Numerical Flooding Simulations- A Useful Tool For Marine Casualty Investigations

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ABSTRACT

The recent developments in numerical tools for the prediction of the sinking process of a ship have nowadays resulted in quite reliable methods which can be applied during the design of a ship for all kinds of damage stability investigations. Such tools are most useful, too, to compute intermediate stages of flooding. Another aspect of the application of such computations is the numerical investigation of marine casualties and eventually the preparation of possible salvage operations. The paper describes some aspects and challenges of the application of such methods in the context of marine casualty investigations and discusses some principal requirements and drawbacks of such methods.

Keywords: *Sinking Simulations, Marine Casualty Investigations*

1. INTRODUCTION

Marine casualties are typically complex event chains, especially when the casualty leads to the total loss of a ship due to capsizing or sinking. Whenever such a casualty needs to be investigated, lots of computations need to be made to figure out the (most probable) event chain which has lead to the final loss. During these investigations, a variety of different computational methods is applied nowadays, which extends from simple hydrostatic calculations to complex dynamic computations. The problem exists that all these methods require more or less sophisticated computational models, and they need to be validated. The validation of such methods can be performed by computing theoretical test cases, by the comparison with experiments or by full scale accidents. The validation by experiments has the advantage that all data and test conditions are well defined, which makes it quite easy to re compute these cases. Further, any deviations between experiment and computation can in most cases be reasonably explained, and such deviations often result in the refinement of the computational procedure or in the model, or both. Therefore it is a conditio sine qua non to validate numerical methods by experiments. However, with respect to marine casualties, experiments never reflect the full event chain as they can only focus on a small part of the problem, and they are always performed under ideal conditions. Therefore it seems plausible to also use full scale accidents of ships for validation purposes. Besides the validation problem, investigations of full scale accidents do in fact require that the methods are applied to the real case. But the problem exists that these accidents never happen under ideal conditions where all data is exactly known. Mostly the ship has sunk and it cannot be accessed, important data are not known with sufficient accuracy and the surviving witnesses often do not clearly remember important facts. This makes the analysis of full scale accidents always challenging, and often it is not clear whether a numerical model or a computational procedure is actually suitable for the analysis. Therefore, we are running research projects where we systematically collect data of full scale capsizing or sinking events, prepare the calculation models and figure out the relevant event chains. These data are collected in a database which are used for the validation of other methods. In the framework of this paper, we have performed several root cause analyses for the German Fedral Bureau of Marine Casualty Investigations (BSU). During our analyses of such accidents we always identified some technical challenges which made a further development of our methods necesseary. This paper describes some of these challenges and the related methodological improvements. At first, a classification of marine casualties is presented from a methodological viewpoint.

2. SINKING CASUALTIES OF SHIPS

If a ship has a stability event or a flooding accident, it may capsize or sink. In such cases, the event chain is always quite complex, and other technical issues than stability or water tight integrity must be treated as well. This may include inter alia steering, power generation, propulsion and other related issues. Consequently, not a single method can be used for the analysis of such events. On the other hand, during such investigation time is an important factor, because the determination of the most probable root cause (or event chain) requires that many different scenarios have to be evaluated. Therefore it is very important that computational times are as low as possible. This requirement also forces a specialization of the computational methods for a clearly defined purpose. If we once accept that different methods are used for the investigation of such casualties, it makes sense to classify the casualties accordingly. This paper focusses on events where the ship has sunk due to ingress of water. From a methodological point of view, such events can be classified as follows:

- Water ingress occurs due to ship motions, and only the later accident phase may be seen as a slow sinking event. Example: The sinking of ESTONIA.
- Water ingress occurs after the ship has taken already a large heel angle due to a combination of roll motion and other heeling moments. Example: The capsizing of the SEWOL.
- Water ingress and flooding are sufficiently slow (e.g. due to a damage), and ship motions play a minor role only. Example: The sinking of the COSTA CONCORDIA.

The first and the second type of accident strongly depend on the ship motions and the water ingress due to the ship motions (at least during the first accident phase), or due to a permanently increasing heel, and this requires seakeeping analyses including dynamic treatment of the free surfaces. But these methods have limitations when the heel angle is large, and then classical sinking analyses are used to investigate the later phase of these accidents.

