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Design for Stability and for Instability – Finding the Right Balance for Small Craft

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Abstract

The fundamentals of stability have been understood for over 200 years, however it is only in the last two decades that detailed consideration has been given to the stability behaviour of small craft at very high angles of heel, up to the completely inverted condition. The importance of this knowledge in the design of yachts and other small craft is considered, and the significance of our current understanding is reviewed in the context of procedures based on static stability analysis. The results of undertaking a design exercise with stability as the principal design driver is explored, and the practicality of such a procedure is discussed. Recent research that has produced results relevant to the stability of vessels in the inverted condition is briefly described and reviewed.

Introduction

Many competing requirements drive the design of yachts and other small craft. 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 (that are in keeping with the owners taste), and reasonable costs (controlled to stay within the owners budget), are all objectives that the designer has to balance in order to achieve a compromise solution. And a solution that does not just suffice, but one that excels in the aspects of greatest importance to the new owner.

Adequate stability is also a requirement of every boat design, but if we look at the usual design process we find that stability is not an early element of the activity, but is undertaken at the later stages. Design is often characterised by a spiral [1], Figure 1, with a series of sub problems being addressed in turn, iteratively. However the weight calculation and 'stability check' is inevitably one of the latter activities in each iteration. By working with a tried and tested concept as the basis of the design there is an assumption that the stability will be adequate, although clearly if it is found that this is not the case adjustments are made.

This approach has proved successful over many decades, although one particular issue does give cause for debate on a regular basis, and that is the problem of recovery from a capsize. Ships are designed on the basis that capsize 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. On several occasions in the last 25 years the design process outlined above has failed to produce an adequate solution to this problem. Three examples are worth mentioning: the Fastnet disaster of 1979 [2], the Danish lifeboat disaster of 1981 [3], and the experience of Tony Bullimore in 1998 [4]. For the designers of multi-hulls this is an ever present issue.

An understanding of the fundamentals of stability was established by Bouguer in 1746, and independently by Euler in 1749 [5], since when research has continued around the world into many complex and subtle developments of stability theory [6]. 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. It is therefore interesting to postulate an alternative approach to the design problem. Can we design for stability, using stability as the driver of the design process, rather than simply evaluating stability after the vessel is designed?

If we are to do this we need to be able to *design 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. In this paper it will be shown what the results of such a reversal of the normal design priorities are, recognising that such an approach is not likely to be suitable for many genuine design problems. However it is 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.

Stability Objectives

In order to implement a design for stability approach we have to decide what are the stability objectives we wish to achieve. In the traditional approach to design the stability achieved is evaluated against specific criteria. Formalised stability criteria have been set for most vessel types by different organisations. The International Maritime Organisation (IMO) has set out criteria [7] 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. Individuals have also suggested other proposals for relevant stability criteria, often with real benefits even if they have not been formally adopted (such as those of Admiral Pascual O'Dogherty, Director of El Pardo tank and model basin, Madrid, for fishing vessels [8]). These criteria are often empirically based, although they do also include assumptions about the stability hazards to which the vessel may be subjected, such as waves, wind, down flooding, shift of cargo, and crowding of passengers.

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.

The formalised stability criteria discussed above all refer to the static stability curve. 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 initia stability (GM) proportiona to the gradient of the curve ath zero degrees); the range of stability, the reserve stability (proportional to the area under the curve); and for the value and heel angle of GZmax, see Figure 2. It is interesting to note however that for all these criteria capsize is still considered to be an event to be avoided (by ensuring a supposedly sufficient range of stability) 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. If we think of the inverted craft as another vessel, then in this situation we are seeking to maximise instability.

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.

While the criteria discussed above can give provide a lower bound for the GZ curve they do not provide a true or complete stability objective. In a design for stability process, where stability is the primary objective, we can rightly aim to achieve the optimum for this aspect of the design. The criteria give us minimum values from the perspective for safety, however this does not imply that we are seeking to achieve the maximum possible stability, as this will be unsatisfactory from the point of view of accelerations. 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. No one has yet attempted to produce such an envelope, although some work in this direction with respect to high speed craft has been undertaken in Newcastle [9]. This work has indicated that the upper bound will vary according to the type of craft, and will in addition be dependent on other variables such geometry induced damping and the mass moment of inertia. However we can propose the probable form of a stability envelope intended to be used as a design objective, Figure 3.

Theoretical Influences on the Righting Lever (GZ) Curve

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. If we go back to the fundamentals of stability we find that this is not so difficult: GZ, the righting lever arm, is the distance between the line of action of the weight force and the line of action of the buoyancy force. As such it is a distance that is entirely dependent on geometry. Only two things can change the distance GZ at any given angle of heel, the position of the centre of gravity and the position of the centre of buoyancy, and these in turn are dependant on the distribution of mass, and the distribution of volume. It is possible to explore how changes in the distribution of mass and of volume impact on the GZ curve, as shown in Figures 4 to 9, and discussed here.

