CAPSIZING SCENARIOS AND HAZARD IDENTIFICATION

Lech Kobylinski, Professor
Polish Academy of Sciences and Foundation for Safety of Navigation and Environment Protection,
(Poland)

Abstract

Recently IMO recommended application of the Formal Safety Assessment (FSA) methodology to the development of safety rules. There are known already some attempts to apply this methodology, at least partially, to stability problems, however, in general, the application of FSA to stability faces serious difficulties. The FSA methodology includes identification of hazards and assessment of risk. Hazards could be identified on the basis of the analysis of casualty data and on the opinions of experts. For the purpose of assessment of probabilities involved various scenarios leading to ship capsizing or foundering have to be analyzed.

In the paper an attempt is made to identify hazards and the most probable capsizing scenarios. The majority of stability casualties occur in rough seas but almost always capsizing occurs as a sequence of events where factors other than waves and wind play important part. Probability of capsizing could be assessed using mathematical simulation. There are known numerous computer simulations of capsizing when only effect of rough seas is considered but even then the problem is far from providing reliable quantitative results. Formulation of mathematical models for complex scenarios is much more difficult. The possibilities of formulating mathematical models describing various capsizing modes are considered in the paper and the prospects of calculating risk of capsizing considering complex scenarios are discussed.

1. INTRODUCTION

Existing stability requirements are included in the IMO IS Code. The IS Code incorporated stability criteria and requirements which were developed for various types of ships up to 1993. Amendments to the Code were adopted in 1998, some others are in the pipeline. Because the criteria as in the IS Code were considered as not entirely satisfactory the idea of so-called “rational” criteria was advanced at IMO in early seventies. Not much has been achieved in this direction in spite of many contributions because of difficulties that prohibited its advancement [1]. Recently, however, this idea came back to life again and the IMO SLF Sub-Committee included in its work programme development of such criteria under heading “performance oriented criteria”. Presumably the criteria should be based on probabilistic approach and are geared to the new philosophy of safety that includes the application of Formal Safety Assessment (FSA) to the IMO rule making process [2].

2. FSA METHODOLOGY

FSA is a formalized methodology of the System Safety Assessment. FSA was considered by IMO as a methodology that should be applied in the future to the rule making process. Following the new philosophy of safety, IMO adopted in 1997 Guidelines for the application of FSA [2].

FSA 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.

Since the adoption of the recommendation on FSA few attempts to apply this methodology to safety against capsizing are known. Erickson et al [3] considered the case of shifting cargoes in holds. Alman et al [4] and McTaggart, de Kat [5] considered application of FSA methodology, at least partially, to stability of naval ships in a seaway.

Application of the FSA methodology includes risk assessment. Knowing that risk is equal to probability of an accident times its consequences, the crucial element of this methodology would be calculation of the probability of capsizing.

3. LONG AND SHORT-TERM PROBABILITY OF CAPSIZING

There are two possible options of the calculation of the probability of capsizing: long-term and short-term probability of capsizing.

Long-term probability of capsizing in principle has to be calculated for the whole lifetime operation cycle of the ship. During its lifetime, the ship may find itself in a number of different situations where each situation is characterised by heading and speed, loading condition, sea state and wind force and direction as well as other factors influencing stability.

If 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:

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

Where: P_{Ck} is probability of capsizing in the k-th situation, i.e. short-term probability of capsizing in this situation, C_k is probability of occurrence of this situation. It is assumed that in each of the mentioned situations stationary conditions exist.

This approach was for the first time proposed by the USRR [6] and later discussed in several papers presented to various international conferences (e.g. [7]) but actually was never included in the work programme of IMO.

Short-term probability of capsizing in a selected situation may be calculated by the formula:

$$P_{Ck} = 1 - \exp(-\lambda \cdot t_k) \tag{2}$$

where: t_k is the time during which the ship remains in this situation and ë is the so called risk function that is the probability of capsizing within the period (t, $t+dt$) on the condition that until then capsizing did not occur. ëis assumed constant in each situation.

When calculating the lifetime probability of capsizing (or non-capsizing) it is necessary to take into consideration a great number of possible situations and to calculate the short-term probability of capsizing in each of them. This may pose some problems. However, in reality in the great majority of situations the probability of capsizing is so low, that obviously there would be no need to take those situations into account. Because of that, the concept of calculation of probability of capsizing (loss of stability accident) in selected situations deemed to be dangerous was advanced (short-term probability of capsizing). This concept was discussed in several papers, e.g. by Boroday and Rakhmanin [8], Kobylinski [9], Takaishi [10], Cleary [11], Dorin et al [12] and formally proposed to IMO by Poland [13]. The crucial point in this concept is identification of hazards and capsizing scenarios.

