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Numerical Simulation Method for a Coupling Motion of Ship and Tank Fluid

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1. Introduction

It is an important issue to accurately estimate a dynamic coupling effect between ship motion and fluid behavior inside a ship, for sloshing problems of LNG carriers or FPSOs, safety assessment of damaged ships with flooding from a damage opening, capsizing prevention of small vessels with deck wetness and trapped water on deck etc. To obtain a reliable solution for these nonlinear coupling problems, an advanced numerical simulation method is required, which can predict dynamic coupled motions of ship and tank fluid with nonlinear coupling effects taking into account.

For this purpose, the authors developed a hybrid numerical simulation method for coupled motions of ship and tank fluid by combining the MPS (Moving Particle Semi-implicit) method [1], which is a mesh-less CFD scheme and can treat a significant deformation of fluid, and an ordinary prediction technique of ship motion utilizing differential equations of ship motion expressed with hydrodynamic forces calculated by a potential theory. The procedure of time marching in this simulation is as follows. Firstly tank fluid behavior at certain time step is calculated and the pressure distribution in a tank is obtained. Then a coupling force is estimated by integrating a local pressure at each boundary particle along with an inner face of tank wall. Then a ship motion is predicted by numerical integration of a differential equation of ship motions considering the estimated coupling force as an external force. Displacement of wall particles due to the ship motion is calculated, and it is given to the MPS computation. By solving the ship and fluid motions simultaneously, a coupled motion can be simulated in time domain as a nonlinear solution. As a first step, the roll motion of a ship with a water tank is treated in this research. Here a 2-dimensional shape tank is assumed for neglecting 3-dimensional effects.

2. Coupling Forces from Fluid in a Tank to Ship Motion

Firstly series of forced roll motion tests of the water tank (rectangular and U-type) were carried out with various roll amplitudes, roll periods, heights of center of rotation, water levels and tank shapes etc., to examine the applicability of the MPS method for estimating the dynamic coupling effect from tank fluid to ship motion. Calculated results of coupling forces and moment by the MPS method are compared with experimental results as shown in Figs.1-2. Principal dimensions of the tank model are; length of 0.12m, breadth of 0.42m, and water height of 0.04m. These comparisons indicate that the MPS method can well calculate the coupling force both in magnitude and its phase even in large amplitude oscillation condition. Comparisons of a fluid behavior are shown in Figs.3-4, and they demonstrate the MPS method well reproduces water behavior for both tanks.

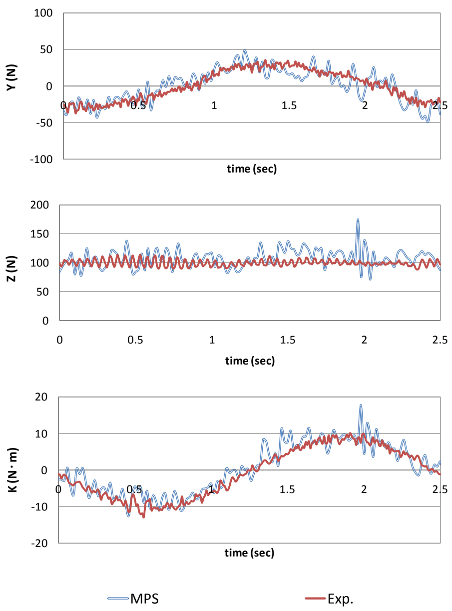

Fig.1 Comparison of the coupling force for a rectangular tank with ϕ_a=15deg. and T_ϕ=2.5sec.

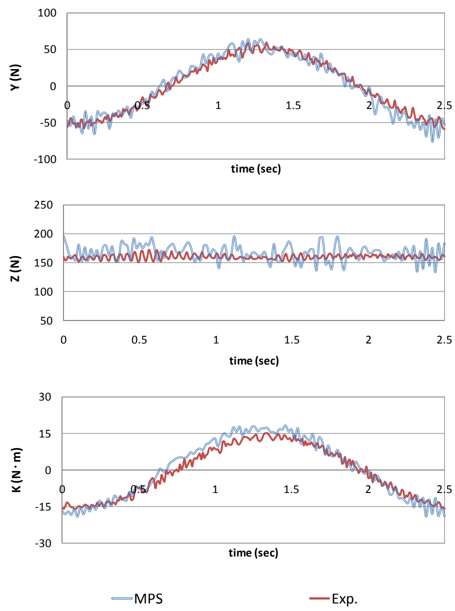

Fig.2 Comparison of the coupling force for a U-type tank with ϕ_a=15deg. and T_ϕ=2.5sec.

