The Numerical Study on the Coupled Dynamics of Ship Motion and Flooding Water

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ABSTRACT

This paper presents a numerical method to solve the ship motion with internal fluid. Physically the internal fluid is coupled with the ship motion. Hitherto the numerical results of the coupled motion predict the general tendency with experiments. The main reason of inaccuracy is that the coupled dynamics of ship motion and internal water motion is not accurately accounted.

In this study CFD technique based on VOF is employed for the accurate analysis of flooding water motion. Some cases of ITTC benchmark study for tanker with internal fluid are analyzed by coupling the ship motion and sloshing dynamics.

Keywords: *damaged stability, coupled dynamics, flooding water motion, CFD*

1. INTRODUCTION

Many efforts have been made for the research on damaged stability and amendment of regulations in association with ship safety. Damaged stability is a very important design parameter for RORO-passengers and naval vessels for which crews and passenger's safety is the most important requirement for design. ITTC organized the special committee for ship stability and has been carrying out the international benchmark study. Up to the present the numerical results predict the general tendency of the damaged ship motion with experiments (Papanikolaou, 2005). The most researches (Letizia, 2004, Palazzi, 2004, and Spanos, 2002) on the flooding water dynamics used the hydraulic model that regards the flooding water as a lumped mass. Such a quasi-static modelling has the advantages of the flexibility of modelling and the simplicity of implementation for various conditions. But this approach is inaccurate when the flooding water is coupled with the ship motion. The reason is that the numerical methods consider the flooding water having its free surface continuously horizontal and could not capture the flooding water dynamics properly. The way to improve the accuracy is that calculate directly the free surface motion of internal water using CFD technique. But it is considered more expensive than modelling method (Spanos, 2002). Recently advances of computer technology and numerical method for free surface analysis have made it possible to use the CFD method simulating the coupled dynamics. The study on the coupled dynamics using CFD is relatively not in mature status. The studies have been introduced a few decades ago, e.g. Kim (2002), Spanos (2002), Rognebakke (2003).

In this study CFD technique based on VOF is employed for the accurate analysis of internal water motion. The accuracy of CFD method is validated by comparing the results of sloshing problem with the experimental results. Some cases of ITTC benchmark study for tanker with internal water are analyzed by coupling the ship motion and sloshing dynamics. The ship motion is solved in time domain by taking account of memory effects.

2. THE NUMERICAL SIMULATION METHOD

2.1 Ship motion

To analyze fluid field, velocity potential is introduced and boundary value problem is formulated. As a scheme for solving boundary value problem, high order boundary element method (HOBEM) is applied. Choi et al. (2000) showed that the results of HOBEM are accurate and convergent.

The radiation condition is expressed as below ;

$$\frac{\partial \phi_j}{\partial n} = -i\omega n_j \quad \text{on mean wetted surface} \qquad (1)$$

In above equation, j is counted from 1 to 6 and generalized directional cosine (nj) is expressed as directional cosine of rigid body motions.

The boundary condition of diffraction problem is next.

$$\frac{\partial \phi_S}{\partial n} = -\frac{\partial \phi_I}{\partial n} \quad \text{on mean wetted surface} \qquad (2)$$

With help of Green’s second identity, the velocity potentials are solutions of boundary integral equation. Discretization of integral equation is performed using bi-quadratic 9 node quadrilaterals and 6 node triangular elements. More details are given in Choi et al. (2000)

Time domain equation can be obtained by Cummins (1962)

$$\begin{bmatrix} M_{11}+m_{11} & \cdots & m_{16} \\ \vdots & \cdots & \vdots \\ m_{61} & \cdots & M_{66}+m_{66} \end{bmatrix} \begin{Bmatrix} \ddot{\vec{x}}_1 \\ \vdots \\ \ddot{\vec{x}}_6 \end{Bmatrix} + \begin{bmatrix} \int_0^t R_{11}(t-\tau)d\tau & \cdots & \int_0^t R_{16}(t-\tau)d\tau \\ \vdots & \cdots & \vdots \\ \int_0^t R_{61}(t-\tau)d\tau & \cdots & \int_0^t R_{66}(t-\tau)d\tau \end{bmatrix} \begin{Bmatrix} \dot{\vec{x}}_1 \\ \vdots \\ \dot{\vec{x}}_6 \end{Bmatrix} + \begin{bmatrix} C_{11} & \cdots & C_{16} \\ \vdots & \cdots & \vdots \\ C_{61} & \cdots & C_{66} \end{bmatrix} \begin{Bmatrix} \vec{x}_1 \\ \vdots \\ \vec{x}_6 \end{Bmatrix} = \begin{Bmatrix} \vec{F}_1 \\ \vdots \\ \vec{F}_6 \end{Bmatrix} \qquad (3)$$

where m denotes ship mass matrix, m the added mass matrix at infinity frequency, R the retardation function (memory function) matrix, C the hydrostatic restoring coefficient matrix, F the external force vector and x the motion vector. Subscript denotes the mode number. External force vector F includes wave exciting force, drift force, current force, wind force, sloshing force of internal flow. Hamming method (Hornbeck, 1975) is used for the integration of equation of motion in time domain. The details of the present numerical methods can be found in Hong et al. (2005).

