On the Motions of a Flooded Ro-Ro Ferry in Beam Seas

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ABSTRACT

The assessment of ship’s damage stability in waves by testing a series of damage scenarios is nowadays accepted both scientifically as well as in relevant SOLAS regulations (performance based stability standards). Numerical simulation methods assisting the above procedure may significantly enhance the overall assessment efficiency. The main objective of these procedures is the prediction of ship motions and instabilities in extreme seaway excitation. Obviously, when validating such a simulation method, the flooded ship dynamics in stable conditions should be firstly ensured before concluding on the suitability of the method in marginal cases, where instability can occur.

In this paper the behaviour of a damaged Ro-Ro ship model with water on car deck in beam waves was investigated, both numerically and experimentally. The experimental ship model was restrained to only allow three degrees of freedom motions, namely that sway, heave and roll. This restriction ensured increased control of the experimental parameters and repeatability of the model experimental results. Steady state conditions of the flooded ship model motions in regular and irregular waves were achieved and a comprehensive comparison between numerical results and experimental measurements was carried out providing satisfactory results.

INTRODUCTION

The damage stability of passenger/Ro-Ro ferries is a topic of great research interest to maritime industry and scientific community. The assessment of ship’s damage stability through model experiments has been already established by the so-called Stockholm Agreement (Res. 14, SOLAS 95) as an alternative assessment procedure to the formal provisions of the Stockholm Agreement (“Equivalent Model Test Method”). However, several details of the specified experimental procedure still need to be further improved, in order to arrive at a scientifically sound experimental procedure. The effect of the restraint measuring system on the model responses, the significance of the initial stages of flooding on model capsizing, as well as the procedure of water accumulation into the damaged compartments, are still considered open research subjects. Damaged ship motion simulation codes are employed on the stability assessment method, furthermore, they comprise a competent method to address the various related issues above stated.

An efficient numerical simulation of the motions and flooding procedure of a damaged ship in waves has been developed at the Ship Design Laboratory of NTUA, providing a satisfactory theoretical approach to the assessment of ship’s damage stability Papanikolaou et. al. (2000), Spanos et. al. (1997), (2001). A series of model experiments were set up at the CEHIPAR model tank, aiming to confirm the theoretical findings of the motion behaviour. The motion of the model was investigated, both numerically and experimentally, with three degrees of freedom, namely sway, heave and roll. The other degrees were restrained as their influence is of lower significance, but herein essentially in order to exclude uncertainties associated with the experimental measurements, when the model is kept in beam seas.

The present paper presents results of the above theoretical-numerical and experimental studies within the concept of “Total Safety Assessment” when addressing the damage stability of passenger/Ro-Ro ferries by state of the art scientific procedures, Vassalos et al. (1994).

NUMERICAL SIMULATION METHOD

A brief outline of the employed ship motion simulation code CAPSIM of the Ship Design laboratory of NTUA and the underlying theory is provided in this paragraph. More details can be found in Papanikolaou et. al. (2000), Spanos et. al. (1997), (2001).

The underlying theoretical model is a nonlinear, time-domain simulation procedure, allowing the consideration of large amplitude motions and the stability of a ship in extreme environmental conditions.

The flooded ship is assumed as a two mass system consisting of the intact ship and the flooded water mass. The ship is considered as a rigid body having six degrees of freedom, while the flooded water effects are approximated by the lump mass concept, namely the mass of flooded water is assumed concentrated in its centre of mass. The floodwater centre is assumed moving over a predefined surface domain, corresponding to the flooded compartment geometry.
Papanikolaou et al. (2000), in two degrees of freedom. Considering also the change of mass of water in time, a suitable mathematical model for the motion of the resulting overall inertia system, with nine degrees of freedom, has been formulated and implemented in a numerical time-domain code.

