# Numerical Study of Damaged Ship Motion in Waves

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## ABSTRACT

An integrated numerical method, which couples a seakeeping solver and a Navier-Stokes (NS) solver with the volume of fluid (VOF) model, has been developed to study the behavior of a damage ship in waves. The dynamics of water flooding and sloshing in the compartments were calculated by the NS solver, while the hydrodynamic forces induced by the sea wave on the external hull surface were calculated using the seakeeping solver. To validate its performance, the solver was applied to the flooding problem of a damaged Ro-Ro ferry in regular beam seas. The computed results are satisfactory in comparison with the experimental data

## KEYWORDS

Flooding; damaged ship motion; floodwater motion; interactive dynamics

## INTRODUCTION

When a ship is damaged in waves, the ship behaviour is not only influenced by the excitation of sea wave but also influenced by the internal liquid loads due to water flooding and sloshing. Simultaneously, the hydrodynamics of flooding and sloshing is also affected by the ship motion. Limited understanding of these interactive dynamics impedes the study on damaged ship stability.

Numerical studies on this intricate dynamic problem have been conducted since the 1990s. Mathematical models presented in the earlier works are normally based on the potential flow theory with a simple model for floodwater motion (Vassalos and Turan, 1994; Papanikolaou et al., 2000; Jasionowski, 2001; Palazzi and De Kat, 2004). The ship hydrodynamic forces due to external wave excitation are calculated using the potential flow method. The viscous effects are treated by semi-empirical approaches. The inflow and outflow of water through the openings is determined by the modified empirical Bernoulli's equation. The non-linear sloshing effect inside the compartment is neglected, and the internal water surface is assumed to be either horizontal or a freely movable plane. Numerical tools based on the above assumptions of floodwater motion can not precisely predict the behaviour of a damaged ship upon flooding, as reported in the ITTC benchmarking study for damaged ship stability (ITTC report, 2002). To model the floodwater motion more physically, Santos and Guedes Soares (2008) employed the shallow water equation to calculate the internal water dynamics. The improved model has the ability to address the motion of internal water displaying non-linear behaviour. However, this method can not fully account for the influence of compartment's internal layout on the floodwater motion and is ineffective if the depth of internal water is larger compared to the width of compartment.

Over the past few years, with improvements in the capabilities of high-performance computers, the computational fluid dynamics (CFD) method based on solving the Navier-Stokes (NS) equation with the volume of fluid (VOF) model (Hirt and Nichols, 1981) has been increasingly applied to the flooding problem of a damaged ship. By employing this sophisticated method, all of the flow characteristics and parametric effects can be considered in the numerical simulation. Cho et al. (2005), Nabavi et al. (2006) and Strasser (2010) used the CFD method to investigate the effect of damaged opening geometry, compartment internal layout, turbulent flow or air compression on the flooding process. Gao et al. (2004, 2010a) employed the CFD method to analyse the hydrodynamics of a damaged ship section under forced heave or roll motions.

Numerical simulation of damaged ship flooding in waves solely based on CFD method is time-consuming. On the other hand, the potential flow method is practical and efficient to solve general seakeeping problems of ship. To ensure high fidelity in flooding simulations while reducing the computational cost, it is rational to conceive the idea of coupling the CFD and potential flow methods, i.e., the floodwater dynamics is calculated using the CFD method while the ship hydrodynamics induced by sea wave is predicted with the potential flow method. Woodburn et al. (2002) developed a coupled model based on this idea to assess the survivability of a damaged ship in waves.

In this study, an integrated numerical method, which couples a seakeeping solver based on potential flow method and an NS solver with the VOF model, was developed to study the behavior of a damage ship in waves. To assess its performance, the method was applied to solve the flooding problem of a damaged Ro-Ro ferry in regular beam seas. The computed results were validated against the experimental data.

## MATHEMATICAL MODEL

The ship is considered as a rigid body with six degrees of freedom (6-DOF), and its motion is governed by the following linear and angular momentum equations described in the body-fixed coordinate system:

$$m\left(\dot{\boldsymbol{u}}_C + \boldsymbol{\omega} \times \boldsymbol{u}_C\right) = \boldsymbol{F} \tag{1}$$

$$\boldsymbol{J}_C \cdot \dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{J}_C \cdot \boldsymbol{\omega} = \boldsymbol{M}_C \tag{2}$$

where $m$ is the mass of the ship; $C$ refers to the centre of $m$; $\boldsymbol{u}_C$ is the velocity vector of $C$; $\boldsymbol{F}$ is the resultant vector of external forces acting on the ship; $\boldsymbol{J}_C$ is the tensor of inertia moments of the ship with respect to $C$; $\boldsymbol{\omega}$ is the angular velocity vector of the ship; and $\boldsymbol{M}_C$ is the resultant vector of external moments acting on the ship with respect to $C$.

