An Experimental Study on Progressive and Dynamic Damage Stability Scenarios

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ABSTRACT

Current damage stability rules for ships are based on the evaluation of a ship’s residual stability in the final flooding stage. The consideration of the dynamic propagation of water within the inner subdivision as well as intermediate flooding stages and their influence on the resulting stability is very limited in the current damage stability regulations.

The investigation of accidents like the one of the Estonia or the European Gateway reveals that intermediate stages of flooding and the dynamic flooding sequence result in significant fluid shifting moments which have a major influence on the time-dependent stability of damaged ships. Consequently, the critical intermediate stages should be considered when evaluating designs with large cargo decks like RoRo vessels, RoPax vessels and car carriers. Also the safety of large passenger ships with respect to damage stability is affected by the aforementioned effects.

In this context a new numerical flooding simulation tool has been developed which allows an evaluation of a ship’s time-dependent damage stability including all intermediate stages of flooding. The simulation model is based on a quasi-static approach in the time domain with a hydraulic model for the fluxes to ease the computation and allow for fast and efficient evaluation within the early design stage of the vessel. This allows studying multiple damage scenarios within a short period.

For the further validation of this numerical simulation method a series of model tests has been particularly set up to analyse the time-dependent damage stability of a floating body. The test-body has been designed specifically to reflect the most typical internal subdivision layouts of ships affected by the effects mentioned above.

The experimental study covers a static model test series as well a dynamic one. The static model test series has been set up with the aim to analyse the progressive flooding of selected compartments in calm water. Within the dynamic model test series, the model is excited by a roll motion oscillator to evaluate the influence of the ship motion on the water propagation and the associated damage stability.

The model tests presented in this paper comprise side leaks in typical compartments which are used for a basic validation of the simulation tool and the measurement devices. Particular attention has been drawn on damage scenarios with critical intermediate flooding stages in consequence of restricted water propagation. The presented results enable a further validation of the numerical flooding simulation and give an insight view on the chosen experimental setup.

QUASISTATIC FLOODING CALCULATION

The static testcases are compared with a quasi-static flooding simulation method developed by Dankowski [1]. The results from the presented model tests will be used to further validate the flooding simulation. On the other hand, the static testcases are pre-computed by the numerical method to get an idea how the model will react on the water ingress. This is assumed to be acceptable, since the numerical method has already been validated by other model tests and verified with the help of accident investigations.
The numerical flooding simulation determines the fluxes through the openings by means of a hydraulic model. The propagation of the water volumes is computed by a predictor-corrector scheme for the integration of the volume fluxes to each compartment in question.

**Flux Determination**

The in- or egress of flood water through the internal and external openings can be idealised 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:

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

The dissipative energy term \(\varphi_{ab}\) accounts for pressure losses through the openings and is assumed to be proportional to the kinetic energy of the flow. This loss is modeled by a semi-empirical discharge coefficient \(C_d\) reducing the flux velocity. The pressure height difference \(dz\) yields the fluid velocity

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

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

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

The solution of this integral becomes more complicated if the opening is large and of arbitrary shape and orientation. Therefore, larger openings are discretized in smaller, elementary parts for which an analytical solution of the volume flux can be determined as described for example in Dankowski [1].

**Flooding Paths**

Directed graphs are used to describe the flooding paths. The openings are the edges of the graph connecting the different compartments representing the nodes. The direction of the edges defines the sign convention for the opening fluxes. The mass balance for one compartment is given by the sum over all edges connected to one node.

An example of such a directed graph is given in Fig. 1. This graph describes the flooding paths from the validation test case B in Ruponen [2].

**Propagation Step**

The amount of water propagated in one time step to one compartment from its neighbor(s) is given by the integration of the sum of the volume fluxes \(Q_o(t)\) obtained from all connected openings:

\[
dV = \int_{t_1}^{t_2} Q_o(t) \, dt.
\]

The propagation of water leads to a new distribution of the flood water and new volume fillings in the compartments. These volumes depend nonlinear on the water levels of the compartments and has to be determined iteratively. The flux function \(Q_o(t)\) is a also nonlinear function over time. To account for this nonlinear characteristic for the time integration, a predictor-corrector scheme is applied, which is 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 scheme avoids efficiently the flux direction change during one time-step caused by the explicit characteristic of the method and stabilizes the whole numerical simulation.

