Sailing Vessel Stability: A Review of the Current State of the Art and Proposals for Worthwhile Research

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INTRODUCTION

Yacht and sailing ship designers, together with regulatory authorities, use very simple formulae to determine the stability of vessels under sail. These methods were generally derived in the nineteenth century when the machines enabling fast and accurate determination of ship stability were not available. Now that the statical and dynamic stability characteristics of a vessel are readily obtained to a high degree of accuracy, the wind heeling and capsize phenomena are more precisely defined and assessed in a more realistic manner.

The following review examines the methods typically used and the assumptions upon which they are based. The validity of the assumptions and the accuracy of the calculations are assessed. In the light of these considerations, the regulations for sailing school vessels employed by the United States Coast Guard, and those of other regulatory authorities, are investigated in terms of their ability to identify those vessels most vulnerable to stability incidents.

In order to develop a better understanding of sailing vessel stability, it is recommended that certain aspects be investigated through mathematical and physical modelling techniques, combined with full scale measurements at sea.

Much of the information contained in this paper has been derived from Reference 1, the report of a research project carried out for the UK Department of Transport.

MODES OF CAPSIZE

Whilst every stability incident is unique in detail, there are five general processes which, in isolation or combination, result in the majority of capsize:

1. BREAKDOWN BY WIND. It is rare for a sailing vessel to become overpowered by a steadily increasing wind since sail area is normally reduced in good time. Many incidents occur when a vessel is struck by an unforeseen gust, often in relatively light wind conditions when a large proportion of the sail plan is set. The vessel may be knocked briefly to such an angle that downflooding or capsize occurs, or may be pinned down by a gust of longer duration so that downflooding becomes extensive and the vessel sinks.

2. ROLLED BY A BREAKING WAVE. When a vessel is caught broadside on to a wave at the point when it breaks, a powerful roll moment is produced by the force of the crest on the topsides opposed by the side force on the hull and keel as it is swept sideways through the water. Such a capsize may be arrested by the impact of the mast and sails on the water surface, or if the wave is sufficiently large, may result in inversion of the hull. If the vessel is stable when up side down it may remain in that state until further wave action returns it to upright, if on the other hand it is only marginally stable when upside down, it would probably continue to roll through 360 degrees and return immediately to upright.

3. BROACHED BY A FOLLOWING SEA. If a rolling downwind or with waves on the quarter, as a wave lifts the stern and carries the hull forward, it has a tendency to turn it broadside on. At the same time the bow will be depressed into the trough and this increases the turning moment. Vessels which lack directional stability, or which have excessive weather helm, are particularly vulnerable to broaching. Once the hull has turned broadside it is, of course,
Dellenbaugh Angle = \[ 57.3 \times \text{Sail Area x Heeling Arm} / \text{Wind Pressure} \]

Displacement x ON

These terms are similar, one being virtually an inverted form of the other. The Dellenbaugh Angle formula gives an indication of the angle to which a yacht will heel under ideal steady wind conditions; the Power to Carry Sailing formula results in a less meaningful number and has consequently declined in popularity. The use of either of these terms requires a knowledge of one of what is termed to be acceptable for a particular type and size of vessel and neither gives accurate predictions of stability under sail. The methods remained in use for many years because to improve upon them in terms of accuracy requires calculations of the static stability righting arm or GZ curve for the hull, a daunting and tedious task for the designer without access to a computer and the appropriate software. The formulae remain in use today to assist in the early stages of new designs.

Most designers now have access to computer programs which readily perform the static stability calculations and enable them to carry out a more accurate prediction of how a hull angles resulting from steady winds. The new technology has also enabled the calculation of stability through the complete range of heel angles to 180 degrees. This was previously not possible because as a yacht heels, it also trims slightly and it is difficult to determine the equilibrium draught and trim at each heel angle. Most computer programs depend on a large extent on the skill of the user, in this case, the computer. Although the computer programs have been immensely helpful, it is sometimes a matter of judgement regarding the computer output.

In the modern design office, therefore, the scope for a designer is to calculate accurately for the vessel held at rest in calm water. This is compared with the heeling angle in the proposed rig at typical wind speeds to determine the sailing heel angle.

