

SELF-RIGHTING BOAT DESIGN

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ABSTRACT

The stability behavior of small craft is of great importance at very high angles of heel, up to the completely inverted condition. The fundamentals of stability in the design of yachts and other small craft is considered, and the significance of our current understanding is reviewed based on static stability analysis.

There are three main self-righting methods examined in this study. These are; inherent self-righting method, inflatable bag method and moveable ballast method. All of them have their advantages and disadvantages. Inflatable bag is easy to apply and maintenance, but there are very small area of applicability and does not ensure safety of the crew. Moveable ballast method practically applicable only for small craft and maintenance of mechanical components is hard. On the other hand, it can be designed to be self-operating system and fitted to small open boats where buoyant superstructure is not a feasible option. Although designing inherently self-righting craft is challenging due to the difficulty of weight distribution's uncertainty during the design process, it is the best option for any self-righting vessel.

Keywords: Self-Righting methods, Self-Righting stability, Capsizing.

1. Introduction

Regardless of the type of floating structure that is being designed, one of the designer's main tasks is to ensure the safety and seaworthiness of the structure, a prime consideration being the safety against capsizing. Despite recent advances in ship hydrodynamics, the possibility with a good measure of confidence, and in fact relatively little attention has been paid to the mechanism of capsizing.

The solution of the ship capsizing problem is one of the major challenges that scientist and naval architects have to meet. The problem is as old as shipbuilding itself. It concerns ship operators and designers and has preoccupied researchers' attention for many years. Capsize disasters are so painful, not only because of material losses, but primarily because they take human lives.

It is not strange, therefore, that the matter is raised and discussed so frequently. It is amazing, however, how little progress is being made despite the considerable amount of research that has been carried out in this field worldwide.

At present, there is no scientifically based stability safety criterion, and there is no mathematical model of ship capsizing in the general case of operation in extreme waves.

Two predominant approaches to the ship capsizing problem can be observed at present. One of them is based on the classical assessment of stability safety by analysis of the righting moment

curve in comparison with external, usually stipulated, heeling moments. The major efforts are focused either on establishing requirements for the shape and values of the GZ curve (calculated in calm water or on a wave crest) so that a required safety level can be maintained during ship operations in unspecified sea conditions, or on establishing the nominal heeling moments which the ship has to withstand (statically or dynamically or both) [1].

The required safety standards are usually a result of a detailed stability analysis of a particular type of ship or some statistical studies of safe ships and casualties, and reflect so-called “good marine practice.” They may provide a reasonable safety level for some classes of ships or some operational situations but in other cases they are not satisfactory or fail completely.

The second trend represents efforts to base the stability criteria on more sound theoretical models. However, the studies are focused on some selected simplified cases which are related to ship behavior either in beam or following seas. Although the selected situations are realistic, they do not represent the most severe scenarios of ship operation in oblique extreme seas, and none of the proposed approaches is general enough to represent the whole range of phenomena affecting ship stability.

2. Design And Stability Objectives

Many competing requirements of the design of small craft such as minimum resistance and windage, adequate power from engine and sails, sufficient strength and structural redundancy, low weight, maximum comfort below and protection on deck, good aesthetics, and reasonable costs, are all objectives that the designer has to balance in order to achieve a compromise solution. Adequate stability is also a requirement of every boat design.

Ships are designed on the basis that capsizing must be prevented, and its occurrence is considered a catastrophe that will inevitably lead to the loss of the vessel, and in all probability the loss of life. This approach cannot be taken with small craft. On many occasions the energy available in the environment in which the craft is operating is overwhelmingly greater than the work required to capsize the vessel, and so the designers of small craft have to countenance this possibility and design accordingly [2].

2.1 Ship Stability Basis

An understanding of the fundamentals of stability was established by Bouguer in 1746, and independently by Euler in 1749 [3], since when research has continued around the world into many complex and subtle developments of stability theory [4]. However it is only in the small craft world that stability at all angles of heel, including 180 degrees, is of crucial concern. Since 1980, and as a result of actual or near disasters, there has been much research undertaken into the stability of yachts and small craft at all angles of heel. The availability of economical stability modelling programs for PCs since the mid 1980s has greatly facilitated the exploration of high angle stability, both in a research and design context, so that now the behaviour of vessels in the inverted state is widely understood [2].

