A Numerical and Experimental Analysis of the Dynamic Water Propagation in Ship-Like Structures

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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. Up to the stage of this report, the dynamic water propagation within the inner subdivision as well as intermediate flooding stages and their influence on the resulting stability are considered on a very basic level in the damage stability regulations and may thus lead to an inappropriate evaluation of the safety level in damaged condition.

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 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.

Within this report, an enhanced numerical flooding calculation method is validated by a series of model tests with the aim to investigate its capabilities and limitations and to improve the understanding of a ship's time dependent damage stability. The model tests haven been carried out with a ship-like test body which comprises a typical subdivision. In this respect, emphasis has been given on the evaluation of critical intermediate stages of flooding which are characterised by large roll angles and roll velocities.

By the end of this report, the results of the model test campaign and the calculation method are compared and discussed in the context of the observed influencing factors on the flooding process to evaluate its' prediction accuracy for intermediate stages of flooding.

Keywords: *intermediate stages of flooding, ship design, damage stability*

1. INTRODUCTION

The recent introduction of the harmonized, probabilistic damage stability regulations in 2009 [SOLAS II-I, Part B-1] let to a new assessment of the damage stability of RoPax and Pax vessels where the time dependent evaluation of the ships damage stability has become more important. This damage stability regulation requires for passenger ships the evaluation of intermediate stages of flooding with respect to the maximum righting lever, its range, cross flooding time and the equilibrium heel angle. The damage stability assessment of contemporary RoPax and Pax vessels may comprise several hundred leak cases, so that the evaluation of these intermediate stages of flooding can be very time consuming if carried out by use of the available methods.

Furthermore, the results of the first study of the European Maritime Safety Agency (EMSA) has indicated, that the attained safety level of RoPax vessels can be significantly lower according to the harmonized damage stability regulations (SOLAS 2009) in comparison to the old deterministic damage stability regulations (SOLAS 90) in combination with the Stockholm agreement (EC-Directive 2003/25/EC).

This is due to the fact that the SOLAS 2009 regulations do not require considering accumulated water on vehicle decks for the stability assessment (compare Valanto, 2009).

For this reason, a research project called LESSEO had been introduced in 2011 with the aim to develop new calculation methods for the evaluation of a ship's time dependent damage stability and to propose a new approach for assessment large free surfaces on vehicle decks within the current regulation frame work.

This report focuses on the validation of a quasi-static calculation method which has been developed by Dankowski 2013 to evaluate a ship's time dependent damage stability. This calculation method has already applied for accident investigations (e.g. in Krueger et al. 2012, Dankowski 2013) and its' basic functionality has been tested with the model test results of (Ruponen 2007). In the investigations of this report, emphasis has been given on the validation by damage scenarios with initial flooding prevention. These damage scenarios are of particular interest with respect to their intermediate stages of flooding and are derived from a model test campaign with a test body, which has been conducted within the LESSEO research project. The comparison between measured and calculated results illustrates the potential and limitations of the calculation method and enhances the understanding of such complex flooding scenarios.

The following sections give a brief overview about the theoretical background of the calculation method and the conducted the model test campaign. Within the validation section, the model test results are described and compared to results from the calculation method.

At the end of this report, a summary of results of the validation is given and put into the context of further research and possible areas of improvement.

2. NUMERICAL METHOD

This section comprises a brief overview about the theoretical background of the quasi-static calculation method. For further reading please refer to Krüger et al. 2012, Dankowski 2013, Dankowski 2012, Dankowski & Krüger 2012, Dankowski et al. 2014.

