IX International Conference on Computational Methods in Marine Engineering
MARINE 2021
I.M. Viola and F. Brennan (Eds)

NUMERICAL SIMULATION OF STRONGLY COUPLED LIQUID FLUIDS IN TANKS INSIDE OF FLOATING BODY AND ITS MOTIONS WITH INCOMING LATERAL REGULAR WAVES

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Key words: Sloshing, Incoming Waves, Body Motion, CFD

Abstract. Numerical method to simulate the motions of the floating body coupled with the tank liquids inside of the floating body using the overset grids method is developed. An in-house structured CFD solver which is capable the moving grid technique and overset grids method is utilized. The governing equations are 3D Navier-Stokes equations for the incompressible flow. Artificial compressibility approach is used for the velocity-pressure coupling. Spatial discretization is based on a finite-volume method. An interface capturing method based on a single phase level set approach is employed to simulate the liquid surface. Lateral regular waves are generated in the regions inside of the computational domain. The motions of the floating body are introduced by solving the motion equations and the hydrodynamic forces of the tanks are treated as the external forces in the motion equations. The computational grids of the floating body and tanks deform with the motions using the moving grid technique. The weight values for the overset-grid interpolation are determined by an in-house system which is based on Ferguson spline interpolation. The present method is applied to the condition with the floating box which has the 4 tanks inside and the lateral incoming regular waves. The overset grids are composed by the grids of the floating box, 4 tanks and background rectangular grid which generates the lateral regular waves. The amplitudes of the motions of the floating box are compared with the measured data and the present results show the features changing with the wave length ratio which are strongly affected by the liquid fluids inside of the tanks. The free surfaces around the floating box and inside of the tanks are indicated, and the interactions between the floating box and the liquid fluids of the tanks are revealed.

1 INTRODUCTION

The numerical method to simulate the motions of the floating body coupled with the tank liquids inside of the floating body using the overset grids and moving grid methods is developed. The case with the floating box which has the 4 tanks inside and the lateral incoming regular waves is selected, and the overset grids are composed by using the grids of the floating box, 4 tanks and background rectangular grid. The motions of the floating body are introduced by solving the motion equations and the hydrodynamic forces of the tanks are treated as the external forces in the motion equations. The motions are taken into account by a moving grid technique with the grid deforming methodology. The applicability of the present method is examined through the comparisons of the amplitudes of the motions of the floating box with the measured data, and the free surfaces around the floating box and inside of the tanks are indicated, and the interactions between the floating box and the liquid fluids of the tanks are revealed.

2 COMPUTATIONAL METHOD

2.1 Base solver

An in-house structured CFD solver[1] is employed. The governing equation is 3D RANS equation for incompressible flows. Artificial compressibility approach is used for the velocity-pressure coupling. Spatial discretization is based on a finite-volume method. A cell centered layout is adopted in which flow variables are defined at the centroid of each cell and a control volume is a cell itself. Inviscid fluxes are evaluated by the third-order upwind scheme based on the flux-difference splitting of Roe. The evaluation of viscous fluxes is second-order accurate. For unsteady flow simulations, a dual time stepping approach is used in order to recover incompressibility at each time step. It is consisted from the second order two-step backward scheme for the temporal time stepping and the first order Euler implicit scheme for the pseudo time. The linear equation system is solved by the symmetric Gauss-Seidel (SGS) method.

For free surface treatment, an interface capturing method with the single phase level set approach is employed. Incoming regular lateral waves are generated at the region inside of the computational domain[1]. Body motions are obtained by solving the equations of motion, and motions are taken into account by a moving grid technique with the grid deforming methodology. Grid velocities are contained in the inviscid terms to satisfy the geometrical conservation law. The grid velocities are derived from the volume where an each cell face sweeps. The boundary condition on a body is given as the velocities of the body motion.

The regions where the overset relations are composed deform with the body motions to maintain the overset information, and the amount of deformations gradually decreases with the distance from the body surfaces. Such the way is adapted to be able to avoid the computational load with using the dynamic overset-grid method[2]. The main body and tanks move with the motions which is obtained by the motion equation and the forces which are induced by the free water inside of the tanks are account for by the external forces on the motion equation.

2.2 Overset-grid method

The weight values for the overset-grid interpolation are determined by an in-house system[3]. The detail of the system can be found on [3], the summary is described.

1. The priority of the computational grid is set.
2. The cells of a lower priority grid and inside a body is identified (called as in-wall cell in here).

