Risk Analysis of a Stability Failure for the Dead Ship Condition

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ABSTRACT

In this article, the application of the risk analysis of a stability failure for the dead ship condition is presented. The analysis combines deterministic and probabilistic approach. First, the number of simulation runs is carried out for a specific RoPax ship with the use of LaiDyn model. Second, the obtained results were organized in a probabilistic meta model with the use of Bayesian Belief Network. Finally, the BBN-based model was used as a platform for risk assessment. The adopted measure of risk is a number of fatalities that results from an accident, when a ship is in Dead Ship Condition (DSC) capsizes. The results are presented in a form of F-N. Finally the sensitivity of the model is evaluated along with the assessment of associated uncertainties.

Keywords: *stability, Dead Ship Condition, risk, Bayesian Belief Network*

1. INTRODUCTION

Discussions on the improvement of the IS Code(Francescutto, 2007), which were conducted at IMO forum, resulted in the identification of several major stability accident scenarios(Umeda, 2013):

- events related to the changes of righting arm – the parametric resonance and the pure loss of stability
- Dead Ship Condition - ship losing propulsion and manoeuvring characteristics (DSC)
- Problems with manoeuvrability on the wave - broaching, surf-riding,
- Problems with excessive accelerations.

Because the scenarios proposed by the IMO, still do not provide all possible causes of the loss of stability, it is necessary to approach the problem in another way. Consequently, the new rules are loosing their passive and retroactive approach and shift towards active feature. Which are not the result of the study of the stability accidents, but are based on the previous in-depth analysis of the phenomena associated with the behaviour of a ship on a wave. Such an approach allows the extension of regulations of further scenarios more easily.

This means that when creating the next generation of rules, it is advisable to develop methods for assessing the safety of the ship, where they not only physical, but also the operational characteristics of vessels will be taken into account.

Well known methods, which take into account the above mentioned elements are methods based on analysis and risk assessment, such as the one based on Safety Cases(Wang, 2002), widely used in the offshore industry - or another one called Formal Safety Assessment (Psaraftis, 2012)(Montewka, Goerlandt, & Kujala, 2014), which is used in the shipbuilding industry to create new rules(IMO, 2002). There is also a Risk-Based Design methodology(Papanikolaou et al., 2009), which is more and more widely used in the design of ships in the damaged condition.

Risk-based methods allow taking into account even the most unlikely accident scenario, and also the interactions between the scenarios, or some of their components. The probabilistic causal models (Bayesian networks (BN), Fault Tree (FT) and Event Tree (ET))(Goerlandt & Montewka, 2015; Montewka, Ehlers, et al., 2014; Pillay & Wang, 2003) are more and more frequently used as a tool in the risk assessment process.

The main objective of this project was to create a probabilistic risk model of the ship stability accident, which might be applied to the assessment of the intact stability safety with the usage of the probabilistic casual model. One of previously presented scenario, i.e. Dead Ship Conditions, was chosen for the further analysis. The following sections will present the risk model built with the usage of the Bayesian Network and its application in RoPax ship. They allow exploring easily the influence of particular elements on the other ones, and in both directions. Having BN at disposal, it is possible to conduct the casual analysis, examine the strength of the impact of some elements on the other ones and make decisions under conditions of uncertainty.

2. RISK MODEL OF DEAD SHIP CONDITION ACCIDENTS

The aim of the proposed method is to estimate the risk of the stability accidents in the intact condition for the loss of the propulsion and manoeuvrability scenario. Such scenario might results in ship drifting, increased rolling, which in turn may lead to the capsizing and the ensuing loss of life by passengers. For the given meteorological conditions, the probability of exceeding the limits of ship motions is determined with the usage of 'LaiDyn' model. The following factors are taken into account concerning: meteorological conditions, ship dynamic and ship loading conditions. The total number of fatalities (N) resulting from an accident is modelled using the concept of death rates. This factor is determined with the participation of evacuation time and time of capsizing. The number of passengers on board is modelled based on data from the operators of RoPax form the Gulf of Finland. All these elements together, also with the associated probabilities (P) of the number of victims, is shown in the graph FN. The risk is measured adopting societal measure pressed as the probability of a given number of fatalities.