Within the quasi-static approach, the sinking sequence is estimated by a finite number of consecutive quasi-static changes of the floating position. The floating position in the respective time step is determined under equilibrium condition of the hydrostatic and gravity forces. These forces change within the flooding process due to the propagation of water volumes through internal and external openings. The water volume within a compartment is determined via the integral of the inflow and outflow fluxes (mass balance). The governing equation for the determination of the fluxes is the Bernoulli equation, formulated for a streamline between the points a and b:

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

The term φ_{ab} accounts for energy dissipation along the stream line which is mainly caused by the jet expansion behind the opening (Dankowski 2013). This energy loss is assumed to be proportional to a semi-empirical discharge coefficient C_d, which reduces the flux velocity u:

$$u = C_d \cdot \sqrt{2g \cdot dz} \tag{2}$$

The discharge coefficient has been determined from outflow experiments for the applied opening types in the model test campaign (compare Dankowski et al. 2014) and depends on the shape and size of the discharge opening. The applicability of such determined model scale discharge coefficients to full-scale ships has been investigated e.g. in (Stening 2010), (Ruponen, 2010) and (Ikeda et al. 2004). The results of the FLOODSTAND research project in (Stening 2010) indicate that full-scale openings show larger discharge coefficients than corresponding model-scale openings. Anyhow, full-scale measurements in (Ruponen 2010) have revealed that the general course of the flooding sequence can be predicted with satisfactory accuracy even if a rough estimation for the discharge coefficient is used in the calculation method.

From the given brief overview about the theoretical background, the following assumptions can be summarized for the quasi-static calculation method:

- The flooding process is assumed to be sufficiently slow e.g. as a consequence of small
- leaks and large compartments so that the change in the ship's floating position can be regarded as quasi-static
- Water propagation is exclusively driven by the static pressure differences at the openings.
- Besides the energy loss at the openings, no further energy loss is accounted for. Thus, frictional losses e.g. due to wall friction, flow separation, circulation or wave breaking are assumed the play a minor roll in the flooding process.
- The free surface of the water is assumed to be flat so that no waves or sloshing forces are accounted for.

3. MODEL TEST CAMPAIGN

The model test campaign of the LESSEO research project comprises roll damping experiments for the determination of the effective roll damping coefficients, inclining experiments for the determination of the vertical centre of gravity, outflow experiments for the determination of the empirical discharge coefficients and sinking experiments with symmetrical and asymmetrical subdivision. While a brief overview about the model test campaign has already been given in Dankowski et al. 2014 this section summarises the main particulars of the developed test body. The main dimensions of the test body are given in Table 1:

Length over all	**2.02**	**m**
Breadth	**0.42**	**m**
Depth	**0.42**	**m**
Draft	**0.20**	**m**
Displacement	**159**	**kg**
Vertical Centre of Gravity	**0.178**	**m**

Table 1: Main dimensions of the test body

The test body is depicted in Figure 1**.**

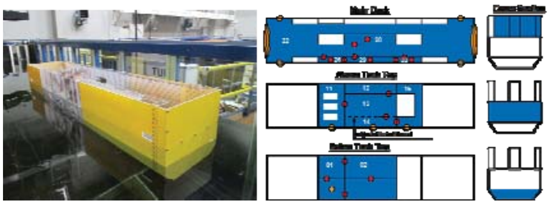

Figure 1: Test body 1

The test body consists of three parts: A yellow coloured aft body, a transparent mid ship section and a yellow coloured fore body (compare left hand side of Figure 1). The floodable compartments are located in the mid ship section. The internal subdivision is shown on the left hand side of Figure 1 and has been derived from contemporary RoRo and RoPax ships. The main deck (compartment 22) e.g. represents a typical vehicle deck with centre and side casing, compartment 11 represents an engine room compartment and compartment 15 has been derived from a void space around a bunker tank compartment. Compartment 14 comprises an adjustable bulkhead which can be located at the position B/5, 2B/5 or B/2. The test body can be flooded through 10 external openings: One at the bottom of compartment 1, three at the side of the compartments 11, 14, 15, four freeing ports and a stern and bow door in compartment 22 (compare left hand side of Figure 1). The external openings are either closed or dynamically opened by pulling a plug. Furthermore, the test body is equipped with 18 internal openings which are either open or statically closed by a tape to generate the respective leak case.

