Dynamic Extension of a Numerical Flooding Simulation in the Time-Domain

Hendrik Dankowski, dankowski@tu-harburg.de

Stefan Krüger, krueger@tu-harburg.de

Institute of Ship Design and Ship Safety, Hamburg University of Technology

ABSTRACT

A fast and explicit numerical flooding simulation has already been validated with the help of results from model tests and successfully applied to the investigation of several severe ship accidents like the one of the Costa Concordia. The progressive flooding method in the time-domain computes the flux between the compartments based on the Bernoulli equation combined with a quasi-static approach for the evaluation of the current floating position.

The numerical method is now extended to take into account the effects of the dynamic motion of the vessel during the flooding. As it has been observed by recent model tests, the dynamic motion of the vessel might play an important role for the flooding process especially during the initial transient phase after the damage occurred. To take this into account, the hydrostatic evaluation during each time step is replaced by an integration of the equation of motions in the time-domain.

The extended method will be validated with results from the model tests to demonstrate the in-fluence of the dynamic motion of the vessel on the flooding process. In addition, the new model test campaign of various flooding cases are described. The enhanced method allows to give an in-depth view on the dynamic propagation of the flood water after a damage to the watertight integrity of a ship occurred. Effects like the acceleration or delay of the flooding by the dynamic motion of the vessel itself are investigated. In addition, the dynamic extension is compared with the results obtained from the quasi-static approach to demonstrate the applicability of both methods.

The extension of the already very powerful numerical flooding method will not only better resolve the initial phase of flooding. It will also accelerate the existing method, since the search for a new hydrostatic equilibrium is replaced by fewer volumetric calculations for the integration of the equation of motions. Applications of such a fast numerical flooding simulation in the time-domain are complex accident investigations and next generation damage stability tools to be used on-board for decision support. A reliable and fast prediction of the flooding sequence after a damage occurred assist the crew to decide whether an evacuation of the vessel is required or not.

Keywords: *Progressive Flooding; Sinking; Dynamic Flooding; Ship Design; Accident Investiga-tion; Ship Safety*

1. INTRODUCTION

In the past, a numerical flooding simulation has been developed and presented in several publications (Dankowski, 2012; Dankowski and Dilger, 2013; Dankowski, 2013; Dankowski et al., 2014). To further extend and validate the method, a research project called LESSEO has been initiated. Within this project, a model test campaign has been conducted and the numerical methods to compute the time-dependent damage stability of ships were extended or newly developed.

First results of this research project were presented in Lorkowski et al. (2014). Additional test cases and new results are also given in Lorkowski et al. (2015). The focus of this paper is on the dynamic extension of the numerical flooding simulation. The underlying physical model is described together with the validation on two test cases from the model test campaign.

The numerical methods are implemented in the ship design environment E4, a first-principal ship design software used and developed at our institute together with partners from the German shipbuilding industry. In doing so, direct access to the whole ship data model and already implemented computational algorithms like hydrostatic evaluations is granted.

2. NUMERICAL METHODS

First, the quasi-static method is summarized. A more detailed description including validation test cases can be found in Dankowski and Krüger (2012; 2013). Second, the dynamic extension of this method is described, which takes into account the dynamic movement of the ship and its influence on the flooding process. This is accomplished by the solution of the non-linear differential equation of motions of the vessel.

2.1 Quasi-Static Method

The quasi-static method has been developed to estimate the time dependent damage stability of ships. It is assumed that most flooding incidents are mainly driven by the relatively slow progressive flooding of the ship and dynamic effects can be neglected. Its focus is on the fast and accurate computation of different scenarios to investigate full scale accidents. Several accident investigations have already been successfully performed, while the last investigation was on the accident of the Costa Concordia (Dankowski et al., 2014).

The method is in general capable to consider time dependent openings by a pressure height criterion and defined closure/opening times for watertight doors. Furthermore, an air compression model according to Boyles law has been implemented to account the effect of trapped air within the compartments.

The floodwater ingress and the spreading of the floodwater inside the vessel are computed by a hydraulic model for the water fluxes. For each time step, the new distribution of the floodwater inside the complex inner subdivision of the ship is computed and a new floating equilibrium position is determined based on the new resulting hydrostatic moments caused by the floodwater.