By plotting the two curves at the same scale, the point at which they cross defines the steady heel angle. The area under the wind heeling curve represents the work done by the gust of wind and clearly shows which areas under the GZ curve, traditionally known as the ‘dynamic stability’, represents the energy in the hull. The angle at which these areas are equal defines the angle to which a vessel will be knocked down by the gust. Figure 1 illustrates the relationship between the righting and wind heeling arm for a typical yacht.

Designers of racing yachts would normally try to maximise the righting moment of the vessel in normal sailing conditions since yachts perform best if kept upright. Yacht rating rules introduced in recent years have penalised stability for this reason and the way in which the rating was calculated led to the familiar broad, shallow hulls with fine keels. The designers of such yachts clearly had to compromise between performance and rating with no room for considering stability at large angles.

More recently, rating rules have been developed to discourage this trend and attempts have been made to incorporate an assessment of the stability at 90 degrees. In addition, recommendations have been made to the ORC for the adoption of screening values which would prevent the entry of unsuitable yachts in offshore category races. One such screening was suggested by the joint committee on Safety from Capsizing of the USRC and SMAC (Reg 2). It uses just the maximum beam and the displacement calculated by the IOA rule to calculate a yacht’s vulnerability to capsize. Another, the Stability and Screening Calculation Scheme, suggested by the ROE, incorporates many features in an attempt to judge the overall safety of the yacht. The adoption of such requirements will, in some way, be improving the seaworthiness of racing fleets in general but still may not persuade the racing yacht designer to consider safety as a high priority in the design.

Most cruising yacht designers now consider the range of positive stability which has been shown to be important by recent research into the problems of wave induced capsizing of yachts. It has been shown that whilst some aspects of the design do affect the ability to withstand a capsize by a breaking wave, it is possible to capsize any yacht with a wave of sufficient steepness and height. Atten is therefore been focused on the importance of a yacht’s ability to return to the upright position quickly after a capsize. This ability is assessed by examining the GZ curve between 90 and 180 degrees.

The greater the range of positive stability and the smaller the area under the negative portion of the curve the more readily will the yacht right herself.

ASSUMPTIONS MADE IN CONVENTIONAL CALCULATIONS

The following assumptions are inherent in most methods currently in use to determine and regulate sailing vessel stability.

1. The vessel floats in calm water.
2. The water surface is at the same level as the deck of the vessel.
3. The free surface effects of ballast tanks remain constant at all heel angles.
4. The wind has uniform velocity at all elevations.
5. All sails are aligned fore and aft along the centreline.
6. All sails have a heeling force coefficient of unity.
7. Overlapped sail areas produce no heeling moment.
6. The heeling moment is maximised with the wind on the beam.
9. Heeling moment vary with co (heel angle).
10. The vertical component and bow down trim moment of the aerodynamic driving force do not affect stability.
11. When considering response to a gust the increase in wind speed is instantaneous and its effect is that of an impact on the rig.
12. When struck by a gust the vessel is upright.
13. The vessel's inertia and damping have a negligible effect on its response to a gust.
14. The values of displacement and centre of gravity determined by the inclining experiment remain valid for the period of certification.
15. The vessel's weight remains constant in a seaway.

A brief examination of these assumptions was carried out and, where possible, attempts made to quantify their effects for two types of vessel. The vessels considered were a modern cruising ketch of 36 feet waterline length and a three masted barque of 120 feet waterline length.

1. A vessel at rest in calm water is unlikely to be subject to severe wind heeling forces. When underway the vessel sets up a pattern of waves which, in the extreme case of a vessel at high speed, might take the form of a single wave with a trough near amidships and crest at the bow and stern. The vessel will, of course, sink into this trough in order to remain in equilibrium. To simulate this extreme condition, stability calculations were carried out with the vessel at equilibrium on a wave of length equal to the waterline length and height of length/20. The results of this test and the results obtained in still water are shown in Figure 2 and 3 show how the resulting GZ curves compare with the curves obtained in still water. It is clear that the stability of the modern yacht form is affected little by the wave system whilst the ship form gains a significant margin at all angles of heel.

