Ship Motions Caused by Time-Varying Extra Mass on Board

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ABSTRACT

An existing sea keeping and manoeuvring code LAIDYN is used as a platform to study the dynamic effects of the flooding water to the damaged ship. A simplified model of a lumped mass has been adapted. The dynamic model is presented and the model is applied to a passenger ship design. Flood water volumes at each compartment in a damage case are obtained from an established progressive flooding simulation tool NAPA. Dynamic effects of a time varying mass with two different models of flood water position are studied for a damage case.

KEYWORDS

ship dynamics; damage ship motions; flooding simulation.

INTRODUCTION

Damage of a passenger ship resulting in flooding may endanger life of thousands of people aboard. Decisions to be taken after an accident are possible evacuation of the ship or its transportation to the port. These decisions depend on the damage stability and its rate of deterioration due to progressive flooding. Tools to simulate the progressive flooding in a complex compartment spaces like the ones of passenger ships have been developed Ruponen (2007) successfully using quasi-static simulation of motions. Damaged ship simulations developed for ro-ro/passenger ferries address to the dynamics of the floodwater and its effects to the ship motions (Papanikolaou (2008), Jasionowski (2001), Santos andSoares (2008), deKat (2000)) with a few flooded compartments mainly cardeck or engine room.

As a first step to couple the ship dynamics with progressive flooding, flooded water is modeled as a lumped mass with time-varying weight. Flooded water and its position is calculated at calm water condition using quasi-static simulation code NAPA Flooding Simulation. This time-varying extra mass at moving position is applied to the LAIDYN-code (Matusiak, 2003) and the ship motions resulting from the extra mass are calculated.

METHODS

The progression of the flooding was calculated in calm water assuming quasi-static ship motions i.e. at each time step the static stability position of the ship was calculated for the current amounts of flood water in the compartments. Simulation of the progressive flooding was performed with the NAPA Flooding Simulation tool, method is described in the Ruponen (2006, 2007).

For the simulation of the dynamic ship motions due to the waves and flood water LAIDYN calculation code is used. LAIDYN code is developed for ship sea keeping and manoeuvring simulations. Non-linear effects of large ship motions and non-linear wave forces are taken into account. Hull form is constructed from thousands of triangular panels. The restoring- and Froude-Krylov forces are integrated in time domain over the instantaneous wet surface of the hull. Radiation forces are calculated in frequency domain and translated into time domain. The LAIDYN method is described more in detail in Matusiak (2003,2007,2010). First phase of the implementation of flood water effect into LAIDYN is described in this document.

Studied Ship and Damage Case

A concept passenger ship design was used for the study. Ship design is denoted as Concept ship B. It was designed by Meyer Werft within the FLOODSTAND WP1 (Deliverable D1.1b, Concept Ship Design B). Principal dimensions of the ship are given in the table 1.

Table 1: Principal dimensions of the Concept Ship B

Length (L_{PP}), m	216.8
Breadth, m	32.2
Draft, m	7.2
GM_0, m	2.62
Displacement, ton	35 367

Damage opening is located on the starboard, extending over the outer shell of the garbage room and the engine room compartments. Opening area on the outer shell of the engine room compartment is 2 m^2 and on outer shell of the garbage room 15 m^2.

Three compartments were flooded; engine room, garbage room and boiler room. Boiler room is flooded through the garbage room. The cross-flooding arrangement between the garbage and boiler room is modeled as an opening with an area of 2 m^2. Flooded compartments and the overall ship layout are shown in the figure 1. All flooded compartments had the permeability of 0.85. Discharge coefficient C_d=0.6 is used for all the openings. Compartments are numbered as; 1) engine room, 2) garbage room, 3) boiler room.

Lumped Mass Method

The amount of flood water in each compartment obtained from the quasi-static flooding simulation is taken as an input for the calculation of ship motions. This means that the flooding is not affected by the dynamic ship motions.