3. DEFINING THE RISK MODEL

The risk model of the DSC accident for RoPax ship was built with the support of the probabilistic casual model, which is the Bayesian network (BBN). The BBN structure was built with the participation of experts. The parameters were developed with the participation of the PC classifier based on the training data. It was created using the GeNie software developed at the University of Pittsburgh(Drużdzel, 1999).

Due to the limited statistic data, it was primarily the knowledge of experts that was used to create the structure of the model.

The analysed system is quite wide and multidisciplinary, therefore the model is divided into sections associated with (i) stability, (ii) propulsion and manoeuvring system, and (iii) finally with the consequences of an accident.

Experts' knowledge about the domain was used during a brainstorming session and individual meetings. During the session, they were presented with a preliminary version of the structure. Then, based on their advice, the structure under went the further modifications. Once the final structure of the model was established, it was necessary to define the qualitative part of the model.

The structure of the risk model is shown in **Figure 1**.

Table 1 contains all the variables included in the model. If the variable is determined by means of literature, it is marked by reference.

Variables marked as E are determined with the support of experts' knowledge. Simulations were used for variables marked with the letter S. The letter N in the description of a variable indicates that it was obtained by numerical analysis.

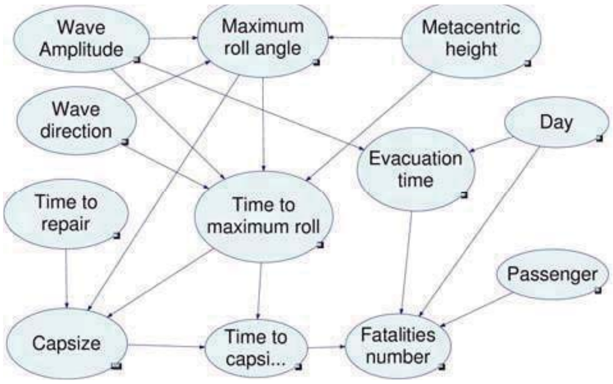

Figure 1 Structure of risk model

Table 1 Parameters of risk model

Name	Symbols	Source
Wave amplitude	Ampl	(IMO, 2013)
Wave direction	Beta	E
Maximum roll angle	$Roll_{max}$	S
Metacentric height	GM	E
Day	DAY	E
Time to repair	TTRep	(Ravn, 2006)
Evacuation time	TTE	(Montewka, Ehlers, et al., 2014)
Time to maximum roll angle	TTR	S
Capsize	Capsize	N
Time to capsize	TTC	S,N
Passenger	N_{PASS}	(Montewka et al., 2011), E
Fatalities number	N_{LOSA}	N

The simulation was conducted with the usage of the numerical model of the ship's movement on the wave. 17388 simulations of ship motions on the wave were performed. The simulation results were used to estimate the probability of exceeding the angle, which is considered to be the angle of capsizing. The results of simulations provided also data about the time at which the ship reaches the capsizing angle ('Maximum roll angle').

4. PARAMETERS OF THE RISK MODEL

This section describes the methods adopted to determine the parameters of the risk model.

The analysed accident scenario involves RoPax ship, which due to various reasons loses its propulsion and manoeuvring characteristics and enters a dead ship condition. This transition may be caused by a spontaneous failure of systems as well as the environment (large motions).

The basic elements of the model are:

- the probability of staying in a blackout state and time needed to exit this state,
- wave parameters,
- hydrostatic properties and ship loading conditions,
- ship's response to waves,
- the probability of capsizing of the ship in the DSC,
- elements related to the rescue of passengers, cargo and the ship,
- the number of victims of the stability accident.

Elements of the model presented in this paper relate to the ship RoPax, for unrestricted service area. However, the manner of use and modularity of the methodology allow its (this model) use for other types of ships, as well as for limited service areas.