Details of the method will roughly be sketched in the following. The pressure head differences at the openings lead to a water in- or egress to the watertight integrity of the ship or between two inner compartments:

$$\mathrm{d}z = \frac{p_a - p_b}{\rho\, g} + \frac{u_a^2 - u_b^2}{2\, g} + z_a - z_b, \qquad (1)$$

$$u = \sqrt{2\, g \cdot \mathrm{d}z}. \qquad (2)$$

By integrating the velocity u over the area of the opening, the volume flux is determined assuming a perpendicular flow direction to the opening. Any dissipative losses are taken into account by a semi-empirical discharge coefficient C_d:

$$\frac{\partial V}{\partial t} = Q = \int_A \mathbf{u} \cdot \mathrm{d}\mathbf{A} = \int_A \mathbf{u} \cdot \mathbf{n}\, \mathrm{d}A. \qquad (3)$$

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.

The connection of all compartments by openings can be modelled by directed graphs.

Each compartment is represented by a node and the openings are the corresponding edges.

2.2 Dynamic Flooding Simulation

Especially during the initial phase of flooding, the dynamic motion of the ship can have a significant influence on the flooding process. Larger roll oscillations are also observed during the model tests. To better study the influence of the dynamic motions of the vessel, the existing flooding model is extended by means of the numerical solution of a non-linear ordinary differential equation of motions of all six degrees of freedom. The general structure of this equation with $\mathbf{x}$ as the state vector writes as follows:

$$\mathbf{M} \cdot \ddot{\mathbf{x}} + \mathbf{B} \cdot \dot{\mathbf{x}} + \mathbf{C} \cdot \mathbf{x} = \mathbf{F} \quad (4)$$

where $\mathbf{M}$ is the generalized mass matrix including added masses, $\mathbf{B}$ is the damping matrix and $\mathbf{C}$ is the stiffness matrix together with the external forces $\mathbf{F}$ as the right hand side. All of the components of this equation are strongly non-linear, since these depend on the changing mass properties of the vessel by the ingressing flood water and the right hand side is evaluated by a direct computation of the hydrostatic properties for the current floating position.

Since the focus on this method is on a first study of the influence of the dynamic motions on the flooding process and to even improve the computational runtime of the method, the following simplification is applied: The damping matrix is assumed to be a percentage of the mass matrix, as so for the hydrodynamic masses.

On the other hand, the stiffness matrix is directly derived from the current hydrostatic stiffness matrix and no linearization is done here. The external forces on the right hand side are defined by the resulting hydrostatic forces due to gravitation and buoancy for the current mass properties and the floating condition at each time step.

During the flooding process, it is supposed that especially the changing mass distribution has a large impact on the motions. The current fluid masses in the different compartments are known at each time step, such that these can be compiled to update the mass matrix concurrrently.

In practice, this is done by initially computing the overall mass matrix of dry and wet (filling in tanks and the flood water) components from the current loading condition, then subtracting again the wet part at the beginning and by updating the current wet part of the mass matrix from the distribution of the flood water at each time step.

The numerical solution of the differential equation is performed by the adaptive 4-5th order Runge-Kutta method by Fehlberg (1969). Due to the fact that the search for a new hydrostatic equilibrium is now replaced by the numerical efficient integration of the differential equation, less costly hydrostatic evaluations are required and the computational runtime is significantly reduced. In addition, it is in most cases sufficient to update the mass matrix only at each outer time step and not in between the Runge-Kutta steps, which further reduces the required computational effort.

This model will be compared to the test cases to identify if it is appropriate to compute such physical problems with this numerical method. The validation will also be used to identify important effects which play an important role in this scope to further improve the model.

3. MODEL TESTS

Before coming to the results from the validation, the model test setup will briefly be described. Further details can be found in Lorkowski et al. (2014; 2015).

The model is shown in Figure 1 together with its main dimensions in Table 2. The whole model is build out of acrylic glass. Around one third of the model around the mid section can be flooded including the main deck. Most of the measurement equipment is located in the aft and

Figure 1 The inclined model in the test basin after flooding

fore part of the model below the main deck.

