Possibilities of application of FSA methodology to stability of ships

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Abstract

Recently IMO recommended application of the Formal Safety Assessment (FSA) methodology to the development of safety rules. The main purpose of the paper is to analyse the difficulties that arise with the application of FSA methodology to stability problems and eventually to propose ways to solve some of them. The first two steps in the FSA methodology are identification of hazards and assessment of risk. With regard to intact and damage stability problems hazards that may lead to loss of the ship should be identified. The hazards could be identified on the basis of the analysis of casualty data and of the experts opinions. For the purpose of assessment of probabilities involved various scenarios leading to ship capsizing or foundering have to be analysed. Statistical methods, model tests and mathematical simulation have to be used. Risk, which is the product of probability of the hazard and its consequences has also to be assessed and the main difficulty would be evaluation of consequences. In the paper methods of identification of hazards are discussed and various possibilities to assess the risk involved are considered.

1 Introduction

In 1993 by resolution A.749(18) Intact Stability Code was adopted comprising intact stability requirements for all types of ships [1]. At present this code composes the latest achievement in the development of stability requirements, nevertheless there are opinions expressed that they are not satisfactory. The existing stability requirements are criticized because of the obvious shortcomings of statistical criteria and excessive simplifications in weather criterion.

Moreover, stability accidents happen with ships that meet all existing IMO criteria.
Following the idea that prescriptive criteria have to be replaced by performance oriented criteria, recently IMO adopted recommendation on application of the FSA methodology [2]. Bearing this in mind possibility of application of FSA methodology to ship survivability comprising intact, damage stability and safety against foundering problems is considered.
Basically FSA methodology should be applied to the entire ship safety system. However application of the relevant parts of this methodology to selected subsystems may provide useful tool to evaluate particular safety problems related to those subsystems. In the paper discussion is concentrated on the possibility of application of FSA methodology to stability problems and safety against capsizing. This obviously is only one of many aspects of safety of ships at sea.

2 Formal safety assessment (SA) methodology

Possibility of applying SA to safety against capsizing was discussed quite a long time ago (Kobylinski[3,4]). Recently formalized methodology of Safety Assessment (FSA) was recommended by IMO as a methodology that should be applied in the future to the rule making process [2].
FSA according to the definition is "a structured and systematic methodology, aimed at enhancing maritime safety, including protection of life, health, the marine environment and property, by using risk/cost benefit assessment".
FSA methodology should comprise the following steps:

1. Identification of hazards
2. Risk assessment
3. Risk control options
4. Cost-benefit assessment, and
5. Recommendations for decision making

FSA methodology is thoroughly described in ref. [2].
In the paper only the first two, however, most important steps of the FSA methodology in application to intact stability are discussed because of the limited length of the paper which does not allow to elaborate on the further steps.
Since adoption of the IMO recommendation few applications of FSA methodology to safety problems of ships are known, and the most thorough is trial application of FSA to high-speed catamaran craft. There are also known attempts to apply this methodology to ship capsizing taking account of shifting cargoes in holds [5]. In this reference thorough analysis of events that may lead to shifting cargo are considered using fault tree method.
In references [6] and [7] application of FSA methodology, at least partially, to stability of naval ships in a seaway is considered.

3 Risk assessment- problems to be solved

All attempts to apply FSA methodology to stability problems revealed that there might be very serious difficulties in this application that may not be easily solved. When applying FSA it is necessary to assess risk, to identify possible hazards and their probabilities on the basis of scenarios that may lead to capsizing. Probabilistic approach to safety against capsizing is an obvious approach in this case.

Probabilistic approach to stability requirements was considered at IMO in mid-seventies when work was initiated on "rational" stability criteria that possibly should be based on probability of capsizing (Kobylinski [8], Sevastyanov [9]). Due to serious difficulties, however, this task has never been completed and only recently this idea came into being once more.

Risk is equal to the product of probability of hazard and its consequences. Consequence when analyzing probability of capsizing is always of the catastrophic nature, therefore even with remote probability of hazard risk is great and undertaking requires action to eliminate hazard.