Ships are designed for stability when the vessel is operating normally and upright, but also to design for instability in the crisis situation where the vessel is inverted and we want it to rapidly

capsize back to the upright condition again. It is also intended that this exploration of the idea will enhance the understanding of the impact of stability considerations on the design of all small craft, and enable stability to be considered at the earliest stages of the design process.

The International Maritime Organisation (IMO) has set out criteria [5] which have been implemented in national legislation in most countries, but for small craft there are often other bodies (such as the MSA and RYA in the UK) that have developed more relevant standards and codes. The stability behaviour of a vessel at sea is highly complex, and the static stability diagram which plots the righting lever (GZ) against heel angle, can not model such phenomenon as surfing, broaching, and parametric rolling. However it does capture many of the key stability characteristics of a vessel, and can be used as a remarkably powerful analysis tool.

In a design for stability exercise any of these criteria could be used as objectives, in which case the design task would be to achieve a static stability curve that had certain attributes, defined in terms of minimum values for the following: the initial stability (GM), the range of stability, the reserve stability (proportional to the area under the curve), and for the value and heel angle of GZmax (Figure 1).

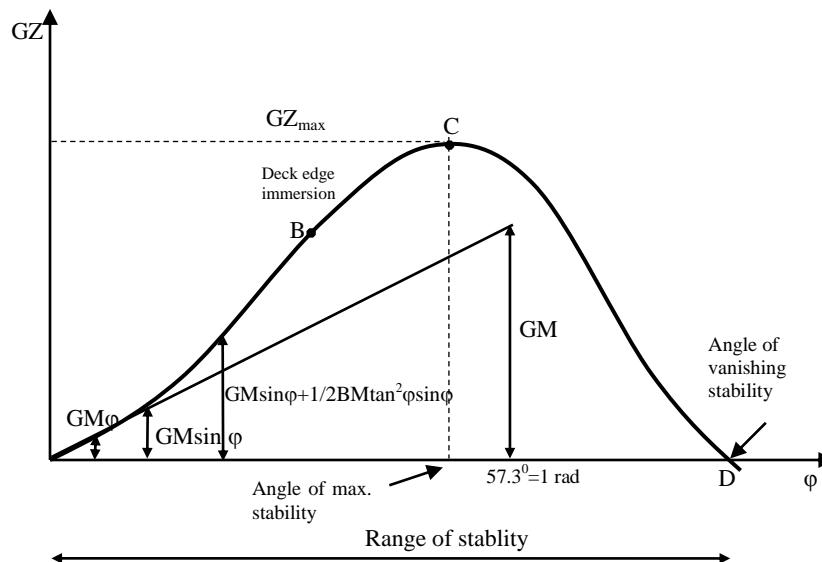


Figure 1. Statical stability curve

However, capsize is still considered to be an event to be avoided and that there is no guidance as to the relevant criteria for the stability of the vessel in the inverted state, once capsize has occurred. For a craft to be automatically self righting there must be positive stability at all angles of heel. If this is the objective then the criteria for the inverted state (heel angles greater than 90 degrees) should be that GZ must be greater than zero. However if assumptions are made as to the stability challenges the inverted craft will be subjected to (waves, wind, human intervention), then we could propose other limiting values for this condition also, such as maximum value and angle of occurrence of the negative GZmax and maximum value of reserve stability in the inverted state[2].