**Air Compression**

The compression of entrapped air is modeled by Boyle’s law stated as follows:

\[p_0 \cdot V_0 = p_1 \cdot V_1.\]
The decrease in the air volume leads to an increase in air pressure. The air flow itself is not taken into account, but the automatic determination of entrapped air pockets is included.

**Simulation Overview**

The flooding simulation is briefly summarized for one time step as follows:

1. Check of opening conditions
2. Pressure iteration of full compartments
3. Fluxes 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.

For completely flooded compartments it is required in this scheme to iterate the inner pressure of compartments until the total flux sum for one time step becomes zero. The water must still be propagated through the compartment in question and the only remaining free variable here is the pressure. An alternative would be to assume a small amount of compressed air before a compartment becomes completely flooded but this leads to numerical instabilities due to the different scaling of the air phase compared to the water.

The numerical flooding simulation has already been successfully validated with the ITTC benchmark model test for the prediction of time to flood (compare [3]). In addition, three full-scale accidents have been investigated with the help of the method. The general chain of events of these accidents are well reconstructed by the numerical method. Further details can be found in Dankowski [1].

**DYNAMIC FLOODWATER SIMULATION**

The dynamic testcases of the presented model tests are used to validate numerical methods for the prediction of the dynamic motion of entrapped floodwater.

As reasoned for example in Soeding [4] the motion of floodwater can be computed by a numerical solution of the shallow water equations. Only for shallow water depth on for example large vehicle decks, the water surface in these compartments deviate from a plane surface. Otherwise, the compartment can either be treated in a hydrostatic manner like in the previously sketched flooding simulation or as a one (or two) degree of freedom mass oscillator.

The numerical method is based on the work by Dillingham [5] and has further been extended by Petey [6]. It is coupled with the nonlinear seakeeping code E4-ROLLS, which is in detail described by Kröger [7].

**The shallow water equations**

The water movement is forced by the external accelerations issued by the moving ship. This can be described by the following shallow water equations sketched here for the one dimensional case:

\[
\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial y} + f_z \frac{\partial h}{\partial y} = f_y \\
\frac{\partial h}{\partial t} + v \frac{\partial h}{\partial y} + h \frac{\partial v}{\partial y} = 0
\]

The forces \( f_{y,z} \) depend on the external accelerations.

**Coupling of tank and ship motion**

The external forces acting on the water in the compartment depend on the motion of the ship like the heel and pitch angle, angular velocity and the accelerations as sketched in Fig. 2.

**FIGURE 2**: Coupling of ship and fluid motion according to Dillingham [5]

**Numerical solution**

The equation system is discretized on a uniform grid and solved with the help of Glimm’s method for nonlinear hyperbolic equations (compare Glimm [8]). This special solution scheme is
required due to the frequent occurrence of hydraulic jumps which introduces instabilities in the solution. The solution scheme is based on analytical solutions of the dam-break problem at each boundary of the fluid cells. The discontinuities are avoided by a random staggered grid.

DESCRIPTION OF THE MODEL

The model has been designed with the aim to investigate the dynamic propagation of water and intermediate flooding stages of ships with large cargo decks such as RoRo / RoPax vessels and car carrier. The model is fully made of plexiglass and consists of three parts: fore body, mid ship section and aft body. The measurement devices are located in the fore and aft body of the model. The transparent mid ship section comprises the floodable compartments. Sufficient longitudinal strength is provided via the screw connections of the sections and a dock made of steel, which is used to launch and transport the model. A picture of the model is shown in Fig. 3.

FIGURE 3: The model in the test basin prior to flooding at design draft with closed bow and stern door

The model is equipped with eight ballast weights, which are located in the fore and aft body. The ballast weights are mounted to the hull via a shelf-like structure and allow a systematic variation of the vertical center of gravity. This functionality is used to investigate test cases with a differing initial stability to be able to evaluate bifurcation problems. The main dimensions of the model are given in Tab. 1.

The main dimensions are chosen with respect to the maximum available space in the water basin. The length to beam ratio and draft to height ratio are chosen similar to typical main dimensions of RoRo ships. The model is capable to perform up-and down flooding events through side and bottom leaks as well as through the bow or stern door opening.