Within the framework of potential flow theory, the components of external forces and moments can be generalized as follows:

$$\begin{aligned} F_i = (F_{\mathrm{FK}})_i + (F_{\mathrm{D}})_i + (F_{\mathrm{R}})_i + (F_{\mathrm{B}})_i \\ + (F_{\mathrm{G}})_i + (F_{\mathrm{W}})_i, \qquad i = 1,2,\ldots,6. \end{aligned} \tag{3}$$

where $i$ denotes the components of the external forces or moments (moment understood for $i$ = 4, 5, 6); $F_{\mathrm{FK}}$ is the Froude-Krylov force; $F_{\mathrm{D}}$ is the diffraction force; $F_{\mathrm{R}}$ is the radiation force; $F_{\mathrm{B}}$ is the buoyancy force; $F_{\mathrm{G}}$ is the gravitational force; and $F_{\mathrm{W}}$ is liquid load due to the motion of floodwater inside compartments.

## NUMERICAL METHOD

### *Seakeeping Solver*

An in-house seakeeping solver PROTEUS3 (Jasionowski, 2001) is used to calculate the hydrostatic and hydrodynamic forces induced by the sea wave on the external hull surface. The hydrostatic and Froude-Krylov forces are evaluated by integrating the pressure over the instantaneous wetted surface of the ship. The diffraction and radiation forces are first derived from the linear potential flow theory in frequency domain, applying strip theory, and then transformed into time domain applying convolution and spectral techniques, respectively. Viscous effects on the roll motion are treated through a semi-empirical mean.

### *NS Solver*

A finite-volume-discretisation based NS solver (Gao et al., 2010b), which is developed to solve the problems of incompressible two-phase flow, is employed to calculate the dynamics of water flooding and sloshing. Fig. 1 shows the computational domain, which includes the ship's floodable compartments and an external flow region around the damaged section of the ship. A VOF family algorithm, CICSAM, is used to capture the free surface. The well-known SIMPLE algorithm is employed for pressure-velocity coupling. The ship motion is tackled with the dynamic mesh technique. Turbulence modelling is omitted.

