The influence of ship’s stability on safety of navigation

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Abstract. Ship’s stability is one of the most important and complex concept about safety of ship and safety of navigation and it is governed by maritime law as well as maritime codes. The paper presents the importance of ship’s intact stability as part of the general concept of ship’s seaworthiness. There is always a correlation between ship’s stability and safety of ship and safety of navigation. Loss of ship’s stability is presented as a threat to safety of navigation. We are going to present the causes that lead to ship stability failure and their impact on safety of navigation. A study of various ship stability casualties in heavy weather conditions are going to be presented, the causes are going to be analyzed and the possible ways of stability failures are assessed. Vessel’s intact stability is a fundamental component of seaworthiness so it is in the interest of all owners/operators to learn about this topic and ensure that their vessel possesses a satisfactory level of stability in order to ensure its safety as well as that of the people on board the ship. Understanding ship's stability, trim, stress, and the basics of ship's construction is a key to keeping a ship seaworthy. The findings of this study can be beneficial to the maritime safety administrations to adopt decision-making on maritime safety management, but it is also important to carry out statistics and analysis of marine casualties to help to adopt proper safety management measures. Moreover, the study can be a useful guidance for masters and officers on board vessel in order to understand the factors that contribute to ship stability failure during the voyage not only in port during loading operations and to take preventive measures to avoid to put the ship in such a dangerous situations.

1. Introduction
Nowadays, loss of ship stability leads to an increasing number of accidents having unfortunately serious consequences such as damage of goods, loss of ships and lives. Ships design and construction also suffered a great deal of change when it comes to deadweight capacity and hydrodynamic forms due to the fact that the variety of cargo carried by ships increased, cargo which also needs to be rapidly delivered to consignees and therefore ships’ speed also needed to be improved. In the last decade, losing the stability of the ship created significant trouble especially due to the different ways in which such a situation happened. This is why attention needed to be paid to each one of this ways separately and also considering the context of rough seas. Therefore, the new ships were confronted with large amplitude rolling caused by parametric rolling, loss of stability broaching or surf-riding, all of these being considered significantly relevant for large container vessels. Even though from a theoretical point of view these dangers were very well known in the past, it was only recently that further attention was given to preventing and regulating such situations. Unfortunately an increasing number of ships were affected by such dangerous situations which led to loosing cargo and ships sometimes even affecting human lives.
Presently, specialized publications approach the subject of identifying the causes leading to loss of stability which actually affects safety of maritime transportation, the subject being also approached in some presentations debated upon on an international level. This is why authorities decided to regulate these situations by improving the requirements which could make a ship safer from this point of view.

1.1. Ship stability as part of seaworthiness

For a vessel to be considered seaworthy, she needs to have an intact stability therefore all parties involved in operating a ship should be well informed on this matter and provide the proper necessary conditions for the ship to have satisfactory level of stability making sure in this way that both the ship and those on board will be safe in all conditions. In order to maintain a ship in a seaworthiness condition all the time, basic technological knowledge is necessary on the following aspects: trim, stability, ship's construction and stress. We consider a ship to be seaworthy when it comes to stability if the following two conditions are fulfilled:

1. While at sea, the ship shall never be unstable when upright at the beginning or at the end of any given voyage. [3]
2. The worst conjunction of wind and waves that can possible be encountered during the given voyage shall not cause the ship to roll beyond the safe effective range of heel. [3]

Two of the most relevant reasons which endanger the initial stability of a ship are:

1. When under the action of wave and wind pressure, the ship is very easily heeled.[3]
2. When a certain course is maintained and is a great tendency for cargo to shift so that the angle of heel is continuously increasing and tends to become greater.[3]

The ship needs to have a sufficient margin of metacentric height for any loss of stability situation to have a solution as in maintaining the limit level of safety. Even so, practically before starting the voyage, many situations are identified in which the metacentric height is quite accurately known. Moreover, there are cases in which the metacentric height is more accurately determined, but still no reassurance may be given about the ship’s stability for the whole voyage.

During the voyage, the ship should be verified at all times, because sometimes it might be necessary to commence voyage with a higher metacentric height, in order to counteract conditions which arise at later stages.

The safe limit of ship’s intact stability depends mainly on two very important factors:

1. Nature of the carried cargo. Properties of cargo limit the safe effective range of the ship (such as angle of response in case of liquefaction and shifting of bulk cargoes).
2. Environmental factors.