When sailing in following seas a vessel may remain poised in a wave trough or on a crest for several seconds, perhaps long enough to be capsized if struck by a sudden gust of wind. Calculations were carried out with the vessel at equilibrium on waves with a crest amidships and with a trough amidships. Waves of length equal to the waterline length and a height of length/4 were used to represent a very extreme case. An alternative case of a vessel twice the length and a height of wavelength/10. CZ curves calculated for these conditions are presented in Figures 4 and 5. The results indicate that the stability of the ship form is severely diminished when on a wave crest and this result would be expected by naval architects working in other fields. For the yacht form however, the variations are less significant and the trend is less obvious.

2. A sailing vessel working to windward produces a hydrodynamic sideforce to balance the aerodynamic sideforce generated by the rig. This is generated by a low pressure region on the windward side of the hull and keel and a high pressure on the leeward side. This results in an alteration of the water surface elevation, lowering it on the windward side and raising it to leeward. This adjustment will be at a maximum near to the centre of lateral resistance and reduce to nothing at the ends where the pressures must be equal.

These waterline adjustments may, therefore, be thought of as approximating to an increase in the effective heel angle, the higher waterline to leeward perhaps influencing the angle of downsloping. Typical values for the forms considered would be 6 tonnes of sideforce resulting in a peak difference between the port and starboard waterlines of about 9 mm for the ship form at 10 degrees heel, and 1 tonne of sideforce resulting again in 9 mm difference between waterlines for the yacht form at 20 degrees heel. These equate to effective increases in heel angle of 0.06 and 0.13 degrees respectively and can therefore probably be neglected.

3. When a partially full tank of fuel or water is heeled in a ship, the contents move transversely and have an adverse effect on stability. This is conventionally taken account of by the use of an adjustment to the ship's vertical centre of gravity, or free surface correction.

This is defined as:

\[ FSC = \frac{\text{(Transverse Second Moment of Area of the Tank x Density of Content)}}{\text{Displacement of Vessel}} \]
This adjustment is correct for small angles of heel but not for the large angles of 30 to 90 degrees which are of interest in sailing vessel survival. To quantify the likely errors, two imaginary tanks were chosen to test their influence on the ship form. They were of dimensions:

Tank 1 - length 6m, breadth 1m, depth 4m
Tank 2 - length 4m, breadth 4m, depth 1m

Thus both had a capacity of 10^3 m^3 and would be considered as very large tanks for a vessel of this size. GZ curves were calculated for the vessel with each tank in turn, half full. In each case the conventional calculation using the appropriate free surface correction was compared with the correct calculation allowing the liquid to find its true level at each heel angle. The results are compared in Figures 6 and 7. They indicate that for a deep, narrow tank the conventional calculation gives a good result. For a wide shallow tank the conventional calculation gives a rather pessimistic result at large angles.

4. The atmospheric boundary layer and wind gradient are now well documented and result in considerably higher wind speeds at themasthead than at the dock.

Nominal wind speeds are normally quoted by meteorologists for a height of 10 metres or 30 feet above the ground or water surface and so in the wind gradient calculations the velocity is lower below this height and higher above it. The gradient takes the form of a logarithmic function of height, reaching a maximum at several thousand feet. For the two rigs considered, the conventional calculation, using a uniform wind speed, was compared with a calculation taking account of the wind gradient. The wind gradient affects both the total force on the sails and the height of the centre of effort. A nominal wind speed of 10 knots was used.

The results are presented in the table below:

<table>
<thead>
<tr>
<th>Sailing Vessel</th>
<th>Moment kg m</th>
<th>Force kg</th>
<th>LEVER kg m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ketch</td>
<td>509</td>
<td>8.38</td>
<td>6076</td>
</tr>
<tr>
<td>Barque</td>
<td>5173</td>
<td>15.75</td>
<td>78610</td>
</tr>
</tbody>
</table>

5. Most conventional wind heeling calculations are carried out on a sail plan drawn with all sails set flat and parallel with the vessel's centreline. This can never be the case with square sails and very rarely with fore and aft sails. In fact, for a square sail set at 45 degrees to the centreline, its projected profile area is only 70% of its actual area.