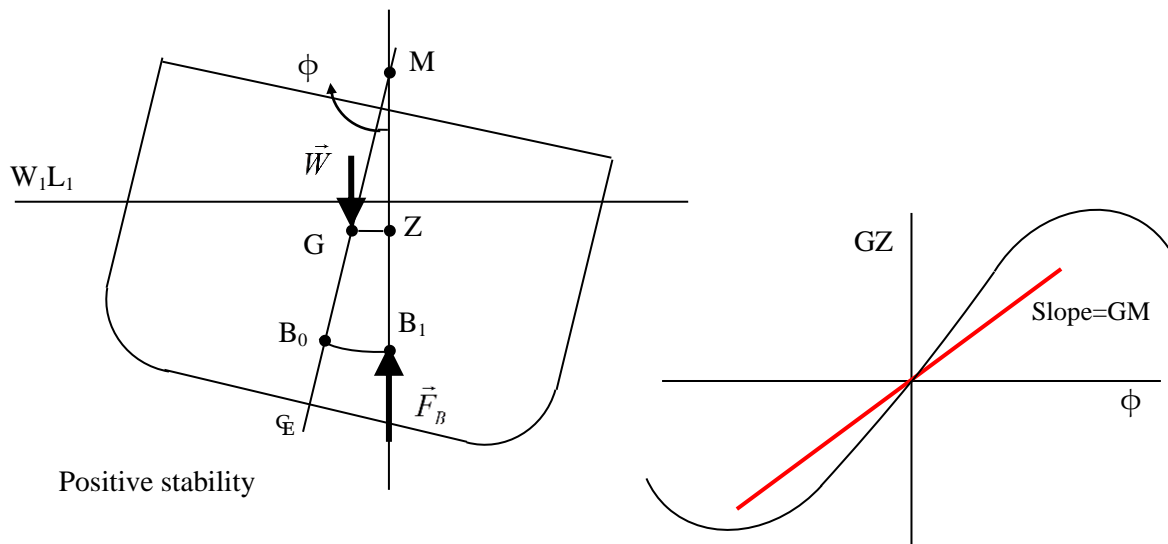
The criteria give us minimum values from the perspective for safety. In a design for stability process, high values of GZ at small angles of heel result in an excessively stiff vessel with sharp

motions, and high values at very large angles of heel (above 90 degrees) result in a violent righting action. The combined requirements of safety and comfort suggest that it should be possible to define an ideal GZ curve, or more realistically an acceptable stability envelope, with minimum values defined by the safety criteria, and maximum values by reference to acceptable motions. It can be proposed the probable form of a stability envelope intended to be used as a design objective [2]. If the objective of a design for stability exercise is to create a vessel that has a GZ curve that lies within a defined envelope, then we have to be able to directly control the shape of the curve. Analysis of the stability of a vessel based on the righting lever arm over the entire range of angles of heel, the GZ curve, has its limits. Despite the limitations of parametric rolling, surf riding, broaching, effects of heave accelerations on the righting moment and the impact of a wave waterline on the behavior of the vessel, it is a valuable model of many aspects of the behavior of a vessel and the sufficiency of the stability of all types of craft.

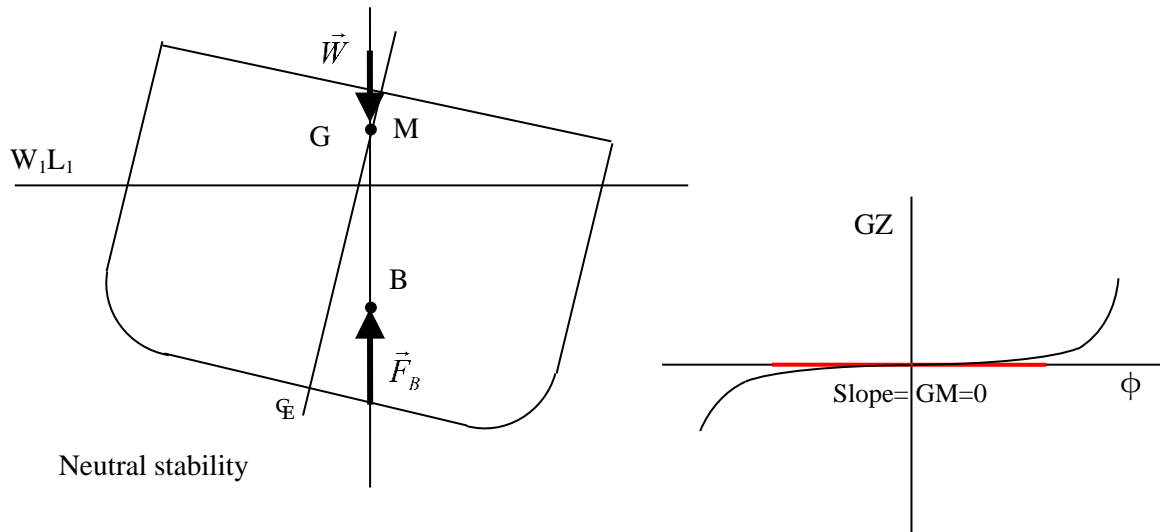
Reserve stability can be evaluated through a curve of righting arms, also called stability curve, which plots the righting arm GZ, against heel angle. As long as GZ is positive, the boat will self-right. At the angle the GZ turns negative, the boat will capsize. This shows immediately as the range of stability. The curve also shows other important things. The area under the positive portion of the righting arm curve represents the energy required to capsize the boat. The more energy required, the stronger the wind gust and the more sustained it must be to create a capsize. Alternately, the bigger and faster moving the wave must be to capsize the boat. Similarly, the area under the negative side of the curve represents the energy required to re-right a boat once it's been capsized.

