An Application of CFD to Recent Ship Stability Problems

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ABSTRACT

Latest CFD techniques are applied to recent ship stability problems to evaluate their ability for advanced stability assessment tool. Firstly the Reynolds-averaged Navier-Stokes (RANS) equation solver of CFDShip-Iowa is applied to the estimation of heel-induced hydrodynamic force in calm water and sway-roll coupling effect in drift condition, which are essential factors for quantitative broaching prediction. Secondly the MPS (Moving Particle Semi-implicit) method is applied to the estimation of damping force of inside water of Anti-Rolling Tank (ART). By combining a computational test by the MPS method with ordinary numerical simulation, the ART performance as a parametric roll prevention device is estimated without any tests using a scaled tank model.

KEYWORDS

Broaching Prediction, RANS Solver, CFDShip-Iowa, Parametric Roll Prevention, Anti-Rolling Tank, MPS Method

INTRODUCTION

The performance-based intact stability criterion is now under discussion at the IMO, and is desired to cover the dangerous phenomena of broaching, which is a great thereat to high speed vessels. However a lot of captive model experiments are required for quantitative broaching prediction as an alternative to existing prescriptive criteria. Free running model experiment is one of the most reliable and direct ways for the ship stability assessment, but it is time- and cost- consuming and cannot be applied in the early design stage. Therefore it is required to develop an advanced numerical prediction technique. For this purpose, we started to develop the CFD-based mathematical modeling for broaching prediction by applying latest CFD technique in place of conventional captive model experiments. The essential factors for quantitative broaching prediction had been demonstrated so far[1)-3)]. By following these outcomes, the capability of the RANS equation solver of CFDShip-Iowa is investigated whether it could be applied to the estimation of these essential factors. As a first step of this direction, towing tests in calm water with constant heel angle and drift angle are selected as the test cases for validation of the code. Since the estimation of these hydrodynamic forces is difficult because free surface and hydrodynamic lift effect should be taken into account appropriately, systematic captive model experiments are usually required for the accurate mathematical modeling. In this study, the CFDShip-Iowa is applied to these two test cases, and compared its results with EFD results.

Parametric rolling is a dangerous phenomenon for conventional ships, which should be covered by the new performance-based criteria as well as broaching. Recently serious accidents due to parametric roll particularly in head seas were reported and its prevention becomes an urgent task. Anti-Rolling Tank (ART) is one of the options to reduce the danger of parametric roll without any change of original hull design, and its effectiveness was confirmed by free running model experiments[4)] and numerical simulations[4)-6).] However, to estimate the performance of ART, damping coefficient of inside water of ART is required for a numerical simulation of parametric roll. Therefore forced or free oscillation tests with a scaled tank model are normally executed. To overcome this drawback, Iglesias et al. tried to represent a forced oscillation test of ART by the Smoothed Particle Hydrodynamics (SPH) method[7)]. In this study, the Moving Particle Semi-implicit (MPS) method is applied to estimate tank water behavior and its damping in place of a free oscillation test. The numerical estimation method with use of MPS method for damping force estimation is developed to evaluate the performance of ART as a parametric roll prevention device without any tank model tests for a practical use.

BROACHING PROBLEM

RANS Solver

This study uses the CFDShip-Iowa[8)] for the numerical tests. CFDShip-Iowa solves the RANS equations using a blended k-ω/k-ε model for the turbulence. The free surface is modeled using a single-phase level set approach, in which the air/water interface is the zero level set distance function. The domain is discretized using multiblock/overset structured grids. The capability of the overset is fully dynamic, which allows simulating large amplitude motions in waves. Numerical methods include a finite differences discretization, with second-order upwind discretization of the convection terms and second-order centered scheme for the viscous terms. The temporal terms are discretized using a second-order backwards Euler scheme. Incompressibility is enforced by a strong pressure/velocity coupling by using PISO. Regular waves are implemented through initial and boundary conditions. The fluid flow equations are solved in an earth-fixed inertial reference system, while the rigid body equations are done in the ship system, so forces and moments are projected appropriately to perform the integration of the rigid body equations of motion, which are solved iteratively. The overset connectivity can be obtained using the code Suggar[9)].

CFD condition

The ONR tumblehome designed as a next generation surface combatant is selected as the subject ship because such high speed vessels are prone to suffer broaching rather than general commercial ships. Principal particulars and the geometry are shown in Table.1 and Fig.1, respectively.