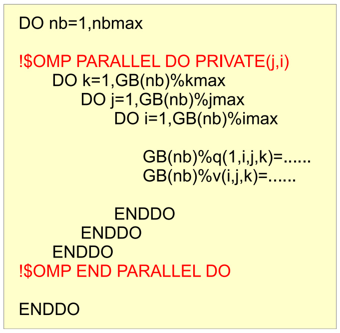
3. Receptors cells which the flow variables have to be interpolated from donor cells are defined. Two cells on a higher priority grid and facing to the outer boundary are set as receptor cells to satisfy the third order discretization of NS solver. Additionally, two cells neighborhood of in-wall cells, the cells of a lower priority grid and inside the domain of a higher priority grid are also set as the receptor cell.

4. The weight values for the overset interpolation are determined by solving the inverse problem based on Ferguson spline interpolation.

Flow variables of the receptor cell are updated when the boundary condition is set. The forces and moments are integrated on the higher priority grid to eliminate the lapped region on body surfaces. At first, the cell face of the lower priority grid is divided into small pieces. Secondly, the small piece is projected to the cell face of the higher priority grid by using the normal vector of the higher priority face. Then the 2D solid angle is computed and the small piece is decided in or out of the higher priority face. Once the small piece is in the higher priority face, the area ratio of the piece is set to zero. Finally, the area ratio is integrated on the lower priority face, then we have the ratio to integrate the forces and moments on lower priority face.

2.3 Parallelization method

The paralleization method based on the shared memory type with the OpenMP is applied for the loops (i, j, k) of the structured grid using the directive defined by the OpenMP method (Figure 1). The process of the SGS method for solving the linear equation system is modified by using the red-black ordering method which is the similar way in ref.[4] to avoid the race condition which means that the solution is not uniquely determined at the thread number and loops on the OpenMP method.



```
DO nb=1,nbmax

!$OMP PARALLEL DO PRIVATE(j,i)
      DO k=1,GB(nb)%kmax
           DO j=1,GB(nb)%jmax
                 DO i=1,GB(nb)%imax

                      GB(nb)%q(1,i,j,k)=......
                      GB(nb)%v(i,j,k)=......

                 ENDDO
           ENDDO
      ENDDO
!$OMP END PARALLEL DO

ENDDO
```

Figure 1: Sample code for parallelization of loops by OpenMP

Additionally, the Message Passing Interface(MPI) based on the domain decomposition method is applied to exchange the information which is mandatory for solving the equations over the computational machines. The computational grids for the overset grids method are simply separated for the MPI (Figure 2) ,and the data communications are processed to synchronize the solutions to satisfy the overset relations. The hybrid method which the loops of the structured grid is parallelized and the data is communicated based the OpenMP and MPI methods is applied in the present study.

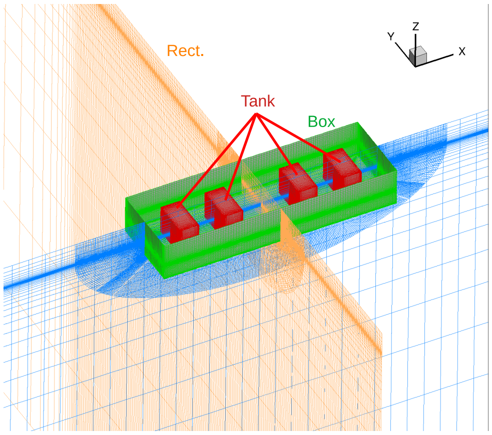


Figure 2: Present computational grids for the overset grids and parallelization methods

3 COMPUTED RESULTS

The box type floating body which has the 4 rectangular tanks in side of the box and examined in ref.[5] is selected. Figure 3 shows the layout and global view of the box and tanks and Table 1 shows the major particulars. The length of the floating body is $L = 2.47m$ and 4 tanks which the length 0.2m, the width 0.4m and water level 0.11m are located inside of the floating body. The center of the gravity in the height direction KG is 0.0921 from the tank bottom, and the radius of gyration in x-axis k_{xx} is 0.1386m. The lateral incoming waves are generated in the computational domain, and the ratio based on the wave length and the width of floating body λ/B is selected as $\lambda/B = 1.25(case1), 1.37(case2), 1.5(case2), 2.5(case3)$ to examined the effect of the ratio λ/B and the case number is identified with the name in Table 2. The wave height ratio based on the length of the floating body h_w/L is 0.01215, and the floating body is free for the sway, heave and pitch motions. The temporal time step is set as $\Delta t = 0.005$ in non-dimensionalized value, and the restoring force which maintains the lateral position contains the steady force which is equivalent to the wave drifting force and the extremely weak spring force.

