How to buy time following a flooding incident – intelligent quantification of emergency response measures

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ABSTRACT

Increasing vessel size and complexity creates high uncertainty in flooding situations, and it is challenging for the crew to obtain a complete overview and make fully informed decisions. Time is of the essence, and to optimise decision making and ensure decisions are made on time, we propose adopting the concept of *Dynamic Barrier Management* through increased use of sensors and analytics. Focus will be placed on emergency responses as their impact on safety has not been quantified in terms of risk reduction to the same extent as for passive design barriers. Based on the idea of increased use of advanced analytics and sensors, particularly flooding sensors, this paper aims to present current research ideas and planned development of a method in which active mitigation measures such as emergency response actions can be quantified in terms of effective risk reduction based on real-time measurements and simulations during an accident, i.e. intelligent quantification of emergency response measures.

Keywords: *Dynamic Barrier Management, Emergency Response, Decision Support, Flooding, Mitigation*

1. INTRODUCTION

As the world is changing fast, so is the maritime industry. New megaships continue to outsize older designs as economies of scale continue to offer a competitive edge to ship-owners and operators in an ever-competitive market. The new giants of the sea and the increasing complexity of their on-board systems and their interactions are posing challenges to the maritime industry in terms of potential hidden risks. We continue to strive towards a safer industry, but are we able to keep up with today's immense pace of change?

An intensive search for better and more optimised design solutions has been seen in the last few decades, especially following the introduction of risk-based ship design methods (Papanikolaou et al., 2009) and the introduction of risk-based standards such as the probabilistic damage stability regulations outlined in Ch. II-1 of SOLAS (2009). Utilising these methods of risk reduction, numerous means for reaching more optimal and cost efficient designs have been developed through the introduction of risk control options or safety barriers aimed at either accident prevention, or mitigation post-accident.

With regards to hull breach and flooding, development of such measures has been focused primarily on survivability and mitigation rather than prevention. It seems now, however, that this is about to change as focus has shifted towards research and developments of preventative measures for avoiding hull damages altogether, a concept that has shown to be more cost efficient if successful. The various safety barriers introduced to reduce risk are many, and can roughly be classed as passive means built in to the design, i.e. inherent safety, or as active means which may relate to process, people, technology, environment, etc. Several of the built-in barriers need physical activation to be in their functioning state, e.g. sliding watertight doors, pumps/valves, cross/down-flooding, etc. and are therefore highly dependent on active means in terms of human response and actuation.

The way we handle and manage these barriers during the life-cycle of a vessel has lately been questioned. What happens to risk of a vessel when the barriers change and deteriorate and how can we ensure that this does not result in risk reaching unacceptable levels during the vessel operational-life? Trying to answer such questions, a new concept has emerged with roots in the offshore oil and gas industry, namely *Dynamic Barrier Management*.

The concept is aimed at continuous monitoring and management of safety critical barriers by utilising sensor measurements and analytics (Astrup et. al 2015). Despite the fact that focus has shifted from mitigation towards prevention, it is the authors' belief that there is still room for great improvements in a vessel's survivability through optimising active barriers such as emergency response actions and their interaction with available systems.

The impact of emergency response on safety has not yet been quantified in terms of risk reduction to the same extent as for purely passive design barriers. Based on the idea of increased use of advanced sensors and analytics, especially flooding sensors, this paper aims to present current research ideas and planned development of a method in which active mitigation measures such as emergency response actions can be quantified in terms of effective risk reduction based on real-time measurements and simulations during an accident, i.e. intelligent quantification of emergency response measures.

2. CURRENT CHALLENGES

The increase in vessel size and system complexity introduces new challenges in any emergency situation, hull breach and flooding situations being no exception. It is difficult for a human to grasp the immensity of such situations, the numerous possible damage conditions, water propagation and progressive flooding through pipes, doors and other internal openings. This also includes multiple free surface effects and motions induced by external forces.