Table.1 Principal Particulars of the subject ship

Items	*Ship*	*Model*
Length: *L*	154.0 m	3.147 m
Breadth: *B*	18.78 m	0.384 m
Depth: *D*	14.5 m	0.296 m
Draught: *d*	5.5 m	0.112 m
Displacement: *W*	8507100 kg	72.6 kg
Longitudinal position of center of buoyancy from midship: *LCB*	2.587m aft	0.053 m Aft
Metacentric Height: *GM*	2.0 m	0.041 m
Block coefficient: *Cb*	0.535	0.535
Radius of gyration in pitch: *Kyy/L*	0.25	0.25

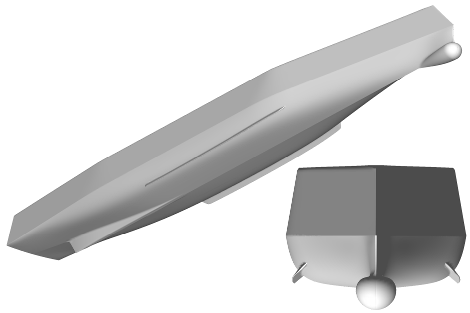


Fig.1 Geometry of the ONR tumblehome

The overset grid design consists of 5 grids as shown in Fig.2. Two double-O boundary layer grids model the starboard and port sides of the hull to solve the asymmetric problem due to heel or drift. Cartesian grid is used as background for the free surface. Since the subject ship has large bilge keels, overset grids to accurately capture its effects are needed. The starboard and port bilge keels use H topology and overset the boundary layer grids.

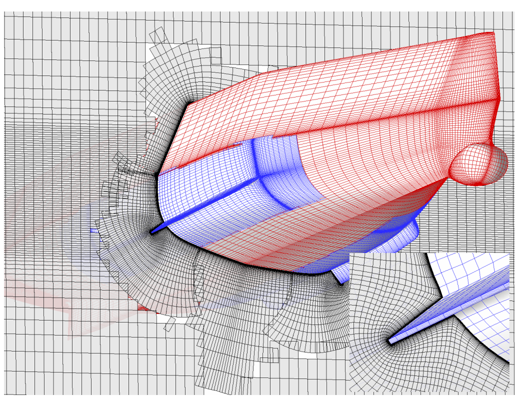


Fig.2 Overset grids

The tests for the validation of the code are that a ship model is towed by a towing carriage in calm water with constant heel angle and drift angle in several Froude numbers. In this study, 10 degrees of constant heel angle and 5 degrees of drift angle are selected as examples. The EFD data was obtained by a captive model experiment with a 1/48.9 scaled model at the towing tank of Osaka University. Surge force, sway force, roll moment and yaw moment are measured by a dynamometer in each case. In this experiment, sinkage and trim are free while other motions are fixed.

Result

The hydrodynamic forces acting on a towed model with 10 degrees of heel angle are measured. Coordinate systems of the measurement are shown in Fig.3. Here roll moment and yaw moment are obtained around the center of ship gravity. The comparison of heel-induced hydrodynamic forces between CFD and EFD are shown in Fig.4. Here CFD results are continuously obtained with the very small acceleration of 0.01 m/sec^2.

CFD result of surge force quantitatively agrees with the EFD one even in a heeled condition up to Fn=0.6. CFD can estimate the values and trends of sway force, roll moment and yaw moment with practical accuracy up to Fn=0.4. This result indicates that CFDShip-Iowa can predict longitudinal and vertical application point of sway force in a moderate speed region. From the EFD result of heel-induced yaw moment, this subject ship might be likely to suffer significant broaching because heeling of a ship induces yaw moment significantly while conventional ships are not so. This characteristic of the ONR tumblehome was confirmed by a free running model experiment[10].

