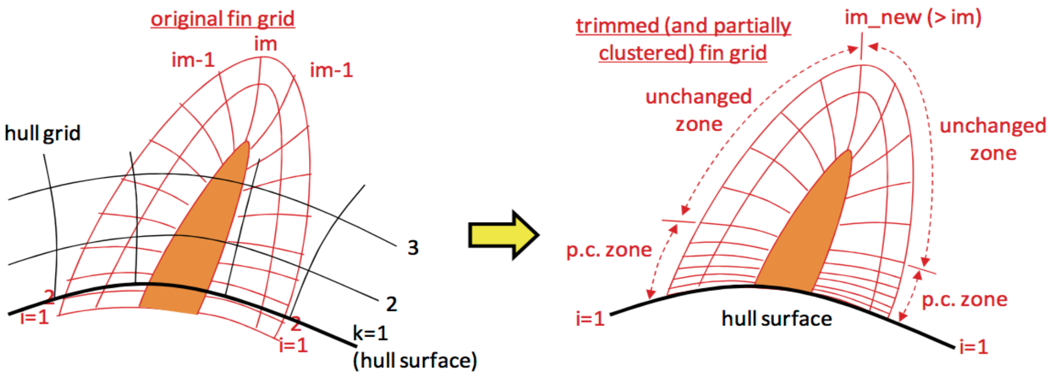


Fig. 1 Trimming and partial clustering (a fin attached to a hull): left: original, right: applied.

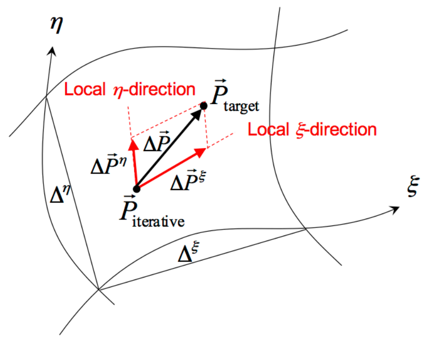


Fig. 2 Solving Inverse Problem.

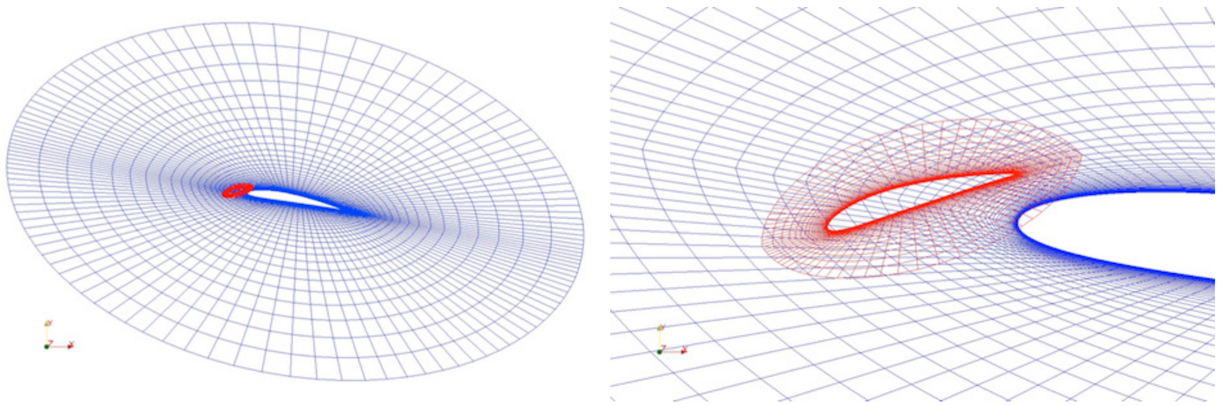


Fig. 3 Grid (Over view) and Zoomed to around the leading edge.