2.2 Internal Water Motion

To calculate the internal water motion, we adopt the CFD method based on VOF (Volume Of Fluid). The used VOF method is developed to simulate the free surface around the ship in MOERI (Park, 2005). The VOF method is modified to calculate the sloshing motion and validated by comparing the results of sloshing problem with the experimental results (Hadzic, 2001).

The continuity and momentum equation is as follows.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{4}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + f_i \tag{5}$$

where u_i is the velocity vector, p the static pressure, τ the viscous stress tensor and f_i the body force term.

The cell-centered finite volume method is utilized to discretize the governing equations. The convection terms are discretized using the MUSCL (Monotonic Upstream Centered Scheme for Conservation Laws) of third order and the central difference scheme is used for the diffusion terms. The Euler implicit method is adopted for the time integral. To ensure divergence-free velocity field, the SIMPLEC method is employed. The details of the present numerical methods can be found in KIM et al. (2002).

2.3 Sloshing problem

The VOF method is modified to calculate the 6 dof sloshing motion of internal water. To validate the method, compared the numerical results with the experiment results (Hadzic, 2001). Figure 1 shows the results of sway sloshing motion and Figure 2 the results of roll sloshing motion. The results are very accurate. Through this sloshing test, we confirmed the accuracy and the possibility of CFD method for coupled analysis.

2.4 Coupling Problem

To couple the ship motion and the sloshing motion, a sloshing force can be added into the equation of motion. The coupled scenario is shown in Figure 3. The motions of ship affect the internal water and the sloshing forces act on the ship as external forces. This interaction is considered simultaneously by coupling.

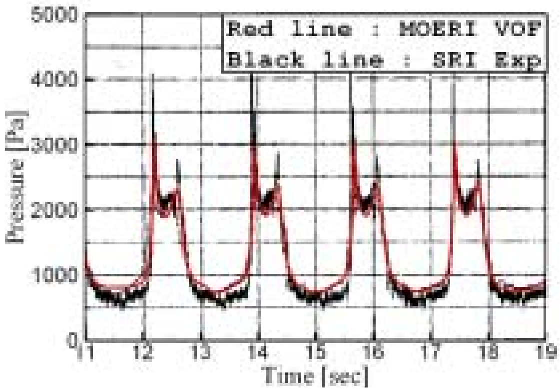

Figure 1 Result of sway sloshing motion

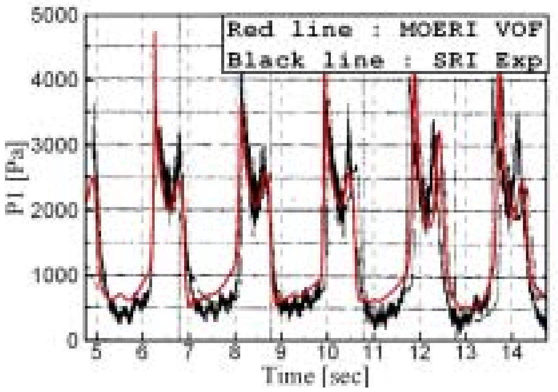

Figure 2 Result of roll sloshing motion

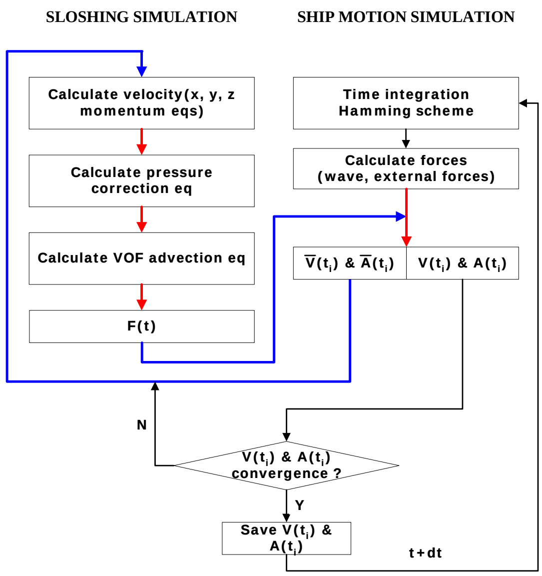

Figure 3 Flow chart of coupling

3. ITTC NUMERICAL STUDIES

ITTC organized the special committee for ship stability and has been carrying out the international benchmark study from 2003. The benchmark studies are composed of four tests and Test C is the free roll decay about flooding water motion and its effects (Papanikolaou, 2005). Test ship is 200 kDWT tanker and the model test has been carried out at MARIN. The particulars of the tanker are given in Table 1 and in Figure 4. The tanker was equipped with a compartment containing water; the length is 82.5 m and width 31.76 m. The cases of Test C are following.