TABLE 1: Main Dimensions of the Model

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over all $L$</td>
<td>2.02 m</td>
</tr>
<tr>
<td>Breadth $B$</td>
<td>0.42 m</td>
</tr>
<tr>
<td>Depth $D$</td>
<td>0.42 m</td>
</tr>
<tr>
<td>Draft $T$</td>
<td>0.18 m</td>
</tr>
<tr>
<td>Displacement $\Delta$</td>
<td>144 kg</td>
</tr>
</tbody>
</table>

Subdivision

The subdivision of the model is shown in Fig. 4. The subdivision of the mid ship section has been designed according to a typical subdivision layout of a RoRo vessel. The floodable compartments are indicated by the light blue color.

FIGURE 4: General arrangement drawing of the test body

In horizontal direction, the model consists of the main and the tank top deck. In longitudinal direction, the model is subdivided through the side and center casing on the main deck, the center line girder in the double bottom (compartments 01 and 02) and the two longitudinal bulkheads in compartment 13. The longitudinal bulkhead at starboard can be adjusted to the positions 0.2 B, 0.35 B and 0.5 B. At position 0.2 B, compartments 02, 12 and 14 form a U-shaped tank.

Compartment 11 represents a typical engine room compartment. The displacement of the engines has been considered through three watertight boxes. Compartment 15 is similar to a typical bunker tank compartment. Compartment 22 has the shape and layout of a large cargo hold compartment of a RoRo vessel. This compartment comprises a closeable bow and stern door opening.
and four freeing ports. Every floodable compartment is equipped
with an air pipe to avoid incomplete flooding events as a result
of trapped, compressed air pockets.

Openings
The geometry of the openings has been derived from typical
openings on board of ships such as stair cases, bulkhead doors,
man holes, holes for pipes in the double bottom etc. The four
different types will be further described in the section about
the determination of the discharge coefficients.

The openings are indicated by the colored boxes in Fig. 4:
Openings through bulkheads are marked with a crossed box,
openings in decks are marked with a blank box. The external
openings are indicated by the green color, internal openings are
indicated by the yellow color.

The model can be flooded through ten external openings:
One in the bottom below tank top, three side openings above
tank top, two doors and four freeing ports on the main deck.

Opening Mechanism
The external bottom and side openings are located below
the water surface and can be opened by pulling a plug, which
is connected to a thin rope. The surface of the plug has been
manipulated with fabric-tape, to ensure satisfactory sealing char-
acteristics. Compared to other sealing materials such as rubber
or foam, the chosen material offers the advantage that the surface
of the plug can be accurately adjusted to the opening dimensions
by adding very thin layers of tape. In addition, some grease were
applied to further improve the sealing. This procedure allows to
keep the required pulling force to a minimum to avoid any in-
duced side or roll motion of the vessel while opening the plug.

All other openings are either open or closed at the investi-
gated test case and can not be dynamically opened. For closing a
certain opening, a transparent tape is used.

Motion Exciter
The model can be excited via a motion exciter, which has
been developed by Otten [9]. The motion exciter consists of two
masses, which are driven by an electrical motor. The masses ro-
tate about the vertical axis in contrary direction and at the same
speed. Depending on the orientation of the motion exciter, the
masses overlap either in longitudinal or transverse direction in
such a way that a roll or pitch moment is induced to the model.
The frequency of the motion exciter can be varied by adjusting
the voltage of the electric motor via a transformer. Further de-
tails are given in [9].

Roll Damping Devices
The model is equipped with two roll damping devices: One
rectangular tank mounted on top of the vessel and an U-shaped
compartment, which consists of compartment 02, 12 and 14 (see
Fig. 4). The natural frequency of the rectangular tank can be ad-
justed by the filling level, the one of the U-shaped compartment
in addition by the internal openings of bulkheads and decks.

MEASUREMENT EQUIPMENT
The measurement devices have been set up to measure the
following quantities:
1. Filling level in the flooded compartments
2. Motion of the model in all six degrees of freedom
3. Pressure of compressed air in the double bottom

The measurement setup has been developed at the Institute
of Mechanics and Ocean Technology of the Hamburg University
of Technology (TUHH). In the following, a brief overview about
the measurement setup is given. Further details about the mea-
surement setup are given in Pick [10].

Filling Level
The filling level in the flooded compartments is measured
by filling level sensors, which have been developed at the Insti-
tute of Mechanics and Ocean Technology of TUHH. Each sen-
or consists of four pairs of wires: Two in longitudinal and two
in transverse direction. The chosen setup allows to measure the
filling level as well as the inclination of the free surface at the
filling level position, which is related to the heel and trim angle
of the vessel.