4. MEASUREMENT DEVICES

Within the test campaign, the following quantities have been measured:

- Angular velocities and longitudinal accelerations in 3D (ship fixed coordinates),

- Translation and rotation on of the test body in 3D (earth fixed coordinates),

- Filling level in the flooded compartments (ship fixed coordinates)

- Pressure in the double bottom compartment.

The measurement devices are located in the fore and aftbody and are powered by three Lithium-Polymer rechargeable battery packs. The accumulated, measured data are transferred via a local WiFi connection the data processor, which is located next to the test facility. Through the chosen measurement device set-up it is ensured that the test body's motion is not influenced by any cable connections. Anyhow, some uncertainty considerations with respect to applied measurement devices have to be taken into account when evaluating the measured signal. The uncertainty of the measured signal depends on the measurement device and is given in this case for the 95% confidence interval.

The angular velocities and longitudinal accelerations are measured by an inertial measurement unit (IMU), which is placed in the forward compartment of the test body. The uncertainty of the measured values is +- 1E-3 rad/s for the angular velocities and +- 1E-2 m/s² for the accelerations. The angles and translations are measured by a stereo camera system. These magnitudes are measured with an uncertainty of 1E-3 deg and 1E-4 m respectively. The filling levels are measured via resistive wave probes. The uncertainty of the filling level has been determined to +- 1 mm. In this respect it is worth to mention that these sensors are sensible to the environmental conditions such as tank water quality, gas content of the water, ambient temperature and manufacturing imperfections on the wire distance of surface quality. Thus, these factors have to be taken into account within the calibration of these sensors to obtain a sufficient accuracy of the measure signal. The pressure of the double bottom compartments is measured by two piezo resistive pressure transducers. The uncertainty of the measured signal is +- 0.2 mbar.

More details about the measurement devices are given in (Dankowski et al. 2014) and (Pick 2009).

5. VALIDATION

For the validation of the quasi-static calculation method, test cases with initial flooding obstruction e.g. through longitudinal bulkheads, engine casings and girders have been selected to quantify their influence on the course of flooding. Within the following evaluation, emphasis has been given on the evaluation of the roll angle, since this quantity is also of interest of the evaluation of the intermediate flood stages within the current damage stability regulation framework. At the following leak cases, the test body has been tested at its' design condition (compare Table 1).

5.1 Leak Case 1

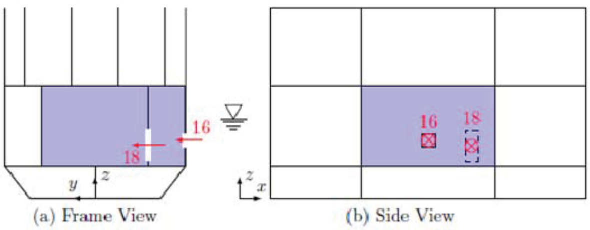

Figure 2: Side damage and long. bulkhead at B/5 with door opening

The first leak case presented here is a damage scenario with initial flooding prevention through a longitudinal bulkhead. The leak case is shown in Figure 2. The model is flooded through a side damage opening (16) and a door opening (18) in the longitudinal bulkhead at B/5. The initial flooding prevention is caused by the longitudinal offset of these two openings.

The measured roll motion and filling level is shown in Figure 3. The filling level sensor 27 is located in compartment 14 close to the shell, sensor 28 is located in compartment 13 at mid ships. The plug has been pulled at time instant 0s. After opening the leak, the test body starts rolling to starboard after 1s at a nearly constant roll velocity of 9 deg/s. The water propagation in the compartment is characterized by an inhomogeneous water distribution, caused by the jet and spray in compartment 14.

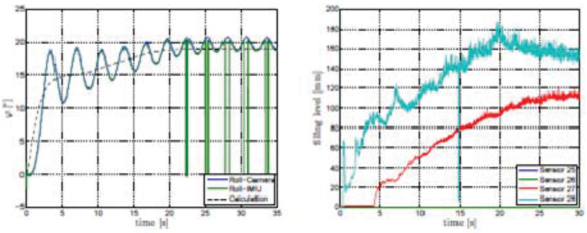

Figure 3: Roll motion (left) and filling level (right) of leak case 1.