In this case, there are three different ship conditions in the following:

a) A ship with positive GM: In this condition, the center of gravity is below the metacenter point so that a righting arm will begin to develop as soon as the ship heels over.



b) A ship with zero GM: In this condition, the center of gravity coincides with the ship metacenter point, in other words, there is zero distance between two points. That is, there is no internal couple created to return the ship to upright position.



c) A ship with negative GM: In this condition, the center of gravity is above its metacenter point. The slope of the righting arm curve is negative at zero degree heel.

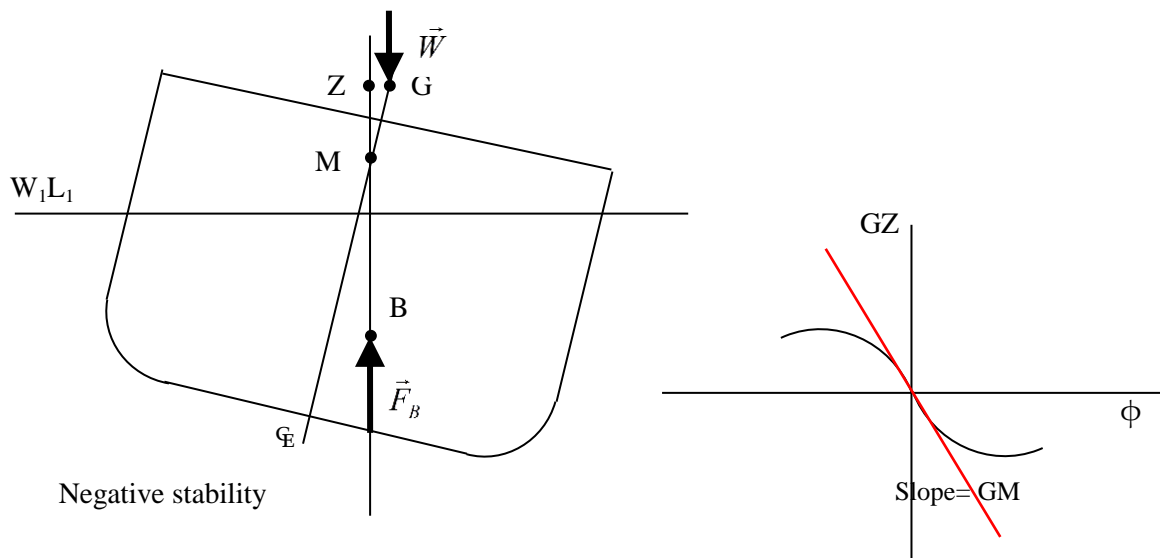


Figure 2. Ship's Stability Conditions

2.2 Self – Righting Stability

Self-righting stability is an old term in naval architecture history but, it is relatively new practical concept. On any self-righting vessel, GZ curve does no turns negative throughout 360° of roll cycle.

All traditional boats have a heel angle which righting levers have degraded to zero. This term is defined as Point of Vanishing Stability. Frequently, this point does not occur until ship is completely inverted, but for those have enough buoyancy to stay afloat, any heel angle beyond

Point of Vanishing Stability will result in rotation until equilibrium is maintained. With this attitude ship can be more stable when upright.

In order to achieve a self-righting design, the vessel must fill three fundamental requirements [6]:

- Possess a curve of righting levers for which there is no Point of Vanishing Stability which possible with positive GZ curve throughout the full 360 degrees' rotation.
- Become unstable when inverted to initiate the righting process until vessel become upright position.
- Remain buoyant and watertight.