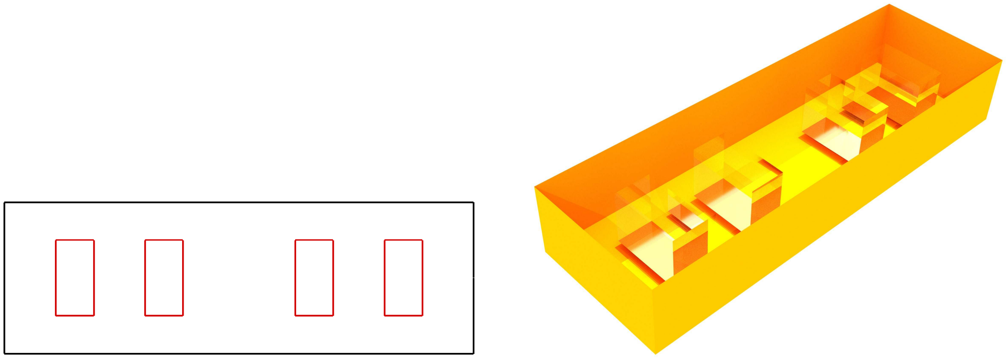


Figure 3: Layout and global view of box type floating body and tanks

Table 1: Particulars of floating body and tanks

Length(m)	2.47
Breadth(m)	0.8
Draft(m)	0.16
KG(m)	0.0921
k_{xx}(m)	0.1386
Tank length(m)	0.2
Tank breadth(m)	0.4
Tank draft(m)	0.11

Table 2 shows the division number of the computational grids with the arrangement of the priority of the overset relation. IM means the longitudinal division number, JM is lateral direction, KM means the division number in the height direction. The three rectangular grids are chosen in accordance with the wave length from case1 to case3, and the computational domain has the 1.5L in the fore and aft longitudinal directions and 2.5L in the depth from the center of the floating body. The lateral regular waves are generated at the left-side of the floating body, and the domain has 1.0L for the left hand side and 2.5L for the right hand side. The domain is divided by the equal intervals $\lambda/50$ in the lateral direction until 1.5L from the center of the floating body for the right hand side and at least $h_w/10$ in the height direction to generate the regular waves properly. The wall function is applied on the body surfaces.

Table 2: Division number of computational grids

Grid	IM×JM×KM
Tank	37×73× 89
Box	193×177× 65
Rect.(case1)	57×381× 49
Rect.(case2)	57×305× 49
Rect.(case3)	57×173× 49

Figure 4 shows the comparisons of the response amplitude operator (RAO). The computed result is only shown in the heave motion due to the lack of the experimental data. The free water effect due to the sloshing phenomena can be observed in the computed and measured data which the RAOs of the sway and roll motions increase gradually until $\lambda/B = 1.3$, then, RAOs become smaller around $\lambda/B = 1.5$. The RAO of the heave motion shows the similar feature. The RAOs take larger amplitudes over $\lambda/B = 1.5$. Although, the computed results show the difference near $\lambda/B = 1.4$ which is expected to be due to the effect of the spring force of the sway motion, the present results show the agreement with the experimental results.

Figure 5 depicts the instantaneous of free surface viewing from the left front at the condition with $\lambda/B = 1.25$. Once the floating body inclines to left hand side with the maximum angle, the free waters inside of the tanks lean to the right hand side, then, the floating body takes the even condition, the free waters take flat shapes. In case the floating body inclines to the right hand side with the maximum angle, the free waters toward largely to the right hand side.

At the condition with $\lambda/B = 1.5$ (Figure 6) which the RAOs of the sway and roll motions become smaller than other ratios, when the floating body and tanks incline to left hand side with the maximum angle, the free waters move to the right hand side with the small amount comparing with the case $\lambda/B = 1.25$. Additionally, the free waters lean largely to the left hand side when the floating body takes the even condition on the roll motion, and then, the floating body inclines to the right hand side in the maximum angle, the free waters take lower water level comparing with the roll angle zero condition. Consequently, the phase difference between the motion of the floating body and the free waters can be found at the condition $\lambda/B = 1.5$, and the RAOs become smaller than the other conditions. The free waters are almost stable even though the roll motion becomes large at the condition with $\lambda/B = 2.5$(Figure 7) due to the difference of the period of the roll motion and natural period of the free water.