The physical principle of these sensors is based on Ohm’s
law: The water changes the electrical resistance and thus the volt-
age between the wires. The change in voltage is proportional to
the filling level. The relation ship between voltage and filling is
derived from the calibration of the sensors. Trim and heel can be
calculated from the filling level difference in longitudinal and
cross direction.

The data of each filling level sensor is stored continuously on
its own memory card with 228 Hz and written to a file. Through
this procedure, it is ensured that the filling level data is at any
time step synchronously with the other measurement devices.

Furthermore, the water level in the compartments is
recorded by three high speed cameras. These cameras are ca-
capable to capture the filling level of the flooded compartment with
a bitrate up to 240 frames per second. The video data of the
cameras is used to verify the measured filling levels of the filling
level sensors and to provide some background information on the
flooding process.

Motion Tracking
The vessel’s motion is measured by an inertial measurement
unit (IMU) and a stereo camera system. The IMU is equipped
with three optical gyros of type LITEF µFORS6U and three acceleration sensors of type LITEF B-290S Triade. The IMU is capable to measure translational and angular accelerations with a high accuracy, whereas the stereo camera system is a very precise measurement device for the vessels altitude. The data of both measurement devices is combined via a Kalman filter to obtain the overall highest accuracy in terms of acceleration, velocity and altitude in all six degrees of freedom. The accuracy for the translational degrees of freedom is less than 0.1 mm and for the rotational degrees of freedom less than 0.01 degree (compare Pick [10]).

Pressure
The double bottom compartment 01 is equipped with two pressure transducers which are located in the tank top, below the port side and starboard boxes of compartment 11. These sensors are piezo-resistive pressure transducers of type Keller 9 FLC. The measurement principle is based on a change of the electrical resistance caused by the deformation of a semiconductor membrane (silicon) through the pressure in the double bottom compartment. These pressure transducers are used to validate the air compression model according to Eqn. 5.

SELECTED TEST CASES
Determination of Discharge Coefficients
The fluid velocity as determined by the simple hydraulic model based on Bernoulli’s equation (Eqn. 1) is reduced by the contraction of the jet flow and viscous effects. These effects are taken into account by a semi-empirical discharge coefficient, which depends mainly on the shape and geometry of the opening in question.

This coefficient can be experimentally determined for the different opening shapes by an outflow experiment. For this purpose a bucket made of plexiglass is built. In the bottom a flange is located, which allows to change the setup for the different opening types used during the model tests.

In addition, a flange on the side of the bucket is installed. This allows additional inflow tests with upright openings. For this purpose, the bottom opening is closed and the different opening types are tested in the side flange by lowering the bucket with weights in a water basin.

According to [11], the water volume $V(t)$ during the draining of the bucket can be described by the following differential equation

$$\frac{d}{dt}V(t) = -C_d A \sqrt{2g \frac{V(t)}{S}},$$

where $A$ is the area of the ideal opening and $S$ the area of the free surface. If it is assumed that the discharge coefficient $C_d$ is constant during the time of the experiment, this allows to determine an average discharge coefficient by measuring the time $T$ between two filling heights $H_1$ and $H_2$:

$$C_d = \frac{S}{T g A} \cdot \sqrt{2g (\sqrt{H_1} - \sqrt{H_2})}$$

(9)

The four different opening types used in the testcases are summarized in

<table>
<thead>
<tr>
<th>Type</th>
<th>Geometry</th>
<th>Description</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 x 3 cm, 1 mm radius</td>
<td>Small Leak</td>
<td>0.694</td>
</tr>
<tr>
<td>2</td>
<td>1 cm diameter</td>
<td>Broken Pipe</td>
<td>0.669</td>
</tr>
<tr>
<td>3</td>
<td>1 x 2 cm</td>
<td>Manhole</td>
<td>0.678</td>
</tr>
<tr>
<td>4</td>
<td>3 x 7 cm, 1 mm radius</td>
<td>Large Leak</td>
<td>0.689</td>
</tr>
</tbody>
</table>

For the outflow tests, the time when the water level reaches four different equidistant heights is measured. For each pair of filling heights and time values, the mean discharge coefficient is computed. An example for a test series for the opening type 1 is given in Tab. 3.

