NUMERICAL STUDY OF THE DAMAGE STABILITY OF SHIPS IN INTERMEDIATE STAGES OF FLOODING

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SUMMARY

The roll behaviour of a passenger/Ro-Ro vessel in intermediate stages of flooding is investigated by use of a ship motion simulation code and comparison with available experimental data. The systematic numerical investigation on the ship's roll response when water enters suddenly into one compartment and the analysis of the obtained results enables a better understanding of the phenomenon. The response of the ship during transient flooding has been found to be quite non-linear and sensitive to the damage opening.

1. INTRODUCTION

The ship's damage stability in waves has attracted increased research interest in the last decade, in the attempt to answer serious questions arising after recent tragic losses of passenger ships. Assisted by the developments in computer hard- and software, more complicated physical phenomena have been addressed towards better understanding the ship's dynamic stability behaviour in damaged condition. The large amplitude motions of a ship in damaged condition under the action of sea waves and her behaviour in marginal stability conditions has been addressed by various researchers, Vassalos [8], Ishida [2], Papanikolaou [5], [7] de Kat [1], etc.

Actually, the set problem is the investigation of the stability behavior of a damaged ship around a stable equilibrium position. This stable position, if any after damage, is generally different from the stable equilibrium in the intact condition, and is the one reached by the ship under the effect of the floodwater.

Therefore the initial stages of flooding, or the transient flooding, is the stage of change of the ship's equilibrium from that of intact to that of the fully flooded ship in terms of damage hydrostatics. But, the path (transition) between these two conditions is not always possible and also not unique. In case of an impossible path the ship reaches another equilibrium, quite different from that of the fully flooded compartment. Even if the transition is possible, depending on the specific characteristics of the damaged ship, the damage opening and the sea condition, the duration of transient flooding changes and so might change the effects on ship's stability. In both cases the stability of the ship is obviously different from that of the fully flooded ship, considered in hydrostatic calculations and should be therefore evaluated separately.

The present study deals with the behavior of a passenger/Ro-Ro ship in transient flooding. The damaged ship motion and flooding simulation code CAPSIM of NTUA-SDL has been employed to estimate the motion of the vessel when the damage opening is suddenly released and water enters into the compartment. The obtained results are compared with available experimental measurements, published by Ma et al [3]. The study has been carried out in the course of validation studies of the numerical code CAPSIM within the EU funded project NEREUS.

2. SIMULATION BACKGROUND

A brief outline of the employed ship motion simulation code CAPSIM and the underlying theory is provided next. More details can be found in [7], [5], [6].

The flooded ship motion simulation code has been developed at the Ship Design Laboratory SDL, of NTUA. It provides an efficient way to predict the motion of the coupled ship and floodwater system. The model is nonlinear allowing the consideration of large amplitude motions and the stability of the vessel 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 is approximated by the lump mass concept, namely a mass being concentrated in its center of mass. Floodwater is assumed moving over predefined surface domain [5], having two degrees of freedom. Considering also the change of mass of water in time, a suitable mathematical model for the motion of the inertia system, with nine degrees of freedom, has been formulated and implemented in the numerical code.

The motion of the 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. The wave forces are treated in the framework of potential theory employing a threedimension diffraction code, [4]. Non-linear roll viscous effects are assumed to depend on ship's roll velocity by use of the "equivalent linearisation concept" with the proportionality coefficient semi-empirically estimated. 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 capturing of even complicated geometries by proper surface panelling.

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 estimated to be equal 0.67 following the accumulated experience by validation of a variety of flooding simulations by experimental data.

3. THE STUDIED SHIP

The presently investigated passenger/Ro-Ro ferry has been tested by Ma et al [3]. The ship was studied in model scale 1/60. Her principal particulars are listed in the Table 1 and her body plan is shown in Figure 2.