Table 1 Main Dimensions of the Model

Length over all	L	2.02 m
Breadth	B	0.42 m
Depth	D	0.42 m
Draught	T	0.18 m
Displacement	Δ	144 kg

The following quantities are measured during the model test campaign:

1. Filling levels in the flooded compartments
2. Model's motions in six degrees of freedom
3. Air pressure in the double bottom

The measurement setup has been developed at the Institute of Mechanics and Ocean Technology of the Hamburg University of Technology. In the following, a brief overview about the measurement setup is given. Further details about the measurement setup are given in Lorkowski et al. (2014); Pick (2008).

3.1 Filling Levels

The filling levels in the flooded compartments are measured by filling level sensors. The physical principle of these sensors is based on Ohm's law: The water changes the electrical resistance and thus the voltage between the wires. The change in voltage is proportional to the filling level. The relationship between voltage and filling is derived from the calibration of the sensors (see also Figure 2). The data of each filling level sensor is stored continuously on it's 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.

Figure 2 The level sensors during calibration

Furthermore, the water level in the compartments is recorded by three high speed cameras. These cameras are capable to capture the filling level of the flooded compartment with a rate 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.

3.2 Motion Tracking

The vessel's motion is measured by a combination of an inertial measurement unit (IMU) with an optical stereo camera system. 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 (Pick, 2008).

3.3 Inner Subdivision

The subdivision of the model is shown in Figure 3. 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.

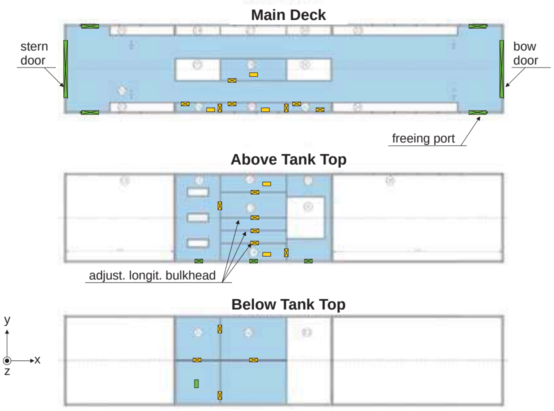


Figure 3 General arrangement sketch of the test body

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 and the two longitudinal bulkheads above the tank top. The longitudinal bulkhead at starboard can be adjusted to the positions 0.2 B, 0.35 B and 0.5 B.

The compartment in the aft of the mid section above the tank represents a typical engine room compartment. The displacement of the engines has been considered through three watertight boxes. The C-shaped fore compartment is similar to a typical bunker tank compartment. The large cargo hold compartment above the main deck comprises a closeable bow and stern door and four freeing ports. Every floodable compartment is equipped with an air pipe to avoid incomplete flooding events as a result of compressed air pockets.

3.4 Openings

The four different geometric shapes 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 openings are indicated by the colored boxes in Figure 3: 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.

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 characteristics. 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 induced side or roll motion of the vessel while opening the plug.

3.5 Motion Exciter

The model can be excited via a motion exciter, which has initially been developed by Otten (2008). The original exciter were newly constructed for the model tests and is shown in Figure 4.

The motion exciter consists of two masses, which are driven by an electrical motor. The masses rotate about the vertical axis in contrary direction and at the same speed. Depending on the orientation of the motion exciter, the masses

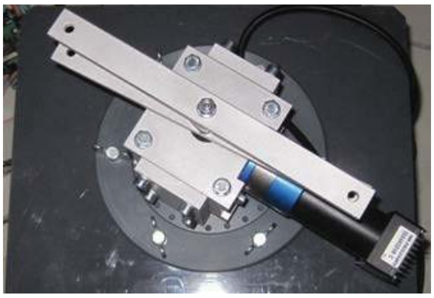


Figure 4 The top view of the used motion exciter

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 an transformer.

4. THE INVESTIGATED TEST CASES

From the comprehensive model test campaign two test case are selected to compare the measured results with the computed values from the quasi-static method and the dynamic flooding computation.

The validation test cases are selected to have a significant dynamic roll motion, where only the average mean values can be reproduced by the quasi-static method. Both cases have a symmetric layout but result in a final equilibrium heeling angle of around 5 degrees, while heeling angles up to 20 degrees occur during the intermediate stages of flooding.