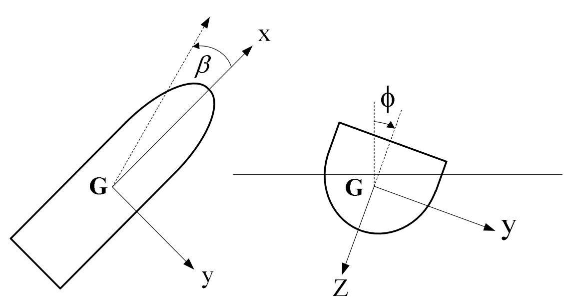
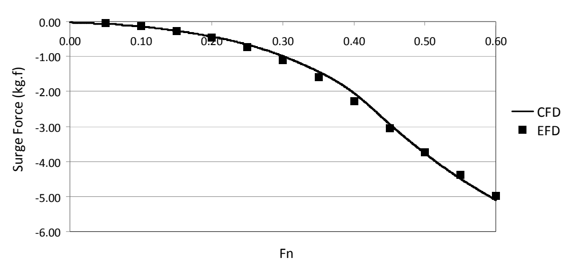


Fig.3 Coordinate systems of the measurement



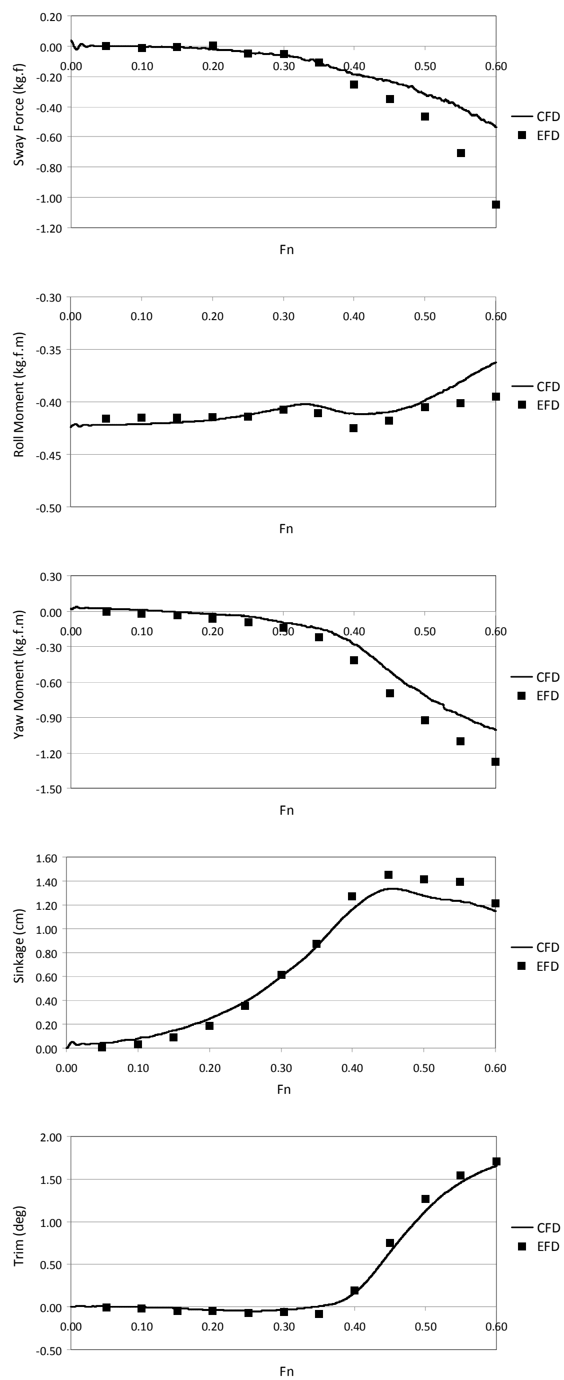
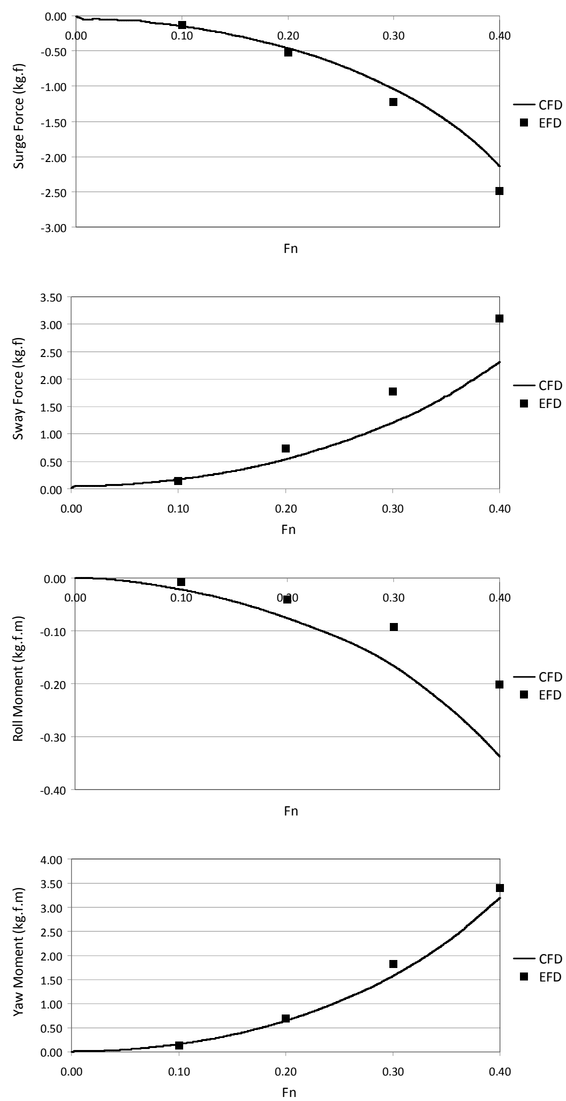