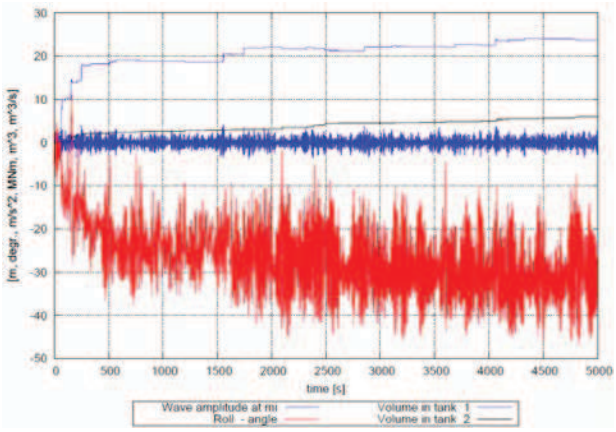

Figure 1: Time plot of roll angle, wave elevation and floodwater ingress into two compartment during the sinking of the ORTEGAL UNO (BSU 14/10), see also Fig. 4, right.

One example of such calculations for the first accident type is shown in Fig. 1 for the sinking of FK ORTEGAL UNO (BSU 14/10). The vessel was fishing in rough weather, and during the roll motion, water entered through a side opening into the fish hold. As the water tight door between fish hold and the accommodation was open, water entered into the accommodation, too. The numerical investigation of the accident showed clearly that if that door would have been closed, that ship would not have sunk. The first phase of this accident ended with a more or less steady equilibrium at abt. 35 Degree heel (see Fig. 6, right). Water then slowly entered the ship through non secured openings, and it then slowly sank. The sinking phase could then be investigated with quasi- static sinking methods.

The third type of accident is a classical sinking event and it can be analyzed with analysis tools where only the inflow fluxes need to be computed in time domain, but the momentary equilibrium floating condition can in most cases be obtained from hydrostatic calculations.

This may be demonstrated by the sinking computations we have performed for the COSTA CONCORDIA accident (Russel, BSU 310/12). Fig. 2 shows the time development of the heeling angle, and on can see that besides the relatively quick initial list to portside (negative heel), the heel angle develops quite slowly in time. The full lines in Fig.

2 stop when the ship has reached the floating position shown in Fig. 6, left.

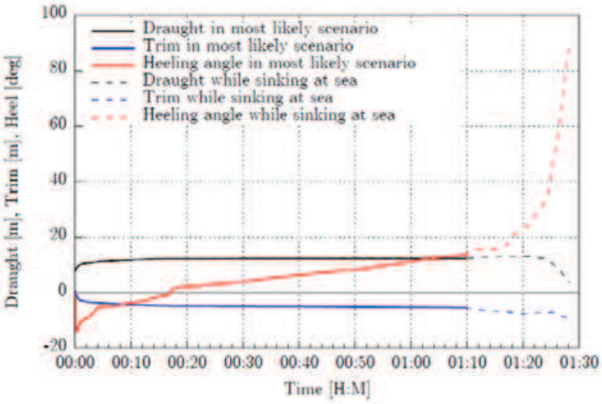

Figure 2: Computed time plot of heel angle, draft and trim for the sinking of COSTA CONCORDIA. At 1.10, the fkoating position shown in Fig. 4 is reached.

It must in this context also be noted that different ship types may have a completely different failure mode (as also the calculation in Figs. 1 and 2 indicate): Due to their specific subdivision, conventional passenger vessels tend to a slow and stable sinking in case of an accident with the ship more or less in an upright position (COSTA CONCORDIA, SEA DIMAOND, EXPLORER), whereas RoRo- Passenger vessels often capsize due to the massive accumulation of water on vehicle decks (HERAKLION, ESTONIA, SEWOL) or through submerged openings (VINCA GORTHON, FINNBIRCH). From a technical point of view, a capsizing during the flooding process is much more challenging compared to a slow sinking. This may be illustrated by the following casualty (BSU 266/14):

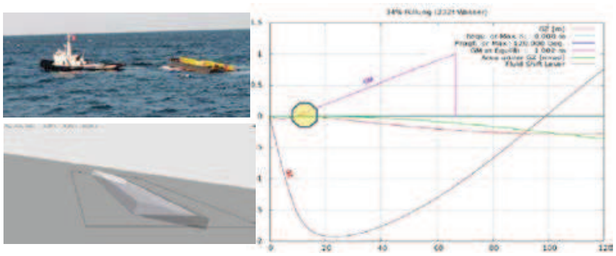

Figure 3: Capsizing of a pontoon due to slow water ingress. (BSU 266/14). Left: Situation immediately before the capsize, right: Righting levers in that situation, free movement of the floodwater. Source: BSU