Extreme weather conditions are the dominant environmental factors that can affect the intact stability of a ship. Some effects of such weather conditions are the rolling angle, water on deck and shifting of cargo which are actually effects of both wind and waves. This is why weather is considered one of the most determining factors influencing safety at sea. Ship’s behavior is also influenced by the forces of wind and sea which sometimes have a strong effect, but in spite of these effect a ship which is properly built with the necessary strengthening shall not be affected by ravages of the open sea. Even so, a problem which is not yet properly solved on the international level is the issue of rolling movement of the ship in rough seas.

Human factors should also be considered as one of the most important influencing factors for ship’s safety. Sometimes the master makes right decisions but unfortunately applying them leads to failure affecting the ship equally as an inappropriate design does. A seaworthy ship may be easily turned into an unseaworthy one by an improperly trained officer, while an unseaworthy ship to failures in design may not be turned into a safe one even if crew members are both properly trained and having the necessary experience.

Good seamanship in heavy weather is not something which one can learn just by reading books. It is, however, expected for someone who learns a lot from his/her own experience to also gain a little from the experience of others, and to be able to combine experience with knowledge acquired through
scientific study. This may prove useful in make the proper decisions when confronted with particular sea conditions needing to develop the adequate strategy.

Four basic elements are considered to be part of the ship’s stability system: ship, environment, cargo and operations. Analysis of accidents caused by loss of the ship stability results in the following causes which may be attributed to such accidents:

1. Functional aspects determined by stability characteristics,[3]
2. Operational aspects determined by the action of human elements handling the system (crew members, ship management, cargo handling, marine administration and owners company organizations),
3. External causes, such as environment, resulting from independent factors which beyond the control of designers, builders and operators.

The necessary level of safety may when it comes to ship’s stability may be reached only by considering all elements which contribute to the stability system. Nowadays safety regulations do not provide full guarantee concerning safety, especially for newly designed ships, and this is because part of the maritime accidents happen due to a faulty or bad design of the ship.

This is why it is considered to be almost impossible to design a perfect ship as in one which would not be affected by any dangers caused by bad weather or any other statistically probable dangerous situations. Therefore, the three main components mentioned above are able to reduce the probability of a disaster. Even so, another important aspect here is identifying the main causes which affect stability. Thus, the main methods used in order to identify the possible hazards affecting a ship are:

1. Analysis of loss of stability data casualties;
2. Statistical analysis of cause of casualties available in various sources;
3. Detailed description of ship stability casualties. [3]

2. Marine Accidents caused by failures in Ship stability, a serious threat to safety of navigation

Maritime transportation is considered to be the fundamental trading means of transport all over the world due to the overwhelming coverage of the earth by seas and oceans. Humanity’s needs from this point of view are covered by a huge number of vessels of various sizes and types, specialized on cargo and passenger trade. Billions of tons of raw materials and finished goods are carried on board ships, between ports, in the proper necessary conditions. In the age of electronic navigation and the satellite era, accidents continue to occur at sea. Safety for maritime transportation is increased by numerous technical measures, such as building safer ships, developing new and more efficient methods of transportation, training of human resources, increasing traffic surveillance and control, issuing new regulations, etc. Nevertheless, accident statistics show that these measures are not enough and sometimes unable to prevent shipping accidents.

Accidents with catastrophic consequences still happen. Any shipping accident, in spite of its nature, is every seafarer’s nightmare should it occur in a confined area, like a channel or a strait where the traffic is heavy. On the other hand, a serious shipping accident becomes even more critical if caused by shifting of cargo or flooding thus possibly affecting the ship’s stability if exacerbated by heavy weather. There are also accidents where the issue becomes environmental due to oil spillage. The causes leading to shipping accidents are many and complex. One of the primary reasons is building larger and larger ships providing an increased cargo capacity. Hence, when an accident occurs, the loss becomes higher. On the other hand, large ships are characterized by reduced manoeuvrability which is also an increased risk and contributing factor in such situations. In order to identify the characteristics of such accidents and to achieve an estimate of successful safety measures, a statistical study of shipping accidents represents an important and effective tool, which has been often used by governments and experts all over the world. This is an important factor for providing references for the maritime safety administrations, having to make reasonable safety decisions, and for seafarers, to be cautious. The different types of shipping accidents and their impact on safety of navigation differ from one another. Capsizing, listing, foundering, grounding and stranding, structural failure, machinery damage, fire or explosion, collision or contact, are the best examples.
2.1. General stability criteria
The IS Code 2008 presents the general stability criteria almost unchanged from A.167. These are shown in figure 1.