Fig.4 Comparison of hydrodynamic force and attitude in heeled condition between CFD and EFD

The comparisons of hydrodynamic forces acting on a towed ship with 5 degrees of drift angle between CFD and EFD are shown in Fig.5. CFD result is continuously obtained in the same procedure as the heeled condition case.

The CFD results of surge force and yaw moment agree well with the EFD up to Fn=0.4. CFD underestimates the sway force and overestimates drift-induced restoring moment to some extent, but its difference is within acceptable level from a practical point of view. This result indicates that CFD can predict hydrodynamic forces in drift condition qualitatively but further investigations, e.g. flow field measurements and grid studies, are required for quantitative prediction as a future task.



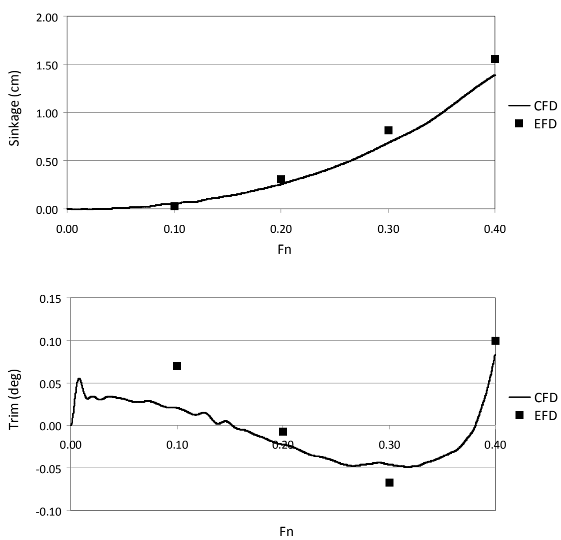


Fig.5 Comparison of hydrodynamic force and attitude in drift condition between CFD and EFD

PARAMETRIC ROLLING PROBLEM

MPS Method

The Moving Particle Semi-implicit (MPS) method was developed by Koshizuka et al.[11)] and was applied to floating body problems by Sueyoshi[12)]. Since fluids are represented by particles in the MPS method, computation grids are not necessary and it can be easily applied to violent flow problem, such as wave breaking. Governing equations are expressed by conservation laws of mass and momentum and Navier-Stokes equation, and they are discretized by particle interaction models. The equation of Lagrangian time differentiation is used, so advection terms are directly incorporated into the calculation by moving particles. Only gravity is considered as the external force. The weight function is used in the particle interaction models. A semi-implicit algorithm is used to simulate incompressibility. For incompressible flow, the fluid density is required to be constant with solving pressure Poisson equation.

CFD and EFD conditions

In this study, a 1/100 scaled tank model was used and principal particulars and definition of ART parameters are shown in Table.2 and Fig.6 respectively.

Free oscillation model test of ART is conducted to obtain damping force of inside water because it is required for a numerical prediction to evaluate ART performance as a parametric roll prevention device while other coefficients are determined from ART dimensions. Free oscillation test is conducted by artificially giving water slope between both side tanks and releasing it at a certain moment. Transient water behavior after releasing was recorded by a video camera, and then damping curve of water slope angle was obtained by simple image analysis.

