ABSTRACT

Rising needs for heavy transport operations are intensified by the expanding offshore industry worldwide. Whenever very large and heavy objects have to be transported, only semi-submersible heavy transport vessels are capable of carrying this special cargo. Accidents in the past during operations of these vessels highlight the requirement of analyzing the operation procedures in more detail. Especially the submerging process of the main working deck is very critical regarding the hydrostatic stability. A new numerical progressive flooding simulation method will be presented for applications like accident investigations or damage stability assessments. This method is modified to fit the special requirements of simulating the operational behavior of semi-submersible vessels in the time-domain. A direct approach is chosen, which computes the flux between the compartments based on the Bernoulli equation and the current pressure heads at each intermediate step. Losses due to viscous effects are taken into account by empirical discharge coefficients. This method will be used to simulate the submerging operation in the time-domain to point out critical situations regarding the stability of the vessels and the cargo. This will be compared to accidents which occurred in the past. Furthermore, recommendations for operational procedures are proposed.

PHYSICAL MODEL

Before investigating practical problems, the physical model with the taken assumptions of the developed progressive flooding simulation method is described. The method is implemented in the ship design environment E4 developed at our institute. In doing so, direct access to the whole ship data model and already implemented computational algorithms like hydrostatic evaluations is granted.

Basic Equations

The flooding of a floating object is driven by certain pressure differences at openings leading to the in- or egress of flood water. These fluxes can be idealized by the incompressible, stationary and viscous- and rotational free Bernoulli equation given in Eqn. 1 formulated for a streamline connecting point a and point b:

$$\frac{p_a - p_b}{\rho g} + \frac{u_a^2 - u_b^2}{2g} + z_a - z_b - \frac{\varphi_{ab}}{g} = \frac{d}{dz}. \quad (1)$$

Any dissipative effects are modeled by a semi-empirical discharge coefficient proportional to the flux velocity. If the outflow is free (left side of Fig. 1), the pressure height difference
becomes:

\[ dz = \frac{p_a - p_b}{\rho g} + \frac{u_a^2 - u_b^2}{2 g} + z_a - z_b. \]  

(2)

The flux through a deeply submerged opening (right side of Fig. 1) is independent of the location \( z_0 \) of the opening and given by:

\[ dz = \frac{p_a - p_b}{\rho g} + \frac{u_a^2 - u_b^2}{2 g} + z_a - z_b. \]  

(3)

This pressure height difference \( dz \) yields a fluid velocity

\[ u = \sqrt{2 g \cdot dz}. \]  

(4)

The integration of the velocity over the area of the opening assuming a perpendicular flow direction leads to the total flux:

\[ \dot{V} = \frac{\partial V}{\partial t} = Q = \int_A \mathbf{u} \cdot dA = \int_A \mathbf{u} \cdot n dA = \int_A u dA. \]  

(5)

Large Openings

More challenging is the determination of the flux over large openings, since the cross section and the fluid velocity may vary over the integration direction \( s \), which does not have to be in the earth fixed vertical direction \( z \). In general, the flux is given by the integral

\[ Q = \int_A u dA = \int_s \int_y u(s) dy ds = \int_s u(s) \cdot y(s) ds. \]  

(6)

To model any shape of opening, it is described as a plane polygon oriented arbitrary in space. For the flux integration it is discretized in several \( z \)-stripes (see Fig. 2), where the free outflow flux of each stripe may be found analytically by the definite integral

\[ Q = -\frac{2}{3s_z} \cdot \sqrt{2 g} \cdot \left[ y_1 \cdot h_1^2 - y_0 \cdot h_0^2 + \frac{2}{5} \frac{(y_1 - y_0)}{z_1 - z_0} \cdot (h_1^2 - h_0^2) \right]. \]  

(7)

with

\[ s_z = \frac{z_1 - z_0}{z_1} \]

\[ h_1 = z_a - z_1 + \alpha \quad h_0 = z_a - z_0 + \alpha \]

\[ \alpha = \frac{p_a}{\rho g} - \frac{p_b}{\rho g} + \frac{u_a^2}{2 g} \]

This integration may also be performed for further basic opening shapes like circular holes.

Flooding System

The connections of all related compartments of the ship by openings are nicely modeled by directed graphs. A simple example is shown in Fig. 4 describing the validation case A from [1].