TABLE 3: Test Series for the Type 1 Opening

<table>
<thead>
<tr>
<th>Height cm</th>
<th>Time s</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>10.89</td>
<td>0.672</td>
</tr>
<tr>
<td>15</td>
<td>22.90</td>
<td>0.692</td>
</tr>
<tr>
<td>10</td>
<td>36.99</td>
<td>0.699</td>
</tr>
<tr>
<td>5</td>
<td>55.62</td>
<td>0.689</td>
</tr>
</tbody>
</table>

This gives four different discharge coefficients for each type. The outliers of the test series is removed and the mean value of the remaining values gives an average discharge coefficient for each opening type. The results are summarized in Tab. 2.
Inclining Experiment

The vertical center of gravity is determined by an inclining experiment. Due to the simple shape of the model some assumptions can be made, which simplifies the test. First, the transverse center of buoyancy is located on the center line. Furthermore, no free surfaces due to partly filled tanks exist.

The test is conducted for the fully loaded condition with all measurement equipment and ballast weights included for the intact condition. The heeling moment is induced by the transverse shift of a small weight with a defined lever. This is repeated for both sides three times, a heel angle larger than five degrees is avoided. The heeling angle is determined by the difference of the draft marks on both sides and in addition by the described motion sensor. To obtain an even trim for the following test cases, small additional weights are added on the tank top of the model.

A preliminary result of the experiment is shown in Fig. 5 where the heeling lever of the inclining weight is plotted over the measured heeling angle. The six measurements are plotted as dots and a linear regression line is added.

![Figure 5: Results from the Inclining Experiments](image)

The slope of this line equals the initial metacentric height \( GM \) of the model. This value is corrected by the inclining weight to obtain the vertical center of gravity of the model with all the measurement equipment, the added ballast and trim weights resulting in a value of \( KG = 16.26 \text{ cm} \) for this lightship condition.

Roll Damping Experiment

The roll damping experiment is carried out according to Blume [12]. The effective roll damping coefficient can be determined by conducting one of the following two experiments:

1. Roll decay test
2. Roll excitation test

At the roll decay test, the model is heeled to an initial heel angle and is then released. At the roll excitation test, the model is excited by a harmonic roll moment at its natural roll frequency, which is generated by the motion exciter. The effective roll damping coefficient can be determined from the ratio of resonant and static roll angle amplitude (the roll angle amplitude induced by the motion exciter at zero frequency).

In the following, both tests will be described briefly by two examples, which have been carried out at zero speed and without any roll damping devices active. Further details about the evaluation procedure can be found for example in [13] and [14]. At the roll decay test, the model has been heeled to an initial heel angle of about 20 degrees. The results of the roll damping evaluation of three test runs are shown in Fig. 6.

![Figure 6: Effective roll damping coefficient for three roll decay tests](image)

A polynomial of 2nd order has been fitted to the data, using a least square approach. The results in Fig. 6 indicate, that the estimated damping coefficients differ among the test runs. This phenomenon has already been observed at other roll decay test and is possibly related to the slightly different initial heel angles, the stochastic nature of flow separation at the sharp edges of the bilge, wave reflections from the tank wall, the induced flow field of previous conducted model tests or the coupling of the roll motion to other degrees of freedom [15].

For the roll excitation test, the model has been excited by the roll motion exciter with a systematic increasing excitation frequency. The resonant roll amplitude and natural frequency can be found from the Fourier analysis of the measured roll angle (compare Fig. 7) and amount to an amplitude of 20.5 degrees at a frequency of 1.8 rad/s.
Applying a correction for the centrifugal moment and estimating the static heel angle gives a \( \phi_{\text{stat}} / \phi_{\text{res}} \) of about 0.065. A difference between the roll decay and roll excitation damping coefficient has already been observed at other roll damping experiments and has been assumed to be caused by the vortex-induced damping contribution, which may not be present at the initial roll amplitudes of the roll decay experiment (compare Handschel [16]). Furthermore, the cables of the measurement devices may have an non-reproducible and random impact on the estimated roll damping coefficients. However, the determined damping coefficients are in a plausible order of magnitude (compare e.g. Kuehnlein et al [14]) and will be used within the simulation of the model’s roll motion for the dynamic model tests.

Example Test Case - Static

At the beginning of the test campaign, a basic test case has been selected from the test matrix to demonstrate the functionality of the measurement equipment and it’s data processing. The test case is shown in Fig. 8.