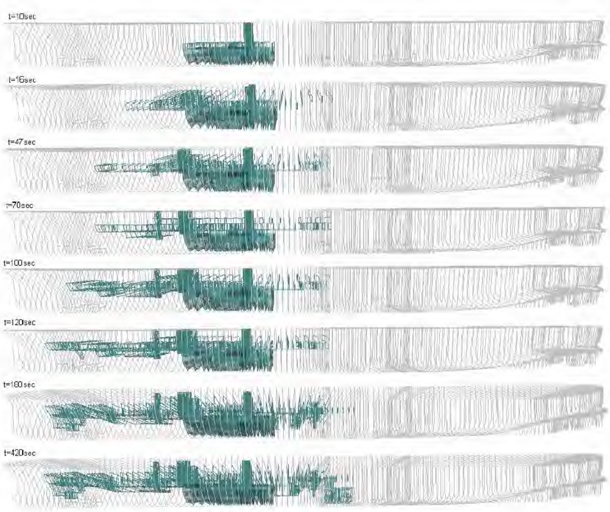

Figure 1: Progressive flooding of vessel during 7 min at Hs=4m. (Tsakalakis, 2009).

Figure 1 illustrates the complexity of a flooding incident, demonstrating the propagation of floodwater in a vessel during only a 7-minute time period. For the crew to have a complete overview of the situation, there are multiple variables that require consideration such as damage extent, flooding rate and taking inventory of available systems, including also all the external environmental variables. Before the crew manage to get hold of all this information and evaluate the situation, the situation can become unmanageable.

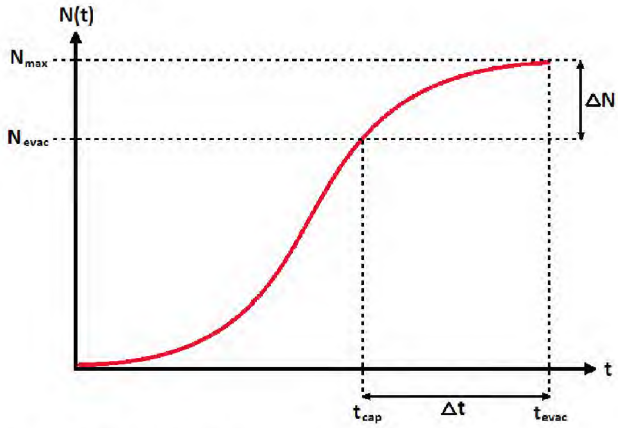

Figure 2: Interplay between time to capsize and evacuation time. Adapted from Papanikolaou et al. (2009).

Even when information is available on the current status, the final outcome is still uncertain and information to take the correct and most optimal decisions is limited at best. The two most important variables in any flooding accident is the time to capsize and the evacuation time, which are depicted in figures 1 and 2. If the time it takes to evacuate is longer than the time it takes for the vessel to capsize and sink, we have to assume there will be losses in terms of human life. The magnitude of loss will be closely related to the difference between these times, but most importantly it can be seen as a measure of potential improvement. If we can implement any active measures to decrease Δt, we can save lives. In an ideal design, the time to capsize should be ∞ for all expected damage scenarios, and as a minimum the following inequality should be true:

$$t_{cap} > t_{evac} \tag{1}$$

But a perfect design does not exist. We do however have the tools available, and it is befit on us to optimise these tools to the highest level possible. Optimised tools will waste less time following flooding incidents, increase Δt, and allow for more effective evacuation, thus saving more lives.

3. PROPOSED METHODOLOGY

As initially mentioned, innovative technologies present a challenge, but in addition to considering their risk contribution, it is important also to embrace the possibilities such innovation can bring. If implemented correctly, it is believed that such technology could be used to optimise the current emergency response and operational measures. Today, the physics that governs the flooding process is well understood, and several tools of replicating the phenomena through time domain simulations are available. By introducing sensors to relevant compartments and available safety critical systems, real-time data and status can be used in combination with flooding simulation software to assist crew in adopting the most optimal measures during emergencies.

In theory, such optimisation techniques can be used for other accident categories such as fire, but in this instance, focus is placed on flooding scenarios. Systematic application of sensors to relevant compartments and safety critical systems would result in a reduction in the high uncertainty following a flooding incident. Information regarding the damage extent and flooding rate would be provided with increased accuracy, i.e. current initial condition and its rate of change. Some uncertainty will still be present, but sensor-based inference could be utilised in order to determine/limit the number of initial damage cases to investigate further using simulations.