Vertical and horizontal movement of the centre of gravity is widely understood, it resulting in the value of GZ being augmented by the value of the shift in the centre of gravity (*D*) multiplied by the sine or cosine of the angle of heel (φ) respectively:

For a vertical shift of centre of gravity: $GZ_{NEW} = GZ_{OLD} \pm D\sin\varphi$

For a horizontal shift of centre of gravity: $GZ_{NEW} = GZ_{OLD} \pm D\cos\varphi$

Figures 4 and 5 show the impact of a change in the centre of gravity on a vessel with neutral stability initially (i.e. GZ equals zero for all angles of heel) and on a vessel with a GZ curve typical of a modern yacht. The figures demonstrate that such shifts impact on both the value of GZmax, and on the range of stability. A vertical shift has the greatest influence at angles of heel of ± 90 degrees, while a horizontal movement has the greatest influence at heel angles of 0 and 180 degrees.

Changes in the distribution of volume are also well understood, if less widely considered. Increasing the beam of a vessel produces a more form stable craft. The shape of a purely form stable craft such as a catamaran is shown in Figure 6, which demonstrates the effect on the GZ curve of increasing the hull separation. These curves are based on the assumption that the centre of gravity is located centrally and on the water line, in which case once one hull has emerged from the water GZ is given by the cosine of the distance of the centre of buoyancy of a hull from the centre line, which is a half of the vessel beam (*B*) less the hull beam (*b*):

For a catamaran: $GZ = [0.5(B - b)] \cos\varphi$

For a catamaran the transverse shift in the centre of buoyancy is given by the expression $0.5(B - b)$. For a monohull this distance is not expressed so easily, but GZ will still be equal to the transverse shift of the centre of buoyancy multiplied by cosφ (ignoring the slight vertical movement of the centre of buoyancy). It can be shown by inspection of the geometry that for a vessel with a rectangular crossection of beam *B*, draught *T* and depth 2*T*, and with the centre of gravity located centrally and on the water line, GZ can be found as follows:

For a monohull: $GZ = [B^2 \tan\varphi \;/\; 12T] \cos\varphi$ if $\varphi \leq \tan^{-1}(2T/B)$

And $GZ = [(B/4) - (T \;/\; 3B \tan^2\varphi)] \cos\varphi$ if $\varphi \geq \tan^{-1}(2T/B)$

Figure 7 shows how using this formula the GZ curve demonstrates increasingly form stable characteristics as the *B* / *T* ratio is increased. The impact of changing the beam to draught ratio of an actual vessel will be similar, and can be estimated by combining the formula above with a yacht stability curve, as is shown in Figure 8. As can be seen increasing the beam to draft ratio results in greater stability at small angles of heel, but a reduced angle of vanishing stability, and increased stability in the inverted condition – all evidence of the increasing tendency to form stability.

Finally we can consider the effect of moving the vertical distribution of volume. A volume located on the centre line some distance above the waterline has no impact on the stability curve until the angle of heel reaches (or is near to) 90 degrees, when the volume will enter the water and cause a shift in the centre of buoyancy. Similarly volume low down (when in the upright condition) has no impact after an angle of heel of 90 degrees. Figure 9 shows the GZ curve for an object with neutral stability as the centre of buoyancy is moved vertically. As can be seen the impact on stability is greatest at ±90degrees. This is the concept utilised by self righting lifeboats which have a large volume located well above the deck. This can be a watertight wheel house, or it can be a large volume of foam contained in the wheel house coach roof. These design features only influence the GZ curve at angles of heel approaching 90 degrees, but beyond that angle of heel they have a significant impact, providing very large righting levers when in the inverted condition.

The effects on stability of the distribution of mass and volume, as demonstrated in Figures 4 to 9, can be applied simultaneously, and the impact on the stability curve will be summative. It can be seen therefore that in principle the designer has complete control of the shape of the GZ curve. By judicious adjustment of the distribution of mass and volume it should be possible to create a vessel with any desired stability characteristics as represented by the GZ curve.

Practical Constraints on the Righting Lever (GZ) Curve

The discussion above, which revisits the fundamentals of stability analysis from an unusual perspective, suggests that in terms of static stability the designer should always be able to achieve the desired results. In fact this is not the case for the simple reason that stability is only one of the objectives driving any true design exercise. The concept of design for stability is in fact an unrealistic one. Stability only has to be sufficient, it does not have to be optimised at the expense of other important design drivers.

If we examine the success of the conventional design process we find that in most cases the stability of a vessel is sufficient for the normal working conditions encountered. The criteria established by regulation are for the most part conservative, and casualties are the result of lack of regulation, or non-compliance with the established regulations. The former is often the case for many types of small craft, while the latter is found wherever the operating culture is driven by commercial pressures at the expense of safety. A recent report into the capsize and loss of a Canadian fishing vessel illustrates both these cases [10]. On occasion regulations can inadvertently contribute to the inadequacy of a vessel's stability characteristics, as has been shown both in the context of rating rules for yachts [11] and the protection of fisheries [12].

If the conventional design process can be said to have achieved satisfactory results for small craft when operating under normal conditions, it is not quite so clear that success has been achieved when operating under abnormal conditions, in particular when inverted. It seems that we can design effectively to keep the vessels the right way up, to design for stability, but we have greater difficulty designing a boat that once upside down will re-right, in other words to design for instability. Multihulls, and many modern racing yachts, do not want to right.