	Ship	Model
Lpp	120m	2000mm
B	18.8m	300mm
D	10.0	167mm
T	4.8m	80mm
Displ.	5900tn	27kg
KM	9.39m	156.5mm

Table 1. Main particulars

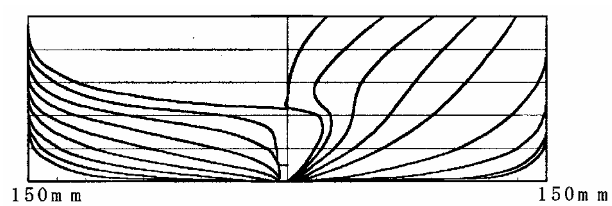

Figure 2. Body plan

There is one compartment in damaged condition extending between stations 4.5 and 6 as shown in Figure 3. Its length is 1/6 of the model length. One rectangular damage opening is located on the compartment's right side having a length according to SOLAS'95 regulations for the study of damage stability by model tests (Res. 14).

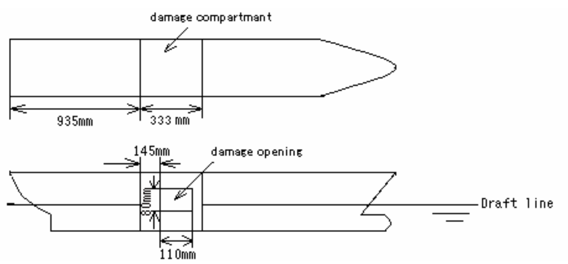

Figure 3. Damage compartment and opening

Two alternative damage compartment arrangements were numerically and experimentally investigated, as shown in Figure 4. Model A and Model B differ only with respect to the existence of a double bottom.

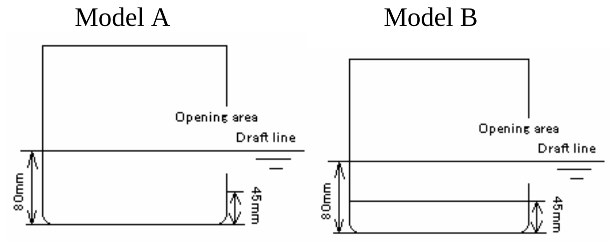

Figure 4. Model arrangements

The lower edge of the damage opening is located 30 mm below the draught line in intact condition for both models, defining the equilibrium position before opening the damage release.

4. SIMULATION RESULTS

The two models A and B described before were investigated in transient flooding using the NTUA-SDL simulation code. Each model is balanced in the intact condition and then suddenly the damage opening is released allowing water to flow into. Under the effect of the floodwater the model performs a roll and a heave decay motion. The model is restrained in the other degrees of freedom following the specifications of the experimental procedure in [3].

Figures 5 and 6 present the response of model A for different values of GM and figures 7 and 8 the results for model B. There are three columns of diagrams. The left one corresponds to the published experimental measurements, the central one to the numerical roll response and the right one to the numerical freeboard. A constant axis scale is used for the calculated results to provide a comparative view of the different GM cases. The same was not possible for the experimental values.

In order to become familiar with these diagrams let us comment one of them, namely the simulated response of Model A with GM=9.6 mm which shows a quite anticipated response. At time equal zero the model balances in intact condition and the damage opening is released. Then water flows into the compartment. The model gradually heels to the opposite side of the opening up to a heeling angle of about 21 degrees. Then the model performs a decay rolling, finally resting around 16 degrees. The corresponding damage freeboard, the distance between the lower edge of the opening and the still water free surface, has an initial value of -30 mm, meaning that water surface exceeds opening edge, at time zero. After resting for about 3 sec then it quickly heels with the opening totally emerging out the water at time 5 sec. The opening does not submerges again, following the decay motion model rests with a lower edge freeboard around 11 mm.