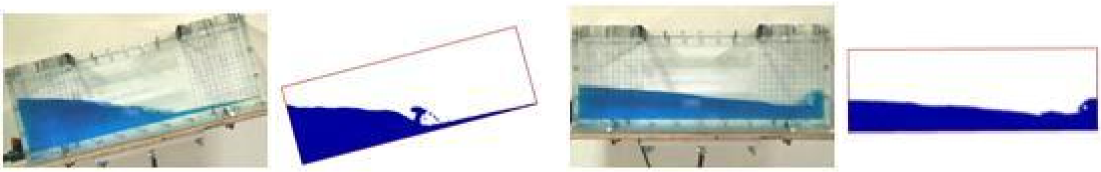

Fig.3 Comparison of water behavior between model experiment and MPS method for a rectangular tank

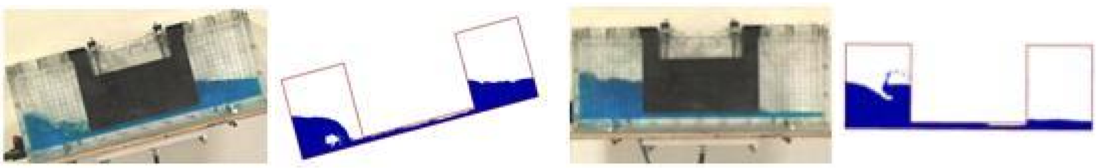

Fig.4 Comparison of water behavior between model experiment and MPS method for a U-type tank

3. Coupled Motions of Ship and Tank Fluid

Secondly model experiments were conducted to measure roll motion of the ship equipped with rectangle or U-type tank. Free roll decay test in calm water and a roll motion measurement in head seas were conducted. In head sea condition, a special wave condition (ω_ϕ=1/2ω_e) was given to observe large amplitude roll motion, so called parametric roll. Ship motions were measured by an onboard gyro scope and a tank water behavior was done by a HD video camera. Model tests were conducted with and without tank water in roll decay test to examine how much does coupling effects affect on a ship roll motion.

The comparisons of time history of roll decay test with/without tank water are shown in Fig.5, and tank water behaviors are done in Fig.6. Here differential equation of ship roll motion, which is expressed by Eq.(1), is solved by the Euler method, and the total number of particles is about 8,000. Time interval for the calculation is 0.0002 sec. In case with tank water, roll period becomes longer due to the free water effect and damping rate does larger because tank water acts like an anti-rolling tank. Numerical simulation reproduces this experimentally confirmed trend with practical accuracy.

$$(I_{xx} + J_{xx})\ddot{\phi} + K_{\dot{\phi}}\dot{\phi} + K_{\dot{\phi}^3}\dot{\phi}^3 + W \cdot GZ = M_{coupling} \qquad (1)$$

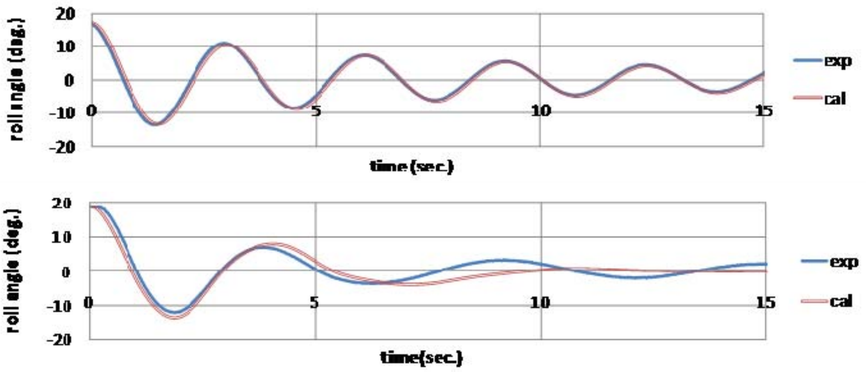

Fig.5 Comparison of time history of roll angle between the measured and calculated results

(above: roll decay test without tank water, below: roll decay test with tank water)