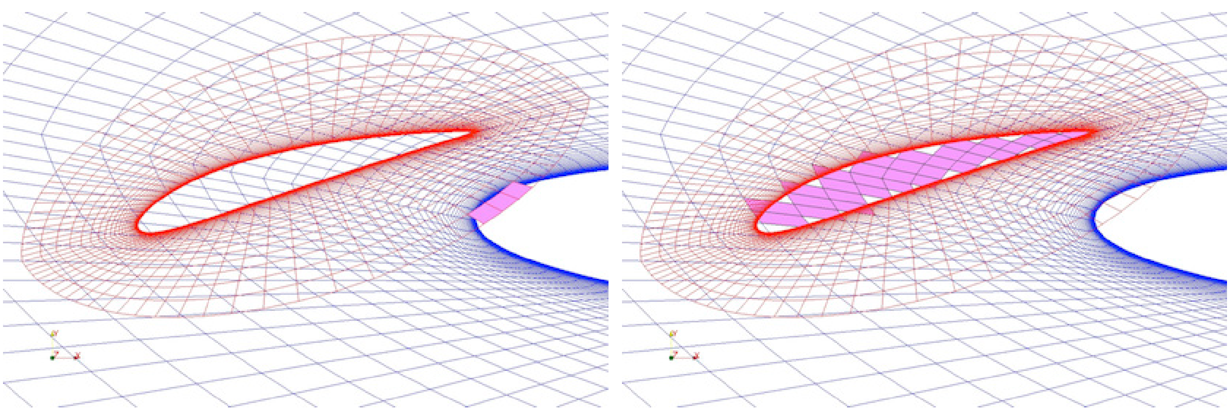


Fig. 4 left: in-wall cells of the slat grid, right: in-wall cells of the wing grid.

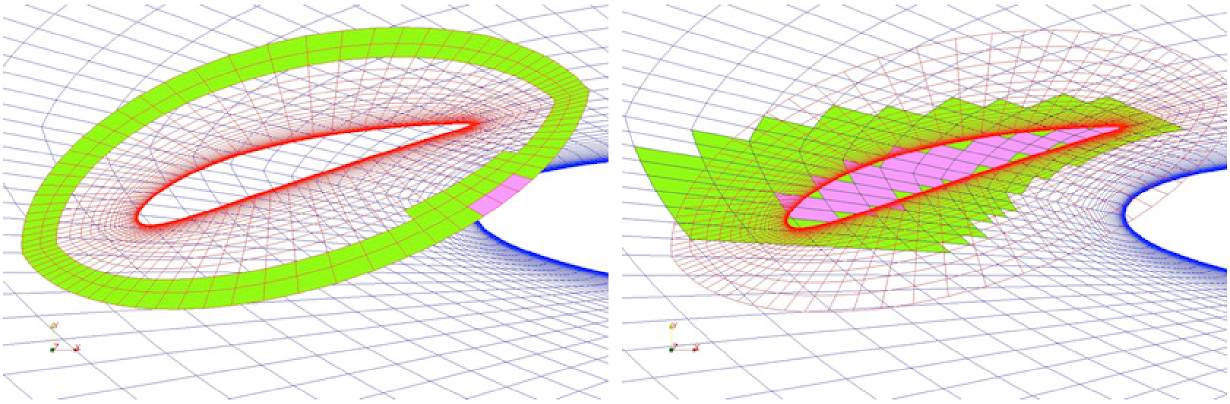


Fig. 5 left: receptor_m cells of the slat grid, right: receptor_m cells of the wing grid.

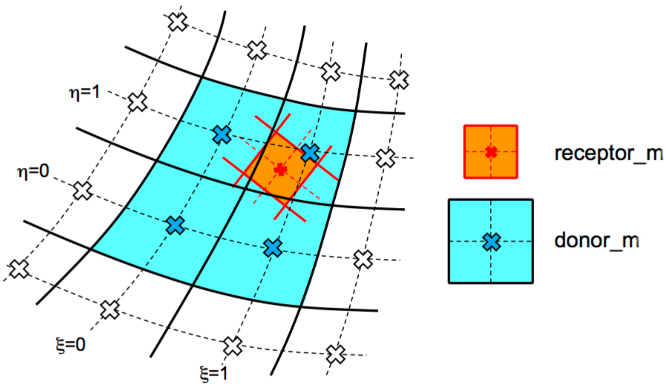


Fig. 6 Donor candidates.