Despite the clear understanding of how to make an inverted vessel unstable the difficulties arise from the many competing requirements driving the design process. In particular many solutions impose added underwater resistance or windage, or compromise habitability, or work against the objective of a minimum weight structure. Each of the four possible solutions derived from the analysis above can be considered in detail. In order to make an inverted vessel more unstable the options are:

- To move the centre of gravity toward the keel. Vessels are usually designed to keep all weights as low as possible. The structural requirements of the rig often force the centre of gravity upward. To move the centre of gravity down can usually only be achieved by the addition of ballast. This is the conventional solution for a cruising monohull which carries much ballast externally. However for modern light weight yachts and multihulls it impacts on performance in terms of acceleration and speed.
- To move the centre of gravity off the centre line. Early non-self righting lifeboats expected the crew to climb up the side of the upturned hull, and some later self-righting lifeboats used tanks to automatically move the centre of gravity transversely [13]. Modern yachts with wing tanks or tilting keels could achieve the same result, however it adds complexity to the design and may require human intervention (during the crises of capsize) to succeed.
- To narrow the volume at the inverted waterline. Again this is the solution for the traditional cruising yacht, however it impacts on performance by reducing stability in the upright condition. It can also compromise the habitability of the vessel if the hull is very long and narrow.
- To add volume high above the deck. As discussed earlier this is found on all modern self righting lifeboats [14], and occasionally on cruising multihulls in the form of a mast head float, however the volumes high up create additional windage and so impact on performance.

Alternative Strategies

Using a fundamental understanding of how the distribution of mass and volume affect stabiity can enable some craft to be designed with satisfactory stability requirements at all angles of heel. As discussed above this includes modern life boats and traditional cruising yachts. However it has also been pointed out that for some craft, especially form stable vessels such as multihulls and modern racing yachts, this approach is not successful. There are however some alternative approaches to the problem. It is possible to recognise that phenomena that are normally considered as stability hazards are also instability enhancers, and use them to advantage. It has also been recognised in recent years that there are some surprising strategies, that although counter intuitive, may be successful.

Firstly let us consider two useful stability hazards: the effects of trim and of a free surface. In the operation of some small craft the onset of excessive trim can be dangerous, for example rig supply vessels with the flat deck and low freeboard aft have different stability characteristics when trimmed down by the stern. Similarly an inverted vessel may be less stable under some conditions of trim. In particular the narrow deck forward contrasts sharply with the wide deck aft, especially on a transom sterned vessel, so forcing the inverted craft down by the head and lifting the stern clear of the water results in a reduced second moment of area of the waterline, and a more unstable condition. Either allowing a forward compartment to flood, or inflating a buoyancy bag placed above the deck at the stern of a vessel can be an effective way of encouraging an inverted vessel to re-right (Figure 10). This has been shown theoretically for yachts [15], and has been implemented by the Royal National Lifeboat Institution (the RNLI in the UK) on some of their RIBs with automatically inflating buoyancy located on a frame at the stern of their vessels.

Similarly partially filled tanks are a recognised stability hazard due to the heeling moment induced by the movement of fluid in the tank as the vessel heels. When tanks are wide, or there are many of them, this free surface moment can have a significant impact on the initial stability of a vessel, and its impact at small angles of heel can be plotted on the static stability diagram as an effective heeling lever arm. This stability hazard has been explored as a mechanism for the righting of an inverted yacht [16], by considering the effect of allowing the inverted vessel to slowly flood (Figure 11). Full scale trials demonstrated the effectiveness of this procedure. The experiments also established that a flush decked vessel would be righted after the ingress of less water than for one with a distinct coach roof, this being due to the wider area generating a larger free surface in the inverted flush decked vessel. While this result is of interest, trying to persuade the crew of an upturned racing yacht somewhere in the Southern Ocean that they should deliberately allow their vessel to flood may be somewhat difficult!

Another result of recent research has caused considerable discussion due to its unexpected nature. Should a capsized vessel retain its rig intact it is usually assumed the damping effect of the rig would impede any action tending to right it. In theory a vessel capsized by breaking waves may be righted again by another wave with similar energy. However as the mast in the water would have a damping effect not present if the vessel had been dismasted it has been assumed that this would slow the righting action. Experimental result from the towing tank in the Australian Maritime College, Tasmania, found that a dismasted vessel required more waves to right it than the vessel with the intact rig [17]. Further experimental work in Newcastle has shown that this effect is a very sensitive one, and that minor variations in the vessels configuration (such as the location of the centre of gravity, the aspect ratio of the sails) can change the outcome of the experiment [18]. Despite this the effect can be demonstrated, and it is argued that the damping effect is in fact helping the righting process. The explanatory theory is that the breaking wave force the hull of the vessel at the surface sideways (in sway), while the rig, deeper in the water is left behind. After the wave has passed the vessel starts to return to 180 degrees of heel (i.e. fully inverted) but the damping effect of the mast slows this such that it is still heeled when the next wave arrives. Each wave arrives with the vessel at a reduced angle of heel (160 degrees, 140 degrees etc.) until the angle of positive stability is reached, and the vessel re-rights. In contrast the dismasted yacht returns to 180 degrees more quickly, so the progressive righting process does not occur.