3. Self-Righting Methods

To provide the criteria mentioned above, self-righting craft usually own a non-flooding hull and sufficient buoyancy suitably placed to ensure that the vessel is unstable when inverted. In case of large vessels size of superstructure generally produce adequate buoyancy, with all hull and opening being non-flooding or self-closed to keep watertight integrity. Such vessels have inherently self-righting the capability is in the design. For small boats, lacks of space for large superstructure usually prevent inherited self-righting ability. In order to achieve self-righting use of inflatable bag can be used. Inflatable bag can be either triggered automatically or manually by crew when vessel is capsized. Third method is the moveable weight method called commonly water ballast. Moving weight causes an instability when ship is capsized resulting a positive righting moment.

Neither inflatable bag nor moving weight prevents capsizing. This methods used after passing the point of vanishing stability to ensure instability until ship is come to its upright position. After that normal form and stability criteria comes into play.

One essential of any self-righting vessel is the relationship between weight and buoyancy to obtain required stability curve. One achieved this curve in rolling process; nothing should disturb it and impaired the recovery process. Meaning that, crew, passengers, and equipment should not move and change the ship's center of gravity. Thus, securing the crew and passengers is also an important criterion for self-righting vessel design.

3.1 Inherent Self-Righting

Boats utilizing this method have their self-righting ability where it is always available and will return upright from any angle of heel regardless of crew's additional action.



Figure 3. Examples of Inherently self-righting boats.

Vital quality of this craft is heaving a watertight hull and mainly watertight superstructure. Strategically located weight and buoyancy distribution is key to achieving inherent self-righting. Ship's main machinery system usually located at aft deck. Thus, in case of capsizing; trimming due to the weight and buoyancy difference must avoid. An extra lift force is required to avoid negative stability curve when the vessel immersed at the aft deck (Fig. 3).

Benefits of inherent self-righting include [6]:

- No working parts that could go wrong
- Self-righting capability is always available and at any angle of heel, so can prevent full capsizes of the vessel.
- Can, within reason, be applied to any size vessel, although weight limitations on very small can limit effectiveness.

Disadvantages of the method include [6]:

- Superstructure volume must be adequate to provide the necessary inverted buoyancy, which often results in the seemingly oversize deckhouse fitted to modern rescue boats.
- All hull and superstructure opening must self-close or remain above the waterline during full 360 degrees roll.
- Structure of hull and superstructure, including any deck recesses, must be designed to withstand hydrodynamic forces resulting from capsize.
- Window and doors must be capable of withstanding the same pressures as hull and superstructure.
- A good effective mechanical ventilation system will be necessary as the vessel will effectively be operating closed down with all doors and windows shut.

3.2 Inflatable Bag

Smaller crafts are generally more viable utilizing inflatable bag method. Rigid inflatable rescue boats (RIBs) are usually featured this method (Fig. 3). It takes the form of an inflatable bag, carried on and securely attached to, a substantial gantry frame located across the stern, straddling the engines or propulsion units. The bags are commonly made from neoprene or

hypalon coated fabric, similar to that used in manufacture of inflatable boats and are inflated using compressed gas injected under pressure. The gas canister is usually fired manually from the inverted vessel and has attached them to a tether line running from the stern. This keeps crew in contact with the boat before, during and after righting. To fire the bag automatically with personnel still underneath could result in injury and, in strong winds, the upright vessel being blown away from the crew before they can re-board. Automatically activated inflatable bags are occasionally fitted on vessels where the wheelhouse volume provides insufficient buoyancy to effect satisfactory and reliable self-righting.

Benefits of the inflatable bag method include [6]:

- Simple and light weight.
- Volume can be adjusted by changing the size of airbag.
- Easy maintenance as bag can be removed and replaced with a substitute.
- Disadvantages of the inflatable bag include [6]:
- Bag must be fitted and folded correctly to achieve reliability.
- Roll bar structure and bag attachment must be substantial to resist the forces present during the righting process, particularly at 90 degrees heel.
- Provides a once only righting ability. Some boats are fitted with duplicate gas cylinders for 100% system redundancies and to provide a second inflation, should this be necessary, but the bag is not repacked between firings.
- Bag liable to damage if inflated in shallow water or close to a casualty.
- Gas pipework and bag injection point must be correctly designed to avoid freezing.



Figure 4. Inflatable self-righting bag on a rescue boat.