In the dynamical model the flood water in each compartment is modeled as a lumped mass. Ship motions are solved from the equations of motion based on the conservation of momentum. Equations of motion for the ship (eqs. 1 and 2) and lumped mass (3) are

$$m[\dot{\mathbf{u}}+\boldsymbol{\omega}\times\mathbf{u}]=\mathbf{f}_{ext}+m\mathbf{g}-\mathbf{f}_i \tag{1}$$

$$\mathbf{I}\dot{\boldsymbol{\omega}}+\boldsymbol{\omega}\times\mathbf{I}\boldsymbol{\omega}=\mathbf{m}_{ext}-\mathbf{r}_i\times\mathbf{f}_i \tag{2}$$

$$\begin{aligned} m_i[\dot{\mathbf{u}}+\dot{\boldsymbol{\omega}}\times\mathbf{r}_i \\ +\boldsymbol{\omega}\times\left(\mathbf{u}+\boldsymbol{\omega}\times\mathbf{r}_i\right) \\ +\dot{\mathbf{u}}_i+2\boldsymbol{\omega}\times\mathbf{u}_i] \\ +\dot{m}_i\left(\mathbf{u}+\mathbf{u}_i+\boldsymbol{\omega}\times\mathbf{r}_i\right)=\mathbf{f}_i+m_i\mathbf{g} \end{aligned} \tag{3}$$

where the expressions are;

m, m_i	ship mass, lumped mass,
$\mathbf{I}$	ship rotational inertia matrix,
$\mathbf{u}$, $\mathbf{u}_i$	ship-, lumped mass velocity,
$\boldsymbol{\omega}$	ship angular velocity,
$\mathbf{r}_i$	lumped mass location in ship coordinates,
$\mathbf{f}$, $\mathbf{m}$	force-, moment vector,
$\mathbf{g}$	gravitational acceleration vector.

Sub index i denotes lumped mass and *ext* external force. Equations (1, 2) and equation (3) are coupled through the interacting force $\mathbf{f}_i$.

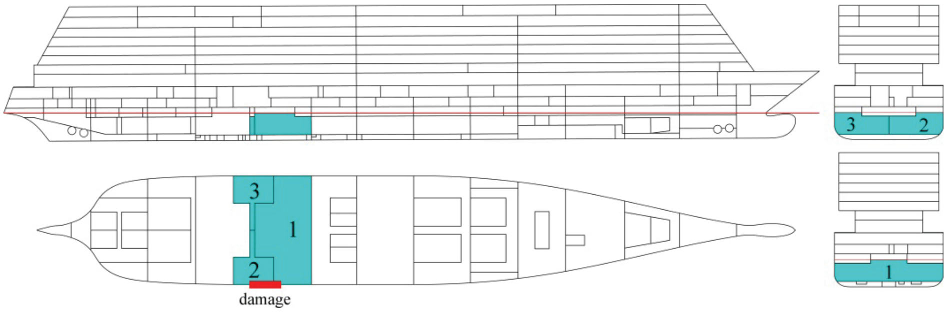

Fig. 1: Flooded compartments.

Lumped mass is located at the center of buoyancy of the flood water in the compartment. An assumption that the lumped mass location is known at each time step is made. Flood water center of buoyancy is calculated from the given compartment geometry and volume of flood water in the compartment as a function of ship's angular position. Hence the interacting force $\mathbf{f}_i$ can be solved from the lumped mass equation of motion (3) and inserted into the ship equations of motion (1, 2) yielding the following equation (4) in a matrix form for the ship-lumped mass system

$$\left(\begin{bmatrix} mI_{3\times3} & 0 \\ 0 & \mathbf{I} \end{bmatrix} + m_i \begin{bmatrix} mI_{3\times3} & -\mathbf{S}(\mathbf{r}_i) \\ \mathbf{S}(\mathbf{r}_i) & -\mathbf{S}(\mathbf{r}_i)\mathbf{S}(\mathbf{r}_i) \end{bmatrix}\right)\begin{Bmatrix} \dot{\mathbf{u}} \\ \dot{\boldsymbol{\omega}} \end{Bmatrix} \qquad \text{(i)}$$

$$\begin{Bmatrix} m\boldsymbol{\omega}\times\mathbf{u} \\ \boldsymbol{\omega}\times\mathbf{I}\boldsymbol{\omega} \end{Bmatrix}$$

$$+\begin{bmatrix} I_{3\times3} \\ \mathbf{S}(\mathbf{r}_i) \end{bmatrix}\left\{m_i\boldsymbol{\omega}\times\left(\mathbf{u}+\boldsymbol{\omega}\times\mathbf{r}_i\right)\right. \qquad \text{(ii)}$$

$$+\, m_i\dot{\mathbf{u}}_i \qquad \text{(iii)}$$

$$+\, 2m_i\left(\boldsymbol{\omega}\times\mathbf{u}_i\right) \qquad \text{(iv)}$$

$$\left.+\, \dot{m}_i\left(\mathbf{u}+\mathbf{u}_i+\boldsymbol{\omega}\times\mathbf{r}_i\right)\right\} \qquad \text{(v)}$$