4. HAZARDS IDENTIFICATION

4.1. General

Hazard is defined as a situation that can potentially result in loss of stability accident. There are numerous hazardous situations that may affect stability and consequently lead to loss of stability accident. They could be categorised according to various principles. For example, Krappinger and Hormann [14] divide all hazards into two groups: hazards, that at least in principle could be controlled and hazards that could not be controlled by the crew. In this paper it is proposed to classify all hazards into three categories:

1. Environmental hazards related to the action of wind and seaway.
2. Hazards related to heeling moments caused by shifting the position of the centre of gravity,
3. Hazards related to heeling moments created by external pulling forces,

The largest data bank on stability casualties was collected by IMO in the years 1963-85, where 166 loss of stability accidents were analyzed [15]. Also Aksyutin and Blyagoveschensky [16] in their book described more than 200 loss of stability accidents.

Hazards identification might be not a very difficult task, much more difficult is to attach probabilities to their occurrences and to assess whether or not they may appear simultaneously.

4.2. Environmental hazards

The most common hazards are environmental hazards, *i.e.* waves and wind. The quoted sources show that the majority of casualties occurred during autumn-winter season and in rough sea (about 70% to 76%). It might be surprising, however, that quite a large percentage of the loss of stability casualties occurred in calm sea. Reference [15] states that 27% of casualties occurred in moderate weather of which 6% happened in still weather. Obviously in those cases other than environmental hazards occur. When considering environmental hazards the important point is to make choice of wave height (significant) that the ship considered must survive, in other words, the probability of the loss of stability accident is sufficiently low. Hogben et al in Global Wave Statistics [17] provided data on wave heights in various parts of ocean and their frequency of occurrence. Data were based on visual observations that provide wave heights very close to significant wave heights. It is well known that wave heights distribution in a given seaway could be approximated by Rayleigh distribution and the formula for probability that wave height exceeds certain assumed wave height H_{W1} is:

$$P_{H_{W1}} = \exp\left\{-\frac{H_{W1}^2}{8m_0}\right\} \tag{3}$$

Table 1 shows the probabilities of occurrence of waves of height exceeding given height, calculated from the above formula, assuming that significant wave height H_S = 9.0m. It means, that about 4 times in 10 hours wave height may exceed 30 m. This has to be taken into account when performing computer simulation of capsizing. When calculating probability of capsizing it is necessary to

Table 1. Probabilities of exceeding 9.0m wave height

Wave height H_{W1} [m]	14	20	25	30
Probability of exceeding H_{W1}	0.29	0.085	0.021	0.0039

decide upon significant wave height (and period) encountered. If the long-term probability of capsizing is considered, all possible combinations of wave height, period and direction against ship's course taken from Global Wave Statistics [17] for the particular route have to be analyzed and their probabilities assessed. When short-term probability of capsizing is assessed, the most dangerous, but realistic, situations has to be analyzed. Ships with unlimited range of operation must survive extreme weather conditions encountered.

For the purpose of assessing ship's survivability Buckley [18,19,20] 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 the measurements taken, envelopes of modal period T_P versus significant wave H_S were drawn (Fig.1). 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.

4.3. Other hazards

Other than environmental hazards could be assessed from the analysis of the above mentioned sources. The main conclusion drawn from those sources is that majority of casualties happened with rather small ships under 60 m in length (83%). Reference [15] shows that 46% of all stability casualties happened to vessels 40 to 60-m in length

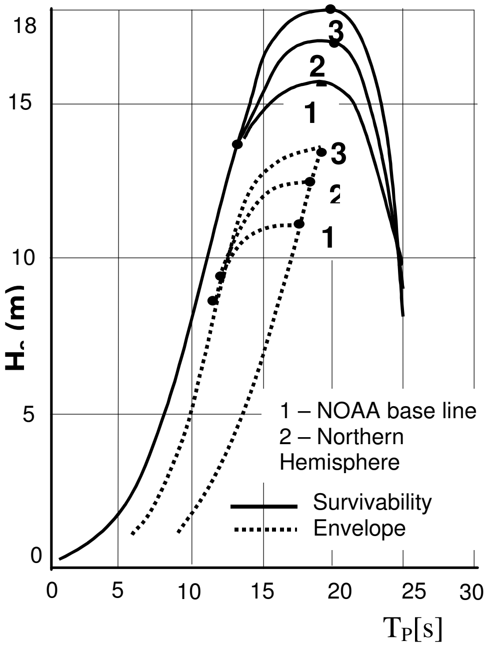

Fig.1 Survivability and operability envelopes (Buckley [20])