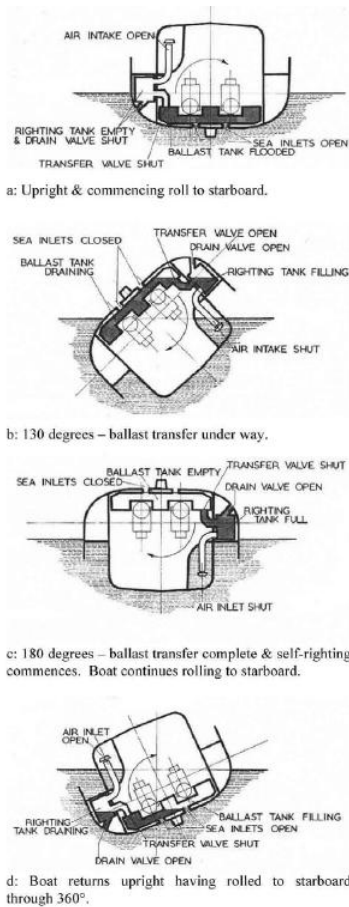


Figure 5. Oakley 37 self-righting sequence capsizes.

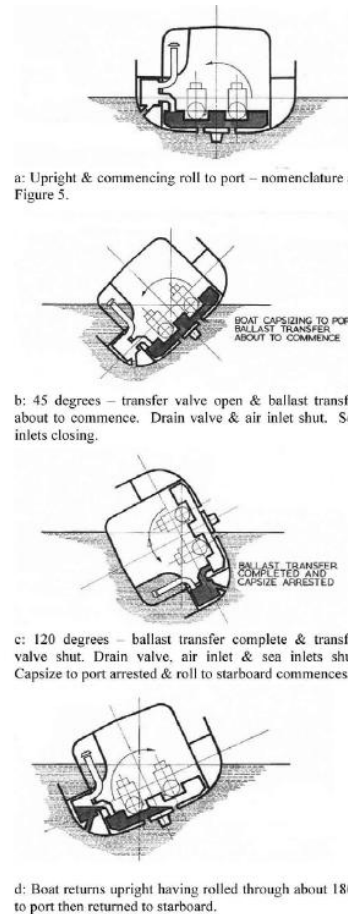


Figure 6. Oakley 37 self-righting sequence capsizes to port. Boat rolls to approx. 180 degrees and returns.

3.3 Moveable Ballast

Although moveable ballast method largely superseded by inherent buoyancy method, it can still be applicable to small crafts which large capacity of buoyancy above waterline may not be achievable. In this method, low volumes of seawater located in the lower ballast tanks, which relocate during capsizes. Relocation of this amount of weight creates enough moment to continue roll movement even after reaches the point of vanishing stability. Required moving ballast is most likely 10% of the ship's lightship weight. Thus, this method is mainly used for displacement ships where additional weight is no harmful to ship's performance. The best example of this method could be seen in RNLi Oakley 37 ft. and 48 ft. 6in lifeboats, produced during the 1950s and 1960s. Both of the boats traditionally manufactured to their time with built in wood with a double ended hull form having a low superstructure and an iron ballast keel [6].

Benefits of the ballast transfer method include:

- Can be fitted to small open boats where buoyant superstructure is not a feasible option.
- Ballast is plentiful and readily available.
- Can be designed to be self-operating.

- Ballast can be used to enhance upright stability.
- Disadvantages of ballast transfer method include:
- High number of mechanical components such as self-operating valves requires maintenance to ensure 100% reliability.
- Quantity of ballast water might restrict application and size of vessel.
- Not viable for planning craft where the additional weight would limit performance. Planning craft also have the difficulty of keeping water ballast in the tank whilst under way.
- Vessel structure must be designed to withstand continuous immersion in seawater. The RNLI Oakley 37 was always kept ashore as incompatible materials used in the ballast tank construction quickly corroded if left afloat(Figs. 4-5).
- System can result in vessel being recovered in one direction irrespective of capsizing.

4. Self – Righting Testing Methods

Determining the buoyancy locations are vital on any self-righting vessel design. For methods like inflatable and moveable ballast, there may not much choice. However, when designing an inherently self-righting craft, hull form, superstructure geometry and distribution of weight play utmost importance. Since, stability data comes late in design process in traditional ship design, naval architect should pay attention to buoyancy locations.