The flooding graph is completely defined by the edges representing the openings together with their neighboring nodes representing the compartments. Each node is defined by an ID and a name. Using this kind of definition for the flooding system is a very convenient and direct way. All methods and algorithms developed in graph theory can simply be applied to flooding systems of ships. This way questions like “Which neighbors are related to a certain compartment in question?” can easily be answered.

Mass Balance

Using a flooding graph, the total flux \( Q \) for one compartment is given by the sum over all openings belonging to this compartment. An example of this concept is given in Fig. 4.
Integrating the flux in the time domain gives the amount of water transported in a certain time-step from one compartment to its neighbor(s):

\[ V = \int t Q(t) \, dt. \]  

This transported water volume leads to new filling levels in the compartments, since the fluid volume in each compartment changes. The determination of this new filling has to be done iterative, since the room geometry is usually arbitrary and the filling level depending on the current waterline and fluid volume is not given analytically.

**Higher Order Flux Integration**

Instead of assuming a constant flux during one time-step one may also use a kind of predictor-corrector scheme for the opening fluxes. This inner iteration can be sketched as follows:

1. Predict opening fluxes
2. Propagate predicted volumes assuming a constant flux
3. Calculate new filling levels
4. Recompute opening fluxes based on these new fillings
5. Estimate mean flux by relaxation
6. Reset volumes and propagate again, recompute filling levels based on the mean flux and proceed

This avoids efficiently the flux direction change during one time-step caused by the explicit characteristic of the method. This happens if the filling levels of two neighbors are very close and the propagated volume assumed by a constant flux yields to a change of sign of the flux. How often this overflowing happens depends on the size of the time-step and the opening size. However, its influence on the integrated values like the ship motion is usually small.

**Propagation of Full Compartments**

If one or more neighboring compartments are completely filled with water, the corresponding compartments are coupled. The following holds in that situation:

1. The total flux of a full one must be zero.
2. The water flux from partly filled compartments must be propagated through this full compartments.
3. The only free variable remaining is the pressure.
4. A nonlinear system of equations must be solved to find these pressure values.
5. This system can be composed by finding a sub-graph of all connected, full compartments.

This nonlinear system is normally not very large and can easily be solved with standard algorithms.

**Conditions of Openings**

To allow the modeling of, for example, breaking doors or windows during flooding, a pressure head criterium is used for the openings. If the water column height above the center of the opening becomes larger than this defined value, the opening breaks and stays open. This technique may also be used to introduce conditional flooding.

**Air Compression**

In some cases, it might also be necessary to take into account trapped air, although in most cases the assumption of fully ventilated tanks is valid. But the occurrence of air pockets might especially be important for the later phases of a sinking sequence. This effect is taken into account by assuming an ideal gas and the compression to be isotherm according to Boyle’s law. The pressure of the corresponding compartment with the trapped air is increased by the reduction of air volume:

\[ p_0 \cdot V_0 = p_1 \cdot V_1. \]  

**Simulation Overview**

One time-step of the simulation will consist of the following steps:

1. Check conditional breaking of openings
2. Pressure iteration for full tanks
3. Flux determination of remaining openings
4. Inner iteration for higher-order integration of fluxes
5. Propagation of water volumes
6. Update of filling levels and determination of full tanks
7. Optional air compression
8. Iteration of new floating equilibrium
9. Check of convergence

This is repeated for each time-step until either the requested simulation time or convergence is reached.

**Validation**

For the validation of this method a comparison with model tests of a box-shaped barge performed by P. Ruponen at the Ship Laboratory of the Helsinki University of Technology is done [2]. These model tests where later also used as validation cases for Ruponen’s dissertation [1].

The simulated results of validation case A shown in Fig. 3 are compared with the measured and computed results from [1].

To illustrate the model of directed graphs for the flooding system, the graph of this arrangement is shown in Fig. 4. The flux for compartment R21 (No. 3) is given by

\[ Q_3 = Q_{o1} + Q_{o2} + Q_{o6} - Q_{o4}. \]
For the computation a time-step of 0.5 seconds is used (compared to 0.05 seconds used by Ruponen). The simulated trim and heave motion shown in Fig. 5 and the water levels in Fig. 6 show a very good agreement with the measurements and the computed values from Ruponen. The simulated results from the method here presented are marked with the prefix “D. calc”, the measured values with “R. meas” and the computed values by Ruponen with “R. calc”. The other computed values are of comparable quality. Further validation of the simulation method has been successfully carried out by the (re)investigation of real ship accidents.