Lastly if should be noted that the most widely accepted strategy for dealing with a capsized form stable vessel is to accept that it will not be righted. This philosophy abandons worrying about reducing the probability of a vessel remaining in the inverted condition, and instead turns to the other element of risk, the consequence of such an event. If the consequence can be mitigated such that it is not catastrophic, the risk to the crew is similarly reduced. If the vessel is designed such that even if capsized it will not sink (by ensuring that there is no flooding) then it can then also be designed so that it is an effective and safe life raft. By ensuring that there is access, even when inverted, to a cabin which can act as a safe haven, with communications, water, food, dry clothing, and flares etc., the fact that the vessel will not self right ceases to be such a crucial issue.

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 behaviour of the vessel. However despite such limitations it is a valuable model of many aspects of the behaviour 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 the empirical knowledge of the stability behaviour of small craft is only know being studied in a rigorous way as it is recognised that events that are common for such craft are rare but significant occurrences for large ships in the extreme situations – now often referred to as the behaviour of ships in abnormal conditions. However the study of vessels such as ocean going yachts and search and rescue craft when rolled to very large angles of heel, passed 90 degrees 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 not only consider stability under routine operating conditions, but also under the extreme conditions of capsize, which while unlikely can not 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 behaviour if a capsize should occur. In addition to criteria based on minimum safety requirements additional comfort objectives based on maximum acceptable accelerations could be defined in the form of a static stability envelope.

This paper has examined how a designer could in theory adjust the distribution of weights and of volume to obtain any required shape of static stability curve. However the conflicts inherent in such an approach, which could compromise other aspects of the design such as resistance, habitability and minimum weight, have also been discussed. While these considerations make it impossible to develop a design that is form stable in normal operating conditions yet unstable when inverted, alternative strategies have been explored, some of which go against the natural instincts of either the designer, or the sailor, or both. Despite this there are possibilities of useful design developments that may emerge from further research in these areas.

It is recognised that the concepts of design-for-stability and its necessary reverse, design-for-instability, are unlikely to be an approach followed by any practicing designer. However exploring this concept in a theoretical way provides useful insights into the stability behaviour of all craft, and into the impact of particular decisions on the development of a small craft design.

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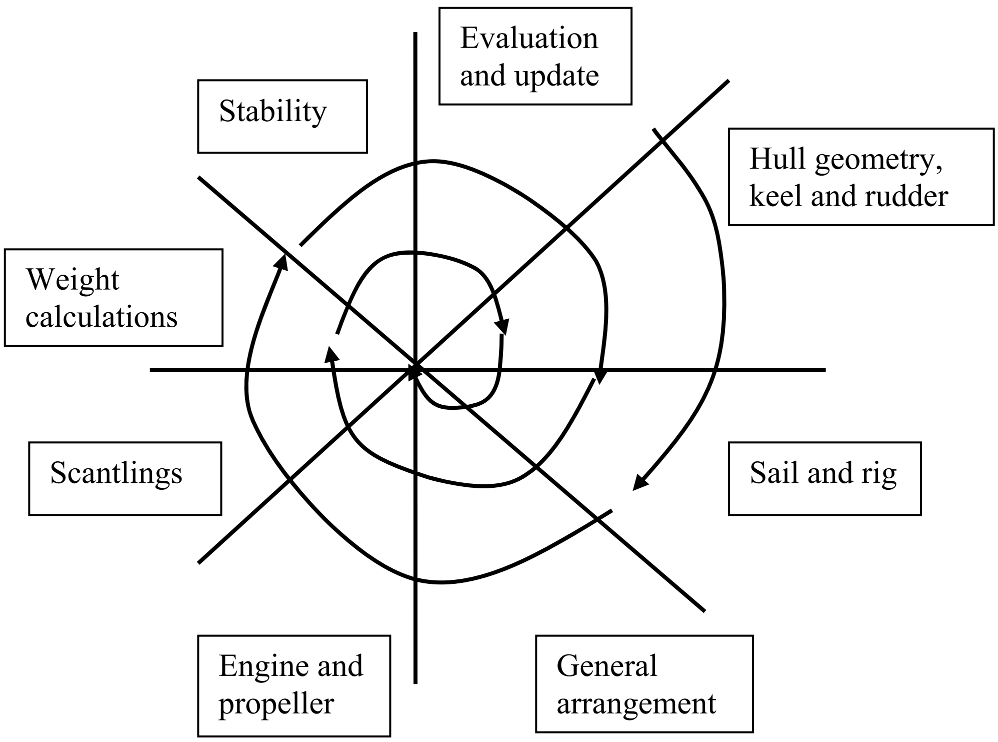

Figure 1: The Design Spiral.