Integrated area below the lever arm curves has to reach the following minimum values:

1. The area under righting lever curve (GZ curve) shall not be less than 0.055 meter radians up to 30 degrees heeling angle

\[ \int_{0}^{30} GZ(\phi) \, d\phi \geq 0.055 \text{mRad} \] (1)

2. The area under righting lever curve (GZ curve) shall not be less than 0.090 meter radians up to 40 degrees heeling angle or the angle of down-flooding if this is less than 40 degrees

\[ \int_{0}^{40} GZ(\phi) \, d\phi \geq 0.090 \text{mRad} \] (2)

3. The area under the righting lever arm curve (GZ curve) between the heeling angles of 30 degrees and 40 degrees or between 30 degrees and the angle of down-flooding, if this is less than 40 degrees, shall not be less than 0.03 meter-radians

\[ \int_{30}^{40} GZ(\phi) \, d\phi \geq 0.030 \text{mRad} \] (3)

The righting lever GZ shall be at least 0.2 m at a heeling angle equal to or greater than 30°:

\[ GZ(\phi = 30^\circ) \geq 0.20 \text{m} \] (4)

The maximum righting lever shall occur at an angle of heel not less than 25°:

\[ \frac{dGZ}{d\phi}(\phi \geq 25^\circ) = 0 \] (5)

The initial metacentric height \( GM_0 \) shall not be less than 0.15 m:

\[ GM_0 \geq 0.15 \text{m} \] (6)
The Code is still based on the same assumptions, according to which the ship indicator of stability is the righting arm curve on calm water.

3. Failure modes of operational ships with intact stability

Transportation is the most important connection in economic relations. Both involved in creating products and delivering them to consumers, the concept of transportation provides the link between production and consumption, between different industries, countries and regions. It affects the development of economy as a consumer of petroleum products, grains, metal, timber, and many other products.

When it comes to external relations, maritime transportation is mainly used. This type of transportation carries more than 80% of the foreign trade goods and it is the cheapest means of transport because maritime exploitation requires lower network costs than other types of transport.

Modern ships can carry cargo of any size and weight. Most cargo carried by sea is liquid cargo – such as oil and petroleum products. These cargoes are considered to be bulk in their basic structure. Dry-cargo vessels have also an important share.

The structure of marine transportation is dominated by specialized vessels – tankers, bulk carriers, container vessels, timber carriers, reefers and dry cargo vessels. Most of these ships are designed according to the type of cargo which they need to carry.

Each type of cargo carried by sea has particular characteristics for loading, stowage, carriage and discharging. These proprieties of the cargo can influence the nautical qualities and seaworthiness of the ship. The ship’s intact stability is one of the nautical qualities, which is influenced, and in many cases affected by cargo proprieties. Inability of acknowledging the proprieties of cargo to be loaded, in many cases, leads to dangerous situations, even capsizing.
Safe carriage of cargo is not just a matter of safe stowage and securing of cargo, but it is also strongly related to the design and construction of the ship, her hull, as well as the way in which the ship is being operated at sea in different environmental conditions.

Minimum stability requirements imposed by authorities do not show clearly on which operational conditions they have been based and do not include any possible risks. They are still seen as guidelines for ship operators. Further information on the actual ship behaviour to be expected in extreme conditions as well as actions for prevention and survival under these conditions are necessary to be provided to the ship’s Master.

As cargo loaded on board ship represents the most of the tonnage of the ship, its feedback to ship behaviour is of paramount importance. In relation to ship stability, some of the main concerns are safety from capsizing and low motion accelerations on the cargo. Seakeeping theory and the results of modern ship motions should be transferred aboard the ship to the operator in a comprehensive way. Information provided on board vessel must include not only measures related to cargo stowage and securing, but also operational measures to reduce ship motions. Maybe naval architects should reconsider the designing of ships which have proper motion behaviour. Furthermore, the ship’s design should account more for a feedback from the practical experience of the ship operator.

Operational stability represents the picture of actual ship stability during the voyage. This kind of stability varies in time due to changes of two important factors: environmental conditions at sea and cargo and/or ballast on board the ship.