Figure 4: Video sequence at time steps 3s, 6s and 20s for leak case 1.

This fact is also visible in the difference of the filling level signals for sensor 28 and 27 in Figure 3. After about 3s, the inner side of the leak opening becomes submerged so that the incoming water flux starts to decrease continuously as a consequence of the rising hydrostatic pressure in the compartment (compare Figure 4 at 3s).

The change in the water flux causes a lower roll velocity so that the test body starts to decelerate**.** Due to the inertia of the test body, an overshoot angle of 18 deg is reached after 3.5s. Form the comparison with the static righting lever curves including fluid shifting moments shown in Figure 5 follows, that the dynamic roll angle is about twice as high as it would be in the ideal static case with an equal filling level distribution (compare curve for 20% average filling level).

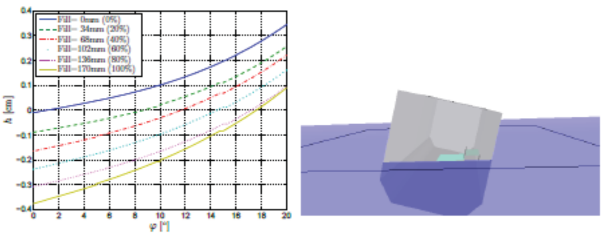

Figure 5: Static righting lever curve (left) and level difference in the compartments 13&14 at 3s (right)

Since the restoring and inclining moments are at this angle not in equilibrium, the vessel starts to roll back to port side. This dynamic process induces a natural roll motion to the test body of about 4 deg amplitude. After about 6s, the inner opening (18) becomes completely immersed and the water level raises quasi-static within the two compartments (see Figure 4 at 6s). At the time instant of 20s, the test body reaches it final floating condition at an average roll angle of 19 deg. The two compartments are almost completely flooded (compare time instant 20s in Figure 4).

From Figure 3 follows, that the basic effect of the initial flooding prevention is the increased roll velocity and large overshoot angle at the beginning of the flooding process. The increased roll velocity is in general well represented by the quasi-static method, as the comparison in Figure 3 illustrates. The quasi-static method shows also a change in the roll velocity where the inner side of leak opening becomes immersed, but the induced roll motion including its' overshoot angle cannot be resolved. The magnitude of the roll velocity has been slightly underestimated by the calculation method which is assumed to be caused by the more inhomogeneous water distribution at the model test and the inertia of the model. Furthermore, the course of the measured and calculated roll motion reveals that the immersion of the leak opening results also in a balancing process of the water levels at the longitudinal bulkhead. At the previous time steps, the water level had been significant higher in the wink tank compartment due to the larger pressure difference at the leak opening (compare Figure 5 (right) and Figure 4 at 3s). As the mass flux through the leak opening decreases, the pressure difference at the longitudinal bulkhead is sufficient to raise the water level up to the values of the wink tank compartment. This balancing of the water levels equalizes the whole flooding process so that roll velocity decreases further between the time instants 5-8s. Finally, both the numerical model and test body reach their final floating position after about 20s. The comparison of the final calculated and measured roll angle indicates that calculated value is slightly lower. This fact is assumed to be related to the accuracy of to the determined vertical centre of gravity. The vertical centre of gravity had been determined from an inclining experiment and turns out to be slightly underestimated for the considered leak case.

5.2 Leak Case 2

This leak case has been selected according to the findings from the European Gateway accident in 1974 (compare Dankowski 2013). A principal sketch of the involved compartments is shown in Figure 6.