6. All sails are assumed to have a heeling force coefficient of 1. That is, the force they generate is equal to the wind pressure times their area.

Wind tunnel tests have demonstrated that sails of different plan forms generate very different force coefficients. High aspect ratio triangular sails do, indeed, have heeling force coefficients of about 1.1 or 1.2 but four sided sails, such as gaffs and square sails, have coefficients as high as 1.6 or even 2.

7. To neglect overlaps may also seem strange when the sails are trimmed, such that their complete area is working. A decision, therefore, has to be made on whether to consider projected areas or total areas. For the steady wind calculation the total area is undoubtedly at work in driving, and hence heeling, the ship, whereas a gust from the beam,
however, the sails will probably stall and their projected area will be more relevant.

8. All sailors will be familiar with the fact that the vessels heel most when pressed hard to windward and hence with no apparent wind from well abaft the beam. Wind tunnel tests have shown, however, that heeling moments are minimized when the wind is abeam and the sails are sheeted for close hauled sailing. The sails are then stalled. In practice, when sailing to windward and struck by a gust from abeam, the helmsman either alters course or eases the sheets to prevent excessive heel. The situation most likely to result in a knockdown occurs when the helmsman fails to see a gust or respond in time and it is therefore relevant for the regulations to consider this.

Model tests indicate that for fore and aft rigged vessels with triangular sails, the assumptions 5, 6, 7 and 8, when taken together, give reasonable estimates of the heeling moment produced by a beam wind with the sails sheeted in hard. For square rigged vessels or those with four sided fore and aft sails, however, the evidence indicates that their heeling moments are underestimated by perhaps 50% in such circumstances.

9. Many performance prediction methods use the assumption that heeling moment varies with cosine, rather than cosine, of the heel angle. This may indeed be the case with all sails drawing when working to windward, but again, when considering the gust from abeam, cosine of the heel angle is more likely to be representative. When at 90 degrees of heel, however, both these functions reduce to zero and in fact there will remain a heeling moment due to the exposed portion of the hull. For the ketch considered here this heeling moment would be 0.77 tonnes metres and for the barque 0.6 tonnes metres with a wind speed of 25 knots. These both represent 5% of the upright values in the same wind speed.

If struck by a gust with a downdraught component, the wind heeling moment will reach a maximum at some heel angle other than upright.

10. The downdraught component of the aerodynamic driving force for the barque at 10 degrees heel would be 3.1 tonnes or 0.25% of its displacement. For the ketch at 20 degrees heel, it would be 0.34 tonnes or 1.9% of its displacement. These forces would result in a draught increase of about 4 m and 10 m respectively. The bow down trim moment resulting from the aerodynamic driving force acting at the centre of effort of the sails might typically result in trim changes of 0.1 degrees for the barque and 0.2 degrees for the ketch.

These effects are less than those resulting from variations in loading condition and are therefore probably not worth considering.

11. Gusts obviously cannot result in an instantaneous increase in wind speed although the duration of the increase might be small in comparison with the duration of the gust. The vessel might, therefore, have a response resulting in a heel angle somewhat less than that which would result from an impact, but more than would result from the steady heel angle at the gust wind speed.

12. When struck by a gust a vessel is most likely to be sailing at some steady heel angle or oscillating about that mean heel angle due to wave action. If she happens to be heeled to windward at the mean angle when struck by the gust, she will not only respond to the gust pressure but also the energy stored in her deviation from the mean angle will be converted into kinetic energy causing a more serious roll to leeward. These two effects are considered together in many current regulations considering wind heeling forces on other types of vessels. By assuming that the vessel is upright a similar effect has, perhaps unintentionally, been built into the conventional methods for sailing vessels. For example, if a vessel has a steady heel angle of say, 10 degrees and a roll motion of 10 degrees to port and starboard, then effectively she will be rolled to windward when upright.

13. The moment of inertia of a vessel governs its speed of response to a gust. A heavy vessel with a high inertia will respond more slowly than a light vessel or one with all its weight concentrated in the canoe body. The moment of inertia is unfortunately very difficult to calculate or measure accurately since it involves not only the components of the vessel, but also the "added inertia" of the entrained water which is induced to move by the motion of the boat itself.
years has forced some authorities to consider their particular characteristics. Table 1 summarises the regulations for the nine countries known to apply them.