The test case comprises of a small side damage in compartment 14 (compare opening 16 in Fig. 8), which is located below the water surface. All internal openings are closed so that the flood chain comprise only one compartment. The adjustable longitudinal bulkhead has been mounted at the B/5 position. The model floats at design draft of 0.18 m and at level heel and trim. The vertical center of gravity has been determined from the inclining experiment and amounts to 16.26 cm above base line.

Example Test Case - Dynamic

The setup of the example test case for the dynamic sinking experiment is shown in Fig. 9.

The bunker tank compartment 15 is flooded through a small side damage (compare opening 24 in Fig. 9). This test case has been chosen to provide an exemplary comparison of a static and a dynamic test case.

Evaluation

The results for heel motion and the filling level sensor of compartment 14 are depicted in Fig. 11 and Fig. 10 and compared to the results of the numerical simulation. In the final floating condition, the vessel floats at a heeling angle of 10-11 degrees. The flooding process is completed after 12 s.

Regarding the heel motion, the simulated data matches approximately the measured values. The vessel heels slightly faster in the simulation compared to the model test and reaches its final floating position a little bit earlier. This delay is assumed to be caused by the fluid motion inside the flooded compartment, which causes an additional energy dissipation. This effect will be investigated in more detail in further model tests.

Regarding the filling level, the simulated flooded volume is significant higher and the compartment is flooded faster in the simulation compared to the measurements. An explanation for this behavior might be an inappropriate calibration of the filling level sensor since model and simulation show the same heel angle in the final floating condition. This assumption is also supported by the recordings of the cameras. This filling level sensors are currently under investigation and will be further tested.

The comparison of the measured roll angle for the dynamic and static sinking experiment is shown in Fig. 12.
The plug has been pulled at the time instant 0 s. At the static test case, the vessel heels to starboard after 2.3 s although the compartment comprises a symmetric subdivision. The heel is caused by the tank walls of the bunker tank compartment, which initially prevent the fluid from flooding to port side. In the final floating condition, the model rests at an upright position (compare time instant at 7 s). This test case is a clear example for a damage case with critical intermediate flooding stages, since the intermediate heel angle is much larger compared to the final floating position.

At the corresponding dynamic test, the model rolls with an initial roll amplitude of about 15 degrees and is exited with its natural roll frequency. Within the first time instants, the roll motion is clearly dominated by the induced roll motion of the roll motion oscillator. At time instant 4 s, the roll motion starts to decrease rapidly due to the damping effect of the flooded water and the increased mass (moment of inertia). The flooded water significantly reduces the natural roll frequency of the model so that the roll motion oscillator, still turning with the initial frequency, turns too fast to induce significant roll angles. The model reaches its final floating condition again at about 7 s.

**CONCLUSIONS AND OUTLOOK**

The presented test results indicate, that the implemented simulation model is basically capable to predict the sinking behavior of the model. The measured heel motion of the model is in accordance with the experimental data of the static example test case. The data of the respective filling level sensor shows basically the same trend but does not match exactly the simulated results. The discrepancy in the results has been assumed to be related to an insufficient calibration of the filling level sensors or an electric interaction of sensors’ wires and will be further investigated in the ongoing experiments. Furthermore, the results indicate that the induced roll motion (e.g. induced by the roll motion oscillator or the dynamic flooding of asymmetric compartments) has an impact on the flooding process.

The limited scale of the model tuned out to be challenging with respect to the conduction of the flooding experiments. The low weight of the model and thus relative small inertia forces require a sensible opening mechanism to avoid any induced drift or roll motion. The chosen plug device, equipped with grease and fabric-tape turned out to show the best performance compared to other investigated opening techniques and materials. Furthermore, the comparatively small beam of the side casings on the main deck turned out to provide only a limited accessibility to the openings in the side casing and the respective screw connections of the three segments.
In the next steps, emphasis will be given on the investigation of the propagation of the water through various compartments to investigate longer flooding chains, the water propagation on the main deck and the influence of induced motions by the motion exciter on the flooding behavior of the model. The next test cases will also comprise flooding events with bottom damages, the freeing ports and the main deck doors. In addition, the influence of entrapped air will be investigated for the double bottom compartments by evaluating the signal of the pressure transducers. The recorded pressure signal will be used to validate the implemented air compression method of the flooding simulation. Furthermore, a selected test case with a bifurcation problem will be investigated in more detail by a systematic variation of the ships vertical center of gravity.

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