Relevant initial damage cases can be prepared using available statistics, and time-domain simulations. This data can be stored onboard in a database from which the system could infer the n^{th} most probable cases using all available evidence. As time progresses, continuous measurements from the sensors would then update this inference as more detailed evidence becomes available and the number of cases would reduce. Furthermore, having sensors on installed safety systems such as doors, valves, pumps, etc. their availability post damage is known. This information combined with knowledge of the initial condition, can be used in advanced flooding simulations to predict the most likely outcomes. Such information can then be used to facilitate the best risk-based decisions for containing or suppressing the flooding process, thus increasing the time available for evacuation, or even safe return to port.

Having real-time data on the initial situation limits the need for extensive simulations and we need only focus on the actual damage cases. This is particularly important if simulations are to be performed in real-time onboard the vessel. This derives from the fact that one of the sources of uncertainty originates from the complexity of the internal architecture in cruise ships, making flood progression a chaotic process. Chaotic processes introduce complexity and uncertainty that is time-consuming to address. The idea of utilising sensors is not a new one, and several developments on the topic have been published. A lot of work has been done during the project FLOODSTAND (2009) where sensors were implemented on watertight doors, including simulations to predict the impact of watertight doors in varying states on the vessels' survivability.

The problem encountered initially in this project was the long simulation time for conducting a global risk assessment, encompassing all damage scenarios. However, this should not be a problem when flooding sensors are used, as they provide an initial indication of the damage extent, thus localising the problem. They also provide information on the path of floodwater propagation, thus removing the uncertainty associated with the flooding process and rendering flooding progression predictable. Instead of thousands of combinations for the whole ship, only a small portion would be required, limiting the simulation time considerably. NAPA has also worked on similar approaches (Ruponen, et al. 2015) using flooding sensors and time-domain simulations but were limited to consider flood-level sensors, door status and loading condition only. Their time-domain simulations have

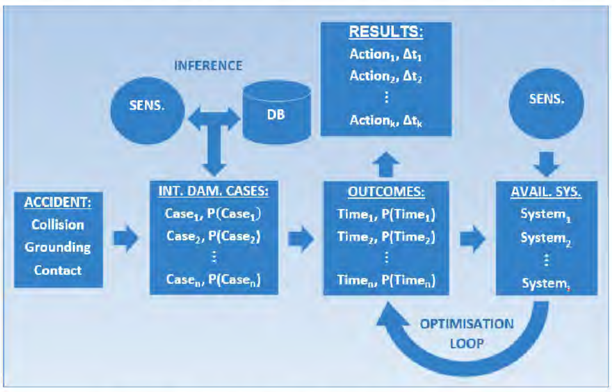

Figure 3: Initial outline of methodology.

further been limited to calm-water, i.e. no influences from waves considered. Their method uses color coding within the user interface for the vessels crew, providing simplistic and transparent representation of the situation and it's severity-potential. The applied color coding is in line with the proposed method for assessing and communicating the safety status of vessels in maritime distress situations, namely Vessel TRIAGE (Nordström et al. 2016).

Earlier developments on the topic comprise of Ölcer and Majunder (2006), where a case-based reasoning decision support method based on pre-calculated damage cases was suggested. Each of these damage cases have corresponding counter-flooding advice for maximising the residual freeboard and stability. This approach lacks the possibility to use real loading conditions, sensors, and status of safety critical systems. The method is highly dependent on the pre-calculated cases, and their sampling density as identifying the closest case necessarily do not mean the actual case.

The innovation behind the proposal presented in this paper is the combined utilisation of flooding sensors and sensors reflecting the availability of safety-critical control systems post-accident. It is an extension of the idea of *Dynamic Barrier Management* but with focus on optimisation of the relationship between procedural and design barriers in the post damaged conditions. Furthermore, decisions will be based on probabilities, meaning that the initial conditions selected for detailed simulation should be the n^{th} most probable cases that could occur considering available evidence from various sensors. An initial outline of the methodology is illustrated in figure 3. It is our intention to use the time domain flooding simulation software PROTEUS3 (Jasionowski, 2001) for the development of the method. The software accounts for transient-, cross-, & progressive-flooding, the impact of multifree surfaces as well as watertight and semi-watertight doors including any damage scenario (collision, grounding, raking, etc.) for a damaged ship in waves. A typical flooding model from Proteus is shown in figure 4.