4 CONCLUSIONS

- Numerical method to simulate the motions of the floating body coupled with the tank liquids inside of the floating body with the incoming lateral waves using the moving grid technique and overset grids methods is developed.
- Parallelization method using the hybrid method with the OpenMP and MPI is applied.
- The present method shows the applicability through the comparisons of the RAOs with the measured data.

5 ACKNOWLEDGEMENT

This work has been supported by JSPS KAKENHI Grant Number JP19K04869.

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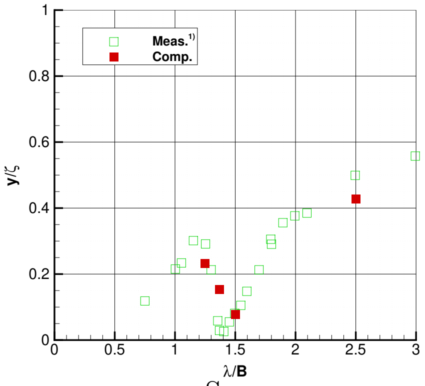
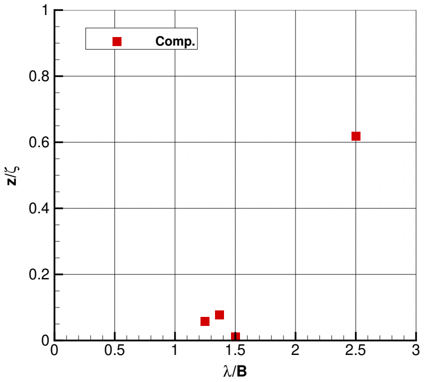
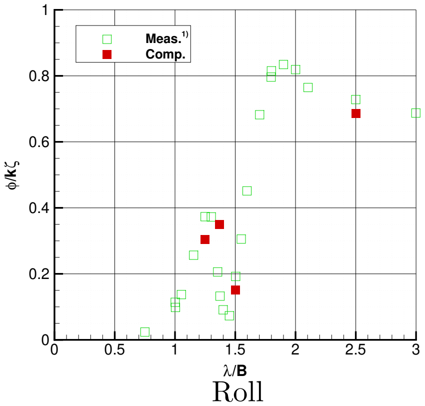


Sway



Heave



Roll

Figure 4: Comparisons of amplitudes of motions

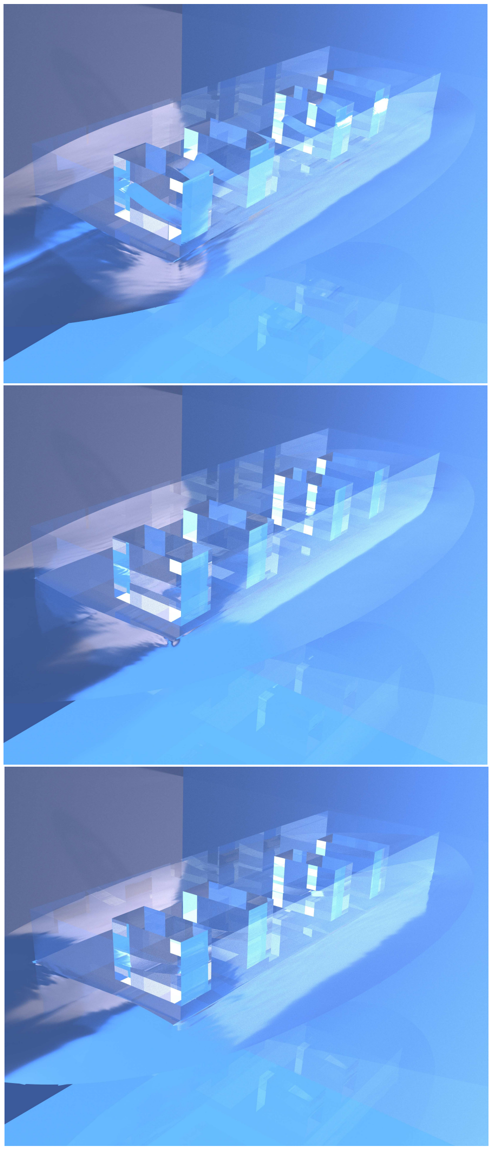


Figure 5: Instantaneous view of free surface at $\lambda/B = 1.25$ (top: maximum left tilt, middle: even condition,bottom:maximum right tilt)