The motion of the overall inertia system is governed by the momentum conservation of the system masses under the action of external forces. The time rate of change of momentum has been suitably formulated considering the full non-linear character to the motion equations. The external forces are mainly the gravity and the exciting wave forces (other forces, like wind, current etc. can be added). The radiation and diffraction wave forces are treated in the framework of potential theory employing the three-dimensional frequency-domain panel code NEWDRIFT, Papanikolaou (1989). Non-linear roll viscous effects are assumed to depend on ship’s roll velocity and use of the “equivalent linearisation concept” is made taking into account semi-empirically estimated proportionality coefficient. Hydrostatic forces are calculated by integration of pressure in the time domain over the instantaneously wetted ship surface, considering incoming waves and caused ship motions, and allowing the capture of even complicated geometries by proper surface paneling.

The time rate of change of the floodwater has been approached by use of Bernoulli’s equation and modified by a semi empirical, weir flow coefficient to account for the local flow effects at the damage opening. This weir coefficient has been herein assumed to be equal to 0.67 based on the accumulated experience by the validation of a variety of flooding simulations by experimental data for the type of investigated damage openings.

**TANK MODEL TESTS**

A series of tank model tests of a damaged Ro-Ro ship model were carried out and the obtained experimental measurements used herein for a comprehensive validation of the numerical simulation method. A common research project of the Ship Design Laboratory of NTUA and the CEHIPAR center, funded by the European Commission as a Transnational Access to Large Facilities project, enabled the model tests at the CEHIPAR model tank of ship dynamics in summer 2001.

The tested passenger/Ro-Ro ferry model has a length of 5.333 m. Its main particulars are shown in Table 3.1 while its body plan is shown in Figure 3.2, and has one compartment damaged, as shown in Figure 3.2. The model was allowed to move in three degrees of freedom, namely sway, heave and roll and was tested in beam regular and irregular waves. Depending on the tested case, the damage opening was extended vertically up to the car deck, letting car space to be intact and the lower compartment, corresponding to engine room, damaged. In other tests it was extended up to the higher end so that car space was damaged and open to the water.

The model was made of GRP with the car deck made of wood as well the transverse bulkheads under the deck. Model tank main dimensions are 150.0 m length, 30.0 m breadth and 5.0 m depth. This large tank size enables the testing of a ship model of reasonable size in beam waves without sidewall effects (tank width to model length ratio equal to 5.62), as well adequate effective tank length, (about 80 m available for the model to drag downstream).

<table>
<thead>
<tr>
<th>MODEL</th>
<th>SHIP</th>
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</thead>
<tbody>
<tr>
<td>Model scale</td>
<td>1:30</td>
</tr>
<tr>
<td>Lpp</td>
<td>5.333 m</td>
</tr>
<tr>
<td>B</td>
<td>1.014 m</td>
</tr>
<tr>
<td>T</td>
<td>0.220 m</td>
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<tr>
<td>Dcar</td>
<td>0.308 m</td>
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<tr>
<td>Displacement</td>
<td>801 kg</td>
</tr>
<tr>
<td>GM</td>
<td>0.153 m</td>
</tr>
</tbody>
</table>

Table 3.1 Model main particulars

The model was made of GRP with the car deck made of wood as well the transverse bulkheads under the deck. Model tank main dimensions are 150.0 m length, 30.0 m breadth and 5.0 m depth. This large tank size enables the testing of a ship model of reasonable size in beam waves without sidewall effects (tank width to model length ratio equal to 5.62), as well adequate effective tank length, (about 80 m available for the model to drag downstream).
Pertaining to the modeled ship’s car space flooding conditions two series of tests were performed. Firstly, the car space was intact and filled with constant amounts of water namely 0.00 kg (intact), 40 kg and 60 kg. These tests were in regular beam waves. Secondly, the influence of the damage opening was tested, namely its width was adjusted to SOLAS’95 provisions and extended upwards so that the car space was now damaged. These tests were for regular waves and irregular waves. The model motion, the wave elevation at a point traveling with the model carriage, the water depth of the flood water on car deck using twelve wave probes and the instant freeboard at the location of damage opening were measured and recorded. The model motion was measured employing an optical data acquisition system, namely KRYPTON, while the water depths/elevations using a standard wire connecting system.