Hazards of the group 2 related to shifting of the position of the center of gravity may include

1. free surfaces of liquids
2. icing
3. water absorption of deck cargo
4. crowding of passengers on one side
5. loose goods
6. water in deck well
7. water inrush, openings not closed
8. suspended loads

Hazards of the group 3 related to external heeling forces may include:

1. forces created in turning
2. forces created by towing hawser
3. forces created by fishing gear
4. forces created by anchor cable
5. forces created at replenishment at sea
6. forces created when grounded

The above lists are not exhaustive and might be supplemented, particularly with regard to special types of ships.

From the other than environmental hazards the most important seems to be shifting of cargo. References [15,16] reveal that shifting of cargo occurred in about 40% of casualties. But other hazards are important as well.

Most of the mentioned hazards are taken care of in the existing stability rules, in all cases in the deterministic way apparently under assumption that every ship should withstand their maximal negative effect. However, in calculations of the long-term probability of capsizing, probability of occurrence of other hazards taking also into account weather hazards should be evaluated. It is assumed that obvious human failure does not occur.

Certainly no ship can be constructed that would not capsize because of faulty operation or negligence. But how to incorporate human factor into design is another problem. It seems that assumption that the master must exercise prudence and good seamanship as stated in the IS Code must be considered as covering this point but, in addition, operational measures have to be developed.

It seems that hazards posed by bad operation should not be taken into account in design criteria. Therefore apart of ships designed to carry loose goods, shifting of cargo caused by improper stowage and securing of cargo and also effect of opening not closed through which water may inrush inside the ship should not be taken into account in the design criteria.

The existing stability requirements take into consideration simultaneous action of some hazards. This is based on experience and not much could be added. Table 2 shows hazards that may be considered when evaluating stability of different types of ships.

The list is in no way comprehensive but may be used for identification of capsizing scenarios. In all cases weather (wind and waves) is taken as a prime hazard. Other hazards depend on the type of ship and they are taken as occurring simultaneously with the weather hazard. The crucial point may be evaluation of the probabilities of their occurrence.

In some cases other hazards should be combined with extreme weather conditions, in other cases – with moderate weather conditions. (for example fishing operation could not be performed in extreme weather, the same may apply to some other hazards)

Table 2. Hazards to stability

Ship's Type	**Weather**	**Other hazards**
Passenger	extreme	Free surfaces Icing (if applicable)
	moderate	Passengers crowding Turning Free surfaces Icing (if applicable)
Cargo	Extreme	Free surfaces Icing (if applicable) Loose goods (if appl) Deck cargo –water absorption Replenishment (if applicable)
Fishing vessels	Extreme	Free surfaces Icing Water in deck well
	Moderate	Free surfaces Fishing gear Suspended loads
Tugs	Moderate	Free surfaces Towing hawser Turning
Supply vessels	Extreme	Free surfaces Deck cargo-water absorption Icing Replenishment Suspended loads

5. CAPSIZING SCENARIOS

Capsizing or loss of stability accident never is the result of a single cause. Always there is a chain of events that results in the accident.

Procedure of identification of capsizing scenarios should take into account conclusions taken from statistics and from detailed descriptions of actual casualties (References {10,15,16,21]). Those sources provide excellent material that could be used for the intended purpose.

The other source of information is model tests of capsizing. Model tests of capsizing are scarce. Some model tests were performed in open waters (lakes), some others were performed in towing tanks. Reference [1] provides comprehensive description of model tests performed in various research institutions. 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.

One of the methods of creating capsizing scenarios is the fault tree method. The difficulty with applying this method lies in the multitude of scenarios possible. One example of application of this method was presented in reference [3] in respect of shifting cargo. Identification of possible scenarios of capsizing could be best achieved by a mixture of different methods which should include descriptions and statistics of casualties at sea, model experiments and opinions of experts – experienced seamen, especially those, who survived casualties.

Capsizing scenarios were considered by IMO at the time when the problem of so called "rational" criteria and dangerous situations for the ship was discussed [22]. The IMO SLF Subcommittee was then of the 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.