Table.2 Dimensions of the ART model

	model scale
B_t	420 (mm)
b_t	110 (mm)
L_t	120 (mm)
D_t	variable
W_t	variable

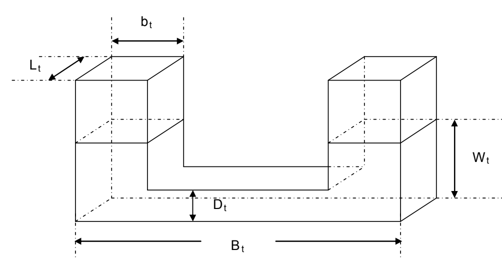


Fig.6 Definition of ART parameters

Mathematical Model

Free running model experiment with the ART model attached to above the upper deck around a longitudinal center of ship gravity of 6600 TEU post-Panamax containership is conducted in regular head waves with wave steepness of 1/30 and wave length to ship length ratio of 1.6. The subject containership was designed by National Maritime Research Institute (NMRI), and principal particulars and body plan of the subject containership are shown in Table.3 and Fig.7, respectively. In the experiment, ship speed is adjusted to satisfy the principal parametric roll condition where roll frequency is a half of encounter frequency. A photograph of the model experiment is shown in Fig.8.

Table.3 Principal particulars of the subject ship

Items	Values
Length between perpendiculars: L_{pp}	283.8m
breadth: B	42.8m
depth: D	24.0m
draught: T	14.0m
block coefficient: C_b	0.630
pitch radius of gyration: K_{yy}/L_{pp}	0.25
longitudinal position of centre of gravity from amidships: X_{CG}	5.74m aft
metacentric height: GM	1.06m
natural roll period: T_ϕ	30.3s

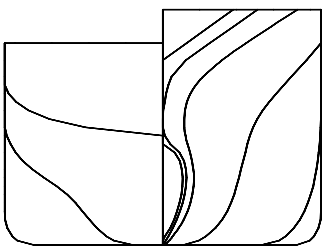


Fig.7 Body plan of the post-Panamax containership

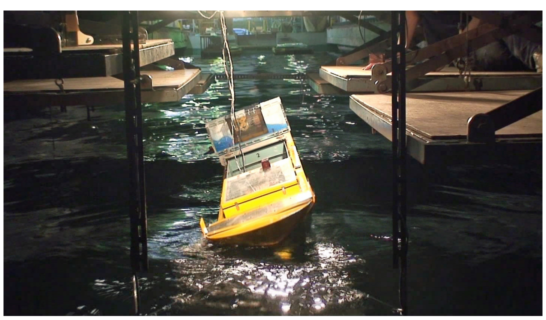


Fig.8 A photograph of model experiment with ART model

Mathematical model for parametric roll prediction for a ship with ART is expressed by Eqs.(1)-(2) as a coupled equation based on the literature[13]. In numerical calculation, roll restoring variation is modeled as GM variation and its amplitude and mean value are obtained from a captive model experiment for 10 degrees of constant heel angle. Linear and cubic coefficients of roll damping are estimated from a roll decay test without ART. Damping coefficient of ART, A_t, was estimated from a free oscillation test of tank model or a numerical test by the MPS method.

$$\left(I_{xx}+J_{xx}\right)\ddot{\phi}+A\dot{\phi}+C\dot{\phi}^3+W\left(GZ+GZ_{wave}\right) + J_{st}\ddot{\theta}+K_t\theta=0 \tag{1}$$

$$J_{st}\ddot{\phi}+K_t\phi+J_t\ddot{\theta}+A_t\dot{\theta}+K_t\theta=0 \tag{2}$$

I_{xx}: moment of inertia in roll, J_{xx}: added moment of inertia in roll, A: linear roll damping coefficient, C: nonlinear roll damping coefficient, W: displacement, GZ: righting arm, GZ_{wave}: wave effect on righting arm, J_t: moment of inertia of tank water, A_t: linear damping of tank water, J_{st}: coupling coefficient between roll and tank water

Result

MPS method is applied to the estimation of damping force of the tank water with 5000 particles as a trial, which equals to 1.5mm distance of each particle. Comparison of transient behavior of tank water between EFD and CFD is shown in Fig.9 and Fig.10. The MPS method can simulate the free oscillation test and predict the natural period and damping curve of ART with sufficient accuracy. CPU time of a numerical test of presented free oscillation is a couple of hours using a normal personal computer. Fig.11 shows the comparison of simulated time history of parametric roll between model experiment and two calculations with a damping coefficient obtained by the MPS method and that by the roll decay test of a ship model with ART. There is negligibly small difference between the two calculations and calculated steady amplitudes are almost same as model experiment. This comparison shows a possibility to design ART as a parametric roll prevention device without any model experiments by combining the MPS method with numerical simulation model.