$$= \begin{Bmatrix} \mathbf{f}_{ext} \\ \mathbf{m}_{ext} \end{Bmatrix} + \begin{Bmatrix} m\mathbf{g} \\ 0 \end{Bmatrix} + \begin{bmatrix} I_{3\times3} \\ \mathbf{S}(\mathbf{r}_i) \end{bmatrix} m_i\mathbf{g} \qquad \text{(vi)}$$

$$(4)$$

where the $I_{3\times3}$ is an identity matrix of size 3×3 and the vector cross product with $\mathbf{r}_i$ is operated by matrix $\mathbf{S}(\mathbf{r}_i)$ defined as

$$r = \begin{Bmatrix} x_i \\ y_i \\ z_i \end{Bmatrix} \qquad \mathbf{S}(\mathbf{r}_i) = \begin{bmatrix} 0 & -z_i & y_i \\ z_i & 0 & -x_i \\ -y_i & x_i & 0 \end{bmatrix} \qquad (5)$$

The effect of the lumped mass consists of an added inertia to the generalized mass matrix of the ship (i), of a force related to the lumped mass centripetal acceleration (ii), force related to the acceleration of the lumped mass with respect to the ship (iii), Coriolis force (iv), lumped mass rate of change (v) and of a gravitational force due to lumped mass weight (vi).

The terms currently implemented to calculation method are lumped mass inertia (i), lumped mass centripetal acceleration (ii) and lumped mass gravitational force (vi).

Two different models for lumped mass position in a compartment are used. First the lumped mass location is taken from the quasi-static simulation, in other words, the free surface of the flood water is fixed to the angle the ship had at the quasi-static flooding simulation (denoted later as '**fixed**'). Second the free flood water surface is assumed to remain horizontal. The position of the lumped mass in a compartment is calculated at each time step at given flood water volume and ship roll angle (denoted later as '**horizontal**'). Figure 2 shows the location of the center of buoyancy for all three flooded compartments at various amounts of flood water at heel angles from -30 deg to 30 deg.

RESULTS

The total simulation time is 10 minutes, where the wave height is increased during the first 50 seconds in order to avoid transient effect of the wave induced motions. Flooding starts at simulation time 60 seconds.

First the results of the quasi-static progressive flooding simulation are presented. Flooding progression in each of the compartments is shown in the figure 6. Water enters directly to the engine channel to the garbage room. The total volume of the engine room is more than four times bigger than that of the adjacent compartments. They are filled first and finally the engine room. The flood water distribution is highly asymmetric at the beginning of the flooding.

Calm Water

Roll angle time histories at quasi-static and dynamic simulations are presented at the figure 3. The maximum heel angle, 4.4 degrees, in the quasi-static simulation is reached at 13.7 seconds (simulation time 73.7s) after the flooding starts. Transient maximum roll angle, 7.3 degrees at dynamic simulation, is almost double the maximum heel angle at the quasi-static simulation. Ship rolls around the quasi-static heel angle. Calculated trim angle is relatively small. Dynamic simulation with LAIDYN produces similar result for the trim angle than NAPA simulation, figure 4.

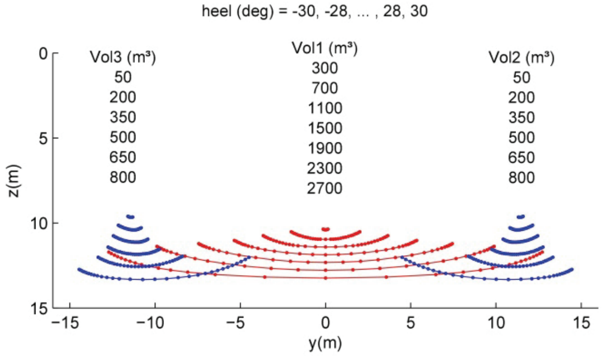

Fig. 2: Location of the lumped mass in compartment 1, 2 and 3 at different flood water volume for heel angles from -30 deg to 30 deg.

The assumption of the horizontal flood water surface does not have a great impact on the maximum roll angle, but it increases the roll period compared to the simulation with flood water position fixed to the quasi-static results i.e. fixed to the average roll angle.

As the flooding progresses and the compartments start to fill up fluctuation of the transversal location of the flood water gets more limited, (figure 2). Roll decays around the final equilibrium heel angle of zero degrees. Transversal location of the flooded water during the simulation is shown in the figure 5. Fluctuation of the flood water location is seen at the calculation with the assumption of horizontal free surface.