The behaviour of the ship on waves was studied using a mathematical model developed by prof. Jerzy Matusiak(2007)(Acanfora & Matusiak, 2014). "LaiDyn" method is based on the assumption that the complete answer of a ship equals the sum of linear and non-linear parts. Such division results from the fact that the linear computation methods are well-known. It causes the situation where the radiation and diffractive forces are presented by linear equations quite well(Kukkanen, 1995)(Journee & Adegeest, 2003). In this method, the main part of the first order load is calculated with the linear approximation, based on the current heading and location in relation to a wave. Defining the non-linear part, such elements as non-linearity as a result of ship shape, hydrostatics, wave force were taken into consideration.(Matusiak, 2011).

The LaiDyn program conducted over 17.000 simulations. The simulations conducted for four loading conditions. The wave statistics were taken from IACS documents(IACS, 2001). The information about the maximum roll angle and the time of reaching it, which were obtained as a result of conducted calculations, were applied to construct a risk model. When the time of reaching the critical angle was smaller then the time of repair, it was stated that the ship will capsize. The probability distributions of the variables, marked with references in **Table 1**, were prepared with the usage of the information included in various publications. The 'Fatalities number' variable includes information about the life lost probabilities of the N-passengers. BBN was created using the GeNie software developed at the University of Pittsburgh (Drużdzel, 1999).

5. RISK FRAMEWORK VALIDATION – SENSITIVITY ANALYSIS

The sensitivity analysis allows to investigate how sensitive the results obtained from the risk model are to changes of individual variables(Montewka et al., 2011). To do this, it is necessary to determine the function of the sensitivity for each individual node in the network(Chan & Darwiche, 2002):

$$f(t) = \frac{(c_1 t + c_2)}{(c_3 t + c_4)} \qquad (1)$$

where f is the output probability of interest given observations, c1, c2, c3 and c4 which are identified based on the risk model(Goerlandt & Montewka, 2015). The effect of small changes in the input parameters on the result is called sensitivity. The sensitivity is determined from the first derivative of the sensitivity function (see eq. (1)).

Figure 2 provides a graphical result of the sensitivity model analysis, on the assumption that the resulting variable is the 'Fatalities number' of the accident.

The presented graph shows that these variables - 'Capsize', 'Time to capsize', and 'Evacuation time' – have the most crucial impact on the results from the risk model. The 'Capsize' and 'Time capsize' variables are considered as ones of the most important in the model constructed with the usage of the simulations and additional transformations. The 'Evacuation time' variable was created using data from the literature. So, if the Bayes network were to be applied in practice, it would be required to prepare a better model of the evacuation.

A similar analysis was performed for the 'Capsize' variable, as it is shown in **Figure 3**.

In the case where the 'Capsize' variable is analysed, it is impossible to observe any strong dominant variable. Concerning their dominant character, the average variables are the following ones: the 'Wave amplitude', 'Maximum roll angle', and 'Metacentric height'.

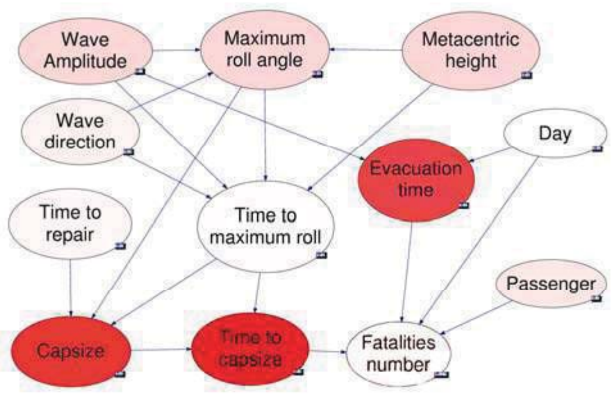

Figure 2 Sensitivity analysis – 'Fatalities number' variable

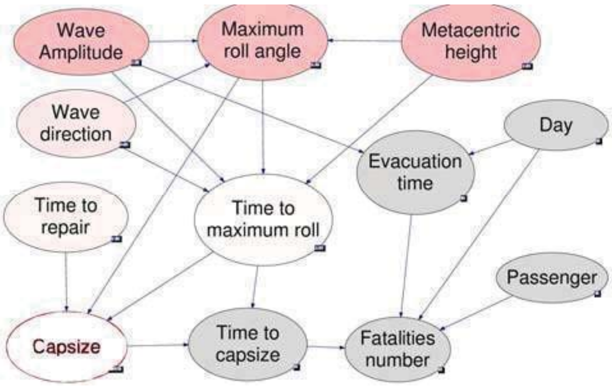

Figure 3 Sensitivity analysis - 'Capsize' variable

6. EXAMPLES

In this section, the methods currently applied to the assessment of stability safety are compared with the results obtained with the method based on risk analysis.