FIGURE 3. OPENINGS FOR TEST CASE A [2]

FIGURE 4. SIMPLE SUBDIVISION MODEL

DESCRIPTION OF THE REFERENCE VESSEL

The described simulation method is applied to the practical problem of the submersion process of a typical semi-submersible heavy transport vessel. As a reference vessel a ship designed by the co-author for a student project is used. The main particulars are listed in Tab. 1 and a side view with the most important ballast tanks of the vessel together with a typical platform cargo is shown in Fig. 7. For the following simulations, the platform will be idealized by a rectangular box of similar dimensions.

SIMULATION OF THE SUBMERGING PROCESS

The submerging of the main deck will be accomplished by gravity flooding of the ballast tanks. The tanks are simply connected to the sea by defining openings at several locations illustrated in Fig. 8 together with the ship data model.

Hydrostatic Stability Issues

The only known regulations for semi-submersible heavy transport vessels are issued by Det Norske Veritas in [3]. These include intact criteria in temporarily submerged conditions regarding the GM, the GZ range and the maximum righting arm.
It is also stated, that it may be required to calculate the stability about additional axis to determine the most onerous result. This is most likely included, because large unsymmetrical flooding (or geometry of the deck cargo) may lead to a rotation of the principal axis of the current waterline. The weakest direction with the lowest stability may no longer be the transversal direction. This will be taken into account by computing a minimum $GM$ value defined as follows:

$$\bar{GM}_t = \frac{I_{\xi_w}}{V} + \zeta_{BG},$$

(10)

$$I_2 = \frac{I_{\eta_w} + I_{\xi_w}}{2} - \frac{1}{2} \sqrt{(I_{\eta_w} - I_{\xi_w})^2 + 4I_{\eta_w}^2}$$

(11)

$$GM_{\text{min}} = \frac{I_2}{V} + \zeta_{BG},$$

(12)

where $I_{\eta_w}$ is the second moment of area around the waterline center axis, $\zeta_{BG}$ is the earth fixed vertical distance of the volumetric buoyancy and gravity center and $V$ is simply the volumetric displacement. These values may also be directly derived from the hydrostatic stiffness matrix, which is equivalent to the Jacobin matrix of the three degrees of freedom and the restoring displacement, trim and heel moments.
All fillings and the resulting moments of the tanks are directly computed at each time-step, i.e. no simplification regarding free liquid surfaces are used.

**Scenario 1: Symmetric Flooding**

As a first scenario, a symmetric submerging is simulated. The loading condition before flooding is chosen to be upright with a small initial trim of 0.2 degrees to the bow with the main deck not submerged.

**Values over Time.** As a useful tool to illustrate the submerging process, the time line of events can be animated, where four interesting time-steps are shown in Fig. 9. Openings which become submerged are colored red, the ones above the waterline are marked in green. In addition, the most interesting variables like the top five flooded tanks and openings with respect to the amount of water/flux are given by the simulation tool, although they are not shown in the frames presented in Fig. 9.

Due to the initial trim, the forward tanks are filled up first and the trim increases. The overall process until convergence is reached after only six minutes, because the openings are chosen to be quite large with around 1 m$^2$ each. Using smaller openings would only stretch the time line of events.

The characteristic stability variables are shown in Fig. 10. To check the submerging of the main deck, control points are added at the corners of the deck and the platform. In Tab. 2 the critical points in time are listed. These points can also be recognized in the curve of the $\text{GM}$-value shown in Fig. 10. They are marked by dotted vertical lines. At first the $\text{GM}$ increases slightly due to a lower center of gravity caused by the floodwater. After the submerging of the forward deck edge at 67 seconds, the stability rapidly decreases before the buoyancy of the platform slows down this process. When the basis of the platform is completely below the water surface, the $\text{GM}$ decreases very fast again by more than 2 m down to around 0.8 m. A very small asymmetry of one tank leads to a small heel after around 200s. When the complete deck is submerged, this heeling increases due to the first flooding of the starboard aft buoyancy column before it slows down again when the portside column is flooded as well.

