Evaluation of Hydrodynamic Performance of a Damaged Ship in Waves

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ABSTRACT

Importance of performance evaluation of a damaged ship in waves has been widely recognized from experiences on accidents of damaged ships which resulted in loss of passengers, crews and ships. Requirements for the evaluation methods for hydrodynamic performance of a ship in damaged condition are time-effectiveness and physically reliable modelling which are essential for finding solutions of highly complicated problems under emergency situations. Three different kinds of numerical analysis methods are investigated to evaluate the performance of damaged ships for various aspects of design and analysis purposes. Numerical and experimental examples are shown for typical behaviours of damaged ships such as free-roll-decay motion, coupled roll motion with flooded water, time-to-flood and wave loads on damaged ships.

KEYWORDS

Damaged ship stability, Ship motion, Dynamics of flooded water, time-to-flood, and wave loads on damaged ship,

INTRODUCTION

Performance of damaged ship in waves is one of important design considerations for assurance of safety of passengers and crews and structural integrity. Performance parameters of damaged ships can be categorized into two types: hydrodynamic and structural problems. Hydrodynamic problem includes analysis of behaviour of damaged ships coupled with flooded water such as estimation of motion response in waves, time-to-flood which have been considered as important factors especially for passenger ships. Methodology adopted for structural safety of damaged ship is almost identical to that for intact ship design except for estimation of wave loads considering damaged condition. While estimation of wave loads considering flooded water dynamics inside ship hull and defect of structural property due to hull damage has not been rigorously considered so far.

Assessment of damaged stability is very complicated since the physical phenomena associated with the behaviour of damaged ships are essentially highly nonlinear and implementation of rigorous approach on that problem is still very limited in spite of rapidly increasing computing power. Basically behaviour of damaged ship in waves is equivalent to that of mass-spring-damper system with time-variant coefficients. There have been several levels of numerical methods for analysis of hydrodynamic performance of damaged ships for solving equations of ship motions and flooded water dynamics. Simplified approaches based on empirical modelling which have been widely accepted due to its simplicity, seem to be most popular for practical purposes in spite of recent rapidly growing full CFD technologies.

In the present paper, three different analysis methods developed for the framework of performance evaluation of damaged ship are described with numerical examples. The first one is a simplified method which adopts so called linear Volterra model for describing wave frequency motion in time-domain, in which Froude-Krylov nonlinearity is included for considering instantaneous wetted surface effect while hydraulic model is employed for flooded water effect in the compartment of a damaged ship. This model is mainly applied to real-time simulation of a ship in damaged condition such as time-to-flood and transient motion at the initial stage of damage.

The second method is similar to the first one except considering dynamics of flooded water. A CFD method is used for flooded water dynamics inside damaged compartment. 3-D HOBEM is used for hydrodynamic forces for solving ship motion.

The third one is developed for evaluation of wave loads under damaged condition in frequency domain. Dynamic effect of flooded water is considered by matching the inner flow and outer flow. Wave Green function is used for describing ship motion while Rankine source is used for analyzing inner flow.

Applicability of the three methods has been investigated both by numerical examples and experimental results.

NUMERICAL ANALYSIS METHODS FOR DAMAGED SHIP IN WAVES

A Quasi-static Model for Flooded Water

Under an emergency situation such as water ingress due to damage of hull, it is very important to make prompt countermeasures based on the timely prediction for safety assurance of passengers. For this purpose, time-effective and physically reasonable model is needed. Most of time efficient time-domain ship motion simulation methods are based on Cummins model(1962) in which transient ship motions and memory effects are treated efficiently using transformation of frequency-domain analysis results. Behaviour of flooded water inside damaged compartment is complicated in nature. In this quasi-static model a simplified hydraulic model is adopted for describing motions of the flooded water in which water flux is estimated by hydrostatic pressure considering orifice effect.

Common features of this kind of model are as follows; Potential flow 2-D(or 3D) theory is adopted for hydrodynamics of ship motion, Froude-Krylov force for nonlinear effect of wave force. Memory effect is considered using retardation function obtained from inverse Fourier transformation of damping coefficient. Roll viscous damping is included using semi-empirical formula. Behaviour of flooded water is treated quasi-statically; amount of flooding water is estimated by simple hydraulic formula. Summary of the present simplified model is presented in Table 1(ITTC 2005). Details of this method could be found in Lee et al.(2007).