The comparison of two methods is used to show the applicability of the risk to the assessment of the ship stability safety. Such a comparison can also show the level of safety of ships built in accordance with modern requirements.
In the comparison, we used a RoPax type of ship, described below.
Table 2contains the basic dimensions and hydrostatic characteristics of a hull that was used in the risk analysis(Mattila, 1999). **Figure 4** presents the hull profile.

Table 2 Main dimension

Name	Symbol		
Length	Lpp	[m]	158
Breadth	B	[m]	25
Draft	T	[m]	6.1
Depth	H	[m]	15
Block Coefficient	C_b	[-]	0.571
Displacement		[ton]	13766
Wetted surface	S	[m2]	4356

Four different loading conditions for the draught of T=6.1 [m] were taken for the calculations.

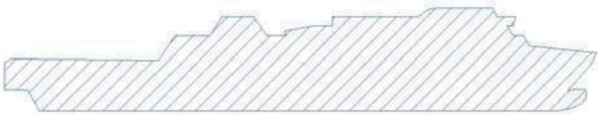

Figure 4 RoPax profile

The standard stability document created in the process of ship design takes a shape of a curve of minimum metacentric heights and maximal centres of gravity. It shows the loading conditions for which the ship complies with the criteria contained in the Code and for which the criteria are not met. The curve of the minimum GM is presented in the **Figure 5**. **Figure 6** shows the curve of the maximum centres of gravity. Both **Figure 5** and **Figure 6** also present the loading conditions used in the simulation.

The analysis of that graphs shows that LC1 condition does not meet the regulations, which are currently in force. Other loading conditions do meet the criteria defined by the rules, wherein LC2 condition is exactly on the limiting curve. According to the approach, that is used nowadays, LC1 condition cannot be considered as a safe one, whereas the remaining conditions are seen as safe ones.

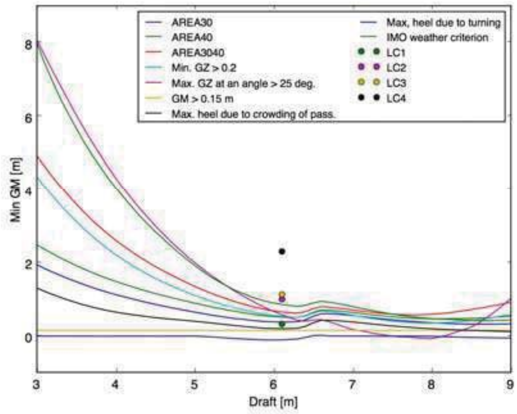

Figure 5 Minimum GM curve

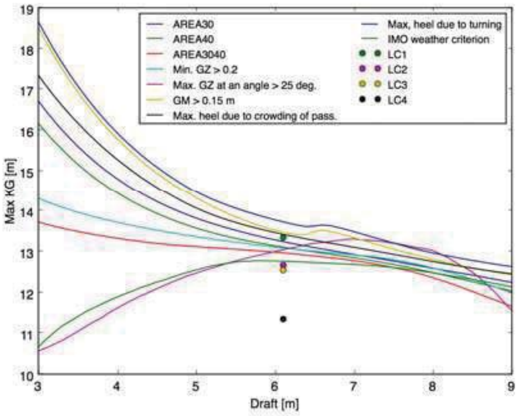

Figure 6 Maximum KG curve

Each FN curve in **Figure 7** corresponds to one load conditions (LC1-LC4). The horizontal position of each curve shows that the higher the GM is the fewer victims of the accident.

Loading condition coded LC4 has the highest GM. This condition meets current stability requirements with a large margin. Also the FN chart confirms this.