Iterative Calculation Round

Using the result of the dynamic roll angle obtained by LAIDYN simulation at horizontal flood water free surface model presented above, an iterative simulation of progressive flooding was performed. In NAPA Flooding Simulation the roll angle was fixed according to the roll result obtained from the LAIDYN, figure 3. The result of flood water volumes at forced roll angle are presented in the figure 6. Dynamic roll angle affects mainly the flood water volume at the garbage room (Vol 2), which has the biggest outer shell opening.

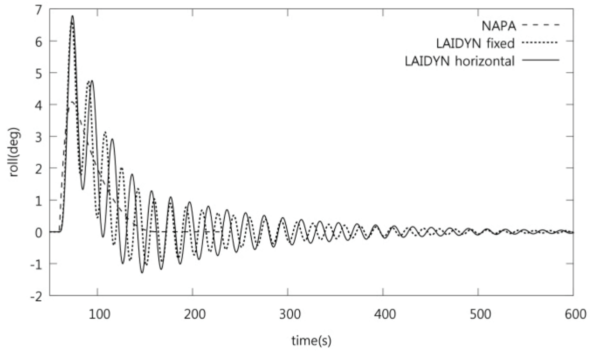

Fig. 3: Heel and roll angle at the quasi-static and dynamic simulation.

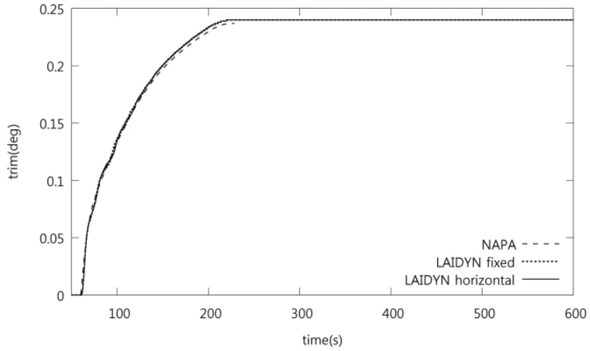

Fig. 4: Trim angle at the quasi-static and dynamic simulation.

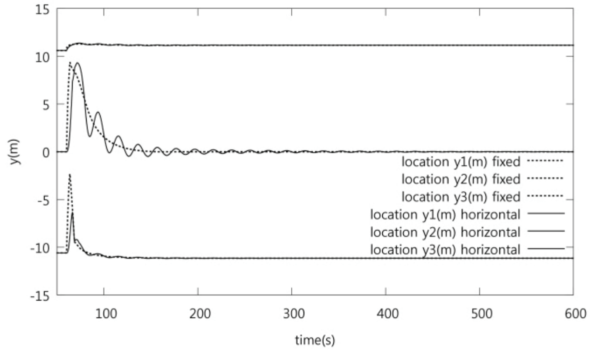

Fig. 5: Flood water transversal location at each compartment.

To complete this iterative round above presented flood water volumes were used for LAIDYN simulation of the dynamic roll angle with the assumption of horizontal flood water free surface. Figure 7 shows the result of roll angle calculated with LAIDYN using the flood water volumes from forced roll angle simulation from NAPA.

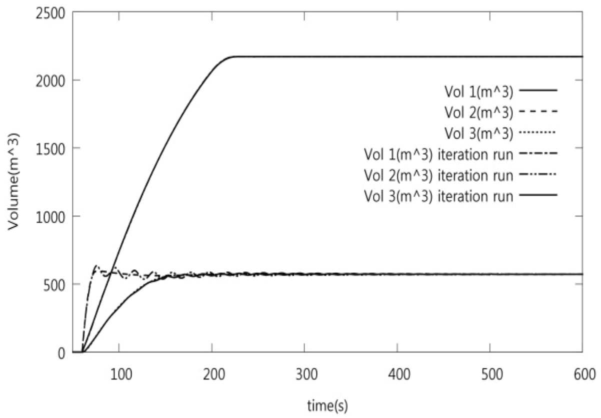

Fig. 6: Volume of the flood water. Quasi-static simulation result and the result obtained at the forced roll angle (iteration run).