Table 1 Description of the quasi-static model

Numerical methods	*Description*
Ship motion degrees of freedom	6
Hydrostatic forces by direct pressure integration	Yes
Potential strip theory	Yes
Potential 3D panel method	No
Incident wave forces by direct pressure integration	Yes
Memory effects	Yes
Semi-empirical roll viscous damping	Yes
Floodwater assumed as a horizontal free surface	Yes
Floodwater assumed as moving plane free surface	No

Internal water motion by shallow water equations	No
Flooding by simple hydraulic model	Yes

This model is applicable to prediction of behaviours of damaged ship such as transient ship motion responses, time-to-flood and wave loads considering nonlinear wave forces and flooded water simultaneously. Validation of this model has been carried out through ITTC comparative studies for free-decay roll motions and time-to-flood.

Dynamic Model for Flooded Water

To analyze fluid field, velocity potential is introduced and boundary value problem is formulated based on generalized mode concept. As a scheme for solving boundary value problem, a higher-order boundary element method (HOBEM) is applied. Hong et al. (1999) showed that the results of HOBEM are more accurate and convergent than constant panel method. For multi-body interactions, the concept of generalized mode is used (Choi et al., 2002). The irregular frequencies are removed with additional distribution of dipole on the interior water plane (Hong, 1987). The bi-quadratic 9 node quadrilaterals and 6 node triangular elements are used for discretization of hull surfaces. The hydrodynamic forces are calculated by integrating hydrodynamic pressure on each body surface (Pinkster, 1976). Time domain equation for multi-body can be obtained by expanding the transient equation of single body (Cummins, 1962). The details of the present methods can be found in Hong et al. (2005).

$$\begin{bmatrix} M_{11}+m_{11} & \cdots & m_{1N} \\ \vdots & \cdots & \vdots \\ m_{N1} & \cdots & M_{NN}+m_{NN} \end{bmatrix} \begin{Bmatrix} \ddot{\vec{x}}_1 \\ \vdots \\ \ddot{\vec{x}}_N \end{Bmatrix} + \begin{bmatrix} \int_0^t R_{11}(t-\tau)\dot{\vec{x}}_1 d\tau & \cdots & \int_0^t R_{1N}(t-\tau)\dot{\vec{x}}_N d\tau \\ \vdots & \cdots & \vdots \\ \int_0^t R_{N1}(t-\tau)\dot{\vec{x}}_1 d\tau & \cdots & \int_0^t R_{NN}(t-\tau)\dot{\vec{x}}_N d\tau \end{bmatrix} + \begin{bmatrix} C_{11} & \cdots & C_{1N} \\ \vdots & \cdots & \vdots \\ C_{N1} & \cdots & C_{NN} \end{bmatrix} \begin{Bmatrix} \vec{x}_1 \\ \vdots \\ \vec{x}_N \end{Bmatrix} = \begin{Bmatrix} \vec{F}_1 \\ \vdots \\ \vec{F}_N \end{Bmatrix} \quad (1)$$

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 is used for the integration of equation of motion in time domain.

To calculate the internal water motion in LNG containments, we adopt a CFD method based on VOF (Volume of Fluid). The VOF method has been developed to simulate the free surface around the ship in MOERI (Kim et al., 2002). The VOF method is modified to calculate the sloshing motion and validated by comparing the results of sloshing problem with the experimental results (Hadzic et al., 2001; Cho et al., 2006). The continuity and momentum equations are as follows.

$$\frac{\partial u_i}{\partial x_i} = 0\,,\quad \frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + f_i \quad (2)$$

$$f_i = \vec{g} - \frac{d\vec{u}}{dt} - \frac{d\vec{\omega}}{dt}\times\vec{r} - 2\vec{\omega}\times\vec{u} - \vec{\omega}\times(\vec{\omega}\times\vec{r}) \quad (3)$$

where u_i is the velocity vector, p the static pressure, τ_{ij} the viscous stress tensor ω the angular velocity, r the position vector and f_i the body force term including the sloshing exciting force. The body force consists of the gravitational force, translational and rotational forces.