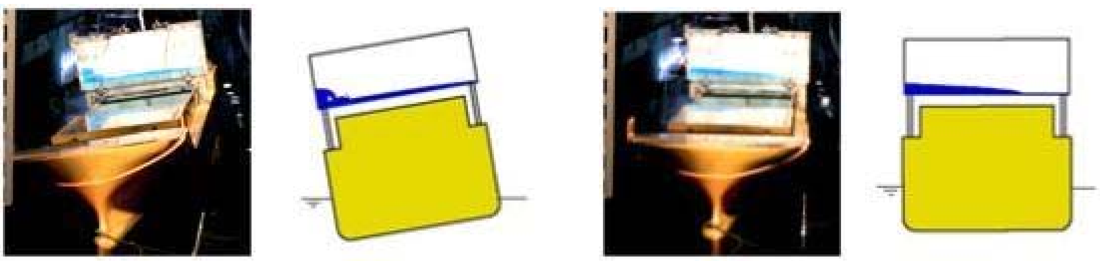

Fig.6 Comparison of tank water behavior in roll decay test at t=1.9sec (left) and t=2.9 sec (right)

The comparison of a time history of parametric roll with tank water is shown in Fig.7, and water behavior is done in Fig.8. In this case, Eq(2) is used for describing ship roll motion. Here the mean and amplitude of GM variation are estimated by a 3DOF of heave-roll-pitch model [2]. Large amplitude of parametric roll is predicted by the numerical simulation with practical accuracy and violent transformation of free surface, running up of water along the side wall of tank, is also well reproduced.

$$(I_{xx}+J_{xx})\ddot{\phi}+K_{\dot{\phi}}\dot{\phi}+B_{\dot{\phi}^3}\dot{\phi}^3+W\cdot GZ+W(GM_{mean}+GM_{amp}\cos\omega_e t)\phi=M_{coupling} \quad (2)$$

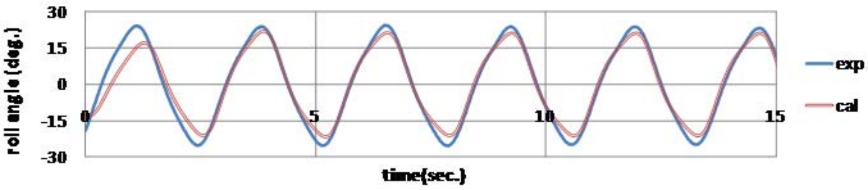

Fig.7 Comparison of time history of roll angle between the measured and calculated results

(parametric roll; regular head seas with λ/L=1.0, H/λ=0.04)

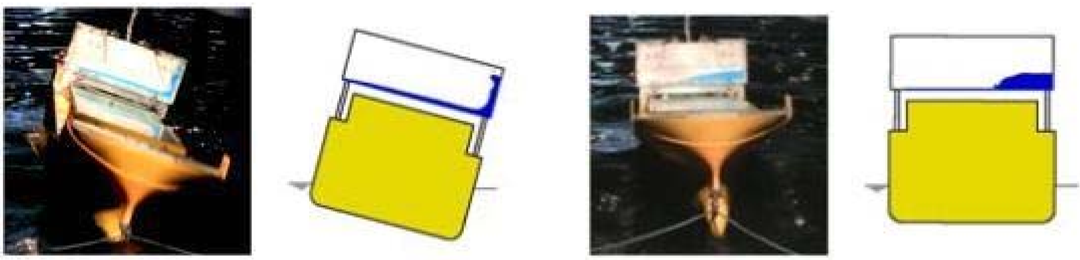

Fig.8 Comparison of tank water behavior in parametric roll at most heeled and upright conditions.

4. Conclusions

Numerical simulation method for coupled motions of ship and tank fluid was developed, which calculate fluid behavior by the MPS method and ship motion by solving differential equations of ship motion with nonlinear coupling effects from tank water to ship motion taken into account. Validation of the MPS method for estimating a coupling force is conducted by comparing with systematic forced roll motion tests, and its' prediction accuracy is satisfactory even for the case with large amplitude oscillation. Finally the proposed hybrid method is validated by comparing numerical results of roll decay and parametric roll equipped with a rectangular tank with experimental result, and it is concluded the proposed method can reproduce a strongly coupled ship roll motion with violent deformation of free surface. This simulation method could be a powerful tool for the problems that a strong/nonlinear interaction between floating bodies and fluid inside is significant.

References

1. Koshizuka, S. and Oka, Y.: Moving Particle Semi-implicit Method for Fragmentation of Incompressible Fluid, Nuclear Science and Engineering, Vol. 123, 1996, pp 421-434.
2. Hashimoto, H. and Sanya Y.: An Investigation on Quantitative Prediction of Parametric Roll in Regular Waves (in Japanese), Journal of the Japan Society of Naval Architects and Ocean Engineers, Vol.10, 2009, pp.65-71.