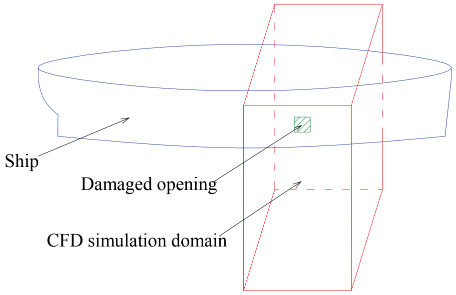

**Fig. 1: Sketch of the CFD simulation domain.**

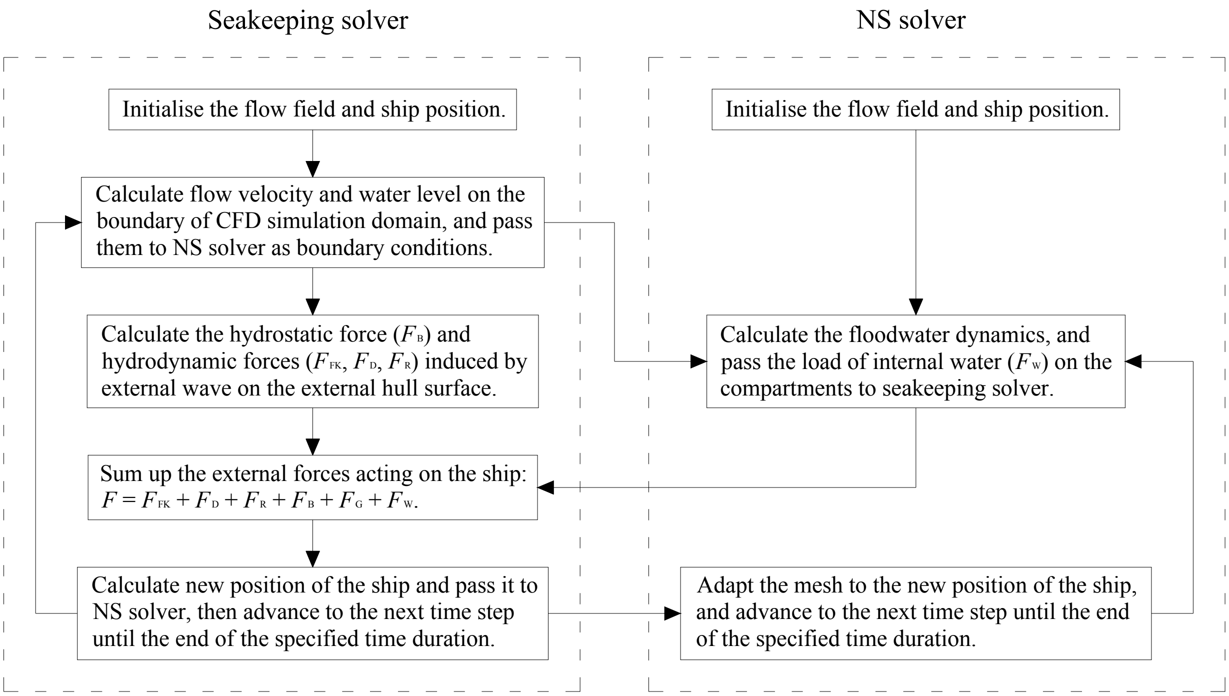

**Fig. 2: Outline of solution procedure of the integrated method**

### *Solution procedure*

The entire flooding problem is solved by a newly developed integrated method that couples the aforementioned seakeeping and NS solvers. The overall solution procedure is shown in Fig. 2

## VALIDATION TEST

### *The Test Ship*

A Ro-Ro ferry, known as PRR1 in the literature (ITTC report, 2002), was adopted herein for the validation test. The main particulars of the ferry are given in Table 1. Fig. 3 shows its general arrangement, in which the parts depicting shadow denote the floodable compartments.

**Table 1: Main particulars of PRR1**

| | |
|---|---|
| Length between perpendiculars ($L_{pp}$) | 170.00 m |
| Breath ($B$) | 27.80 m |
| Draft ($T$) | 6.25 m |
| Depth to car deck ($D_{cd}$) | 9.00 m |
| Damaged length ($L_{dam}$) | 8.10 m |
| Centre of gravity above base (KG) | 12.892 m |
| Metacentric height (GM) | 2.63 m |
| Displacement ($\Delta$) | 17301.7 t |

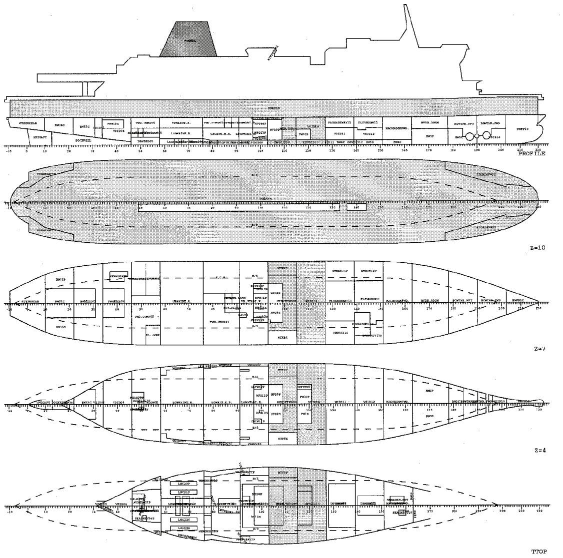

**Fig. 3: General arrangement of PRR1 (from ITTC report (2002)).**

### *Motion of Intact Ship*

Before applying the integrated method to the damaged ship flooding, we first tested the ability of PROTEUS3 to predict the motion of an intact ship in waves. The cases of PRR1 in regular beam seas with wave heights ($H_w$) of 1.2 m and 2.4 m were tested, respectively. Fig. 4 shows the comparisons of roll response amplitude operators

(RAO) obtained by PROTEUS3 and model test (ITTC report, 2002). The computed RAOs are over-predicted at wave frequencies close to the natural roll frequency (approximately 0.49 rad/s) of the ship. In the range of other frequencies, good agreement between the numerical and experimental results is observed.

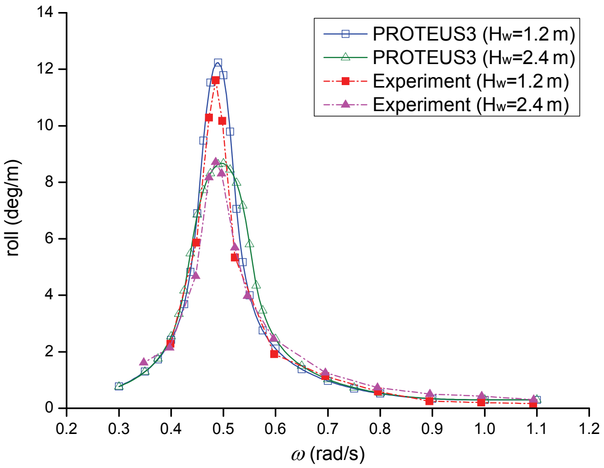

**Fig. 4: Comparison of roll RAO of PRR1 in intact condition.**

### *Motion of Damaged Ship*

As reported in the literature (ITTC report, 2002), the behavior of PRR1 in damaged condition has been extensively studied by various research groups. However, because all numerical tools developed by the participants can not properly address the motion of floodwater inside the compartments, neither the peak response frequency nor its magnitude in the computations agrees with the experimental ones, as shown in Fig. 5. Thus, the same case, i.e., PRR1 in regular beam seas in damaged condition, was used here for the validation of our integrated method. A wave height of 1.2 m was selected in the test. Fig. 6 shows the computational domain for the CFD simulation. The total number of mesh elements was 245,048. Only 4-DOF of the ship (sway, heave, roll and pitch) was considered in the numerical simulation. For each wave frequency, the simulation ran up till the ship motion became stable. It roughly took 69 CPU hours to complete a 200-s simulation on a dual-cores (Intel Core2 @ 3.0 GHz) personal computer.