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 integration. To ensure divergence-free velocity field, the SIMPLEC method is employed. The details of the present methods can be found in Kim et al. (2002).

To couple the ship motion and the sloshing directly, the sloshing force is added into the equation of motion as an external force. The coupled scenario is shown in Fig. 1. The motions of ship excite the internal water and the sloshing forces act on the ship as external forces. This interaction is considered through iterations. In this study the sway and roll motion of ship and the sway force and roll moment of sloshing are considered. The result of coupled analysis was validated through comparison with experiments(Cho et al., 2006).

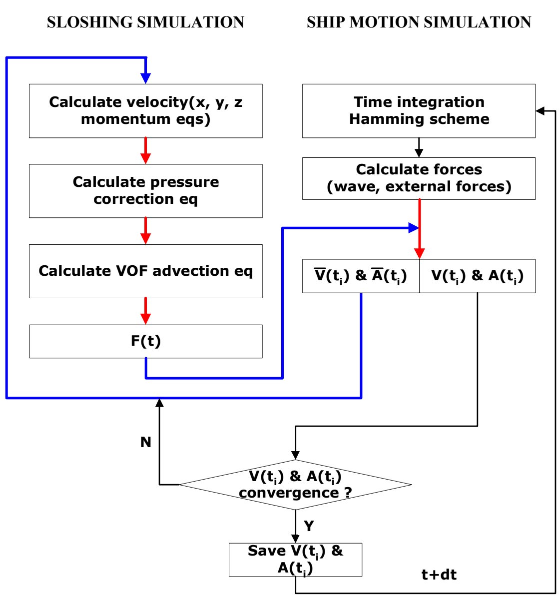


Fig. 1: Flow chart of coupling analysis of ship motion and sloshing

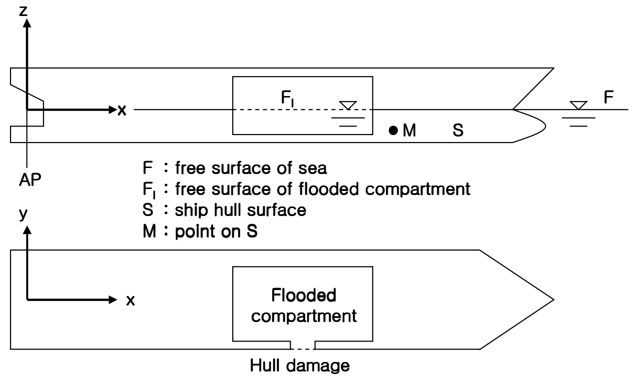


Fig. 2: Coordinate system of flooded ship

Wave Loads on a Damaged Ship

In order to evaluate the wave loads on a ship with flooded compartments, it is assumed that the ship is in a new equilibrium position after the damage. Then the frequency domain approach is applicable to solve equation of ship motion coupled with dynamic behaviours of flooded water. Velocity potential is introduced to describe fluid motions and boundary integral equation is formulated to solve the boundary value problem associated with ship motions in waves and fluid motions inside flooded compartments.

Solutions of radiation and diffraction problems are influenced by irregular frequencies when they are obtained using Kelvin type Green function. In case boundary problems are coupled with inner free surface problem of flooded water, special care should be made for the solutions to be free from irregular frequencies. The present study used the procedure by Hong (1987) to get the solution of integral equation. Velocity potentials inside the flooded compartment can be calculated by the integral equation using Rankine type Green function. Flow in flooded compartment and outside flow share the same surface in the damaged part. Therefore, the matching conditions such as $\psi = \psi^I$ and $\partial\psi/\partial n = \partial\psi^I/\partial n$ are introduced in the damaged part, where ψ and ψ^I are velocity potentials for ship motions and flooded water respectively.

Now, ship motions are calculated by solving the following equation

$$\rho a_0 \omega^2 L^3 \sum_{q=1}^{6} \left\{ \frac{\Delta}{L^3} I_{pq} + M_{pq} + iB_{pq} + M^I_{pq} - \frac{1}{k_0 L}(R_{pq} + R^I_{pq}) \right\} a_q = -\rho a_0 \omega^2 L^3 F_p, \ \ p = 1,2,\cdots,6 \quad (4)$$

where ρ is water density, Δ is displacement, I_{pq} is mass matrix and F_p is wave exciting force. M_{pq}, B_{pq} and R_{pq} are added mass, radiation damping and restoring spring due to fluid flow around the ship, respectively. M^I_{pq} and R^I_{pq} are added mass and restoring spring due to fluid flow in the flooded compartment. Details of the equations are given in Hong and Hong(2005).