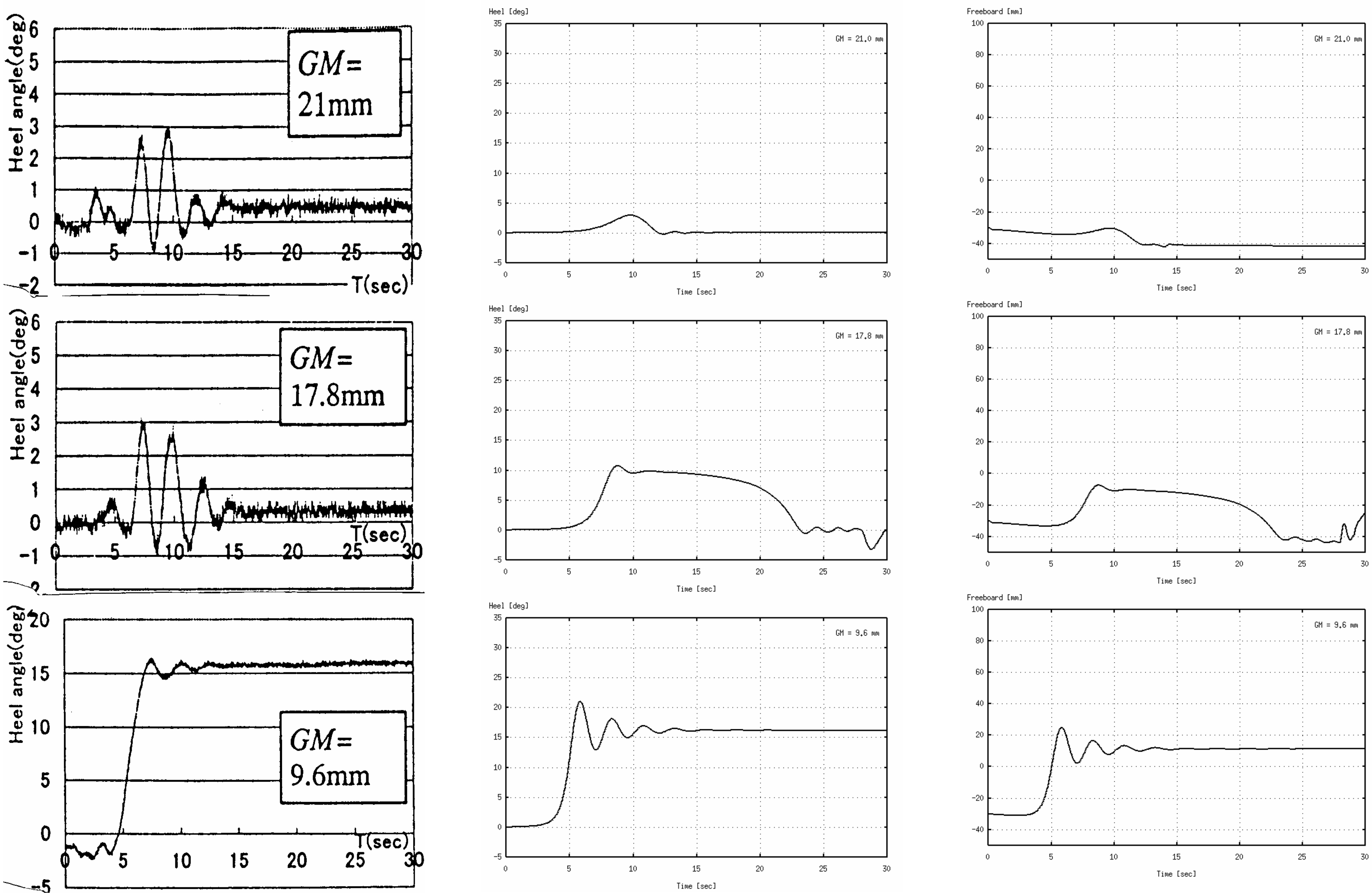

Figure 5. Response of Model A in transient flooding

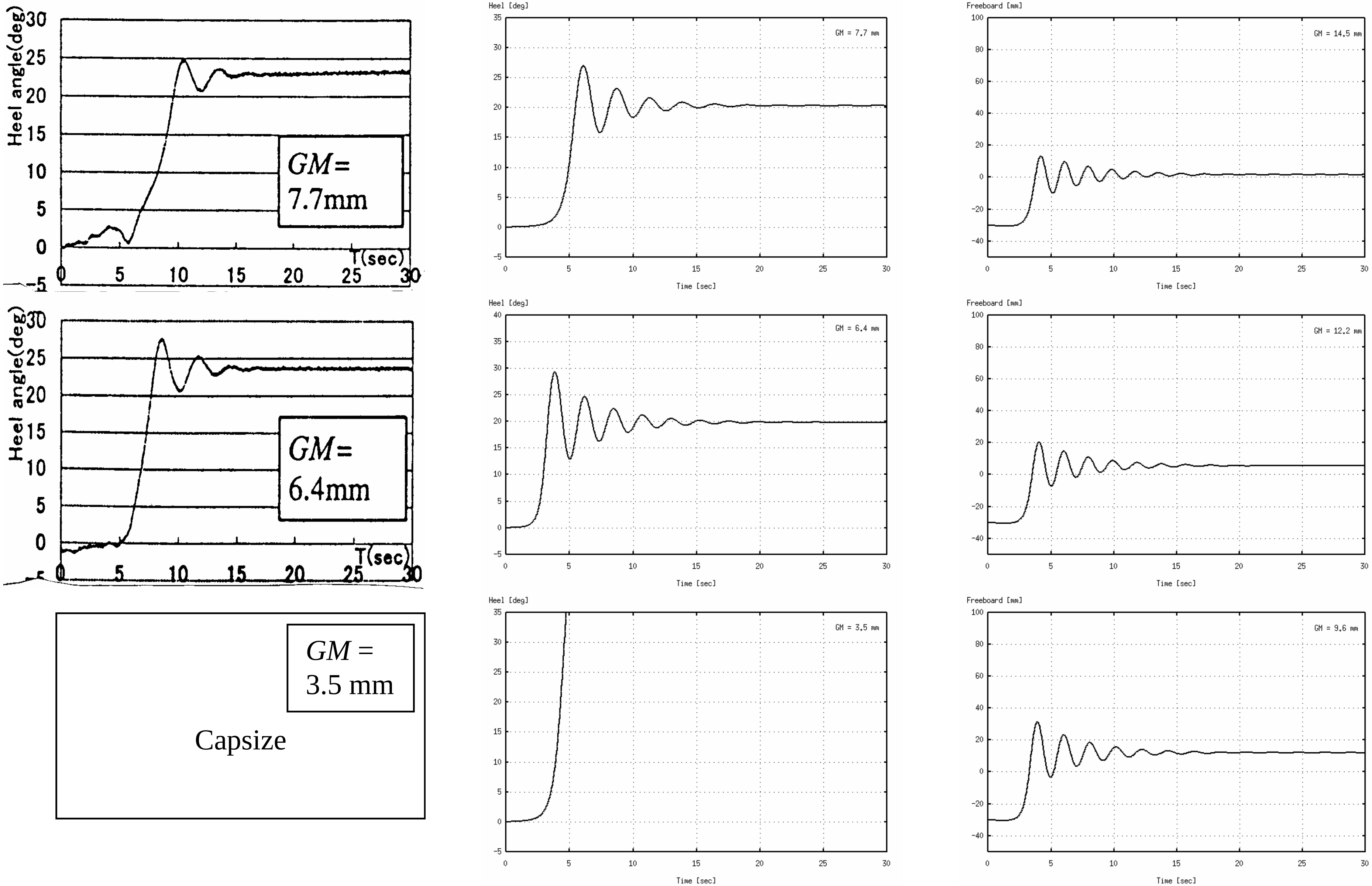

Figure 6. Response of Model A in transient flooding

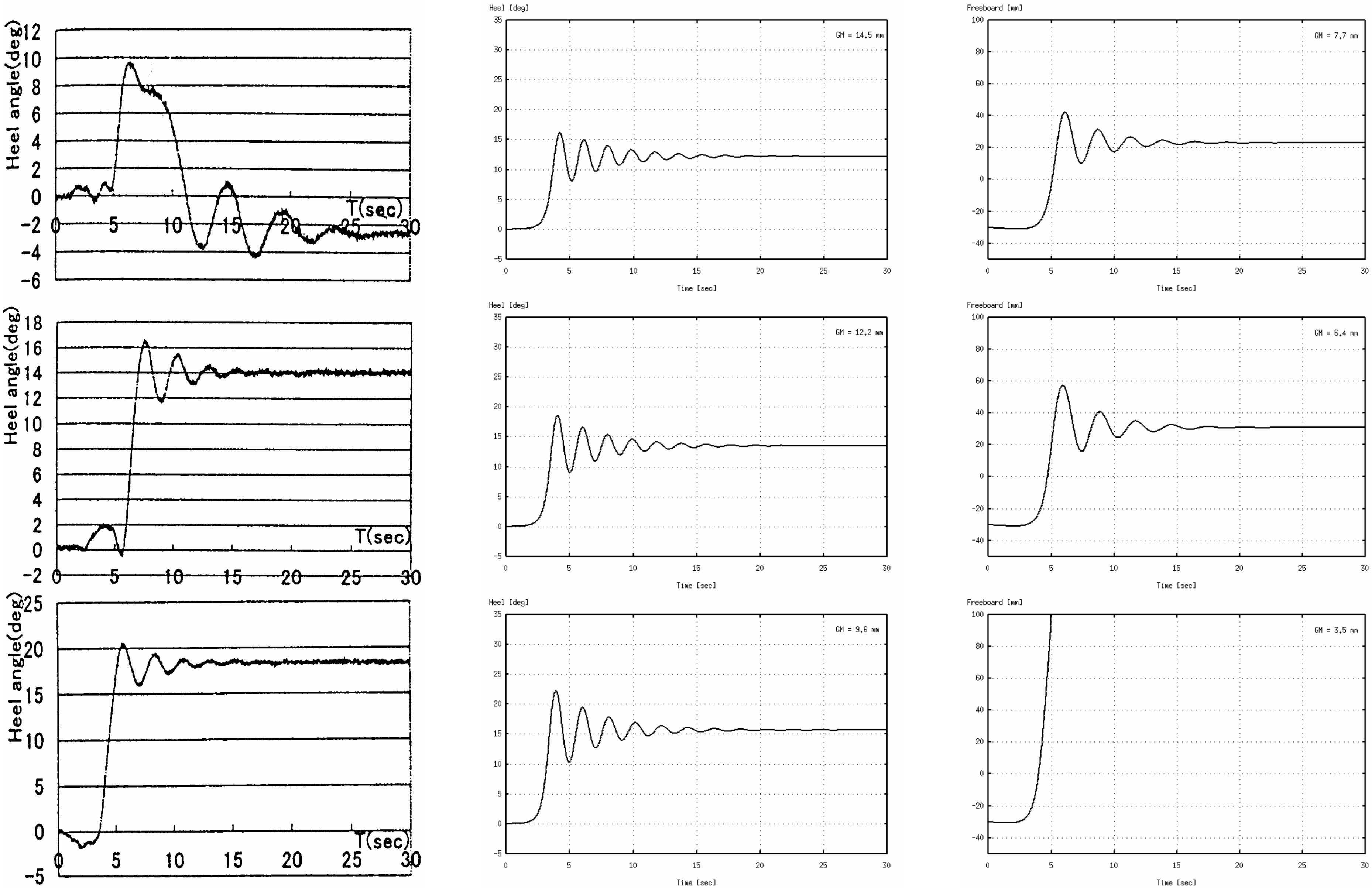

Figure 7. Response of Model B in transient flooding

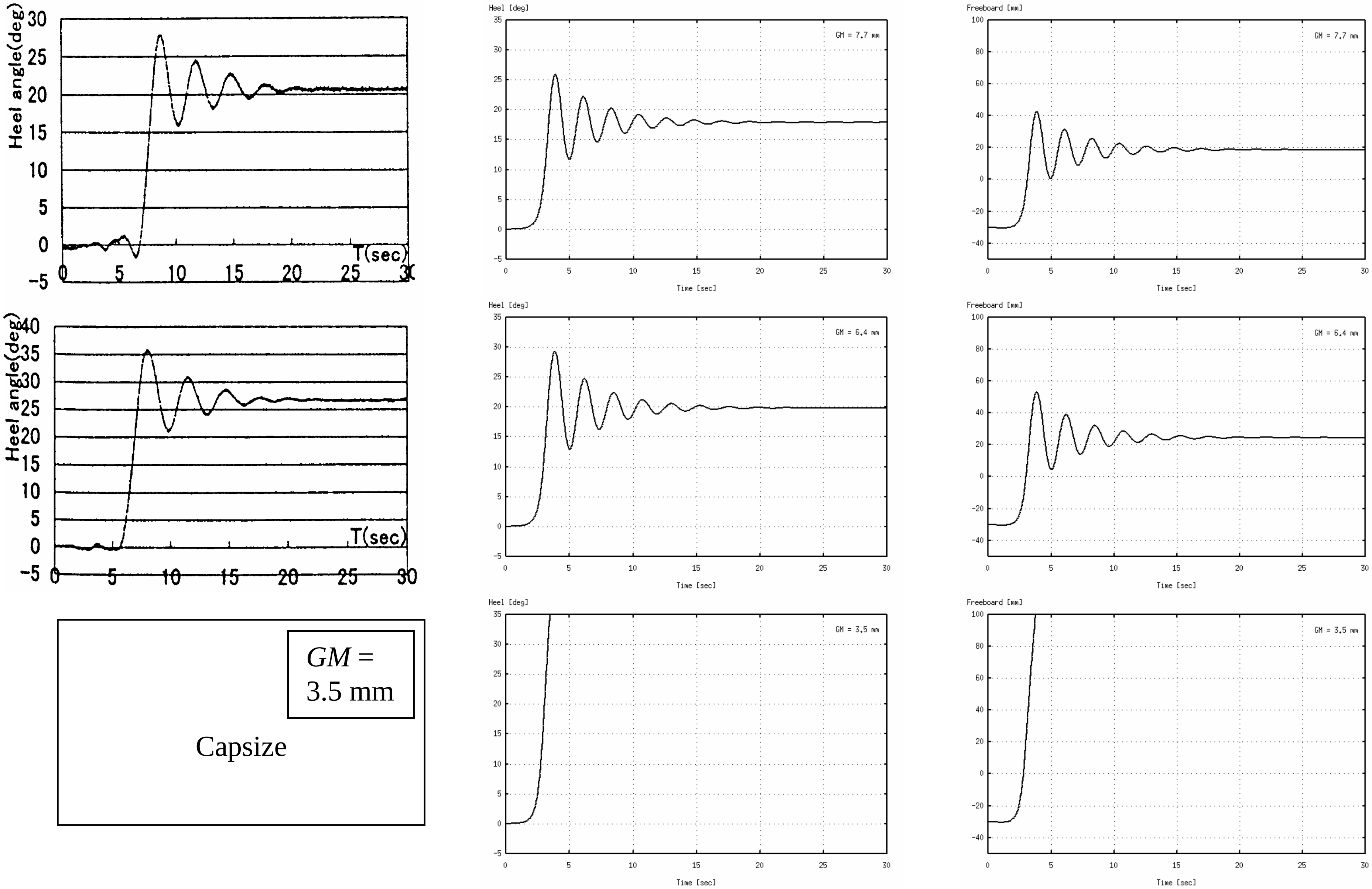

Figure 8. Response of Model B in transient flooding

5. DISCUSSION OF RESULTS

The roll motion results of the vessel in transient flooding, Figures 5 and 6, provide a quite interesting behavior. This presented results concern the behavior of the ship in the initial stages of flooding, in fact of partial flooding. If the damage