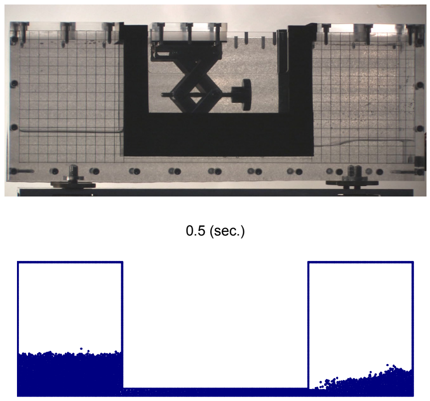


Fig.9 Comparison of water behavior at 0.5 sec. (above: tank model test, below: MPS method)

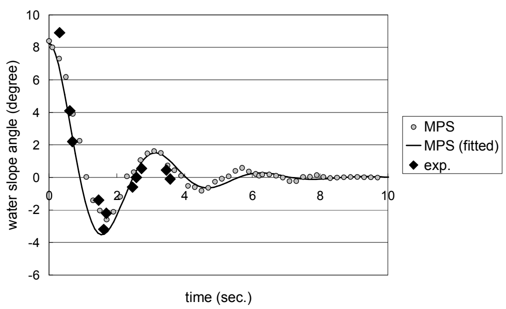


Fig.10 Comparison of damping curve with D_t=7.5mm and W_t=30mm

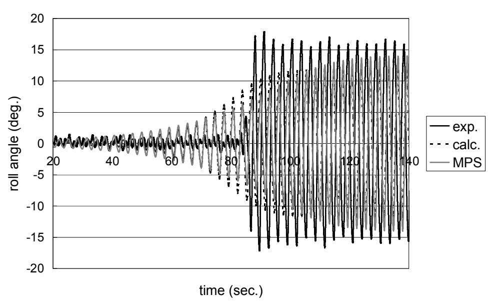


Fig.11 Comparison of time history of parametric roll between model experiment and calculations with H/λ=1/30 and λ/L=1.6

Furthermore the threshold of parametric roll is calculated by proposed numerical prediction with help of the MPS method for determine of the minimal tank water volume for parametric roll prevention as shown in Fig.12. As a result, 29mm of tank water level is critical for the subject ship and wave condition, and its weight is 0.9% of ship displacement.

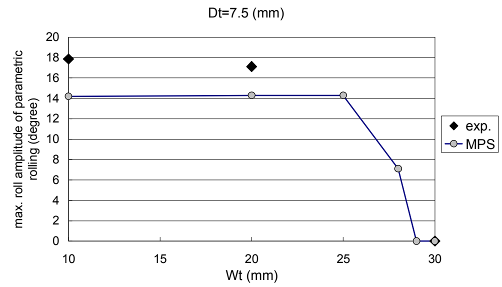


Fig.12 Comparison of threshold of parametric roll between model experiment and calculation with use of MPS method

CONCLUSION

The comparisons of the heel-induced and drift-induced hydrodynamic forces between CFD and EFD are demonstrated as a first trial for realizing the advanced broaching prediction. As a result, the RANS solver code of CFDShip-Iowa can estimate heel-induced and drift-induced hydrodynamic forces with practical accuracy. Further investigations on wave-exciting force and wave effect on hydrodynamic force in following and quartering waves, which are also known as essential factors for quantitative broaching prediction, are desired for the total validation of the code.

Applicability of the MPS method to the estimation of ART performance for parametric roll prevention is investigated. As a result, Tank water period and damping force, which are important parameters for ART design, can be estimated almost quantitatively. Numerical prediction method with use of the numerical free oscillation test of ART by the MPS method is developed and can predict experimental result of parametric roll. Finally optimization of tank water volume is demonstrated for the subject post-Panamax containership as example.

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