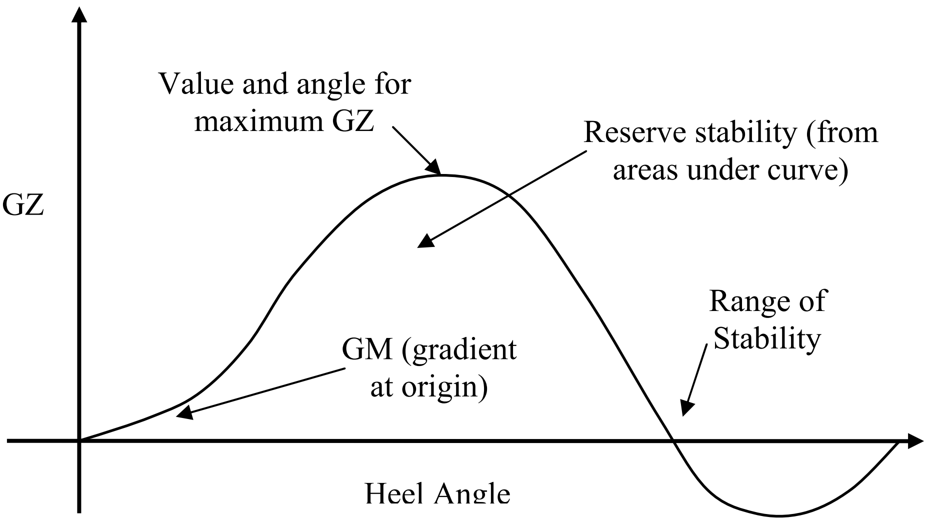

Figure 2: The characteristics of static stability most commonly used in stability criteria.

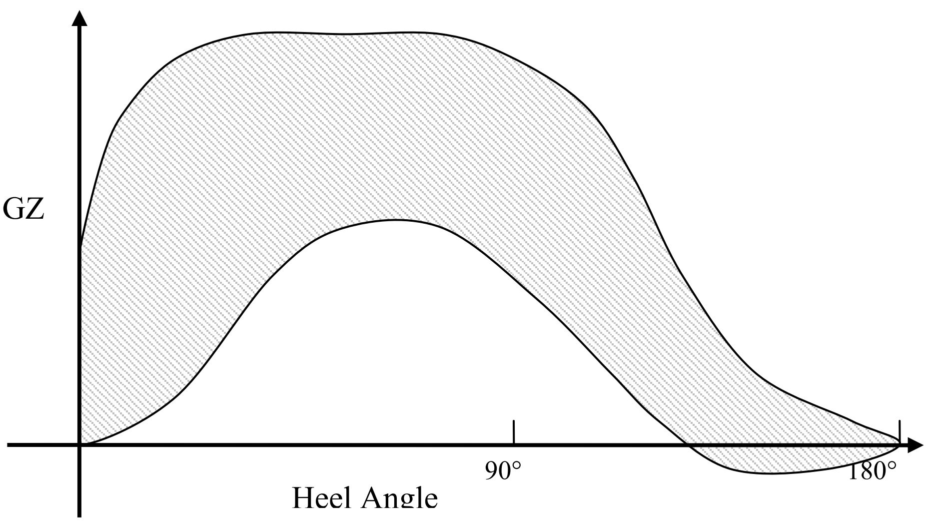

Figure 3: Possible shape of a stability envelope that could be used as a design objective.

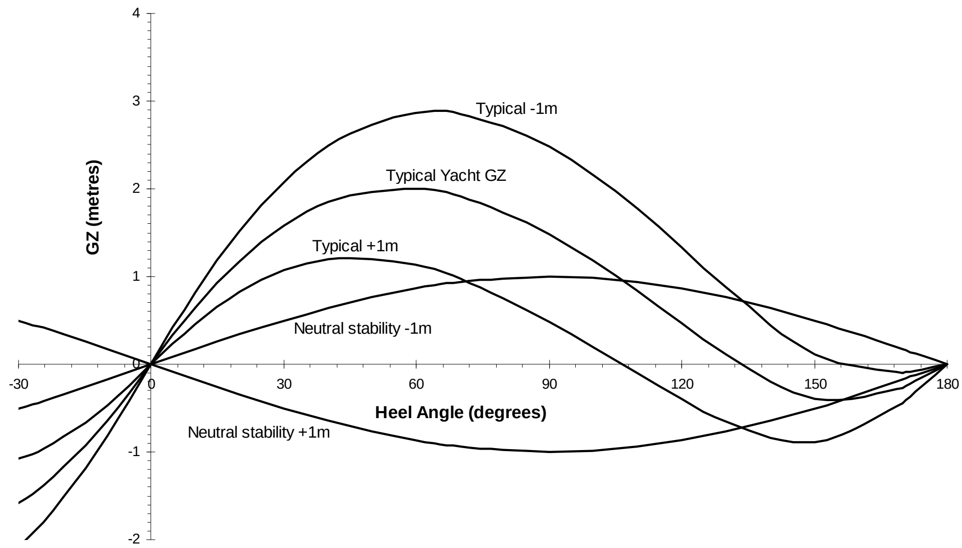

Figure 4: The effect of moving the centre of gravity up (+ve) and down (-ve) on the GZ curve of a typical yacht, and of an object with neutral stability (i.e. GZ = 0 at all angles of heel).