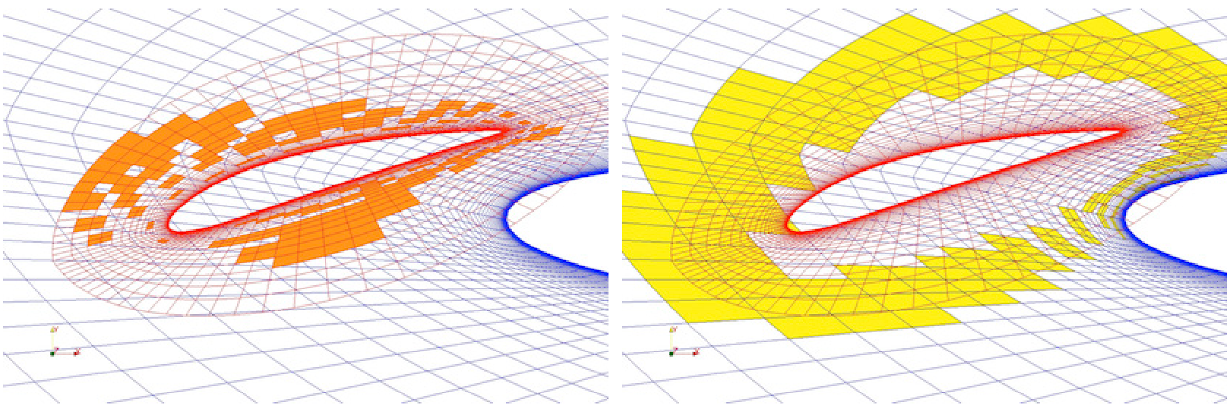


Fig. 7 left: donor_m cells of the slat grid, right: donor_m cells of the wing grid.

In Equation (1), subscriptions i, j and k denotes indices of donor_m cells. Figure 7 shows the donor_m cells of the example. Eight cells (two cells in each direction) should be adopted as donor_m cell for a receptor_m cell in three dimensional problem.

(5) searches receptor_o and donor_o cells.

receptor_o (optional receptor) cell is a cell included in another higher priority grid and is not in-wall, receptor_m and donor_m. To save computational resources, flow solver should not compute flow variables of receptor_o but should interpolate from donor_o (optional donor) of the higher priority grid. receptor_o and donor_o of the example are shown in Figure 8.

In searching donor cells, correction of coordinate values of cell centers is necessary. Since grid points of a grid (colored red in Figure 9) trimmed by another grid (colored black in Figure 9) are on the junctional

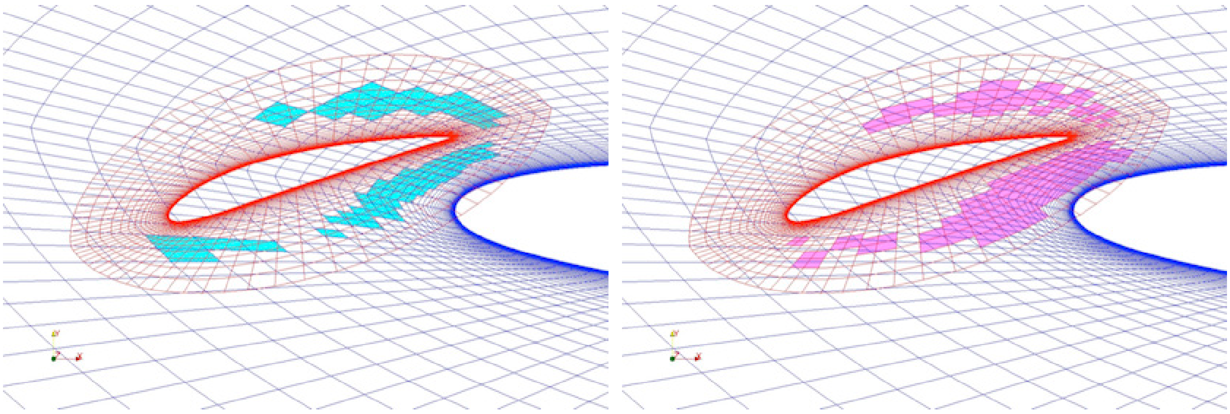


Fig. 8 left: receptor o of the wing grid right: donor o of the slat grid.