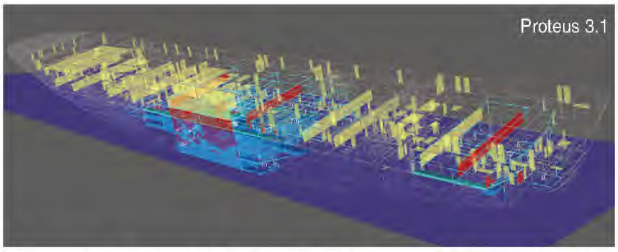

Figure 4: Typical Proteus model used for survivability analysis. (Papanikolaou et al., 2009).

4. INITIAL RESEARCH

The overall idea and concepts have been outlined in the previous sections, however at first, focus will be placed on developing the method of identifying the initial damage extent. One solution to this may be to utilize inference to get the n^{th} possible initial damage conditions based on the available sensor input used as evidence. This will cover the variability of the problem, but the remaining uncertainty in terms of sensor errors and other influences should be considered as well.

The next step is then to consider how to manage the simulations required. This can be done either by using real-time simulations onboard or by having detailed pre-calculated simulations stored in an onboard database. A major determining factor for deciding this will be the speed of the onboard simulations. If the simulation-time is too long, it will erode any safety benefits offered by the methodology. We need also to decide which active measures to assess initially. For a typical cruise vessel, the following main actions are available options for mitigating risk following a flooding incident and are deemed suitable for initial testing of the methodology:

Closing of external and internal openings such as doors, ventilation, damaged pipes, etc.

Counter-ballasting to alter the floating position of the vessel and centre of gravity.

Recovered buoyancy in the form of high expansion foam as suggested by Vassalos et al. (2016).

Any increase in time-to-capsize will result in a subsequent decrease in evacuation time as they share several common parameters such as heel, amount of floodwater obstruction and the availability of systems. There are, however, other pertinent parameters associated with evacuation time which will not be considered under the scope of this investigation.

Being able to find a detailed quantified measure of risk in terms of reduction in potential loss of life, or ΔN from figure 2, would require detailed information on evacuation time. For simplification purposes, it is possible to limit the scope of the research in the initial phases by assuming an overall constant mean evacuation time for quantification of the optimised time to capsize. Alternatively, the time to capsize is itself a measure of risk, so for further simplicity, it could be sufficient to consider optimisation in terms of this variable only.

Finally, an optimal application of the methodology would be to present real-time case-specific decision support. This could be in the form of a list of actions that could be taken by the crew based on the available systems, and rated on optimal added time to capsize. Optimisation techniques for identifying such decisions are currently being investigated, which is a continuation of the work outlined in Vassalos et al. (2015). In any case, developing a method in which uncertainty is reduced, and where an estimated time to capsize is presented to the crew in real-time, is of high value. This is the case even if the real-time decision support is not reached at the first instance. It is not only important to identify actions for increasing the available time, but also for making more efficient use of it in cases where time cannot be increased by any means. Knowing the time available before capsize would have an immense impact on the crew decisions on how to use the time available, and answer questions such as *if* and *when* to commence evacuation.

5. CONCLUSIONS

The concept of emergency response is not a new one and a number of measures are outlined in IMO's IMDG Code (2016), including also the requirement for having damage control plans and booklet for assistance in flooding situations as outlined in SOLAS (2009) Reg. II-1/19. Several class societies also provide emergency response expert services for ship-owners. It is well understood that time is one of the most critical variables in an emergency situation involving flooding. It is therefore important to identify new ways of optimising the time available before a vessel capsizes and we strongly believe there is room for improvement utilising new technologies.

Even if only the time to capsize can be estimated in real-time, it would be of great value in the decision-making process onboard. Our hope is to, in the future, to give decision support to the crew in terms of a case-specific list of actions rated by their added time to capsize. Further, the idea could be extended to other accident categories, and be part of a larger safety management system for the vessel. The method could also be possible to be used on autonomous vessels' for identifying the most optimised decisions for survival and safe return to port to avoid vessel loss. As there will be no crew-members to initiate the damage response, this must be implemented by actuators which will also require a system enabling quantified decision making.

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