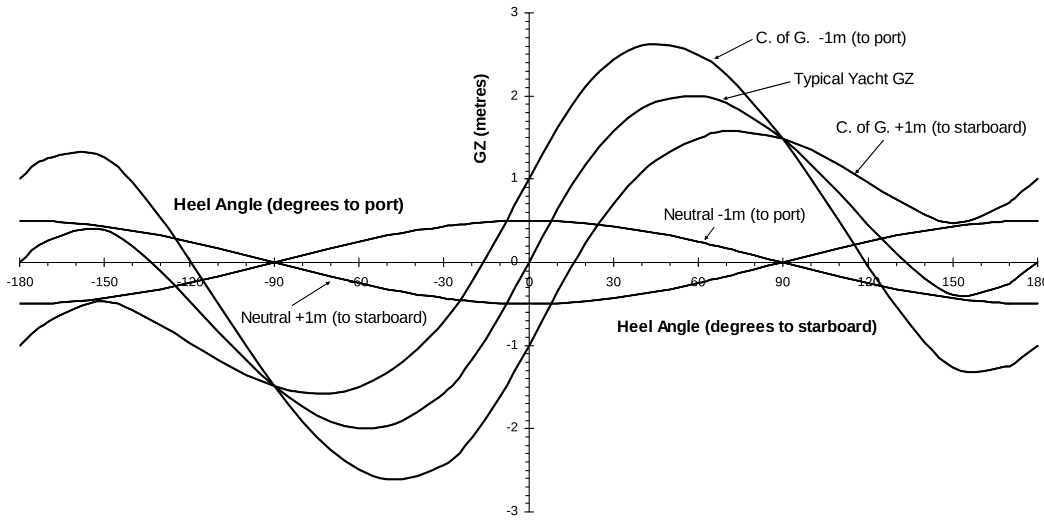

Figure 5: The effect of moving the centre of gravity to starboard (+ve) and to port (-ve) on the GZ curve of a typical yacht, and of an object with neutral stability.

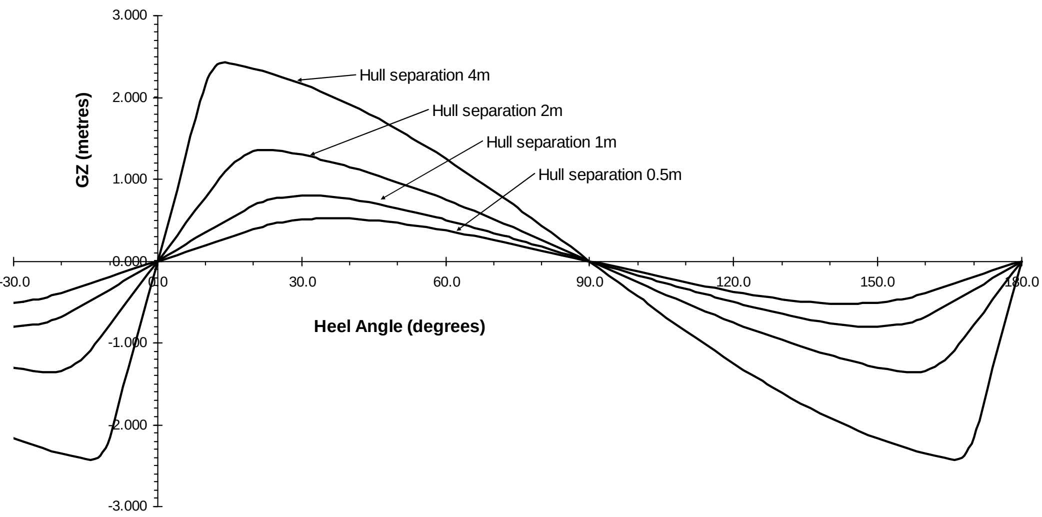

Figure 6: The effect on the GZ curve of a simplified catamaran (hulls of square crossection 1 m by 1m, floating at half depth) as the hull separation is varied.