opening would be extended lower and the water could flood the compartment continuously, then the final position of the damaged model would be unique, namely that resulting by standard stability calculations. The fact that the opening has a certain height, shape and location, is the cause for the partial flooding and the different final positions reached by the model for varying GM values. Therefore the accumulation of water is strongly dependent on the extend, shape and location of the damage opening, and this is the main factor that determines the model behavior.

Regarding the experimental results for the higher values of GM it is observed that the model although it heels some degrees at initial stages of flooding, it finally reduces its heeling angle resting at a quite low heel angle, for model A about half degree opposite and model B about 2.5 degrees against opening. When the GM is reduced the models experience always a finite heeling angle while they capsize for quite small GM value. Numerical calculations show quite similar behavior for the corresponding cases but with partly quantitative differences, which are discussed in the following.

In order to better interpret and understand the behavior of the models A and B the following two diagrams in Figures 9 and 10 respectively, have been prepared.

These diagrams show the equilibrium heel angle of the models, following hydrostatic calculations, as a function of the amount of floodwater into the damage compartment and with parameter KG. For example, in Figure 9, the model A in the presence of 2 kg water inside the compartment obtains an equilibrium stable position at a heeling 15 degrees when the KG=146mm (GM=10.5mm). As a second example, in Figure 10, for the KG=136mm case, the model gradually heels as the floodwater increases, reaching a maximum heel angle about 15 degrees. Then, as the floodwater mass increases for more than about 0.5 kg the ship comes suddenly to the upright position.