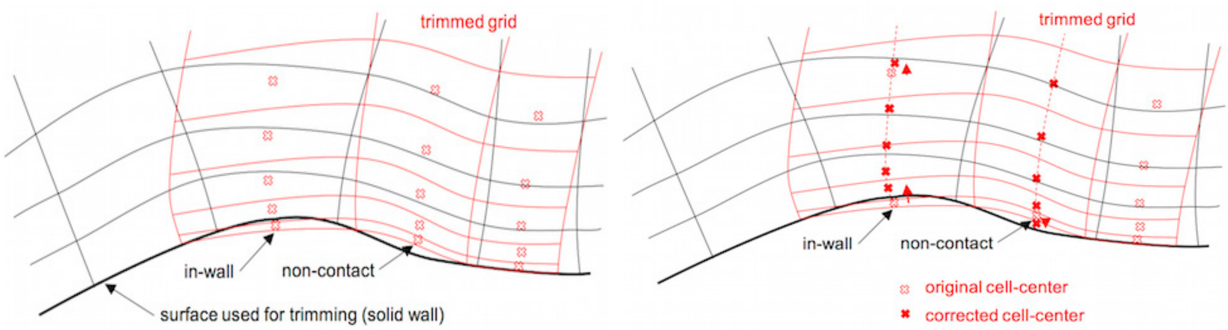


Fig. 9 trim correction.

surface, but cell centers of the trimmed grid occasionally are not (inside a body or detached the junctional surface wrongly). These cells have to be correct according to spline curves through cell centers in order to compute DCI appropriately. Figure 9 shows the method schematically.

2.4 Ill interpolation

In overset assembling, bad situations can occur where interpolation between grids is not possible or inappropriate. Mainly the situation is classified into three types.

(1) Orphan cell : a receptor_m cell to which no donor_m cell is found It is impossible to compute flow field.

(2) in-wall referencing cell : a receptor_m cell whose donor_m has a in-wall cell within its stencil. It is possible to compute but the result is probably wrong.

(3) circular referencing cell : donor_m which is also receptor_m It might influence to convergence but does not cause effect on converged results.

These situations may be caused in a case that size of computational domain which the receptor_m belongs to is not large enough or resolution of a grid which provides donor_m is insufficient. Grids should be generated taking into account these points of view.

2.5 Dynamic overset approach

Overset assembling has capability to deal with moving bodies by computing DCI in each time step. Key issue of simulation are keeping no ill interpolation (i.e. orphan cells) and solving “Inverse Problem” efficiently for saving computational time. Therefore, careful grid generation and preliminary check are necessary.

3. Results and Discussion

3.1 Overset assembling around a bulbous bow and a stern tube with Kriso Container Ship (KCS)

Case 2.1 (towing without rudder, Fr=0.26, Re = 1.4 × 10^7) of the G2010 CFD workshop [8] is studied. The solution domain is composed of three blocks, an O-O type grid around hull ($-1.5 \leq x/L_{PP} \leq 3.0$, $-2.0 \leq y/L_{PP} \leq 2.0$ and $-2.0 \leq z/L_{PP} \leq 0.06$) which covers whole domain, a grid around the bulbous bow and a grid around the stern tube. The grids of the bulbous bow and the stern tube are partially trimmed by the surface mesh of the hull. The origin is located at Fore Perpendicular (FP) on design water line. The axis x is positive streamwise and the vertical axis z is positive upward. The simulation is carried by a flow solver NAGISA [9], which is under development in NMRI. The solver can cope with overlapped grids with DCI generated by UP_OVS. Spalart-Allmaras model is employed for turbulence model.

Figure 10 is schematic view of the grids around the bow and the stern. Computed pressure distribution on the surface and wave elevation are also shown. The grid around the hull is not equipped with the bulbous bow and stern tube. The grids of the bulbous bow and the stern tube are fitted to the hull surface.

Figure 11 shows cross flow vectors and streamlines, and axial velocity contours at x/L_{PP} =0.9825. The left is measured data by Kim et al. [10]. Vectors and contours colored magenta is of the grid around the stern tube and the ones colored blue is of the grid around the hull. The flow field shows good continuity between the grids.

3.1 Dynamic overset computation with rotating prolate spheroid

The problem of the study is flow around a 6:1 prolate spheroid in a pitchup maneuver. The maneuver is a linear rotate from 0 to 30 [deg] in 11 nondimensional time units, $t^* = t\,(U_0/L)$ where U_0 is velocity of uniform flow and L is the length of the spheroid. Reynolds number is 4.2×10^6, which is defined in terms of U_0,