NUMERICAL RESULTS AND DISCUSSIONS

Free Roll Decay

Fig. 3 shows the model test results for free-roll-decay motion of TEST C(tanker with partial filling case) of ITTC benchmark study of specialist committee on stability in waves and corresponding simulation results by a quasi-static model for flooded water motion. It can be said that coupled effect is not so significant for non-resonant sloshing motion due to flooded water but dynamic effect is so strong for the resonant sloshing motion that fully coupled analysis is required for resonant sloshing cases.

Fig. 4 compares the roll motions obtained by model tests and numerical simulation by the quasi-static model for the case of transient flooding. As similar to the case of resonant sloshing case, the quasi-static model is not sufficient for predict transient motion due to impulsive flooding. Since the quasi-static modelling of flooded water basically depends on the partitioning algorithm of the damaged containment and free surface modelling inside the containment which reflects the experience and physical interpretation of analyst on simulation targets, the results of this kind of approximations are more influenced by human factors than other methods.

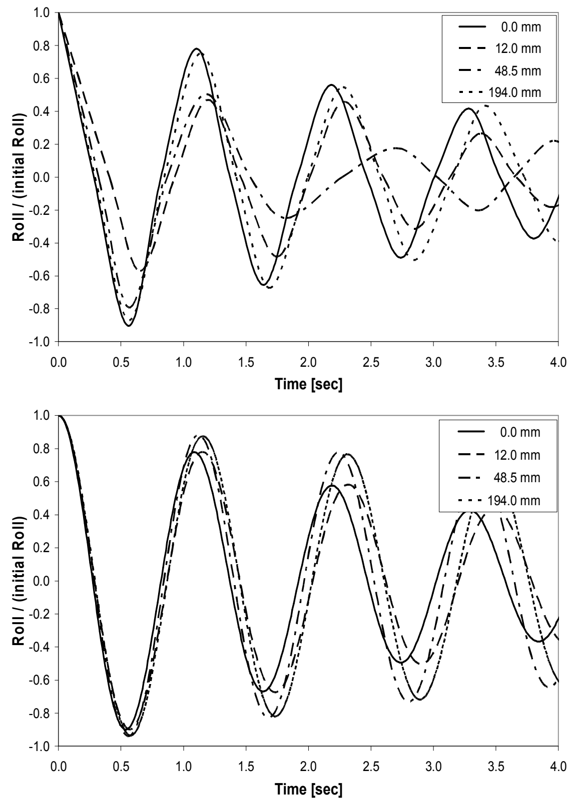
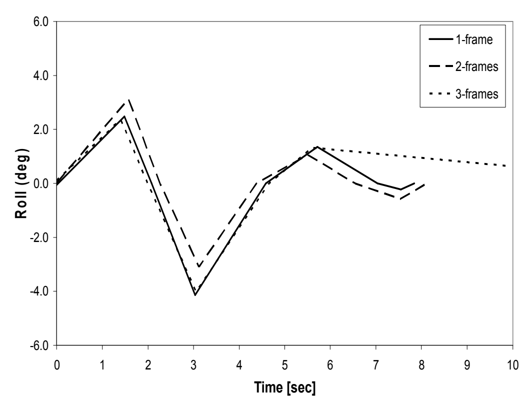


Fig. 3: Comparison of free-roll-decay motions(above: model tests, below: simulations, Cho et al., 2005)

Fig. 5 compares the results of coupled free roll motion analysis for the case of resonant sloshing of partially filled tanker with other approximate methods. It can be clearly seen that consideration of dynamic effects using a CFD scheme based on VOF gives noticeably



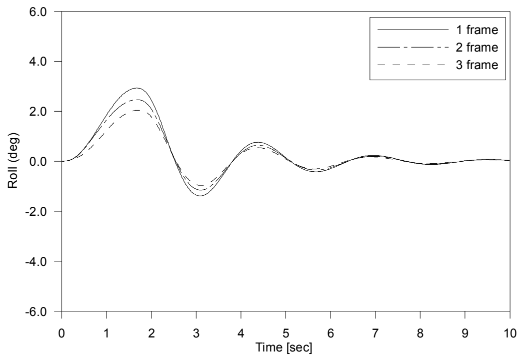


Fig. 4: Transient free-roll-decay motions(above: model tests, below: simulations)