These diagrams provide information about the asymptotic behavior of the model, or the heeling of the model if the flooding were quite slow and inertia and hydrodynamic phenomena were absent. During the actual motion, determined by the hydrodynamics of the studied phenomenon, and for a certain amount of floodwater, the model may reach some other heel angle, with its asymptotic equilibrium angle presented in Figures 9 and 10, which can be regarded as the motion attractors when considering the hydrostatic forces as prevailing.

Therefore, taking into account these diagrams, the actual model behavior observed in the experiments can be explained, even for the higher GM values.

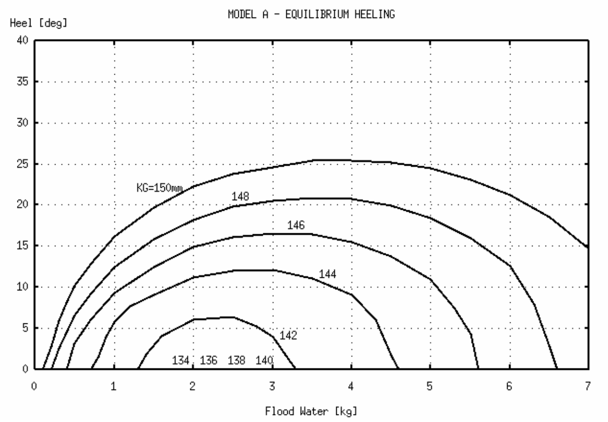

Figure 9. Equilibrium heel angle of Model A

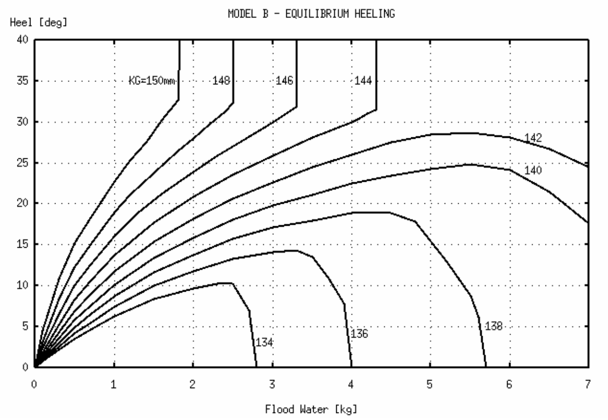

Figure 10. Equilibrium heel angle of Model B

As already stated it becomes obvious that the behavior of the model depends on the amount of floodwater. But at the same time the amount of the floodwater is strongly dependent on the model motion. The submerged portion of the damage opening and the time it remains submerged determine the water inflow, which are directly related to the actual model motion. Considering at the same time the high nonlinear character of the hydrostatics with respect to the floodwater and also other hydrodynamic effects that have not been taken yet into account, the actual motion of the model in transient flooding seems to be quite complicated and sensitive to numerous parameters determining the system. The half kilogram difference of floodwater in case of model B and KG=136mm which leads to 15 degrees difference in heeling could be the result of many of the above not fully explored parameters.

Attention should be paid to the substantial difference between the transient mode of intermediate stages of flooding and the final partial flooding. This distinction is made in order to clarify that intermediate stages of flooding may not finally lead to a fully flooded condition following damage hydrostatics, but to a partial one. In that case the undesirable conditions of partial flooding are present. Even if the model gets finally fully flooded, depending on the damage opening and sea condition, the model may pass through different partial flooding conditions before it reaches the final stage, then the transient flooding could last for long time.

The shape and location of the damage opening proved to be a quite significant factor for the duration and the final result of transient flooding. Obviously other parameters determining the ship motion, like GM, permeability, as well as exciting wave conditions, like sea state, wave heading, affect the flooding procedure and the actual behavior of the model. They should be studied systematically in future research.

6. CONCLUSIONS

A study on the transient flooding of a passenger/Ro-Ro model using a motion and flooding simulation model has been carried out. Numerical simulation results show satisfactory correlation with the available experimental.

The behavior of the model during the initial stages of flooding proved to be quite non-linear and sensitive to various motion parameters. The shape and location of the damage opening proved to a major factor determining the transient flooding, but also the final position of the flooded model.

Transient flooding over extended time might cause serious stability problems. Pending the thorough validation of numerical simulation codes, intermediate stages of flooding should be studied, at least hydrostatically, very carefully, as they significantly affect the assessment of ship's damage stability in waves.

7. ACKNOWLEDGEMENTS

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