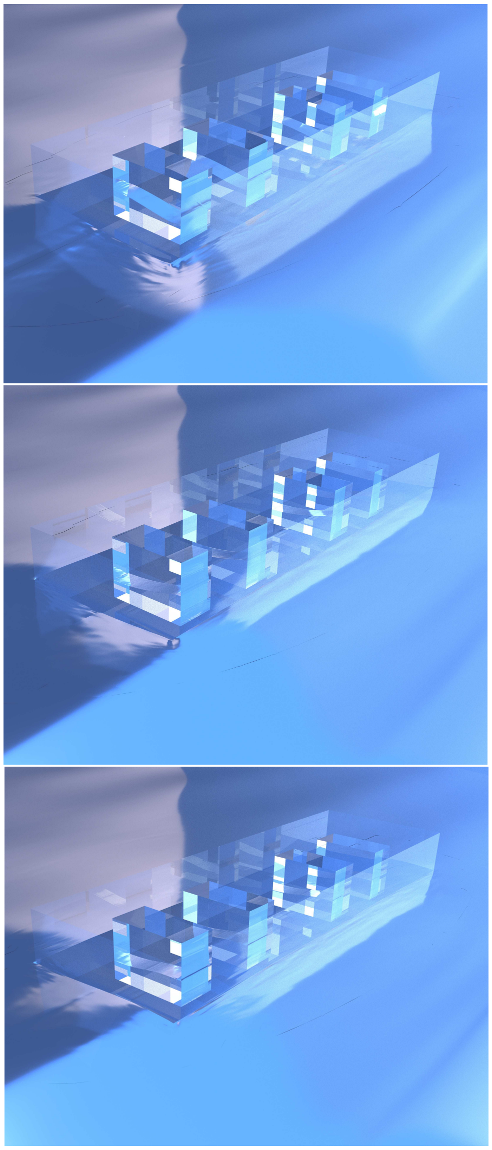


Figure 6: Instantaneous view of free surface at $\lambda/B = 1.5$ (top: maximum left tilt, middle: even condition,bottom:maximum right tilt)

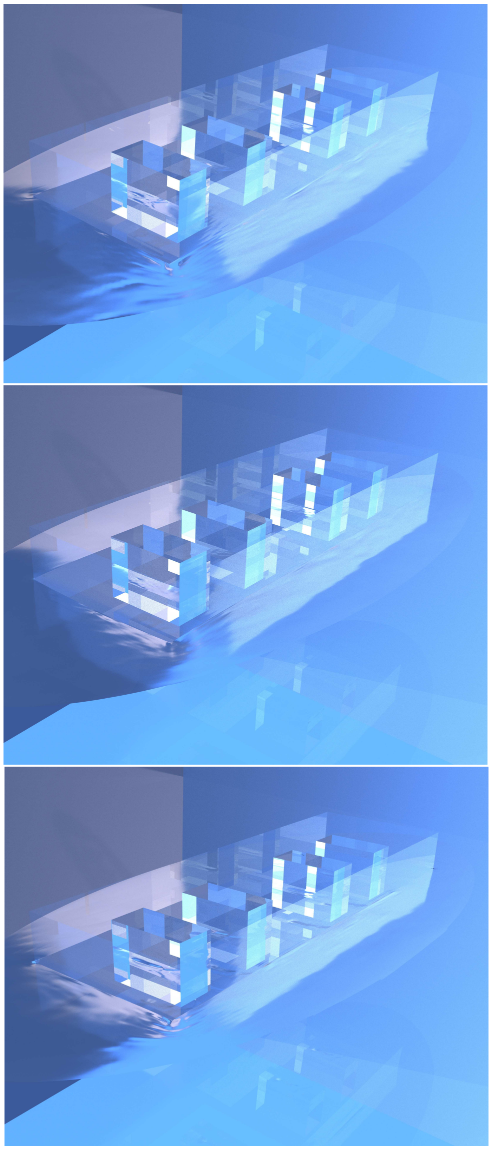


Figure 7: Instantaneous view of free surface at $\lambda/B = 2.5$ (top: maximum left tilt, middle: even condition,bottom:maximum right tilt)