Intact ship (6 deg)

Fluid level: h=1 m-sub-resonant (3 deg)

Fluid level: h=4 m-resonant (5 deg)

Fluid level: h=16 m-no sloshing (6 deg)

Table 1 Particulars of tanker

Length, Lpp (m)	310.2
Beam, B (m)	47.2
Draft, T (m)	16.0
Depth, D (m)	26.07
Displaced weight (tf)	202600
KG (m)	10.0
GM (m)	9.50
Natural roll period (sec)	10.0
Length of compartment (m)	82.5
Width of compartment (m)	31.76
Compartment height above baseline (m)	5.20

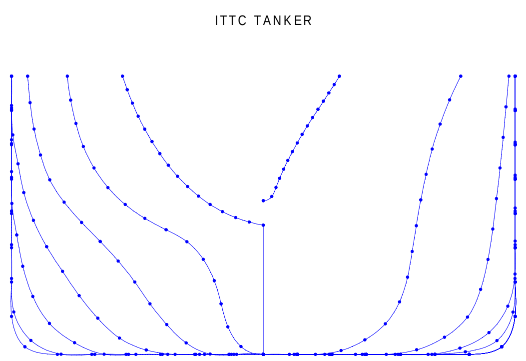

Figure 4 Lines of tanker

4. NUMERICAL RESULTS

The numerical calculations are carried out for 4 conditions. Each result is presented from Figure 7 to Figure 10. The sloshing motions is solved using 2D grid to save the simulation time and to ensure the convergence of grid and time step performed the tests for 2 grids (W×H: 130×70, 100×50) and time steps (dt = 0.005, 0.001 sec). Figure 5 shows the panel for ship motion analysis and Figure 6 shows the instantaneous flow of sloshing motion.

The 6 dof motions of ship and 6 forces of sloshing are calculated. Physically all components of motion and force interact each other. But the roll, sway and the roll moment of sloshing are dominant for roll motion. In this study the roll moment and sway force of sloshing is coupled with the motion of ship.

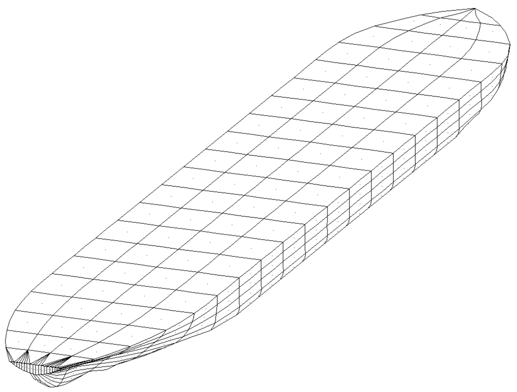

Figure 5 Panel for ship motion analysis

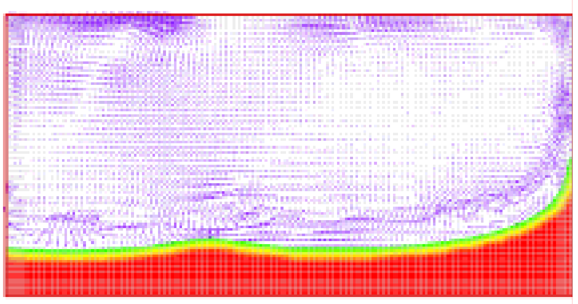

Figure 6 Instantaneous flow for h= 4m condition (t=22.5 sec)

- Intact condition (Figure 7)

The simulation result agrees well with the experiment.

• Sub-resonant condition (Figure 8)

The result of coupled analysis shows the sub-resonant dynamics. But the period and amplitude of roll is different to experiment result. It is regarded that the reason of discrepancy is the different condition of experiment and simulation. In experiment the free surface and added water change the metacenter and hydrostatic property but in simulation such changed situation is not treated yet.

• Resonant condition (Figure 9)

The result of coupling is very close to experiment and shows the resonant dynamics. The coupled method to fully simulate the sloshing motion presents good results than the modelling method of ITTC benchmark study. The result considering roll moment and sway force is more accurate than that including roll moment. It is needed to calculate the sway force and roll moment for accurate analysis of the coupled motion of roll

• No-resonant condition (Figure 10)

The result of no-resonant is different to the experiment. There can be many reasons of this discrepancy. In this case the amount of internal water is 21 % of the displacement. The added mass and free surface change the hydro-property (center of gravity, inertia etc). It is thought that the coupling analysis does not include the changed condition. Also the more accurate calculation of sloshing is needed.