A snapshot of internal water motion is shown in Fig. 7, at the instant corresponding to the maximum heeling of the ship. Fig. 8 shows the comparison of roll RAOs obtained by the integrated method and model test. The frequencies of peak response in the computation and experiment are approximately 0.4 and 0.42 rad/s, respectively, both of which shift moderately from 0.49 rad/s in the case of intact ship. On the other hand, the peak response is weakened significantly due to the presence of internal water which increases the roll damping, and its magnitude is over-predicted by the present method. For the wave frequencies which are less than 0.7 rad/s, the change trend of computed RAOs is consistent with its experimental counterpart. As the wave frequency increases further, a second peak of RAO is observed in the experiment, while it did not appear in the computation. Such discrepancy may be attributed to the grid resolution which is not fine enough to accurately capture the non-linear free surface motion inside the compartments. Further analysis on the disagreement between the numerical and experimental results is on going.

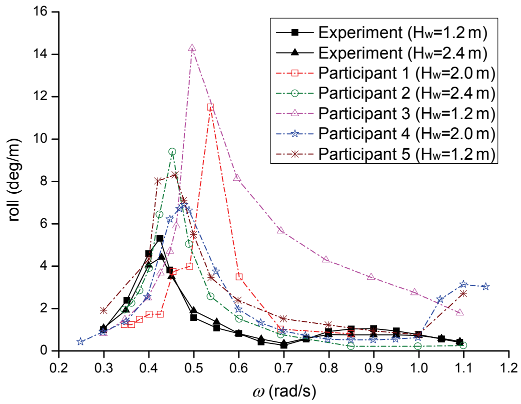

**Fig. 5: Results of the ITTC benchmarking study for PRR1 in damaged condition**

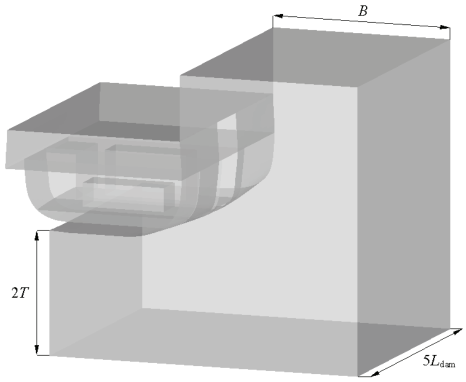

**Fig. 6: CFD simulation domain for the case of PRR1 in damaged condition.**

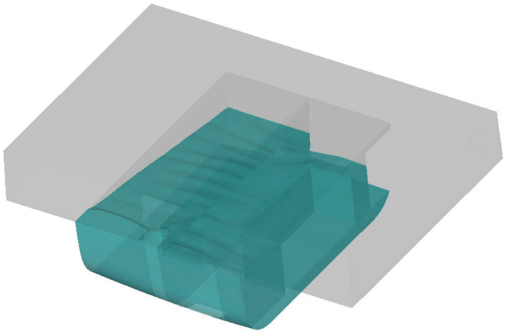

**Fig. 7: Snapshot of floodwater motion inside the compartments (Hw=1.2 m, ω=0.4 rad/s).**

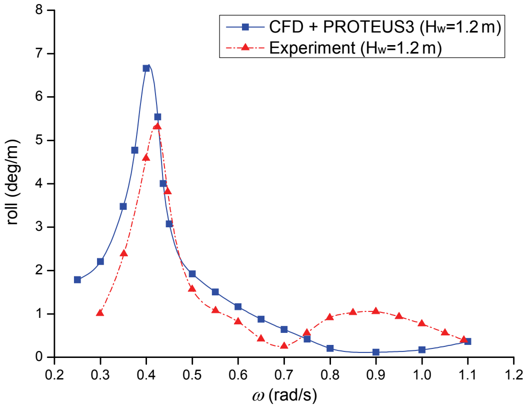

**Fig. 8: Comparison of roll RAO of PRR1 in damaged condition.**

## CONCLUSION

An integrated numerical method that couples a seakeeping solver and an NS solver was developed to study the behavior of a damage ship in waves. Preliminary results shown in the benchmarking study are encouraging. The shift of peak response frequency and increase of damping due to the presence of internal water is predicted reasonably well in comparison with the experimental data. More validation tests will be carried out in the next step.

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