**MODEL IN BEAM REGULAR WAVES**

The obtained experimental measurements are compared with corresponding numerical results deduced by use of the CAPSIM and NEWDRIFT codes of NTUA-SDL. The above presented tank tests were so planned to enable a comprehensive comparison between model tests and theory. A significant effort was devoted to investigate the behavior of the flooded (or damaged) model in regular waves. Obviously, it is of great interest to analyze the flooded model responses in regular waves, as this enables the clearer understanding of the complicated character of the nonlinear flooded model behavior and sets a clear validation test for the relevant theory.

Wavelengths between 0.5 and 2.0 times model length were used for the present investigation. An increased metacentric height GM was selected, which permits testing with increased amounts of water on deck in stable conditions. The model should achieve a steady state condition after a time period and not lead to capsise. Those steady state conditions were one of the mains objectives of the present investigation.

The model with intact car space and one damaged lower compartment was investigated in regular beam seas. The car space was flooded with constant amount of water, namely 0.0 kg, 40.0 kg and 60 kg. The GZ curves corresponding to these three configurations are shown in Figure 4.1. Model holds increased residual stability even in flooded cases for heeling angles up to 20 degrees where the upper edge of model was submerging.

In Figures 4.2(a)-(d) the experimental and corresponding theoretical results for the model responses are presented. On the left column diagrams the experimental measurements for the heave and the roll, for the three amounts of water are shown, whereas on the right column the corresponding diagrams of the numerical results are placed. In these diagrams the solid line corresponds to the 0.0 kg water on deck or intact car space case, while the dashed line to the 40.0 kg and the dotted to 60.0 kg.

As seen in these diagrams, the model heave response does not show any significant variation, as the vessel moves practically quasi-hydrostatically with the incoming wave. It seems that heave do not depend on the amount of water on deck as the three curves of varying water mass are quite close within the range of measuring noise. Theoretical results show quite similar behavior to the experimental ones, implying a presumably effective modeling of heave due to the considerable linear character of that motion.

Roll response motion appears quite more interesting. The effect of the water on deck onto the model roll motion seems to be a clear increase of damping and a slight shift of resonance towards higher frequencies, and, as a consequence, the increase of roll response at higher frequencies as water increases. This behavior has been recognized as an expected behavior of the model in the presence of water on deck, as it has been continuously observed in tests and simulations of similar models, Spanos (2001). Numerical results present quite the same behavior with the experimental ones, at least qualitatively, but in general also quantitatively.

The third measured motion that of sway is not easily depicted as the model drifts downstream with a drift velocity and the mean value of the lateral position of the model changes disabling the direct definition of the oscillation amplitude. Furthermore, the drift velocity changes the wave frequency into frequency of encounter. This change is low enough but for consistent comparison, all the presented diagrams are given with respect to frequency of encounter.

In Figures 4.3(a)-(d) the experimental and corresponding theoretical results for the model responses are presented. On the left column diagrams the experimental measurements for the heave and the roll, for the three amounts of water are shown, whereas on the right column the corresponding diagrams of the numerical results are placed. In these tests the water could flow into and out the car space through the damage opening. After a time period of transient flooding, a steady state condition was achieved and the response of the model in rms values was obtained.
Comparing the behavior of the model with constant water on deck case with that of varying water mass, the heave response appears quite similar between them. Numerical and experimental results are also in close correlation.

To the contrary the roll response of the model with varying flood water mass shows a distinct different behavior. The peak values around resonance are greatly reduced. In the measured range, the lower the frequency the higher the response. Regarding the amount of accumulated water it could not be recognized a clear trend of accumulation with respect to wave frequency. An appropriate water mass was accumulated at each frequency such that the final trend of roll motion, shown in Figure 4.3(c), was formed. The steepness of the waves seems to have low influence on the roll motion. Numerical results give once again similar responses to the experimental ones, with some differences for the lower frequencies.