Assessment of risk related to capsizing of a ship is not an easy task. There are several problems to be considered and possibly solved before assessment of risk could be accomplished. The most important questions to be answered are as follows:

1. Definition of capsizing. What is really understood under capsizing?
2. Whether long term or short term probability of capsizing has to be adopted as a criterion of safety?
3. What kind of hazards has to be taken into account?
4. How to calculate short-term probability of capsizing?
5. What wave climates criteria have to be assumed?
6. What level of probability of capsizing would be acceptable?

Some of the above questions are discussed below.

4 Definition of capsizing

When considering stability problems it is important to define what is understood by capsizing. In common language, capsizing usually is understood as the passing of the ship from the upright position or zero angle of heel to the upside down position or 180 degrees heel. The above concept of capsizing is, however, not satisfactory from the point of view of studying safety against capsizing.

There was the prolonged discussion on the definition of capsizing during the second STAB conference in 1982 and several proposals were considered. Morall [10] proposed to define capsizing, as a situation where amplitudes of rolling motion or heel exceed a limit that makes operation or handling the ship impossible for various reasons but not necessarily taking the position upside down. This situation might be better defined as the loss of stability accident and the definition might be suitable for the purpose of assessing risk of capsizing.

5 Long or short term probability of capsizing

The most attractive application of the probabilistic approach to assess risk within FSA methodology would be to calculate probability of the loss of stability accident during the lifetime of the ship. Some authors, *inter allia* Kobylinski [8] and Sevastyanov [9] considered this approach quite a long time ago.
During the lifetime, the ship may find itself in a number of situations where each situation is characterized by heading and speed, loading condition, sea state and wind force and direction as well as other factors influencing stability.
Supposing there are k- such situations in which the ship may find itself during its lifetime, then the lifetime probability of capsizing could be expressed as:

$$LP_C = \sum_{n=1}^{k} C_k \cdot P_{Ck}$$

where: P_{Ck} is the probability of capsizing in k-th situation (short term probability of capsizing) and C_k is probability of occurrence of this situation.
Identification of all possible situations that may occur during ship's lifetime leads to a very large number, of the order of 10^5 or more.
In spite of the attractiveness of adoption of the lifetime probability of non-capsizing as the criterion of safety, one may argue that if it would be proved that probability of capsizing in certain potentially dangerous situations, as e.g. in extreme sea states, is sufficiently low, then obviously there would be no need to calculate probability of capsizing in situations that are not dangerous. This may considerably reduce amount of work required. Boroday and Rakhmanin [11], Kobylinski [8] and Takaishi [12] advanced this concept.
The essence of this concept consists of the calculation of the probability of capsizing (loss of stability accident), not for all possible combinations of environmental and internal conditions, but in some selected situations deemed to be dangerous. From the statistical records of stability casualties and on the basis of experience it appears that only a few possible situations during the service life of a ship are really dangerous. In particular, capsizing caused by the action of waves and wind may occur only in heavy weather.
Naturally, the choice of dangerous situations is an important issue.
The authors of the above references were of the unanimous opinion that in a stormy sea, the highest probability of a loss of stability accident occurs when the ship is in the following three situations:

1. In a beam sea and gusty wind,
2. In a following sea
3. In a quartering sea in conjunction with broaching.

To those three situations one other could be added after the accident of a post-Panamax C11 ship was analysed [13]:

4. Head sea

In each of the above situations several scenarios of capsizing have to be analysed taking also into account, apart from waves and wind action, also other factors contributing to capsizing.

6 Hazards to be taken into consideration

Statistics and description of stability casualties shows, that environmental effects are rarely single cause of a loss of stability accident. Usually other factors, such as shifting of cargo, crowding of passengers on one side, rudder action, icing, sharp turning, opening not closed, water trapped on deck etc., and also human factors are contributing to the casualty.
Statistics seems to be the best way to judge upon possible hazards. There are, however, rare cases where the sequence of events is exactly known which may make difficult to identify scenarios leading to capsizing. Model test provide good insight into the capsizing phenomena, unfortunately several factors, such as e.g. shifting of cargo cannot be correctly reproduced. Moreover, model tests are extremely costly and time-consuming enterprise.
Eventually hazards identification can be best achieved by mixture of various methods including opinion of experienced seamen, especially those, who survived casualties.
The problem of hazards identification was discussed by the author (ref. [14]).
The main conclusion was, that majority of casualties happened with rather small ships under 60 m in length (83%). The other important conclusion is that in more than 40% of casualties shifting of cargo occurred. In about 48% of casualties to fishing vessels flooding occurred. Water on deck was in 6% of casualties, icing in 11%. Weather conditions obviously have important influence. The majority of casualties occurred during autumn-winter season and in rough sea (about 70% to 76%). Most casualties occurred in river estuaries and along the coast-line (67 to 79%). This is understandable, bearing in mind that casualties occurred mainly with small vessels.
It may be surprising that quite a large percentage of loss of stability accidents occurred in calm sea. Reference [15] states that 27% of casualties occurred in moderate weather conditions of which 6% happened in still weather.