Situation where the ship is in head seas and the possibility of parametric resonance exists was not considered at that time and the attention to this situation was drawn in particular after the accident of a post-Panamax C11 ship was analyzed (France et al [21]).

In each of the above situations several scenarios of capsizing have to be analyzed taking also into account, apart from waves and wind action, also other factors contributing to capsizing. In general, a multitude of capsizing scenarios is possible. Cleary and Letourneau [23] listed 34 possible causes of capsizing, also de Kat, et al [24], Alman, et al [4] discussed scenarios of capsizing.

Table 3. Some simple capsizing scenarios

Scenario	
1	Following or quartering seas, pure loss of stability in wave crest,
2	Following seas, parametric resonance,
3	Quartering seas, broaching in, broadsize to waves,
4	Following or quartering seas, bow submergence, loss of stability
5	Head seas, parametric resonance,
6	Head seas, bow submergence, water on deck, loss of stability
7	Rolling in beam seas, resonance or parametric resonance,
8	Beam seas, group of large waves,
9	Beam seas, strong wind gust in conjunction with other factors (icing, loose goods}
10	Freak, abnormal steep waves of extreme height,
11	Breaking waves and surf riding,
12	Water in deck well, pseudostatic heel,
13	Wing gust, passenger crowding, turning

Some capsizing scenarios are listed in the Table 3. In the list that is not in any way exhaustive mainly environmental factors are included. Obviously some other factors have to be added depending of the type of ship and its cargo. The matrix of possible scenarios is obviously large. 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.

Capsizing scenario or according to former IMO terminology "dangerous situation" should satisfy certain conditions (Cleary [11]; Dorin et al.[12]; Kobylinski [7]; IMO [22]) as follows:

1. The situation should be a realistic one in the sense that the probability of the joint action of several factors endangering safety against capsizing is sufficiently high,
2. The results of action of the adopted combinations of external factors could be related to the sufficient number of ship characteristics (parameters defining hull form, architectural features, mass distribution etc.), and computation procedures for these situations should be manageable.

Few example capsizing scenarios revealed in model tests or taken from descriptions and records of real casualties are shown in the table 4.

Table 4. Some real capsizing scenarios

No	**Vessel**	**Scenario of capsizing**
1	Low freeboard fishing vessel {model tests)	Vessel rolling in beam waves, amount of water trapped in the deck well, freeing ports not capable to clear accumulated water, pseudostatic angle of heel developing, group of large waves capsizes the vessel to windward
2	Fishing vessel (real casualty)	Vessel rolling in heavy seas, reduced stability and static heel due to unsymmetrical icing and partially filled tanks. Strong wind gust suddenly capsizes the vessel to leeward
3	Passenger vessel, (real casualty)	During heavy storm, combined effect of strong wind gust and high waves, large rolling amplitude, water coming on deck, inrush through deck openings, flooding
4	Fishing vessel (real casualty)	In heavy storm vessel sailing in head seas started 'S" turn in order to get into parallel with other vessel, capsized when broadside to waves due to combined effect of waves, wind and rudder action
5	Cargo vessel – collier (real casualty)	Vessel sailing on the course 150^0 to waves, force 8, strong wind. Three very high waves – first inclined the vessel by 30^0, the second increased heel, the third capsized the vessel. Shifting of cargo occurred.

6. MATHEMATICAL SIMULATION OF CAPSIZING

The only practical method to assess the probability of capsizing, whether long-term or short-term, seems to be computer simulation of capsizing scenarios based on mathematical modelling. Currently a great amount of work has been done on this particular subject that was summarized by de Kat [25] and in reference [26].

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 references. [27] and [28]), are not taken into account.

Notwithstanding the great effort the problem of computer simulation is far from solving. Reference [18] states 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 apart of the effect of seaway have to be developed.

7. CONCLUSIONS

Performance oriented or "rational" intact stability criteria used instead of existing prescriptive criteria seems to be natural future development towards increasing safety against capsizing. However, notwithstanding important progress in this direction achieved during last years there still remain difficult problems to be solved.

It would be necessary to decide whether long-term or short-term probability of capsizing should be used as a criterion and what level of probability could be accepted. FSA methodology recommends risk-benefit assessment in this context, but this principle may not be easy to apply. It would be also necessary to further develop reliable mathematical models of complex capsizing scenarios. The other problem is to decide upon probabilistic criteria that might used in assessment if safety. This is a wide field for future research programmes.

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