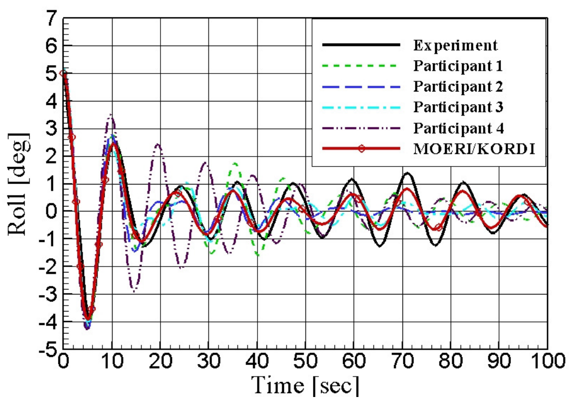


Fig. 5: Comparison of free-roll-decay motion for the case of coupled sloshing resonance

improved results compared with other approximate methods. It can be concluded that using CFD for analysis of violent sloshing coupled with ship motion gives reliable results for estimation of global motion.

Coupled Roll Motion

Analysis of roll motion of a ship with fluid containments such as anti-rolling-tank has been one of classical topics of coupled analysis of ship motions. These days' fluid cargo ships such as tankers and LNG carriers have relatively simple shaped cargo tanks compared with complicated U-shaped anti-rolling-tanks(ART), but the behavior of the fluid motions inside the cargo tanks are much more complicated than those inside the ART. That's the reason why so many efforts have been made for solving sloshing and coupled motions with sloshing.

As already seen in Fig. 5, coupled analysis method combined with potential model for ship motion and CFD model for sloshing gave reasonably good predictions for transient free-decay motion. Fig. 6 compares coupled roll motion under steady state wave action. As shown in the figure satisfactory agreements between numerical calculations and experiments were obtained.

Another application of coupled analysis of sloshing and coupled ship motions is side-by-side moored FSRU and LNGC. In the process of loading LNG from LNGC to FSRU, partially filled LNGC could be influenced by sloshing inside LNG containments. Fig. 7 shows a typical arrangement of a side-by-side moored FSRU-LNGC system. Fig. 8 shows a case of coupled motion roll RAO for beam sea case, as a result of strong coupling between sloshing inside LNGC and multi-body hydrodynamic interactions, roll motion RAO of LNGC is significantly reduced in the range of frequencies of wave spectra(Cho et al., 2007a). Fig. 9 shows nonlinear effects on coupled dynamics between roll and sloshing, in a certain critical case such as 18% partial filling as shown in the figure, very large discrepancies are obtained for incident wave amplitudes.