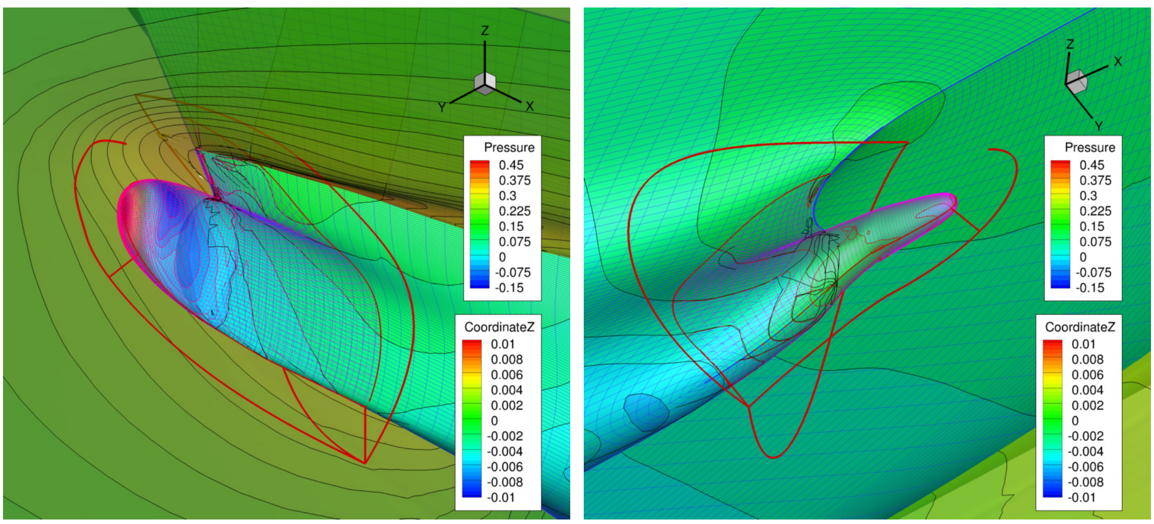


Fig. 10 Schematic view of bow (left) and stern (right). Pressure distribution on the hull surfaces and wave elevation (*$\Delta z/L_{PP}$* = 0.0005) are also shown.

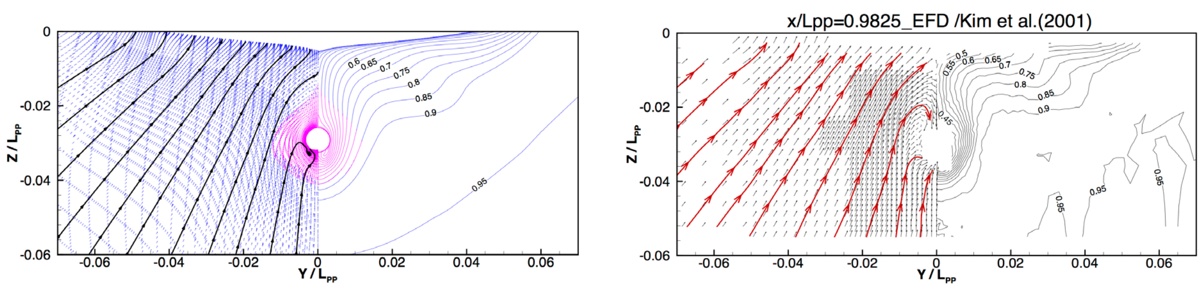


Fig. 11 Cross flow vectors and streamlines, (left) and axial velocity contours (ΔU = 0.05), (right) at *x/L_{PP}* = 0.9825 .
Top: Computed results, Bottom: Measured data

L and kinematic viscosity ν. Experimental data from Wetzel and Simpson [11] are used for comparison.

The solution domain covers a half of the spheroid with the extent $-4.5 \le x/L_{PP},\ y/L_{PP} \le 4.5$ and $-4.5 \le z/L_{PP} \le 0.0$. The origin is located in the body center and the coordinate x is in streamwise direction. The domain composed of two grids, a grid in O-O topology around the spheroid and a rectangular parallelepiped that covers whole solution domain. Only former grid rotates around z axis from 0 to 30[deg] in order to represent pitchup motion of the experiment and the plane z = 0 is set to symmetric. Figure 12 shows the arrangement. In the top of Figure 12, two grids are overwritten for comparison. The red body and the blue z-symmetry surfaces are the one of original position (t^*=0) and the green body and the yellow z-symmetry surfaces are the one of 30[deg] rotated (t^*=11) around z axis. DCI for overset interpolation has to be computed in each time step due to this rotation of the grid.