In order to prevent the ship from capsizing, the actual stability status is compared with the minimum stability requirements. This is the so called “regulatory” stability, while the operational stability is influencing the ship’s motions and the resulting loads that act on cargo. Therefore, the operational stability of a ship and the minimum stability requirements are very clearly distinguished. Ship’s operational stability is often seen as a guideline for ship Masters. Thus, the Master is alone in making such difficult decisions, although he regularly makes decisions for daily operations, which are very often at the limit of safety.

In order to allow the ship to sail, those minimum stability requirements represent the minimum set of standards, but they cannot include all possible risks from any extreme and severe event. Hence, if the minimum levels are set too high, in order to cope with extreme events, transportation may feel drawbacks such as reduced economy, worse ship behaviour at sea, cargo experiences unnecessarily higher motion accelerations, which require more securing and lashing.

On the other side, if the minimum stability levels are set too low, this may be wrongly understood by operators and the ship may not be able to resist severe environmental conditions.

4. Types of ships stability failure in severe sea conditions

4.1. Pure loss of stability in waves

First type of ship stability failure due to physical phenomena is related to the variation of restoring lever in waves; the restoring moment becomes larger on the wave trough and smaller on the wave crest, thus, the result is the occurrence of very large rolling angles in particular situations. The reason is the change of ship’s stability while the wave is passing by. It is mainly the result of the changing underwater hull geometry.

This phenomenon is illustrated in figure 2, where the wave is almost equal with the ship’s length. The forces of hydrostatical nature, however, do not limit physical factors affecting stability such as changes in waves; pressure in waves being distributed differently as opposed to calm water.
Figure 2. Ship hit by a wave with $\lambda \approx L_{pp}$ . The figure illustrates the wave crest (green) and wave trough (blue).

Changes of stability in waves involve two physical mechanisms of stability failure, pure loss of stability and parametric resonance. As the water plane shape is mainly influenced by the reflected waves, the calculation of the change in stability presents certain challenges, especially at high speed. Although this phenomenon has been known for more than forty years, it became a serious problem once the first ships, with large aft body and V-shaped fore body correlated with large flare, were introduced.

Pure loss of stability in waves could happen if a vessel encounters a single large wave and spends a considerable amount of time on the wave crest. If a large deterioration of stability occurs on the wave crest, the vessel may develop a very large heeling angle or she may even capsize.

4.2. Parametric rolling
Another physical mechanism representative for stability failure and caused by restoring lever variation in waves is parametric roll resonance. Parametric rolling behaviour may lead to sudden increase in large roll amplitude angles experienced by the ship typically in longitudinal waves, caused by parametric roll resonance (the encounter frequency of waves of length similar or larger than the ships length is comparable to twice the ship’s natural rolling frequency).

Model tests and full-scale observations have shown that parametric rolling can also occur at slightly oblique headings, and the physical phenomenon is based on successive alterations of the restoring lever between crests and troughs, exhibited by many ships in steep longitudinal waves.

When a ship is sailing through waves, the submerged part of the hull changes. These changes may become especially significant if the length of the wave is comparable to the length of the ship.

New design trends revealed a wide bow section at the upper part as a result of large bow flare. This aspect was taken into considerations from two points of view: the possibility of increasing the deck stowage area in that section and protection against sea water on deck. From the stability point of view, this aspect results in increasing the water plane area as the bow submerges.

For modern container ships, the upper part of the aft section of the hull is considerably increased and this is due to increasing the stowage area. In this respect, when the upper aft part is lowered on the wave trough, the water plane in that section is increased.

4.3. Dead ship condition
The third type of ship stability failure by physical phenomena is ship’s stability under dead ship condition as defined by SOLAS regulation II-1/3-8.

As stated by the Classification Societies, such as American Bureau of Shipping or Det Norske Veritas, dead ship condition is the scenario when the entire machinery installation, including the power supply, is out of operation and the auxiliary services for bringing the main propulsion into operation and for restoration of the main power supply are not available.
The beam seas considerations (currently used in the weather criterion) came from the steam propulsion era, when most vessels had the superstructure in the middle and the upper and underwater body configuration were more or less symmetrical relative to amidships section. For such a vessel, in case of power loss in storm, aerodynamic wind moment and wave drifting moment will turn it into beam seas, so it subjected seas to the action of gusty wind and severe waves. In this respect, ships built in the last decades are characterized by new and various design configurations, which is why the beam sea assumption is not universally applicable.

As a result, dead ship conditions are considered to be more complex than just beam seas being necessary to estimate drifting attitude of ships without power by solving an equilibrium equation of a surge-sway-roll-yaw motion.