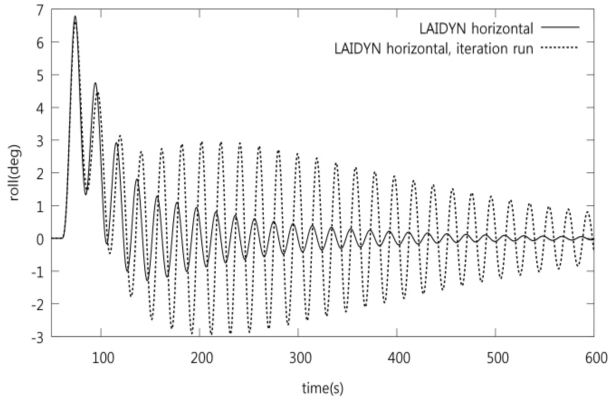

Fig. 7: Forced roll angle at the NAPA simulation and dynamic roll angle.

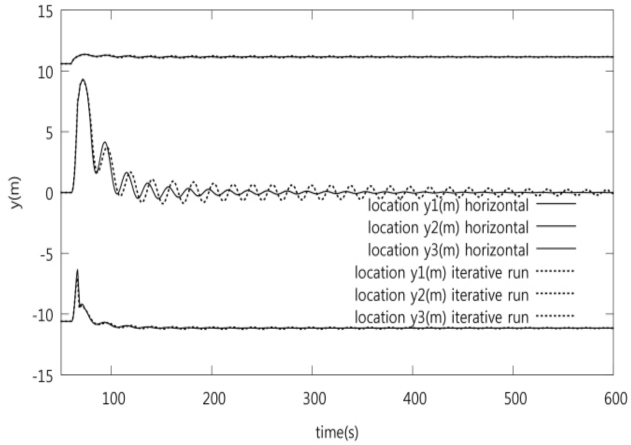

Fig. 8: Transversal location of the flood water at the compartments 1-3. Location at the first run(solid line). Location at the iterative run (dashed line).

After 120 seconds the roll angle starts to amplify as a combined result of fluctuation of the flood water volume (figure 6) and transversal location (figure 8). Combined effect can be seen on the weighted location of the flood water in the figure 9, where the location is weighted with corresponding volume, $y_{w,i}=(V_i/\sum V_i)\ y_i$. The model of horizontal free surface moves the flood water immediately on the heel side regardless of the natural sloshing frequency

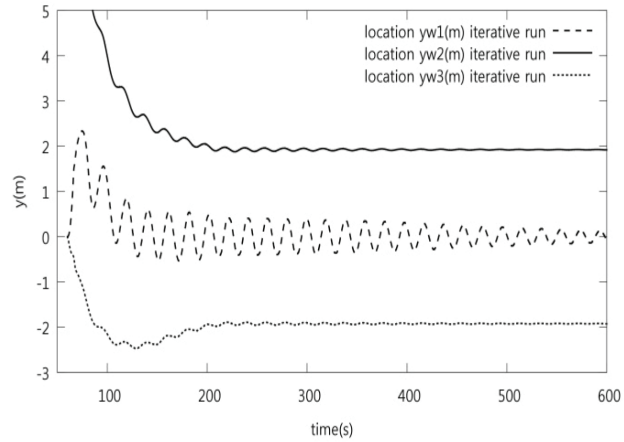

Fig. 9: Weighted transversal location of the flood water at the iterative run.

Sea State

Intact and damaged ship motions were simulated in irregular long-crested beam waves encountering ship on the starboard, the damaged side of the ship. JONSWAP wave spectrum is used at significant wave heights ranging from 2.5 m to 6.5 m. Wave heights were varied at every 0.5 m. Wave steepness $Hs/\lambda=0.04$ at peak period is kept the same between the cases. Exactly the same irregular wave train was used for both the intact and damaged ship.

Results of the simulation at the significant wave heights of 2.5 m and 6.5 m are shown the figures 10 and 11. Maximum roll angle at the damage case is hardly affected at all at this range of wave heights. This is likely explained by the fact that flooding is calculated with the assumption of calm water. After 200 seconds the progressive flooding stage has reached its equilibrium and the compartments are nearly full, with this model the situation after 200 seconds at damage case equals merely a change of load compared to the intact ship. The final stage of progressive flooding results as a change of the total COG and thus slightly higher value of the GM by 0.07 m compared to the GM_0 at the intact condition