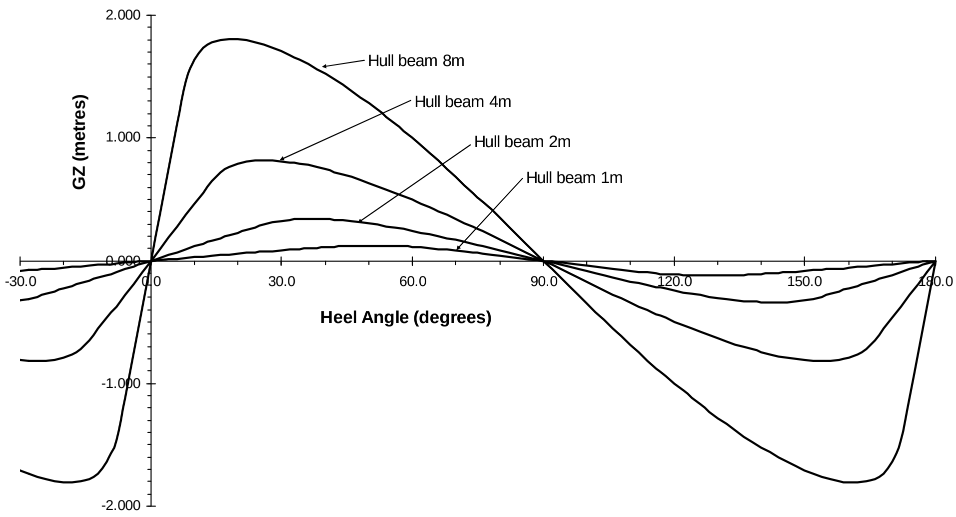

Figure 7: The effect on the GZ curve of a simplified monohull of rectangular crossection (depth 1 m and draught 0.5m) of altering the beam.

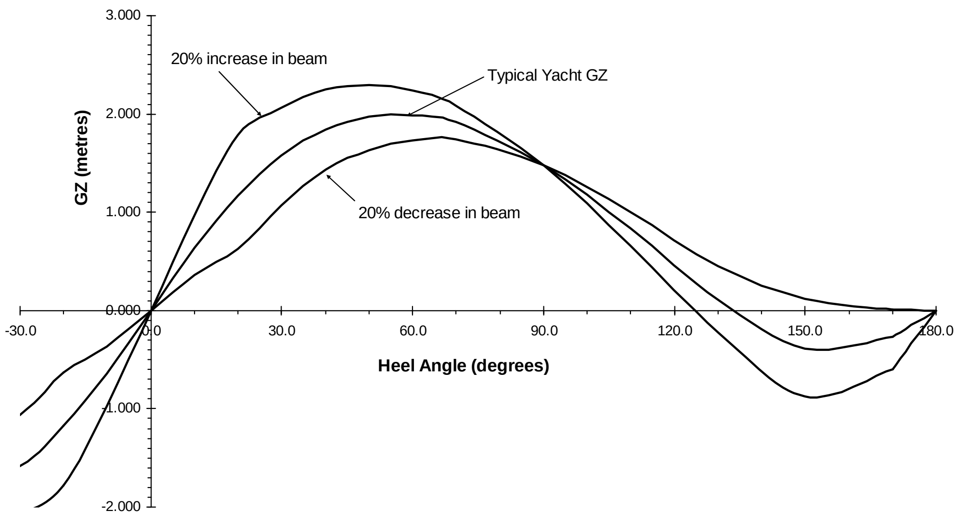

Figure 8: The effect on the GZ curve of a typical yacht of altering the beam.

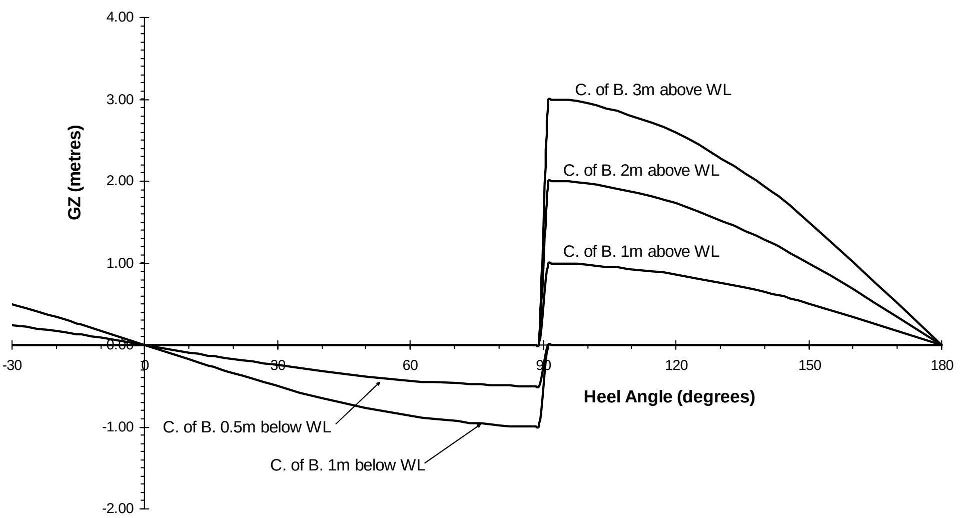

Figure 9: The effect of moving the centre of buoyancy of on object with neutral stability up and down (the centre of buoyancy is modelled as a point, hence the abrupt discontinuities at 90 degrees).