IMO considered that the dead ship condition scenario is one of the most important scenarios for stability loss at sea. It is assumed to be dangerous especially for ships with large lateral areas of the ship which are above waterline, e.g. with big superstructures like Ro-Pax ships, or high stacks of cargo over waterline, e.g. loaded container ships.

4.4. Broaching

Another phenomenon of growing importance is when large heeling angles are developed at sea. Broaching can appear as heeling during an uncontrollable, tight turn during which the stability failure may be “partial” or “total”. Broaching is a violent uncontrollable turn of a vessel, occurring despite maximum steering effort in the opposite direction, which leads to violent yaw motions resulting in a rapid change of ship’s course, when the waves approach the ship from astern or from stern quartering directions. During this high turn, very high centrifugal forces are produced, a very large heeling angle may be developed and this may eventually lead to capsizing or partial stability failure. In other words, broaching is a phenomenon, in which a ship cannot maintain a constant course despite the maximum steering effort of her helmsman. As a result, the loss of keeping the ship’s course is considered, among others, as one of the elements defining the broaching phenomenon.

Broaching is an unintentional change in the horizontal-plane kinematics of a ship and it may be described as the “loss of heading” by an actively steered ship that is accompanied by an uncontrollable build-up of large deviation from the desired course. [3]

The situation of broaching occurs mainly in waves which come from behind towards a 180 degrees direction angle with the longitudinal axis of the ship.

Steering control can be lost if a wave crest is very slow passing the stern and, consequently, the rudder is in reduced flow conditions for a while. The ship starts veering off course during a prolonged period of poor rudder control, yaw increase and increasing wave angle to the stern. The hydrodynamic force increases with the rate of yaw so, as the ship comes abeam onto the sea, the combined heeling moments and the wind may be sufficient to capsize the vessel.

4.5. Surf-riding

Surf-riding is another sea phenomenon often associated with broaching and described as the “catching and dragging” of ship by a wave approaching from stern which accelerates her to the wave celerity. Physically, surf-riding is caused by the equilibrium created by the longitudinal wave force, thrust and resistance.

During surf-riding, the vessel sails with speed equal to the wave celerity and she stays longer in the crest region of the wave. In order for surf-riding to occur, the wave length must be comparable with ship length and the wave celerity must be comparable with the ship speed. This is the reason why large ships cannot surf-ride, as waves of the necessary lengths are simply too fast compared to the ship’s speed. [3]
5. Conclusions
This article presents studies and analyses which reveal that ship's stability is one of the most important nautical qualities having a huge impact on ship’s safety and safety of navigation. A vessel in an unstable condition cannot be considered seaworthy in all respects at all times. Losing stability plays an important part in maritime incidents having a huge impact and being a serious threat for safety of navigation. Thus, the connection between intact ship stability and safety of navigation is obvious.

Any loss of intact stability, due to one of the causes presented in this article, will lead to a dangerous situation that will directly affect the safety of navigation. This article also reveals that continuous learning and training as well as the experience of deck officers are very important for avoiding dangerous situations to which the crew, vessel and cargo could be subjected.

Human factor remains a decisive factor for assessing safety, in spite of the automation development on board ships. Incidents presented above show that human factor is one of the most important elements in the ship’s safety system. The loss of control over a ship, not only in a critical situation, is considered to be one of the main causes of maritime accidents. With a growing awareness of safety issues, public tolerance of accidents in shipping has decreased. So nowadays, maritime incidents are still present despite all of the improvements and advanced technologies, sometimes reaching even a higher rate.

Discussing the human error actually means to consider elements such as a lack of adequate knowledge and experience, technical inability, not paying proper attention to procedures and rules, carelessness in commanding a ship but also misinterpretation of information provided by documentation or computer software.

Presently, in order to avoid dynamic instability of ships, which is actually generated by parametric rolling or pure loss of stability, prevention measures are used such as a simple alteration of ship’s course and speed based on how the ship is reacting to external forces. Guiding information, which might be useful to the master when encountering severe sea conditions, is very little. Moreover, information and guidance for assessing ship’s stability in severe sea conditions is almost absent. Ship designs change very rapidly due to market demands, therefore, neglecting the (dynamical) physical characteristics of modern vessels, the current intact stability criteria are easy to handle.

Geometries of novel ship designs have become considerably different from conventional forms. These differences in geometry may actually create a dynamic behaviour that is drastically different from previous experiences.

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