In today's technology, computer programs help to realize any mistake made in early design process but in order to avoid repetitive calculations, stability data should be produced carefully.

There are several ways to analysis design's self-righting ability. Mainly, they could be grouped as, computer modelling and analysis, model testing.

4.1 Model Testing

Model testing is the most powerful investigation method of any self-righting craft. It is mainly categorized as static model testing and dynamic model testing.

In static model testing, small models are used to investigate the self-righting behavior of design. Different loading situations are examined to check calculated data. In order to create these situations ballast water and loading cells are used.

In this process, static model must prepare very carefully. Hull form and superstructure geometry should meet to required scaling effects. Model needs to be completely watertight and possess all external features of original design.

In example of search and rescue boats where, self-righting is mostly used, survivors that taken onboard on rough sea conditions change the center of gravity of vessels. This kind of weight changes may not be modelled even on the most powerful engineering software. In this type of situations static model testing is the best reliable method of all self-righting methods.

Simulation of capsizing is recorded via video. So, after static model testing completed designers could watch the video on slow motion and determine the real ship's behavior under those

conditions. Differences need to be taken into account, because real life sea conditions could not properly modelled. It is basically up to the designer's skills.

For vessels that operating in rough sea conditions such as search and rescue boats, prediction of characteristic behavior of the vessel is crucial. Cost of prototype is considerably high for rescue vessels, so before executing prototype it is essential to see how ship will handle severe sea conditions. Dynamic model testing is the method for estimating that behavior.

Traditional towing tank experiments are very similar to dynamic model testing method. In towing tank test, non-powered hull is pull in the water. Even so, it is a good way to examine bow wetness, model does not expose to any other wave headings.

Dynamic model testing carried out with self-propelled model in open sea environment. Unlike towing tank experiments, this time model experience several wave heading at once. Although superstructure of model geometrically not as important as it was in static model testing, in order to protect propulsion system, superstructure should be watertight. Also, superstructure weight should distribute as in real design. Then the model can be directed to encounter waves from all headings considering capsizes, broach and knock-down.

4.2 Computer Modelling and Analysis

With the recent technological development computer programs are fairly helpful to a Naval Architect for stability analyze in early design process. Modelling software enables to test different effective hull forms and superstructure geometry. In order to properly model a self-righting craft, software must be able to analyze 180 degrees of roll to starboard and 180 degrees of roll to port. Additionally, software should manage asymmetrical superstructure geometry computation like many rescue boats have in their design. Also, modelling the true shape of design is critically important since any buoyancy location have large impact on self-righting ability on the vessel. Buoyancy sections that are not included on main superstructure body such as mast volume also should be computed on that software.

Computation of weight and centers are standard practice for any ship design. But, weight and weight distribution have utmost importance in any self-righting craft. Even a slight change in weight or weight centers could cause negative GZ curve. Computer software should calculate these weight centers on high accuracy. Any increase in Vertical center of gravity (VCG), also could change the stability curve and cause negative righting levers. Naval architect should have always checked and updated weight calculations as design and construction progress.

When construction is finished, an inclining test is carried out to determine the accurate center of gravity and verify the calculations.

5. Design Criteria

In general, design and outfit requirements for self-righting vessels differ little from those of conventional craft of similar size and function. There are, however, a few areas requiring special consideration.

The craft's weight and center of gravity limits are based on a hoisting weight, speed, stability and seakeeping requirements. The maximum allowable center of gravity is mostly limited by the wind heel criteria. [7].

The structural design of a high speed, self-righting, rescue boat presents some unique problems. As with any high speed craft, the designer is faced with seeking an appropriate balance between craft weight limits and structural integrity under the expected operating conditions and service life. The extreme operating environment, severe mission demands and extended annual operating hours for crafts make achieving an appropriate balance a challenging task. As a general design of high speed craft is based on the idea that the structural design limit exceeds the crew's ability to sustain the maximum expected craft motions. Even though determining the crew's operational limits is subjective some reasonable assumptions can be made. However, in the case of heavy weather motor lifeboat operational limits are at best uncertain. In the surf rescue motion and the magnitude of the loads on the craft are now well known or predictable. An overly conservative design approach might be indicated owing to the uncertainty but, the weight constraints required for high speed performance necessitates a weight conscience structural design approach.