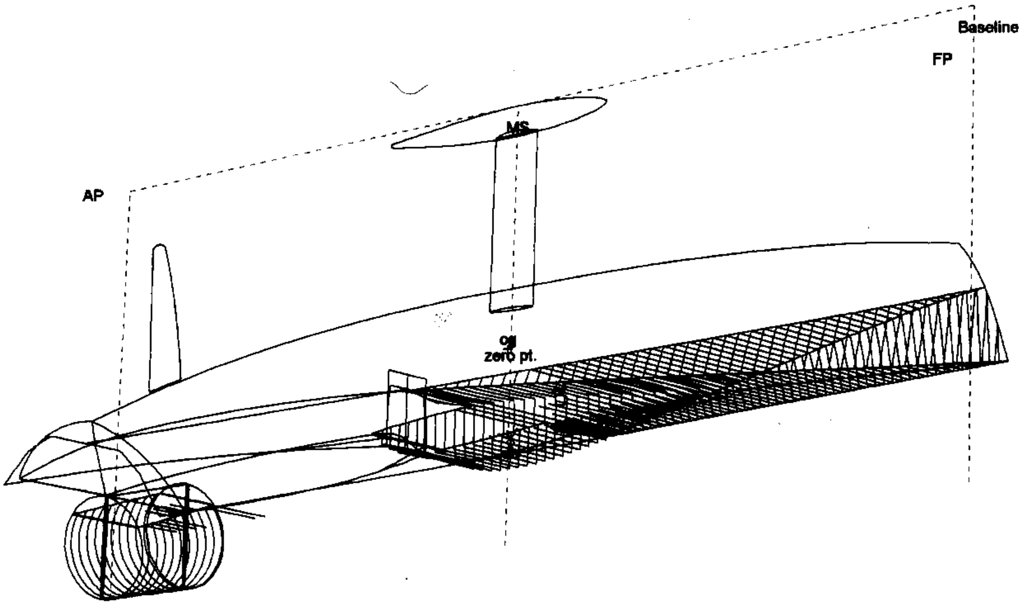

Figure 10: Computer model of an inverted yacht with an inflated buoyancy bag on the deck aft [from reference 15].

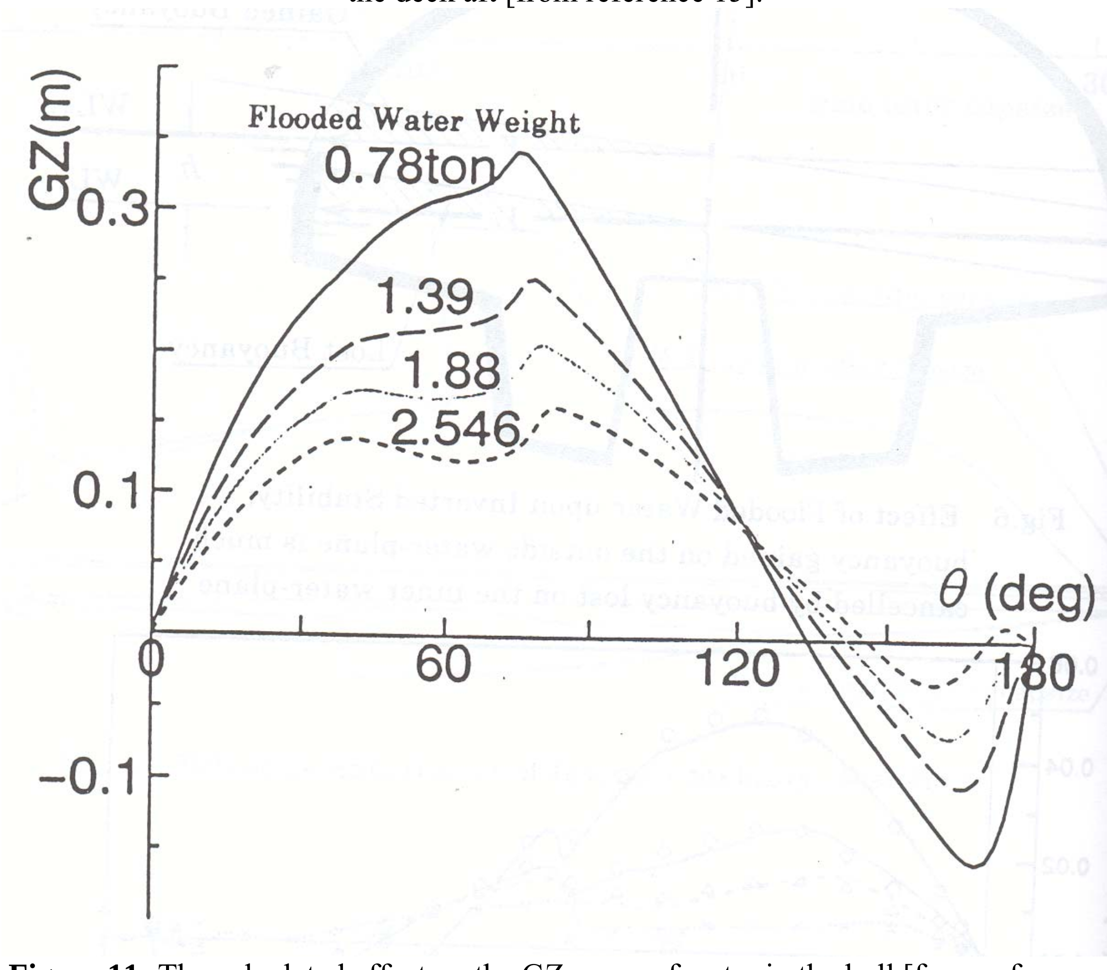

Figure 11: The calculated effect on the GZ curve of water in the hull [from reference 16].