The regulations for sailing vessels are based on height, length, and speed. The height of the sailboat and keel will determine the rating. The regulations are consistent in that they require a minimum height of the sailboat and keel. The regulations also require that the sailboat and keel must be fitted with a bilge keel.

14. It is normal for vessels to grow in weight over a period of years because of new equipment and fixtures. This weight is normally added above and hence raises, the centre of gravity. When under way in severe conditions, the vessel, if made of absorbent materials, may gain a considerable amount of weight of water and raise the VCG further. An allowance ought, therefore, to be made for these and any other factors affecting the vessel's condition, either by a safety margin in the stability criteria or by a weight and VCG margin applied to the lightship weight.

15. The righting moment is defined as the angle of heel where the vessel will return to its upright position. The maximum value of the righting moment is the maximum angle where the vessel will return to its upright position.

The regulations currently under development by the UK Department of Transport have benefitted from all the previous research and recommendations. The authorities have taken into account the results of research and have adapted the criteria to the needs of the sailing community. The regulations are designed to ensure the safety and stability of sailing vessels and to promote fair competition among the different types of vessels.

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In spite of these substantial variations, all but one of these authorities now have a system of classification based on the vessel's length and displacement. This is known as the 'dynamic' yaw criteria, and is again only one exception, they incorporate only a simple energy balance taking no account of damping or inertia.

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1. By incorporating a steady wind heeling criterion without a wind relief angle, all vessels are penalised and very large vessels are not tested severely enough.

2. By using a heeling force criterion, the rating for profile areas and sails, the regulations are less consistent. The regulations are based on square rigged vessels and those carrying gaffs or fisherman staysails.

3. By calculating the downflooding numeral, T, using the area under the downflooding curve at a downflooding angle of 70 degrees, the regulations give little benefit to those vessels with downflooding angles greater than 70 degrees. Furthermore, no benefit whatsoever is gained from having a downflooding angle greater than 70 degrees since the required numeral becomes a constant. There is therefore little regulatory incentive to delay downflooding to the greatest possible angle.

4. Similarly, by calculating the range numeral, U, using the area under the downflooding curve at a downflooding angle of 120 degrees, there is little incentive to maximise the range beyond that angle. Designers and builders should be encouraged to strive for the greatest possible range of stability, as good recovery from a wave induced capsize.

5. The stability numerals used, while not particularly complicated, contain a factor which means that vessels which are not wind pressures and are therefore difficult to capsize, will receive the 'dynamic' yaw criteria, and is again only one exception, they incorporate only a simple energy balance taking no account of damping or inertia.

It is the hope of many designers and operators that the rules will discontinue the regulation of steady wind heeling criterion and leave control in the hands of the skipper. He will shorten sail when he considers it appropriate in the weather conditions, having due regard to our factors of the vessel's ability of his crew, his course, the sea state, the motion and wetness of his vessel, and likelihood of squalls and their visibility. What it is more important that the vessel and its equipment will be continually maintained. The regulations currently under development by the UK Department of Transport have benefitted from all the previous research and recommendations. The authorities have taken into account the results of research and have adapted the criteria to the needs of the sailing community. The regulations are designed to ensure the safety and stability of sailing vessels and to promote fair competition among the different types of vessels.

6. The required numerals are based on a number of samples which are not a representative of the vessel's characteristics. For example, a vessel with a range of stability of 90 degrees or more would usually be required to meet a range of 70% of the pressure (or 84% of the velocity) of the vessel's displacement and the same displacement with a range of 80 degrees would be required to survive.

7. The OM criteria for the vessel in storm conditions is of doubtful value because it is virtually impossible to measure accurately the effective windage of the complete vessel, including a traditional sailing vessel.