7. CONCLUSIONS

The assessment of the safety level has not been performed for the current legislation. So it is unknown how safe ships built with its use are.

Only by using the risk analysis it is possible to decide how safe a ship might be. The measure of safety is presented by the FN curve.

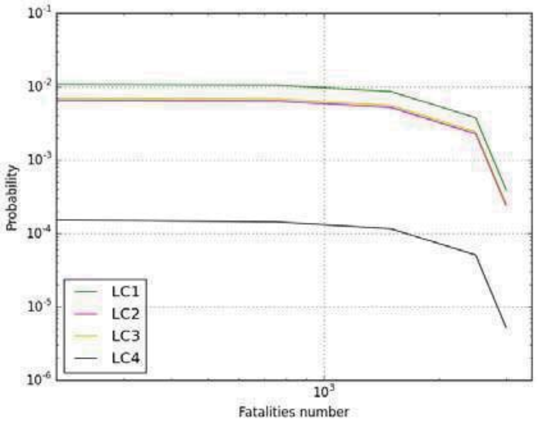

Figure 7 FN curves

Figure 8 is an extension of the graph in **Figure 7** and covers additional ALARP region(Pillay & Wang, 2003). According to the analysis of FN chart include the ALARP area, only LC4 loading condition is entirely included in the area or is located below it. Remaining loading conditions fall outside the area. One should assume that these conditions are not safe. In case of a real project, the group of experts should perform the third stage of

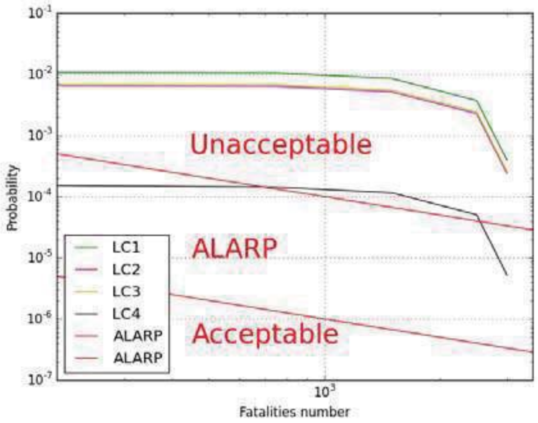

Figure 8 FN curve with ALARP region

According to the designers' experience it should be necessary to check the loading conditions i.e. to verify whether these conditions are realistic. In the case of the situation where there are no results of the inclining experiment, at least not yet, one could verify the weight estimation. If the previous steps did not provide any appropriate outcome, it would be necessary to modify the shape of the hull. One could also develop an operation manual with the basic information about the limitations of loading conditions and the operating areas.

There are advantages and disadvantages of the risk analysis when used as a tool to assess the stability safety of the ship in the intact condition.

The great advantage of the methods based on the risk analysis is the fact that it might be applied in the new projects or even innovative ones, which cannot be compared to data taken from previous projects. In the process of designing modern vessels or offshore structures, it is possible to use model tests or computer simulations. Such an approach enables the prediction of certain properties in a much more accurate way than using a simple empirical formulas based on experience.

It is possible to use the risk analysis in the evaluation of only one of the scenarios; however such narrowing is not practical. Much better results are obtained by the application of a holistic approach using a variety of scenarios. The risk analysis can give an overall view of the causes and consequences of the accident, as well as examine the impact of the Risk Control Options (RCO) at risk.

The disadvantages of the risk analysis may include primarily large costs associated with the time-consuming experiment; regarding not only its financial side but also the issue of time and personnel. To perform a detail risk analysis, it is necessary to collect a group of experts what might be difficult to achieve in a small design office.

The lack of good probability models of the ship capsizing makes it more difficult to accurately estimate the risk. In many areas of technology, a rich statistic material replaces this lack of probability models of accidents. Concerning the stability accidents, such an approach cannot be applied because the statistical material is rather poor and the analysed accidents do not have any characteristics of repeatability.

8. ABBREVATIONS

ALARP – As Low As Reasonably Practicable

BBN - Bayesian (Belief) Network

FN – Fatalities number

LC – Loading Condition

RCO – Risk Control Option

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