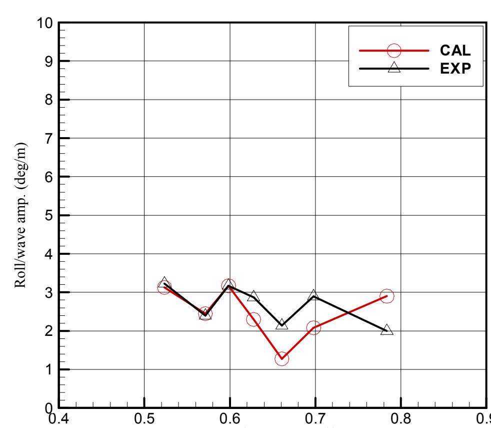


Fig. 6: Roll RAO for coupled ship motion and sloshing

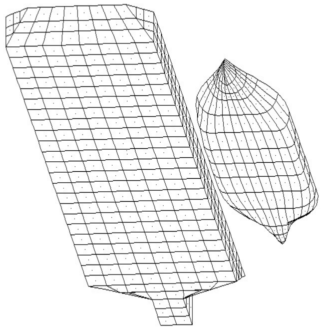


Fig. 7: Panel representation of FSRU and LNGC

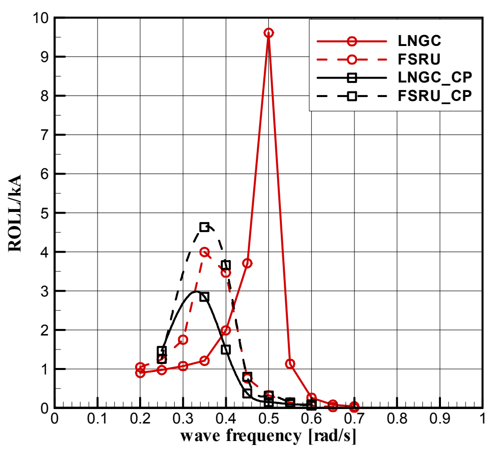


Fig. 8: Coupled roll RAOs for side-by-side moored FSRU and LNGC(30% filling, beam sea, A=1m)(Cho et al., 2007a)

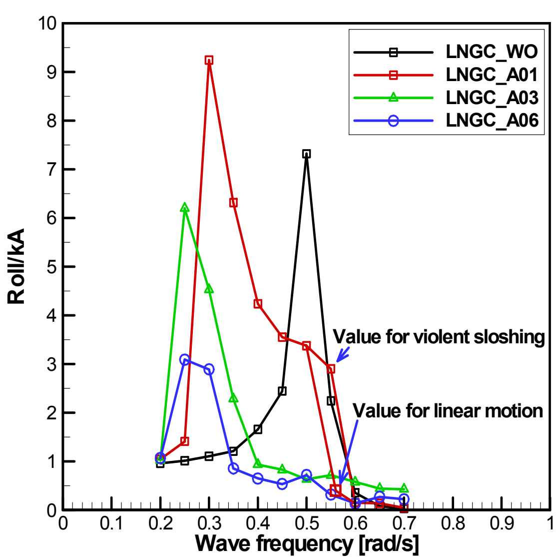


Fig. 9: Roll RAOs for LNGC: different wave amplitude, beam sea, 18% filling condition(Cho et al., 2007b)

Time-to-Flood

One of important functions of analysis tool for damaged ships in waves is to predict time-to-flood when a ship is damaged. It is not so easy to consider all the details associated with flooding process such as detailed shape of compartments, dynamics of flooded water inside compartments and etc.. Unlike transient motion at initial stage when damage occurs, time-to-flood is a physical phenomenon mainly dependent on hydrostatic property unless the damaged compartment is too large to withstand a couple of minutes after damage. With this understanding a simulation to predict time-to-flood was made for the down flooding case of the ITTC comparative study 2007 with quasi-static model for flooded water.

Fig. 10 shows time history of the heave and pitch provided by participants of the study. Most of predictions show generally similar behaviour with model test result except a few results. The reason for some discrepancies are not fully reviewed yet but human factors and partitioning algorithms could be suspects for the results, which is mainly dependent on physical knowledge and experience of analysts determining simulation conditions.

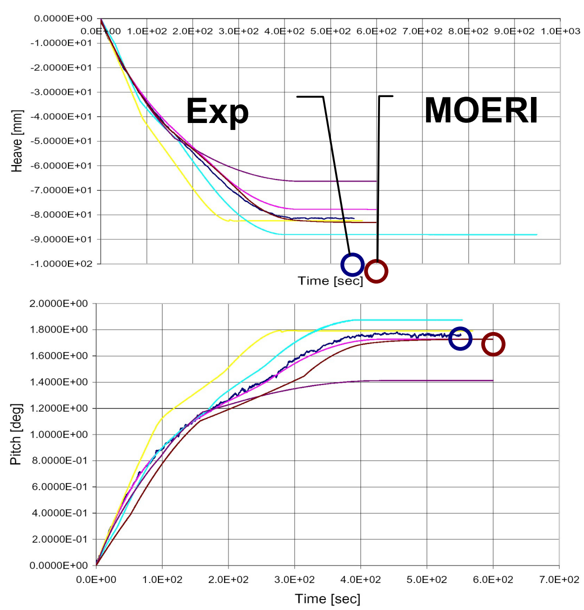


Fig. 10: Comparison of time-to-flood for the case of down flooding(ITTC 2007 comparative study)