Whilst the regulations do not make accurate predictions of the response of a vessel in a practical situation, they enable a comparison of vessels with those of the statistical sample. The regulations of other countries vary considerably in their case of application. Vessel variations in their severity suggest that they were not all derived with thorough investigation and are not valid for a range of vessel types. Rather, they have been adapted to the needs of the sailing community. The regulations are designed to ensure the safety and stability of sailing vessels and to promote fair competition among the different types of vessels.
PROPOSALS FOR FUTURE RESEARCH

With the growing interest in sailing large vessels and in sail training, the need for an improved understanding of data available in the hands of authorities on the stability of vessels of all types has been brought together for the first time in the report. While the authors have made a realistic choice of criteria values, to obtain the greatest number of results, and hence the maximum benefit, the authorities of several countries should make available the data held on their files which might otherwise be assembled for analysis by the appointed researches.

The assumptions outlined earlier in this paper should be examined in more detail to assess their influence and some of these will require wind tunnel tests for an effective investigation. Such tests could be used to establish heeling force coefficients for various sail plan forms and rig types, the variation of heeling moment with heel angle and the effects of wind gradient. These tests could all be conducted using a single hull model with a number of rig alternatives fitted in turn. Wind gradients can be introduced to the wind tunnel flow, hence results could be obtained with and without the gradient to determine its importance.

In order to investigate the validity of predictions of a vessel’s response to steady conditions, observations may be made on board vessels at sea and these observations compared with the calculations. A number of British skippers are currently assisting the Wolfson Unit with such an exercise. Once during each watch they are keeping data such as apparent wind speed and direction, heel angle, sails set, sea state and the vessel’s loading condition.

To investigate transient responses to gusts and waves, however, requires a more sophisticated experiment since wind speed and heel angle measurements must be monitored continuously in order to record the events adequately. It is hoped that suitable data logging equipment may be installed temporarily on a selection of vessels to study this important aspect. A better understanding of the effects of gusts and the importance of the vessels’ inertia and damping characters might then be gained.

Whilst several methods have been proposed in the literature for calculating the roll moment of inertia of a vessel and its associated radius of gyration, these have always been approximate and resulted in errors greater than 10% in some cases. Work currently in progress in the United States on fishing vessel floating, whichever is less. B is displacement.

Therefore the GZ curve is drawn to the angle of deck edge immersion (but not to less than 90 degrees or more than 150 degrees). If the maximum value of GZ occurs at an angle less than 35 degrees, the curve is truncated by a horizontal line through the value of GZ at 35 degrees.

Assume a heeling arm curve of the form

\[ HZ = HZ'\cos\theta (\text{heel angle}) \]

where \( HZ' \) is the heeling arm when upright.

Three heeling arm curves are then calculated to provide a static balance at the angle of deck edge immersion; dynamic balance to the downward angle of 90 degrees whichever is less; and dynamic balance to the angle of vanishing stability or 90 degrees if the angle is less than 90 degrees or 120 degrees if the angle is greater than 90 degrees. (The vessel's range is less than 90 degrees is thus penalised by inclusion of the negative area under the GZ curve up to 90 degrees).

These heeling arm curves have upright values denoted \( HZ_a \), \( HZ_b \) and \( HZ \), respectively.

In each case this arm is then multiplied by the factor 1000 /Ab and the results rounded to the nearest 1, 7, and 9 respectively, where \( A \) is the projected windage area with all sail set but neglecting overlapping areas (except in the case of spinnakers); \( B \) is the height of the centroid of \( A \) above the centroid of the underwater lateral area or the half draught.

The following criteria are then applied:

\[ \begin{align*}
\text{a) Small vessels of less than 65 ft on deck operating in protected or partially protected waters in daylight hours, carrying less than 50 passengers, provided they do not have an overall hull form or rig. To be assessed by the authority taking due consideration of the ability to withstand passenger crowding and wind heeling under full sail and bare poles (or storm sails if there is no auxiliary propulsion) with a crossing half the freeboard. Particular attention would be paid to vessels of broad, shallow form with little external ballast.}
\end{align*} \]

\[ \text{b) Other vessels:}
\]

i) Where under bare poles or storm sails the GM must be at least:

\[ \text{P/H} \text{D} /\text{m} (A) \]

where \( P \) depends varying on the region of service. A is the angle of deck edge immersion or a third of the angle of