The following computational setup for the two test cases are used:

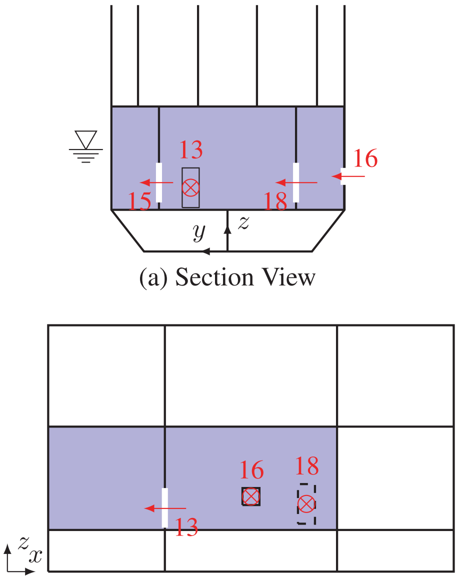
Table 2 Computational setup in full scale

Testcase		A	B	
Outer time step	dt	0.5	0.5	s
Damping factor	f_B	2	5	%
Initial roll velocity	$\dot{\varphi}_0$	-0.4	0.5	°/s
Initial stability	$\overline{GM}$	0.52	0.51	m

The computations are performed in full scale with a model scale of $\lambda = 100$ resulting for example in a time step of $dt = 0.05$ s in model scale. The typical computational time for one of the model test cases, which lasted around 100 seconds, is approximately 3-5 seconds.

4.1 Damage Case A

The setup of the first test case is shown in Figure 5. The model is flooded through a side damage below the water line. The water further spreads to the other side through a longitudinal bulkhead and from the center through a door to the compartment located further aft in model.



(a) Section View

(b) Side View

Figure 5 Setup Case A

The roll angle of the model observed during the model tests together with the computed ones are shown in the plot in Figure 6.

Since the water is first prevented by the longitudinal bulkhead, the roll angle increases very fast at the beginning. After around one second, this increase slows down before the maximum roll angle of a little more than 20 degrees is reached after 20 seconds. After this point, the model uprights again before it comes to rest at around 5 degrees of heel.

Even though the damage case has a symmetric layout, the final equilibrium is not upright. This can be explained by the fact, that the final

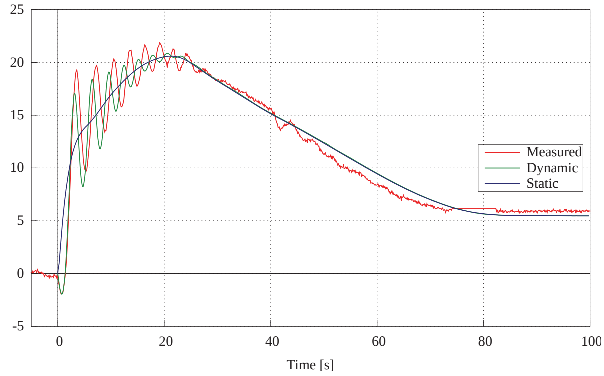


Figure 6 Case A: Roll motion measured and computed

equilibrium would not be stable at an heel angle of zero, but the model finds its new and stable equilibrium at around 5 degrees.

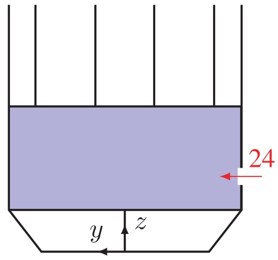
The motion of the vessel highly oscillates at the beginning until the maximum heel angle is reached. After this point, the flooding slows down, the motion is highly damped by the additional flood water and the progressive flooding phase continues.

The quasi-static computation can only predict the mean average motion of the vessel. However, this general mean motion is quite well reproduced.

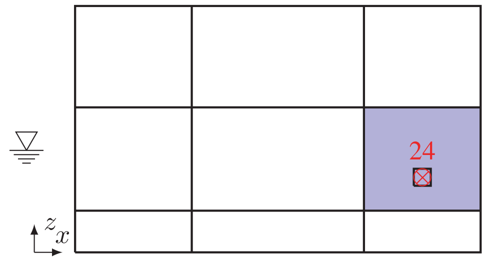
The results obtained from the dynamic flooding method match all phases of flooding of this test case very well. At the start, the initial small roll velocity leads first to a small angle to port side before the very unsteady phase follows. Even though, only a very simplified damping model is assumed, the computed motion matches quite well with the measured one. This can be explained by the fact that most of the damping simply comes from the additional flood water.