Wave Loads on Damaged Ships

When a ship is damaged and one or more compartments are flooded, then the ship will have a new equilibrium position after flooding is completed. Under such a new equilibrium position, wave loads on the ship is different from the ship when she was intact because of change both in hydrostatic and hydrodynamic characteristics. In this section, numerical and experimental results of wave loads acting on a rectangular barge are compared for investigating the effect of damage on wave loads. The rectangular barge has length of 300m, breadth of 38m and draught of 8m. The barge has two flooded compartments fore and after locations at portside, about 13 degrees of heeling was obtained after flooding. Details of the model tests is given in Kim et al.(2007). Fig. 11 shows roll RAO of the damaged barge non-dimensionalized by wave slope in regular head waves. It is observed that noticeable roll response is induced due to heeling by damage, numerical results describes such behaviors generally well. Slightly over predicted responses are obtained near sloshing resonance frequencies because of neglecting viscous effects in the calculation.

Fig. 12 shows surge response, which is very similar to roll response qualitatively, in which over predicted surge appears near longitudinal sloshing resonance. Fig. 13 compares torsional moments at midship section for wave length ratio(λ/L=1.0, λ: wave length, L: ship length). It can be seen that the present numerical model gives good predictions of torsional moment induced by flooded water. Fig. 14 shows surge RAO for oblique seas, which shows similar trend as the case of head sea. Numerically predicted sloshing resonance effect in oblique sea seems to be exaggerated than that in the case of head sea. From Fig. 15, it can be seen that vertical bending moment is not sensitive to flooding outside of sloshing resonance. Fig. 16 compares the vertical bending moment at sloshing resonance frequency(λ/L=0.6), numerical prediction shows a noticeable discrepancy with experimental one. In order to consider the effect of violent sloshing inside cargo compartment, it seems to be needed to introduce the time-domain approach which can handle highly nonlinear hydrodynamic behaviour due to violent sloshing like the same method used for coupled motion analysis. Adding artificial damping onto inner free surface in the frequency-domain analysis tool could be a practical alternative.