**Leverarm Time Dependency.** To further illustrate the hydrostatic stability of the submerging process, the resulting

<table>
<thead>
<tr>
<th>TABLE 2. CRITICAL POINTS DURING SUBMERGING</th>
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<tbody>
<tr>
<td>Forward Edge Deck</td>
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<tr>
<td>Forward Edge Platform</td>
</tr>
<tr>
<td>Aft Edge Platform</td>
</tr>
<tr>
<td>Aft Edge Deck</td>
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**FIGURE 9. TIME-STEPS FROM THE ANIMATION OF SUBMERGING**

**FIGURE 10. SCENARIO 1: CHARACTERISTIC VALUES OVER TIME**

Due to the symmetry of the flooding, no differences occur between the transversal and the minimum $\text{GM}$ values.
righting arm curves at selected time-steps are shown in Fig. 11 together with the initial stability, where the labels of each curve mark the time-step in seconds.

At the beginning, the stability is quite sufficient. The bending of the almost linear curve at around eight degrees occurs when the deck is submerged. After this the leverarm is supported by the deck cargo until the maximum is reached at around 28 degrees. The range of around 50 degrees is quite high.

The start of the submerging of the forward main deck (see also first frame in Fig. 9) leads to a significant drop of the overall stability illustrated in the second curve. At the next time-step (third curve, second frame in Fig. 9) after the deck cargo starts submerging, the maximum of the leverarm is shifted down to around 20 degrees. This maximum probably occurs when the upper limit of the deck cargo is submerged. The difference between the initial stability defined by the GM and the real righting arm is very high during this phase.

The fourth curve illustrates the situation when the aft part of the main deck gets submerged. The maximum righting arm drops below 0.5 m, while the range still amounts to around 40 degrees.

In the final floating position at around 400 seconds, the maximum of around 0.3 m is only slightly above 10 degrees. The righting arm curve shape can be described almost linear.

It should be mentioned that during all phases of flooding, the intact criteria stated in [3] are fulfilled.

Scenario 2: Unsymmetrical Flooding

A slightly trimmed submerging of the main deck avoids rapid changes in the waterline, which highly influences the GM value by the second moment of inertia of the waterline. To allow an even smoother submerging, the vessel will also be heeled slightly. This can be accomplished by choosing an unsymmetrical discharge coefficient for the portside and starboard openings of a pair of tanks or by adding a pressure head criteria on one side.

For this case, a 0.2 lower discharge value is used for the portside opening of tank 7 located in the front of the vessel. After the submerging of the main deck, the heel is decreased again by adding a pressure head of 2 m to the opening connecting the double shell tank on the starboard side above the machine room to the outside.

Values over Time. The developing of the values shown in Fig. 12 are quite similar to scenario 1, only the heel and the GM value differ. To further illustrate the flooding sequence, the tank filling levels of the most interesting tanks are shown in Fig. 13. The heel first increases until the starboard tank 7 is filled completely. At first the flooding of the MR Top PS tank yields first a further heel to the starboard side, but after the complete submerging of the platform bottom on the main deck (at around 180 seconds), the heel decreases again. It follows a phase with an almost constant heel until the aft column on the starboard side starts to fill up. The heel increases further when the pressure head condition yields a breaking of the opening to the MR Top SB tank at around 270 seconds. The last peak is reached when all tanks are filled, except the buoyancy columns. When convergence is reached, the vessel becomes upright again.

The main deck is not submerged at both sides instantaneous but with a delay. This causes the GM to decrease in a more
smooth manner.

Comparison of both Scenarios

In Fig. 14 the characteristic values of both scenarios are compared. The changes of the GM values are not that rapidly in scenario 2 and the dangerous drop down to the minimum value is also less severe with a smaller overall minimum. The developing of the trim values are comparable but delayed in time in scenario 2. The heeling angle is, as intended, larger in the unsymmetrical case, but stays always below 2.5 degrees.

CONCLUSIONS AND OUTLOOK

The developed progressive flooding simulation method has been successfully applied to the submerging operation of semi-submersible heavy transport ships. It has been shown to be a useful tool for the scheduling of such operations. Different scenarios can easily be investigated to find the most secure procedures and to identify critical points. Together with the shown visualization, this method may also be used as an on-board monitoring system. The verification of certain hydrostatic stability criteria may also be done directly in the time-domain for each physically possible intermediate stage of flooding.
This method may also be used to analyze real accidents to avoid these failure modes in the future. One interesting extension for the future would be to dynamically adjust the fluxes through certain openings, if for example certain limiting heel or trim values are exceeded. In addition, the influence of the deck cargo floating free might be another interesting aspect to look at. Another idea might be to include pump elements, where a certain constant flux (or constant pump power) in one tank is realized by ballast water pumps to allow the flooding of tanks above the current waterline.

REFERENCES