4.2 Damage Case B

The layout of the second test case is more simple as shown in Figure 7. Only one compartment is flooded through a side damage. This compartment is of C-shape kind if looking from above. This shape leads to a quite complex flooding behaviour since the small channel at the front prevents an immediate symmetric flooding of the whole compartment.



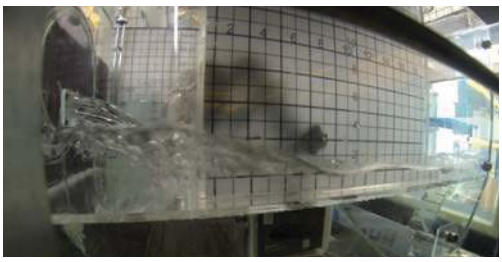
(a) Section View



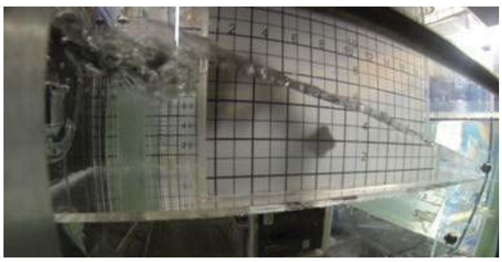
(b) Side View

Figure 7 Setup Case B

To better illustrate the complex and irregular flooding, two snapshots from the video taken during the model test is shown in Figure 8. The camera is located in front of the flooded compartment and looks to the aft in direction of the leak.



(a) After around 2 seconds



(b) After around 4 seconds

Figure 8 Case B: Snapshots from the flooding

It can be depicted from the snapshots that at the beginning the incoming water jet hits the wall opposite to the leak and the water propagates with an uneven and irregular surface further through the channel to the other side.

The measured roll angle is compared to the values obtained from the numerical methods as shown in Figure 9.

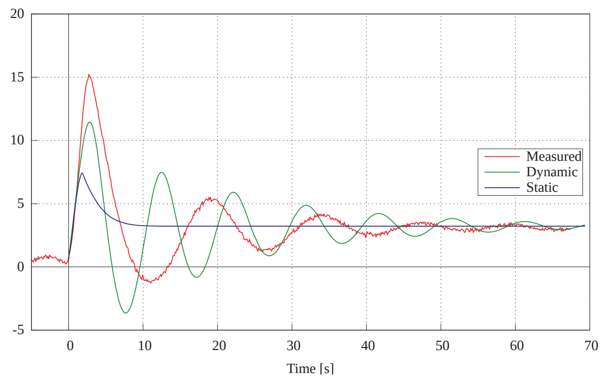


Figure 9 Case B: Roll motion measured and computed

First, the heel angle increases quite fast to around 15 degrees. A strongly damped roll oscillation follows before the model comes to rest at around 3.5 degrees. The final equilibrium is again not at zero degrees, because the initial stability would not be sufficient.

The quasi-static method finds the same final equilibrium but it reaches this point after only 10 seconds. The measured time and the time computed with the dynamic method is around 5 times larger.

The roll oscillation and the movement of the model is again quite well reproduced by the dynamic simulation. However, the damping which is observed during the model is higher and more non-linear. The roll period is faster stretched compared to the computed values. But the general dynamic motion behaviour is also shown by the numerical method, since around the same maximum heel angle is reached and also the overall flooding time is very similar.

5. CONCLUSIONS AND OUTLOOK

An existing powerful flooding simulation method has been successfully extended by a dynamic model. This does not only reproduces the real flooding behaviour better, it is also more efficient by means that the computational time is reduced.

The dynamic extension has been validated with the help of two model tests of a large test campaign. The results and the comparison from these tests are very valueable, since it allows to better understand such complex flooding phenomenons.

The dynamic motions computed with the new dynamic model matches quite well the observed behaviour during the model tests. This could be further improved by a more complex and better computation of the real damping forces and the added masses.