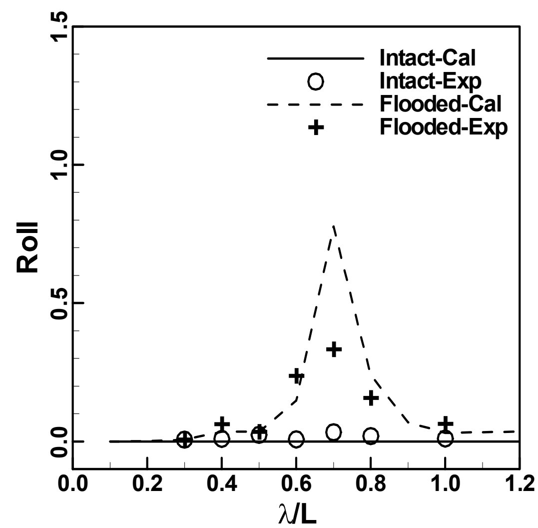


Fig. 11: RAO of roll motion under head wave

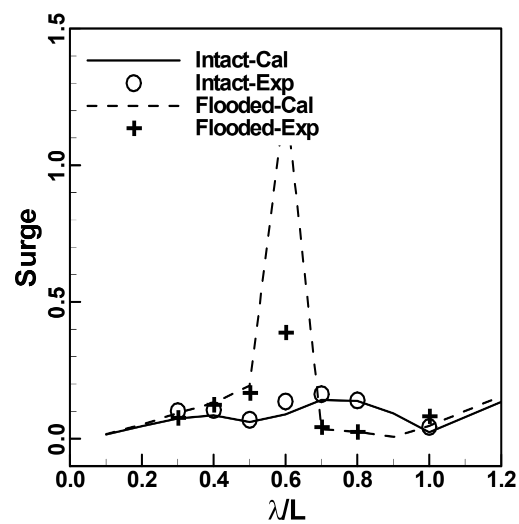


Fig. 12: RAO of surge motion under head wave

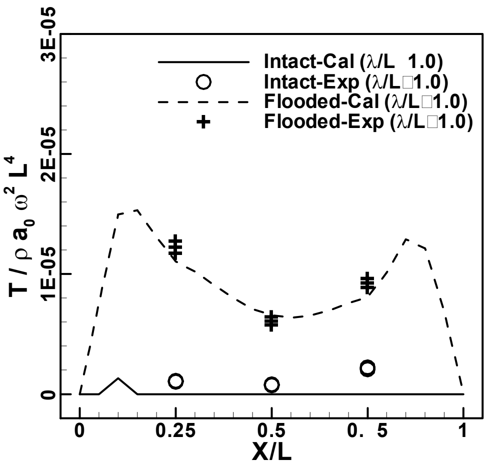


Fig. 13: Torsional moments under head wave

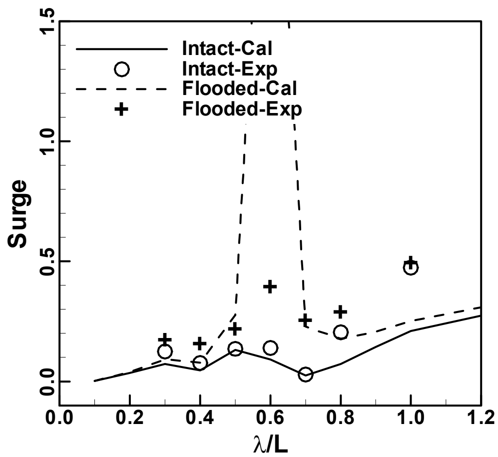


Fig. 14: RAO of surge motion under oblique wave

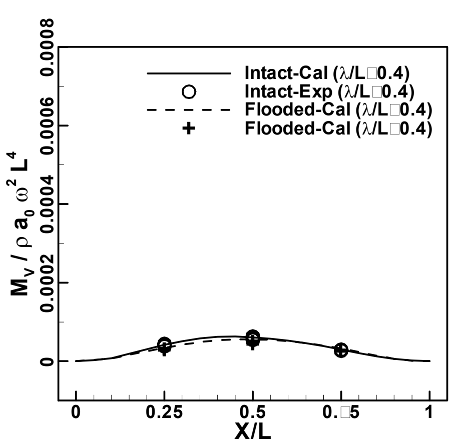


Fig. 15: Vertical bending moments under oblique wave (λ/L=0.4)

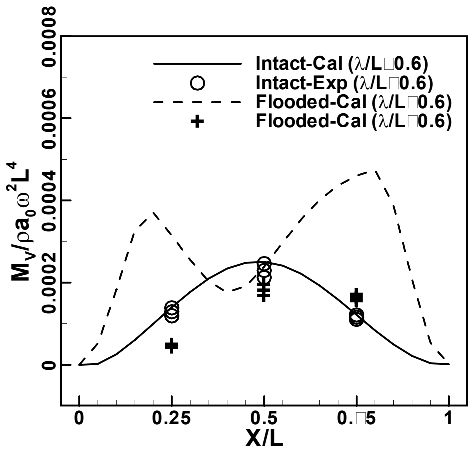


Fig. 16: Vertical bending moments under oblique wave (λ/L=0.6)

CONCLUSIONS

We have investigated dynamic behaviours of damaged ships through three different kinds of numerical models. The performance evaluation of damaged ships in waves were made for free-roll-decay, coupled roll motion, time-to-flood and wave loads on damaged ships. Each method has its own merits and limitations depending on the problems for application.

Quasi-static modelling of flooded water could be effectively applicable to time-to-flood analysis with reasonable modelling for inflow, free surface behaviour and partitioning strategy. For coupled analysis of roll motion and sloshing, the use is limited to the frequencies outside sloshing resonance.

For more accurate prediction of fully coupled roll motion with sloshing, a dynamic modelling using CFD for sloshing with ship motion solver based on potential model gives useful results, this model could be extended to prediction of wave loads of damaged ship considering nonlinear effects due to violent sloshing. Analysis of wave loads on damaged ship by fully potential model in frequency domain gives useful information for change of wave loads due to damage in view of linear sense.

Continuous improvement of the dynamic model combined with CFD and potential based ship motion solver is being carried out by adopting so called hybrid scheme which enhances inflow and outflow model in CFD module. The full potential model for wave loads on damaged ships can be improved by introducing artificial damping inside damaged compartment, but this model should be incorporated with the dynamic model combined with CFD for treatment of highly nonlinear sloshing effect on wave loads.

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