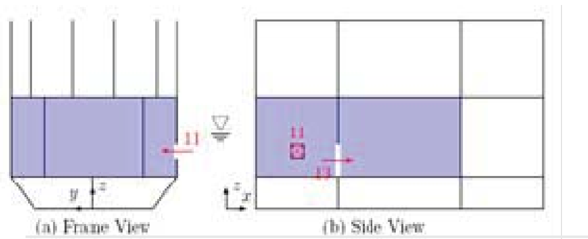

Figure 6: Side damage in the auxiliary engine room compartment and open bulkhead door

The test body is flooded through a small side damage in the auxiliary engine room compartment (11) and progressive flooding is taking place though the door openings in the transversal and longitudinal bulkheads. The measured roll angle and filling level are shown in Figure 7. Level sensor 25 had not been connected during this leak case. Level sensor 26 is located in the auxiliary engine room compartment at starboard, near the leak, sensor 27 is located in the forward compartment close to the bulkhead door and sensor 28 is located in the starboard wing compartment. The plug has been again pulled at time instant 0s. The test body comprises a slight initial heel to portside.

After the leak had been opened, the water starts to flow to portside as a consequence of the initial heel angle. This process induces a corresponding roll motion to the test body. After about 2s, the water level in front of the engine box has increased significantly so that a roll motion is initiated towards the opposite direction, which is characterized by a sudden shift of the water volume to starboard (compare time instant 2s in Figure 7 and Figure 8) and results in a roll velocity of 3 deg/s. After about 5s, the test body reaches an intermediated flood stage at a roll angle of 10 deg.

At this time instant, the inner side of the

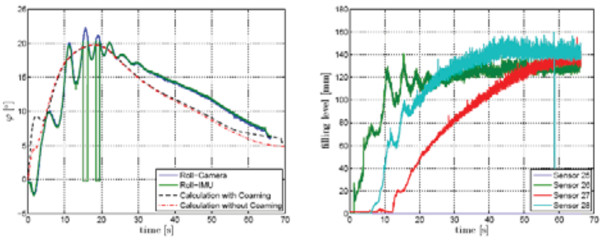

Figure 7: Roll motion (left) and filling level (right) of leak case 2.

Figure 8: Video screen shots of compartment 11 at 1s, 2s und 17s.

leak opening becomes fully immersed so that the mass flux, driven by the pressure head difference in and outside the compartment, is reduced. While the inclining moment through the free water surface remains nearly constant at this time step, the additional water volume causes a reduction of the test body's vertical centre of gravity, similar to the effect of a ballast water tank, which gives in turn a reduction of the roll motion at time instant 5-7s.

After 7s flooding time, the opening in the transverse bulkhead becomes immersed and progressive flooding is taking place in the forward compartments (compare time step 7s in Figure 9 and filling level sensor 27 in Figure 7).

Figure 9: Video screen shots of compartment 12,13 and 14 at 6s, 15s and 30s.

This flooding process yields to a more more asymmetric water distribution within the test body and increases the roll angle up 20 deg after 15s. The test body’s motion at the time instants up to 20s is characterized by an oscillatory roll motion which is assumed to be caused by the sudden immersion and emergence of the door opening in the transverse bulkhead and the inertia of the model. At time instant 20s, the door opening in the longitudinal bulkhead at portside becomes immersed so that the portside wing compartment is flooded correspondingly. This flooding process reduces the roll moment and induces consequently a slow up righting movement of the test body. The up righting process takes about 40s and is assumed to be influenced by the fluid damping within the compartments. This thesis is also supported by the fact that induced roll motion declines rapidly after time step 20s. After about 65s, the test body reaches its' final equilibrium position at a roll angle of 7 deg.

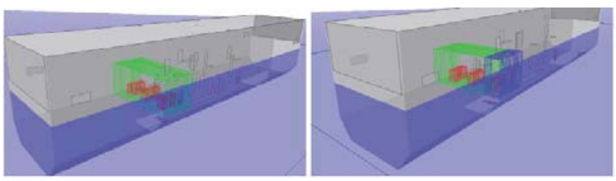

Figure 10: Numerical model without coaming (left) and with coaming (right).

The numerical model has been tested with two configurations, shown in Figure 10. The first configuration considers the compartmentation according to the general arrangement of the test body. The engine casings are modelled as void spaces to cover their displacement effect.