The simulation is carried in $\Delta t^* = 0.01$ with EASM turbulence model by the flow solver NAGISA. Figure 13 shows coefficients for normal force and moment defined as

$$C_N = (\text{normal force}) / \tfrac{1}{2}\rho U_0^2 L^2$$

$$C_M = (\text{moment}) / \tfrac{1}{2}\rho U_0^2 L^3$$

Computed results are in good agreement with the measured data.

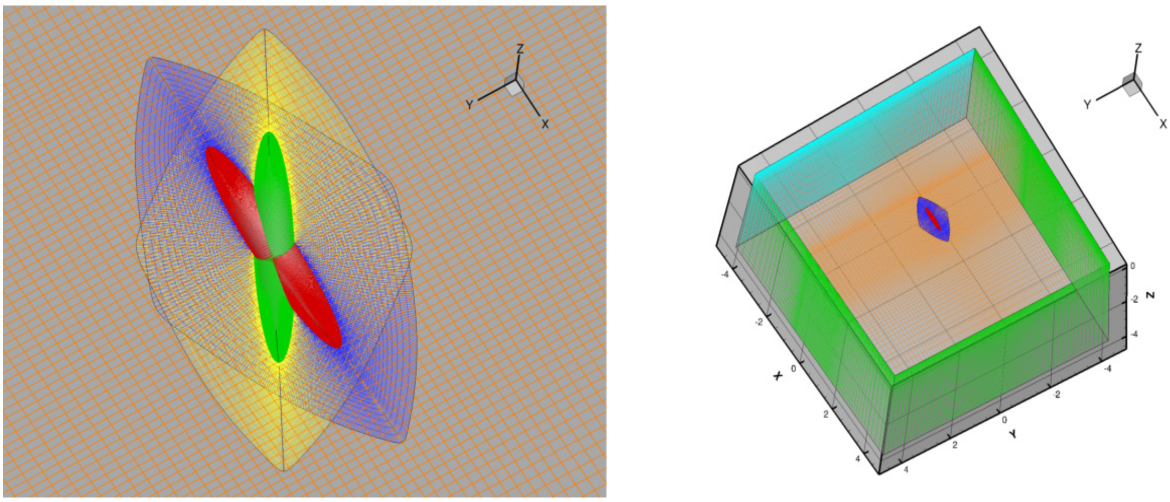


Fig. 12 Schematic View of Spheroid (looking up from the bottom, left: whole domain, right: zoomed to spheroid).

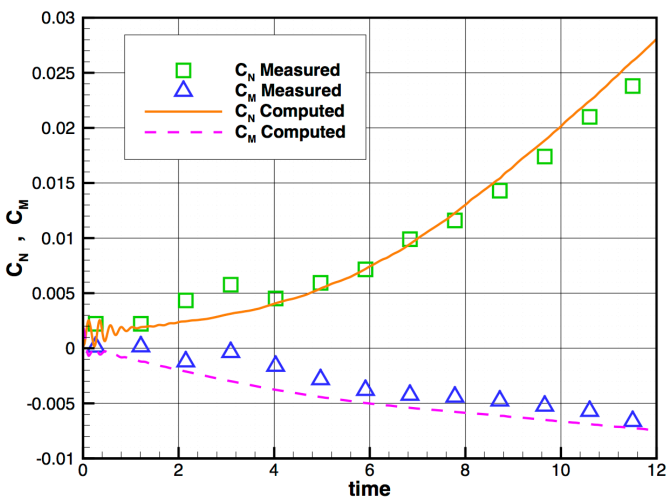


Fig. 13 Normal force (C_N) and pitch moment (C_M).

4. Conclusions

A spline based overset grid assembling system has been developed. The system is based on structured grid approach and covers comprehensive features for overset assembling, i.e., grid generation, grid modification, and computing weight values for overset interpolation. The system uses Ferguson spline curve to represent each grid lines and curves through cell centers. This enables precise modification of grids (trimming, fitting, partial clustering and so on) and accurate and robust computation of weight values for overset interpolation.

Flow simulation around Kriso Container Ship(KCS) with jointed grids shows good continuity of flow field between the grids. And the overset grid assembling is enhanced to unsteady problem as dynamic overset approach coupled with a solver which also has been developed in National Maritime Research Institute, Japan. Computed results for pitchup spheroid are compared with measured data and show good agreement in unsteady force acting on the spheroid.

It is confirmed that the system has capability to simulate flow field around jointed grids and unsteady flow with dynamic overset assembling approach practically.

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