Fig. 3 shows the capsizing event of a pontoon due the slow ingress of water. The pontoon suffered from a very small damage some days before the accident, and the water tight doors of all three compartments were left open. Prior to the capsizing, there was practically no stability left (see Fig., 3, right), and when then critical amount of floodwater was reached, this resulted in a quick turn and a strong alteration of the fluxes through the opening. Due to the pontoon shape of the floating body, the hydrostatic stiffness matrix varies strongly during that phase, and it was numerically challenging to obtain both stable fluxes and a stable time development of heel during the capsizing.

It should also be noted that ships with large weathertight superstructures may stay afloat for a long time even at larger heel angles (COUGAR ACE), but they might be vulnerable with respect to sinking when water ingresses through an opening that is not secured or not water tight.

Further it should be noted that the water ingress into the ship may not only occur due to hull damage, but also due to heeling by external moments (SEWOL) or due to firefighting (LISCO GLORIA, NORMAN ATLANTIC).

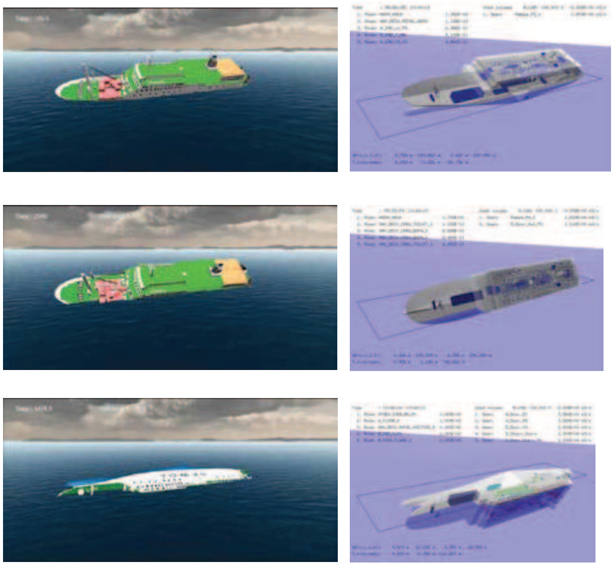

Figure 4: Capsizing the ferry SEWOL due to water ingress through the stern ramp into the ship. Left: Results of Lee (2015), right: Bley and Weltzin (2016).

This may be illustrated by the capsizing event of the SEWOL, see Fig. 4. The ship suffered from insufficient intact stability, and during a turn the cargo shifted, which lead to a steady heel which allowed water to enter the vehicle deck. When the floodwater spread within the ship through several openings, she took a large heel and sank finally.

Other than the casualty shown in Fig. 3, the stability remained positive during the capsizing and the alterations of the hydrostatic stiffness matrix were much smoother. Consequently, the computational challenges were less severe for this case, because from the methodological point of view, this particular accident may still be characterized as a slow sinking event (although the capsizing from a practical point of view was too fast to evacuate most of the passengers).

Some accidents are characterized by the fact that during some intermediate stage of flooding, progressive flooding of compartments took place which would not have been flooded in the final stage (EUROPEAN GATEWAY). These intermediate stages often occurred due to inflow obstructions, and they require adequate modelling. As a consequence it was found that the sinking simulations cannot be based on the ship data model which is usually used for statutory purposes, but a much finer model is required.

It was also found during our analyses that the status of the watertight doors is an important boundary condition for the flooding event. Either, they were open from the very beginning of the accident, or they were opened during the sinking. This was the case for the accidents shown in Figs. 1-3.

For the sake of completeness we would like to mention that there were some accidents which took place du to large free surfaces (intact ship) and a heeling moment during a turn (WALDHOF).