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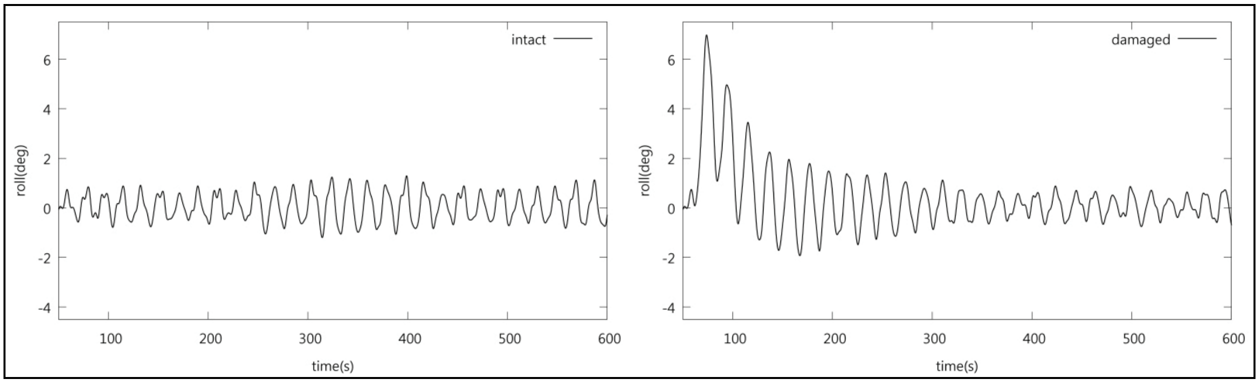

Fig. 10: Case 2. H_S=2.5 m, T_P=6.3s. Roll angle at intact and damaged ship subjected to same irregular wave train.

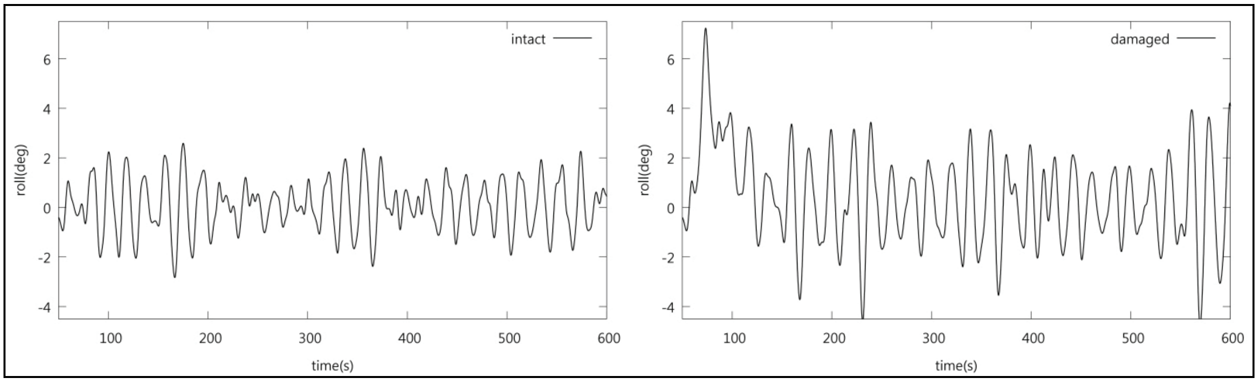

Fig. 11: Case 10. H_S=6.5 m, T_P=10.2s. Roll angle at intact and damaged ship subjected to same irregular wave train.

DISCUSSION

An iterative procedure was only performed ad-hoc at this stage of the implementation of the lumped mass model. Further on the progressive flooding and dynamic ship motions are to be calculated within the same calculation time step. Free surface effect is currently accounted for in a very basic model assuming horizontal flood water free surface which can be questioned to be valid only at very slow motions. Flood water sloshing effect is not taken into account. The lack of sloshing model and the consequent omission of the natural frequency of the flood water causes probably unnatural amplification of the roll motion at the result of the iterative round. A proper and suitable modeling of sloshing for complex compartment geometry of a passenger ship is to be studied. Following step is to consider the pendulum type model which assumes flat flood water free surface.

CONCLUSIONS

Comparison of the results between NAPA and LAIDYN shows that at the beginning of the simulation the transient roll angle is nearly twice as high as the quasi-static heel angle. The ship is rolling around the quasi-static heel angle caused by the gravity effects of the flood water. In calm water the transient roll motion decays eventually. The same final static trim position is found with both codes verifying the hydrostatics calculation of the LAIDYN.

This is an initiative phase of the research aiming to properly model the interaction of the ship motions and flooding progression.

In order to remove the inherent limitation consequent to the assumptions mentioned above at the discussion part the model is to be further elaborated.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 218532 (project FLOODSTAND). The financial support is gratefully appreciated.

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