Key design considerations in the coupling and shafting arrangement included minimizing the coupling joint angles to maximize reliability and locating the engines and gears low in the hull to reduce the KG and increase stability. The parallel arrangement of shaft configuration usually favored because it offers substantial benefits with respect to producibility and alignment.

The heating, ventilation and air conditioning (HVAC) system is required to maintain temperatures between 13°C and 27°C in enclosed bridge and 26°C to 27°C in the survivor's compartment with external air temperatures ranging from -12°C to 37°C. The systems use direct expansion Freon with reverse cycle heating. While the design is relatively conventional, requirements for self-righting and the need to avoid progressive flooding in a damaged condition present special design considerations. Much like the engine air intake, the design of HVAC intakes and exhausts require special attention at various roll angles.

With watertight integrity essential for vessel safety, all doors, hatches and windows fitted to self-righting craft must be capable of resisting the hydrostatic forces associated with capsize. In addition, most will be fitted in compartments or spaces used as part of the vessel's watertight subdivision, so could be required to keep water in as well as out. All doors, hatches and windows fitted to self-righting craft must therefore be as strong as the adjacent structure and capable of accepting hydrostatic pressure from either side. No door, hatch or window can be expected to do its job of keeping water out if not securely closed, so to minimize the risk to vessel safety, all should be kept shut at sea unless actually being used. Those that do need to be opened regularly for crew access to other parts of the vessel, such as wheelhouse doors onto the deck, should remain open for the shortest possible time and must consequently be quick and easy to operate with a positive and secure locking mechanism. Wheelhouse doors on rescue vessel are often located facing aft to protect them from direct wave impact. Even modern lightweight composite doors can inflict serious injury when driven by a heavy roll, so it is important to provide grab rails adjacent all doors to discourage crew members from using the door frame as a handhold when moving around the vessel.

6. Discussion and Conclusions

Analysis of the stability of a vessel based on the righting lever arm over the entire range of angles of heel, the GZ curve, has its limits. It is unable to model effects such as parametric rolling, or surf riding and broaching, and the technique has to be extended if it is to include the effects of heave accelerations on the righting moment and the impact of a wave waterline on the behavior of the vessel. However, despite such limitations it is valuable model of many aspects of the behavior of a vessel, and as such a powerful tool that has long been used to evaluate the sufficiency of the stability of all types of craft.

Since the theory of static stability was first elaborated in the 18th century there has been continual research to further understand the complexities and intricacies of this fascinating area of study. Much of empirical knowledge of the stability behavior of crafts is only now being studied in a rigorous way as it is recognized that events that are common for such craft are rare behavior of ships in abnormal conditions. However, the study of vessels such as lifeboats and rescue craft when rolled to very large angles of heel, passed 90° and right up to the completely inverted condition, is unlikely to be applied to larger vessels. This will probably remain area of interest and concern only to those who go to sea in, or design, the smallest of craft. But for such craft the designer must only consider stability under routine operating conditions, but also under the extreme conditions of capsize, which while unlikely cannot be considered impossible.

The stability criteria for such vessels should not only be concerned with normal conditions, and with preventing capsize, but should also provide guidance on the required behavior if capsizing should occur. In addition to criteria based on minimum safety requirements additional objectives based on maximum acceptable accelerations could be defined in the form of a static stability envelope.

There are three main self-righting methods examined in this study. These are; inherent self-righting method, inflatable bag method and moveable ballast method. All of them have their advantages and disadvantages. Inflatable bag is easy to apply and maintenance, but there are very small area of applicability and does not ensure safety of the crew. Moveable ballast method practically applicable only for small vessel and maintenance of mechanical components is hard. On the other hand, it can design as self-operating system and decent alternative for buoyant superstructure is not feasible. As for the inherent self-righting method, it is the most viable method within the others. Because, there is no working part to go wrong. Although designing inherently self-righting craft is challenging due to the difficulty of weight distribution's uncertainty during the design process, it is the best option for any self-righting vessel [8].

It is recognized that the concept of self-righting craft design is practically new concept and largely applicable to small crafts, technological developments and recent researches are promising for future development of self-righting stability.

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