In the second configuration, additional openings with coamings have been added at the starboard engine box to account for the corresponding water accumulation within the first time instants. A similar modelling strategy had been applied at the accident investigation of the European Gateway (compare Dankowski 2013). The comparison of the measured and calculated roll motion in Figure 7 indicates that the course of flooding has been predicted by both numerical models with a satisfactory accuracy since the up righting and rolling characteristic is very similar. However, the intermediate roll angle at time instant 15s is slightly underestimated which is assumed to be also related to the a difference the vertical centre of gravity (compare also roll angle differences at the final floating condition). In terms of the initial heel angle, it had been observed that an initial heel to portside cannot be correctly covered by the quasi-static method, since this heel angle would also result in a final heel angle to portside (at 65s).

The effect of the coaming and thus initial flooding prevention of the engine box can be identified from the comparison of the two calculated roll motion curves: The initial flooding prevention increase the intermediate roll angle but does not affect the course of flooding in the later time steps. Nevertheless, if it is considered, that the intermediate measured roll angle at time instant 5s comprises a dynamic contribution due to the inertia of the test body, the degree of flooding prevention is well represented by the second numerical model (with coaming).

Finally, the comparison between measured and calculated roll motion indicates, that the up righting process after 20s is significantly slower at the model test than predicted by the numerical calculation. This fact confirms the previous made assumption that up righting process is possibly influenced by the fluid damping of the water e.g. at the longitudinal bulkheads which may have a similar effect as nozzle plates of passive roll damping tank.

6. CONCLUSIONS

The results for above presented leak cases indicate that the course of flooding is well represented by the calculated values of the quasi-static calculation method. Thus, the comparison between the estimated and measured flooding process allows drawing the conclusion that the quasi-static water propagation proves to be the main driver for the flooding of enclosed spaces. Further effects such as additional energy dissipation or the dynamic elevation of the free surface are of minor importance for the considered leak cases. Furthermore, the results of leak case with initial flooding prevention at the engine boxes indicate, that such dynamic water accumulation can be modelled with sufficient accuracy by introducing some virtual coamings at the engine casing. This finding is also in line with accident investigation of the European Gateway in Dankowski 2013.

Nevertheless, the comparison between measured and calculated flooding sequence indicates also an area of improvement with respect to the consideration of water and body dynamics.

These quantities may not be disregarded for cases where the vessels exact motion is of interest. Such cases may comprise a dynamic immersion of non water tight openings which can lead to the progressive flooding of further compartments. The body dynamics could be approximated by dynamic model to solve the corresponding equation of motion. This dynamic model could be connected to the quasi-static method to increase its' prediction accuracy in terms of the roll angle magnitude.

With respect to the evaluation of the full-scale time dependent damage stability of ships, it has to be mentioned that the accuracy of the prognosis depends on the available input data and the level of detail of the numerical model. Chadi et al. 2009 have summarised possible influencing factors on the time dependent damage stability such as scale effects on the fluid flow, geometric similarity (e.g. permeability of the compartments, representation the buoyancy body and weight items, consideration of internal structures etc.) as well as the consideration of the time dependent structural integrity of openings such as windows, doors etc. The presented quasi-static calculation method can account for most of these factors but requires in turn a sufficient accuracy of the input values (e.g. pressure height of collapsing windows, discharge coefficients etc.) which are sometimes not available. Thus, the numerical model may compromise in the level of detail and the respective input data is often subject to assumptions. However, the accident investigations of Dankowski 2013 and full-scale measurements Ruponen 2010 indicate, that the general course of flooding of full-scale ships is well represented by the quasi-static method, even if assumptions regarding the discharge coefficient or time-dependent openings are made.

Summarising the findings above, the quasi-static calculation method is in the view of the authors an appropriate tool for the estimation of a ship's time dependent damage stability and can enhance the identification of critical intermediate stages of flooding.

7. ACKNOWLEDMENTS

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