• Computing times

The CFD technique is expensive than the modelling method. The computing time required to simulate the internal water is reported by Spanos (2002).

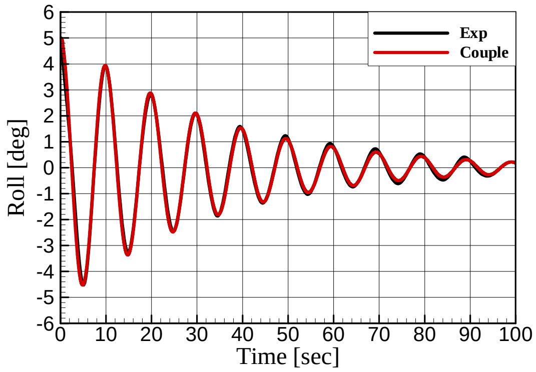

Figure 7 Free decay of intact case

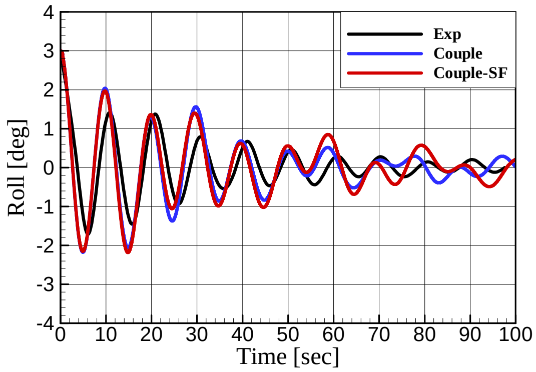

Figure 8 Free decay of sub-resonant sloshing

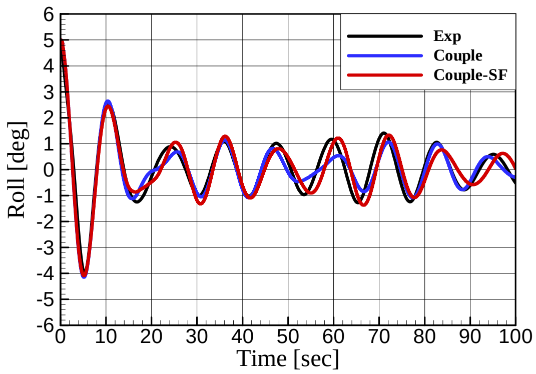

Figure 9 Free decay of resonant sloshing

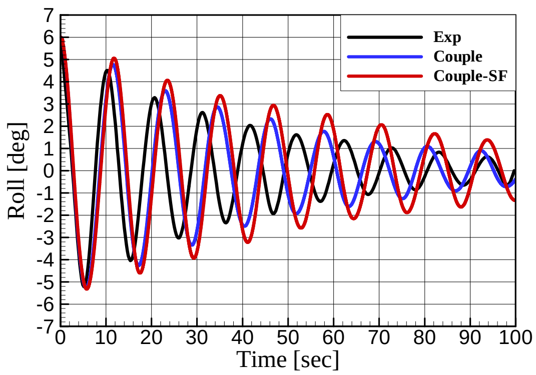

Figure 10 Free decay of no-resonant sloshing

Recently the computer technology advances and computing time decreases. Table 2 shows the required time of the motion simulation. The time decreases significantly.

Table 2 Computing times

Code	CPU Time/Simulation Time
CAPSIM	0.33
NTUA-CFD	3440
CPU	Alpha 64 bits 500 Mhz
MOERI-CFD	108
CPU	Intel Pentium 4 3.4 GHz

5. CONCLUSIONS

The coupling effect between ship motions and internal water has been investigated for ITTC benchmark study. Based on the present study, the following conclusions are made.

- Confirmed the accuracy and coupling possibility of the CFD method based on VOF by comparing the sloshing test results.
- Coupling of ship motion and sloshing module.
- Coupled numerical simulation for ITTC benchmark study (TEST C)
- For resonant case, coupled analysis is accurate. In roll motion, must consider the roll moment and sway force.
- For no-resonant case, the results are inaccurate. When the sloshing motion is weak, the present method cannot accurately predict the changed condition due to the internal water. More research is needed to correct the defect.
- Due to the advanced computer, the computing time to simulate the coupling motion decreases significantly. This required time is acceptable to simulate the damaged ship motion.

6. ACKNOWLEDGMENTS

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