The numerical flooding simulation is improved by its applicability and its performance, which is a very important step to bring such systems also on board of ships. Only an approriate accurate and sufficient fast numerical method to compute the dynamic flooding behaviour of ships in the time domain would help and assist the crew on board to make the correct decision after a severe damage to watertight integrity of the ship happened.

A further extension to include also the influence of waves is possible, but several accidents in the past have shown that many of these accidents mainly caused by a damage to the hull followed by flooding happend in calm water. Vessels like the Costa Concordia or the Express Samina suffered an underwater damage in coastal regions at a moderate or quiet sea state.

In addition, the extended method could also be used to re-evaluate already investigated accidents or to apply it to new accident investigations to learn from these and to improve the overall safety of ships.

6. ACKNOWLEDGMENT

Special thanks go to the Federal Ministry of Economics and Technology (BMWi) for funding and supporting this research project. In addition, special thanks go to our partner in this research project, the Flensburger Shipyard. Furthermore, thanks go to the Institute of Mechanics and Ocean Technology for providing the towing tank and work shop facilities. In particular, the authors would like to thank Marc-André Pick, who supported this research with his ideas, thoughts and expertise regarding the measurement device setup, the integration into the model and the data processing.

7. REFERENCES

The ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, number 33, San Francisco, California, USA, 6 2014. ASME, ASME. geplant.

H. Dankowski. An Explicit Progressive Flooding Simulation Method. In K. J. Spyrou, N. Themelis, and A. D. Papanikolaou, editors, 11th International Conference on the Stability of Ships and Ocean Vehicles, Athens, Greece, 9 2012.

H. Dankowski. A Fast and Explicit Method for the Simulation of Flooding and Sinkage Scenarios on Ships. Ph.D. Thesis, Hamburg University of Technology, Institute of Ship Design and Ship Safety, 8 2013. URL http://doku.b.tu-harburg.de/volltexte/2013/1222/. ISBN 978-3-89220-668-2.

H. Dankowski and H. Dilger. Investigation of the Mighty Servant 3 Accident by a Progressive Flooding Method. In Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering, number ISBN 978-0-7918-4492-2, Nantes, France, 7 2013. ASME, ASME.

H. Dankowski and S. Krüger. A Fast, Direct Approach for the Simulation of Damage Scenarios in the Time Domain. In 11th International Marine Design Conference, Glasgow, UK, 6 2012. University of Strathclyde.

H. Dankowski and S. Krüger. Progressive Flooding Assessment of the Intermediate Damage Cases as an Extension of a Monte-Carlo based Damage Stability Method. In Chang-Sup Lee and Suak HoVan, editors, 12th International Symposium on Practical Design of Ships and Other Floating Structures, number ISBN 978-89-950016-0-8, Changwon City, Gyeongnam Province, Korea, October 2013. The Society of Naval Architects of Korea.

H. Dankowski, P. Russell, and S. Krüger. New Insights into the Flooding Sequence of the Costa Concordia Accident. In Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering ASM (2014). geplant.

Erwin Fehlberg. Low-order classical Runge-Kutta formulas with step size control and their application to some heat transfer problems. NASA Technical Report 315, NASA, 1969.

O. Lorkowski, H. Dankowski, and F. Kluwe. An Experimental Study on Progressive and Dynamic Damage Stability Scenarios. In Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering ASM (2014). geplant.

O. Lorkowski, F. Kluwe, and H. Dankowski. A Numerical and Experimental Analysis of the Dynamic Water propagation in Ship-Like Structures. In K. J. Spyrou, N. Themelis, and A. D. Papanikolaou, editors, 12th International Conference on the Stability of Ships and Ocean Vehicles, Athens, Greece, 9 2015.

N. Otten. Rolldämpfung von Schiffsmodellen mit und ohne Schlingerkiel. Diploma thesis, TU Berlin, 2008.

Marc-André Pick. Ein Beitrag zur numerischen und experimentellen Untersuchung extremer Schiffsbewegungen. Dissertation, Technische Universität Hamburg-Harburg, Denickestr. 22, 21071 Hamburg, Oct 2008.

This page is intentionally left blank