3. CHALLENGE OF MARINE CASUALTIES

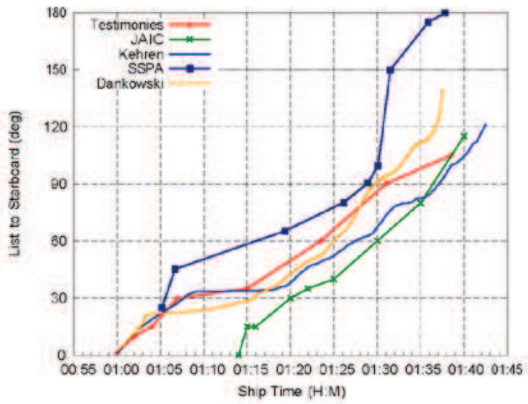

Figure 5: Development of heel angle versus time for the sinking of MV ESTONIA according to different authors. Source: Dankowski(2014)/Valanto(2008)

The main challenge of complex marine casualties is the fact that many important data are not known with sufficient accuracy. This holds for the loading condition, for the status of opening and the possible flux through these openings as well as for other boundary conditions like cargo shift or the actual weather conditions. Consequently, as the results are sensitive to these input parameters, they show significant scatter. This is reflected by Fig. 5, which shows the development of the heeling angle over time for the ESTONIA- accident according to different authors (Dankowski (2014) and Valanto(2008)). Although the general trend is reflected well by all computations, there are significant differences. Due to this fact it has been put forward by many researchers that marine casualties are not suitable for the validation of computational methods due to these uncertainties.

But the authors disagree with this opinion for the following reason: The most important result of a marine casualty investigation is the root cause and the most probable event chain. And despite the uncertainties mentioned, after a computational sensitivity analysis there remains only one event chain which fits to all boundary conditions, and that is typically the result of the investigation. Despite the fact that the authors of Fig. 5 computed a different time series, there was no doubt on the root cause of this casualty.

Figure 6: Two examples of photogrammetric determination of the floating position. Source: BSU 330/12 (left) and 14/10 (right).

What makes the situation easier today is the fact that due to the massive presence of information technology, the documentation of marine casualties has significantly improved. In most cases, photos of the accident exist (see Fig. 6) which allow with modern photogrammetric techniques a quite precise analysis of the equilibrium floating condition during a given time stamp. Such information is much more precise compared to testimonies, and during the re calculation of the accident it is then the boundary condition that the ship in the computation must take exactly the same equilibrium floating position as documented by the photogrammetric investigation. For the cases shown in Fig. 6 it could for example clearly be demonstrated by the computations that the documented floating positions at the given time stamps were only possible due to open water tight doors (see also Fig 1 - 3).

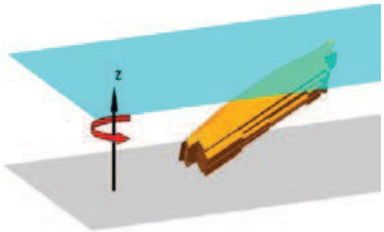

Figure 7: Computed ground contact of MV ESTONIA during the HSVA/TUHH accident investigations (Source: Valanto).

If the ship has finally sunk or grounded, the position of the wreck is most often well documented. This information is extremely useful for the numerical investigation of the accident, because each computation must then lead exactly to this position in the final stage (see Fig. 7). On the other hand, this computation demands to compute also the very final stage of the accident, where many compartments are flooded and the equilibrium becomes unstable in all three degree of freedom. This final stage is often combined with large fluctuations of the hydrostatic stiffness matrix (including floodwater), which leads to significant oscillations of the fluxes.

Therefore, the boundary condition to compute also the very final stage of the flooding poses severe requirements to any computational method with respect to computation time and numerical stability.