7 Short term probability of capsizing

Probability of capsizing in the particular situation (short term probability) due to environmental effects is calculated as:

$$P_{Ck} = 1 - \exp(-\lambda t)$$

Although in principle the lifetime probability of capsizing could be calculated as shown in an example where assumed at choice values of probabilities were adopted [4] there are no known attempts to apply this as a stability criterion. When calculating short-term probability of capsizing it is possible to include,

except of environmental effects, also other factors mentioned above (shifting of cargo, icing, etc) that may cause capsizing (see [3]).

The failure rate (wrongly called commonly: risk function) λ in the formula for P_{Ck} could be, in principle, evaluated by three different methods:

1. statistical analysis of casualty records
2. systematic model tests
3. mathematical modelling

With regard to the first method it is obvious that collecting data on casualties suitable for probabilistic analysis would be extremely difficult, because not only precise stability characteristics of the ship capsized and environmental conditions at the time of casualty have to be known, but also data and time history of the ship operation (i.e. loading conditions) until casualty occurred are necessary. Statistical data on casualties collated by IMO [15] do not include necessary information particularly information regarding time history of ship operation. It is unrealistic to assume that such data will be available in future except, perhaps, in few isolated cases. There are very limited possibilities to perform probabilistic analysis on the basis of available data.

Model experiments provide extremely useful information on the behaviour of ships in a seaway, they also could be used to evaluate rate of capsizing in situations simulated in the tank or in open waters. But due to very high cost of such experiments conducting systematic model tests using a number of models in many simulated situations is totally unrealistic.

Estimation of risk function on the basis of mathematical simulation of ship's behaviour in a seaway is probably the most realistic. Development of the suitable mathematical models of ships rolling in a seaway, which ultimately should provide the possibility to calculate probability of exceeding certain limiting angles of heel considered as capsizing, attracted many scientists and literature of the subject is immense. The difficulty lies in the fact, that the phenomena are highly non-linear and therefore it is in general impossible to obtain closed solutions and it is necessary to apply time domain approaches.

In the most mathematical models only environmental effects are considered, mainly waves, sometimes wind is also considered in a simplified way as additional factor. The other factors that may cause capsizing, except of some attempts to include the effect of water on deck (see ref. [16] and [17]), are not taken into account. There is also the problem of assuming appropriate wave climates and the problem of how to model seaway.

The 23rd ITTC Specialist Committee on Prediction of Extreme Motions and Capsizing [18] reviewed at depth available mathematical models of capsizing and reached the conclusion that: "only a few of these models consistently agree qualitatively with all the extreme motions and modes of capsize identified in free running model experiments. None of the models does so quantitatively."

Apparently much more effort must be put in order to achieve results applicable in practice and in particular mathematical models of capsizing scenarios that include several factors except of the effect of seaway have to be developed.

8 The problem of wave climates

In the numerical simulation of capsizing scenarios it is necessary to assume wave climates. When calculating lifetime probability of capsizing using voyage simulation method, for each situation considered wave data could be taken from the Global Wave Statistics [19]. Using those data (consisting of significant wave height, modal period and direction of propagation for four seasons) short-term probability could be calculated by numerical simulation.
In numerical simulations most often the seaway is assumed consisting of irregular 2-D waves with the spectrum having one peak. As a rule deep water is assumed. It would also be necessary to consider existence of wave groups in the deep sea wave pattern that often cause capsizing. Moreover, in certain areas breaking and conical waves have to be considered that might be very dangerous especially for small vessels.
Data acquired from the Global Wave Statistics are not good enough for assessing ship survivability. Ships with unlimited range of operation must survive extreme weather conditions that might be met during their lifetime. For the purpose of assessing ship's survivability Buckley [20] derived climatic and extreme worldwide wave spectra, which were based on millions of measurements taken primarily by NOAA buoys or taken from other sources.
On the basis of the measurements taken, envelopes of modal period T_P versus significant wave height H_S were drawn. The survivability envelope corresponds to severe storm climatic conditions and it is recommended to use it in safety analysis, the lower one is operational envelope used for evaluation of the design seakeeping characteristics.
It has to be noted that extreme wave heights are much larger than significant heights. Taking for example from the survivability envelope H_S=14.0m with corresponding T_P =13.3s and using Longuet-Higgings formula the following extreme wave heights are obtained (Table 1)[19]:

Table 1: Probability of appearance of extreme wave heights

P_{ex} %	63	10	5	2.5	1
H_{ex} m	30.0	33.5	34.5	35.5	36.7

Interpretation of this table shows that during the 36 hours typhoon the ship will meet waves of 30.0m height with 63 % probability and waves of 36.7m height with 1% probability i.e. about 10 times in 36 hours.

9 Capsizing scenarios

The consequence of adopting of the concept of potentially dangerous situations is the necessity of analyzing of different capsizing scenarios.
As stated above, capsizing scenarios that could be used in hazards identification should take into account conclusions taken from statistics and records of casualties. The other sources of information are model tests of capsizing. Model

tests of capsizing are scarce. Some model tests were performed in open waters (lakes), see references [22,23], some others were performed in towing tanks [24,25].
Interesting conclusions could be drawn from observation of the model behavior in waves, unfortunately other factors, as for example shifting of cargo, wind effect etc can not be reproduced correctly. The other source of information are detailed descriptions of actual casualties, many of them are included in [26].
Some of the possible capsizing scenarios are listed in the Table 2. In the list only environmental effects are taking care of. To each of the scenarios in the list other factors, such as water on deck, shifting of cargo, icing free surfaces of fluids, openings not secured etc. have to be added depending of the type of ship and its cargo. The matrix of possible scenarios is obviously large.

Table 2: Some possible scenarios of capsizing

	Scenario
1	Pure loss of stability on wave crest
2	Broaching in quartering waves
3	Parametric resonance in following waves
4	Parametric resonance in head waves
5	Rolling in beam waves, resonance
6	Low freeboard vessel - rolling in beam waves and pseudostatic heel
7	Breaking waves and surf riding
8	Freak, rogue steep waves of extreme height

The real difficulty lies in assigning the probabilities to each scenario. Statistics is not very helpful in this case and opinions of experts might be more appropriate. One way to organize opinion of experts is Delfic procedure, where a number of experts are individually asked to complete questionnaires in which their replies are required to be substantiated. Then, during a series of iterations, the experts are repeatedly asked the same questions to establish whether they refine their answers in light of being provided (anonymously) with the replies and justifications of the other experts. The iteration continues until satisfactory degree of agreement is reached

10 Acceptability of safety criterion

Even if the probability of capsizing, either long term or short term in extreme seaway conditions could be assessed with sufficient accuracy, there are some problems with the possibility of accepting of the probability of capsizing as a standard. The basic problem is the estimation of the allowable level of probability of capsizing. This problem could be solved in the following ways [21]:

1. By comparing probability of capsizing calculated for the particular design with the probability of capsizing calculated with the same method for existing ships (method of disclosed preferences).
2. By investigating preferences of the public (method of expressed preferences).
3. By risk-benefits assessment.

The first method was applied by developing new safety requirements by IMO where the assumption was adopted that new requirements have to provide at least the same level of safety as the old ones. However, when attempt was made to apply probabilistic criteria to safety against capsizing, calculations of probability of capsizing calculated for number existing ships just meeting IMO criteria using the same method in each case revealed that probabilities differed by three orders.

The second method might lead to absurd results. The public behaviour is often irrational. Probably the most serious problems in accepting the probabilistic concept of safety result from the human nature. The realisation, for example, that safety is never absolute in the quantitative sense seems to disturb or even terrorise some people when the decisions on new enterprises have to be taken. Even if it has been proved that he probability of failure is much less as, for example, such an improbable event as striking by meteorite, the public might consider the undertaking as unsafe. From the other hand the public is not willing to resign from benefits which are related to higher risk.

The third method is most rational and is, in fact, recommended within FSA methodology.

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