MODEL IN BEAM IRREGULAR WAVES

The model performance in beam regular waves, presented in previous paragraph, permitted a thorough understanding of the water on deck influence on the model motion and a substantial validation on the flooded ship dynamics modeling of the employed numerical code. The performance of the model in irregular beam waves, presented in this paragraph, being the ultimate objective of the flooded ship motion investigation, provides an additional global test case for the numerical code.

As described, the increased GM value allows enhanced initial stability of the model and steady state conditions that could be achieved after a transient time period.
The model was tested for three significant wave heights $H_s$ equal to 3.00, 3.45 and 4.05 m, and both in short and long waves for each $H_s$. Wave elevation spectrum was determined according to JONSWAP spectrum. The experimental roll motion in time for the higher $H_s$ is shown in Figures 5.1 and 5.5 for the short and long waves respectively. In Figures 5.2 and 5.6 the corresponding numerical results are presented. Direct comparison between experiment and theory is not feasible using the time series diagrams so the probability densities for the steady state conditions of those runs are presented in Figures 5.4 and 5.8. Probability distribution functions herein are preferable than spectrum representation of the time series when the stability of the vessels is of prime concern. Apparently, in these diagrams the associated theoretical behavior is in close correlation to the experimental one. Short waves result to a density function of steeper peak while long waves to a wider one. A slight shift between the peaks of numerical and experimental functions can be observed for both short and long waves. This shift in peaks could be interpreted as a difference in the finally achieved steady state response between the experiment and the simulation, presumably due to the amount of water finally accumulated on the car deck or the difference of the dynamic behavior that could lead to a different mean roll angle. According to the first interpretation the numerical simulation seems to slightly underestimate the flooded water amount, whereas according to the second an inherent weakness on the modeling of the flooded ship dynamics could be assumed.

![Figure 5.5 Experimental roll response for $H_s$=4.05 m, long waves.](image)

![Figure 5.6 Numerical roll response for $H_s$=4.05 m, long waves.](image)

![Fig. 5.7 Heave probability density ($H_s$=4.05 m, long waves).](image)

![Fig. 5.8 Roll probability density ($H_s$=4.05 m, long waves).](image)
During the simulations two solutions in steady state conditions could be obtained. One with the model rolling having its mean heeling towards the upstream side and one with the mean heeling towards the downstream side. In order to prevent the model heeling to the downstream side, and obtain comparable results, during the simulations at start time an amount of water equal to 1% of displacement was assumed already on deck. Steady state conditions were determined visually, namely after 200 sec for short waves and after 100 sec for long waves. The record time for those tests was 372 sec or about 65 min in full scale. This simulation time is long enough but necessary to definitely recognize the steady state conditions.

In Figures 5.3 and 5.7 the probability densities for the heave motion are presented. Because the origin for the flooding of the car space, as modeled within the theoretical model, is the water pressure head difference internally and externally to the damage opening, the heave motion is first investigated as it affects both heads. Comparison between numerical and experimental results gives practically no differences.

CONCLUSIONS

The performance of a Ro-Ro/passenger vessel in beam waves and in three degrees of freedom, namely of sway, heave and roll, has been investigated both experimentally and numerically. The presently applied model test arrangement allowed a comprehensive validation of the simulation code, with minimized uncertainties. Quite satisfactory correlation between the results of the numerical code and the experimental measurements has been observed.

This investigation provides important information for the better understanding of the complicated flooded model dynamics, as it is derived from tests in frequency domain. In particular, regarding the behavior of the model with constant water on deck, it has been confirmed that an attenuation of the roll in the range of resonance occurs and simultaneously a resonance shift towards higher frequencies as the water gradually increases. In the case of the damaged car space, open to the water, the roll response of the model practically decreases continuously with frequency.

In irregular waves, a satisfactory correlation of results between numerical predictions and experimental measurements has been observed. This leads to the conclusion, that the assessment of ship’s damaged stability behavior in waves and especially in the framework of the provisions of SOLAS’95 (Res. 14) by theoretical tools is nowadays possible, despite the fact that model experiments will be still an indispensable tool for the final assessment of ship’s behavior.

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REFERENCES