4. NUMERICAL METHODS

From the above mentioned findings, we can formulate some basic requirements for numerical tools for the analysis of such casualties: First, it seems reasonable to provide a special set of methods for those accidents which are dominated by ship motions and to combine such methods with the dynamic treatment of water ingress and the motions of the floodwater in the compartments of interest. In these cases, special attention must be payed to the roll motion, and this degree of freedom must definitively be treated non- linearly. For this purpose, we use the time-domain seakeeping code E4ROLLS which was originally developed by Kröger, Petey and Söding. A good and complete description of the underlying concept of this method is given by Söding, Shigunov, Zorn and Soukup. The motions of the free surface are obtained from the solution of the shallow water equations according to Glim (1965) and Dillingham (1981). These equations are combined with the motion prediction of E4ROLLS. Dankowski has alternatively implemented the Kurganov method (2007) for this problem. Although these methods give reasonable results for both ship motions and the water ingress, they have significant numerical problems when the heel angle takes large values (or when the ship capsizes). Most of these problems have their source in numerical instabilities when the water hits the top of the flooded compartment. Further, this dynamic analysis is very time consuming if many flooded compartments are involved, and this makes this set of methods not applicable for the analysis of the complete sinking process of a ship which typically includes many damaged compartments. During the application of these methods on full scale accidents in rough weather it eventually happened that numerical instabilities of the fluid motions occurred, which then lead immediately to unrealistic ship motions (and inflow fluxes, consequently). In all cases, these problems could be (iteratively) healed by adjusting the time steps. However, one must conclude that these methods are not yet stable enough to allow the application by unexperienced users due to these reasons.

For the analysis of the sinking process, Dankowski (2012) has developed a quasi-static method for the (slow) sinking of ships with many flooded compartments. Essentials of this method are the direct computation of the pressure propagation trough full compartments by a predictor- corrector-scheme, the direct numerical computation of the hydrostatic stiffness matrix including fluid shifting moments and the automatic detection of flooding paths by a directed graph. A full description of the method may be taken from Dankowski (2012). The method is quite fast and appeared to be robust when the experimental reference cases of Ruponen (2007) were analyzed. However, the application of this method to some full scale accidents showed the following problems which needed to be solved:

- When the ship capsized during the sinking (HERAKLION, EUROPEAN GATEWAY), the quasi- static determination of the equilibrium needed to be replaced by the solving of a differential equation with small time steps.

- The flux computation had to be stabilized in these cases when large inflow fluxes through large openings were combined with substantial ship motions
- When large compartments are filled quickly and an up flooding takes place through small openings (e. g. escalators), the flux oscillates significantly and requires numerical stabilization (COSTA CONCORDIA).
- When box-shaped objects were flooded and capsizing took place, the equilibrium determination became unstable which required numerical healing of the equilibrium determination and of the inflow- flux computation (BSU 266/14).
- Experiments with a test body having a RoRo-like subdivision showed that there can be a significant influence of the initial roll motion on the inflow flux, which made it generally necessary to replace the quasi-static equilibrium computation by the solving of differential equations. This posed new challenges on the stability of the method for box-shaped objects.
- Manderbacka and Ruponen (2015) have found out that during the initial phase of the flooding, the motion of the ingressing fluid may have a significant influence on the sinking process.
- Additional features like heeling moments, water tight door operations and pump elements needed to be included in the method to account for the individual accident circumstances.

For the sake of completeness we wish to add that during some model experiments there occurred the problem of entrapped air and its consequence on the sinking process. Although we have analyzed this phenomenon during our model tests, too (ref. Krüger, Dankowski, Kluwe et al.) we have come to the conclusion that entrapped air plays a minor role during full scale sinking only. This appears to be a problem during model tests where it may not be possible to sufficiently ventilate the compartments due to model restrictions.

It further turned out that the sinking process is very sensitive with respect to details of the subdivision, which requires a fine model. Our computational model for the COSTA CONCORDIA included 1536 spaces, 642 compartments and 1587 openings to accurately re compute the sinking process. The computations then could be performed slightly faster than real time, but this is of course far too slow if the computations shall serve as potential decision making tools. Unfortunately from our present experience it seems not possible to obtain correct results for the sinking computations if the compartment model is too raw.

Consequently, we must conclude that these methods are useful tools on the one hand, but on the other hand we must admit that the application of such methods still requires a qualified user, which may impede the broad use of methods.

Therefore, the future goal is to stabilize the computations from a numerical point of view and to increase the computational speed significantly. This is important in view of the fact that such kind of calculations shall be performed on board as decision design tools.

5. CONCLUSIONS

The paper has shown that numerical sinking computations can successfully assist the investigation of marine casualties. As the documentation of these casualties has significantly improved, it is today well possible to clearly identify the root cause of such events by computations. Despite the fact that some information on accident data is uncertain, marine casualties are a useful validation basis. As sinking events are very complex, there must exist different computational methods to cope with the individual requirements of each accident. Although these computations are extremely useful, these methods are still not stable enough to be widely used, especially by non-experienced users. Consequently, future efforts shall be put into the problem to increase stability and computational time.

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