THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
601 Pavonia Avenue, Jersey City, New Jersey 07306
Paper to be presented at the New England Sailing Yacht Symposium
New London, Connecticut, March 4 & 5, 1988

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 stability characteristics of a vessel are readily obtained to a high degree of accuracy, the wind heeling and dynamic aspects of stability under sail should perhaps be brought in line 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 capsizes:

1. KNOCKDOWN 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 sideforce 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 upside 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 sailing 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,

at increased risk to capsize from the wind which is then on the beam or the wave, which might break.

4. CYCLIC ROLLING. A vessel's roll motion is governed by the frequency of the passing waves. If their frequency is close to the natural roll frequency of the vessel, resonance will occur. The amplitude of the roll motion will then increase with each successive roll until limited by the damping effects of the keel and rig. If these are insufficient and the wave forcing continues, a capsize could result. A similar effect may be caused by the aerodynamics of the sails when running dead downwind. Vortices may be shed from either side of the sail alternately and these cause a forced cyclic roll to develop if they are shed at the natural roll frequency of the vessel.

5. LOSS OF STABILITY ON A WAVE. When sailing downwind a vessel may remain on a wave crest for a prolonged period. Its stability is typically reduced when poised on the crest because of the hydrostatic characteristics of the modified underwater form. In addition to this the passage of waves causes a vessel to move vertically and hence increase or decrease the vertical acceleration on the vessel, which would otherwise be the constant value, g, due to gravity. This results in an increase or decrease in weight, just as is felt when standing in a lift. Since the righting moment is a function of weight, it too will decrease when the vessel descends from a wave crest and there will be a brief period of increased vulnerability. Whilst a number of fishing vessel casualties are thought to have resulted from loss of stability on waves, it is unlikely to be the sole cause of capsize of sailing vessels which normally operate with much greater stability reserves.

STABILITY ASSESSMENT IN THE DESIGN OFFICE

All yacht designers will be familiar with the terms 'Power to Carry Sail' and 'Dellenbaugh Angle'. These are the traditional measures of a yacht's ability to carry its sail plan without being heeled to unacceptable angles.

$$\text{Power to carry sail} = \frac{\text{Displacement} \times \text{GM}}{\text{Sail Area} \times \text{Heeling Arm}}$$

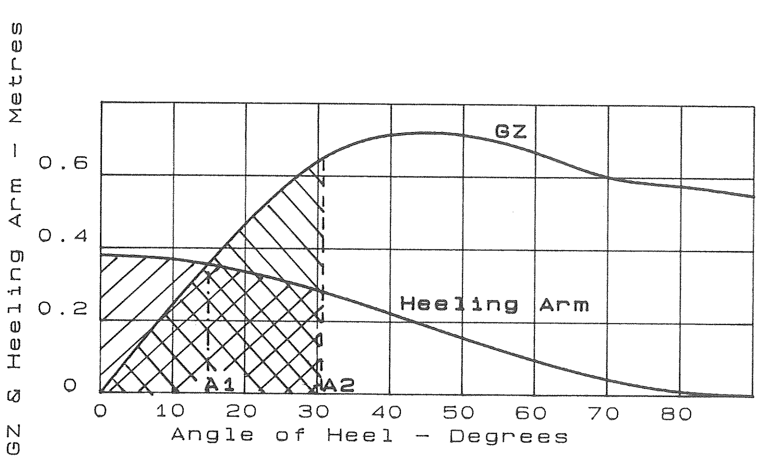
$$\text{Dellenbaugh Angle} = \frac{57.3 \times \text{Sail Area} \times \text{Heeling Arm} \times \text{Wind Pressure}}{\text{Displacement} \times \text{GM}}$$

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 Sail formula results in a less meaningful number and has consequently declined in popularity. The use of either of these terms requires a knowledge of what is considered 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 statical 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 statical stability calculation and enable them to carry out a more accurate prediction of the heel 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 significantly and to determine the equilibrium draught and trim at each consecutive heel angle requires many iterations which could not be contemplated without a computer. Whilst the accuracy of such programs depends to a large extent on the skill of the user, it is reasonable to expect displacement to be correct within 0.5% and GZ within a few millimetres.

In the modern design office, therefore, the GZ curve is calculated accurately for the vessel held at rest in calm water. This is compared with the heeling arm curve for the proposed rig at typical wind speeds to determine the sailing heel angles.

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 arm curve represents the work done by a gust of wind and similarly the area under the GZ curve, traditionally known as the 'dynamic stability', represents the energy absorbed by 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 arms for a typical yacht.



A1: Heel angle due to steady wind loading
A2: Heel angle due to instantaneous gust

Figure 1: Typical GZ Curve & Wind Heeling Arm Curve

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 fin keels. The designers of such yachts clearly had to compromise between performance and rating with no reward for considering stability at large angles.

More recently, rating rules have been developed to discourage this trend and attempts are 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 unseaworthy yachts in offshore category races. One such screening value was suggested by the joint committee on Safety from Capsizing of the USYRU and SNAME (Ref 2). It uses just the maximum beam and the displacement calculated by the IOR rule to estimate the yacht's vulnerability to capsize. Another, the Stability and Safety Screening Calculation Scheme, suggested by the RORC, incorporates many features in an attempt to judge the overall safety of the yacht. The adoption of such requirements will go some way to improving the seaworthiness of racing fleets in general but still may not pursuade 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 capsize of yachts. It has been shown that whilst some aspects of the design do affect its ability to withstand a capsize by a breaking wave, it is possible to capsize any yacht with a wave of sufficient steepness and height. Attention has therefore been focussed 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 elevation on both sides of the hull.
3. The free surface effects of slack 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.
8. The heeling moment is maximised with the wind on the beam.
9. Heeling moments vary with co (heel angle).
10. The vertical component and bow down trimming 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 crests 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 vessels at equilibrium on a wave of length equal to the waterline length and height of length/20. Figures 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 vessels 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/14 were used to represent a very extreme case. An alternative case of a higher but longer wave was represented by a wave of twice the vessel's length and a height of wavelength/10. GZ curves calculated for these conditions are presented in Figures 4 and 5. The results indicate plainly 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 downflooding. 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 tranversely 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 = (Transverse Second Moment of Area of the Tank x Density of Contents) / Displacement of Vessel

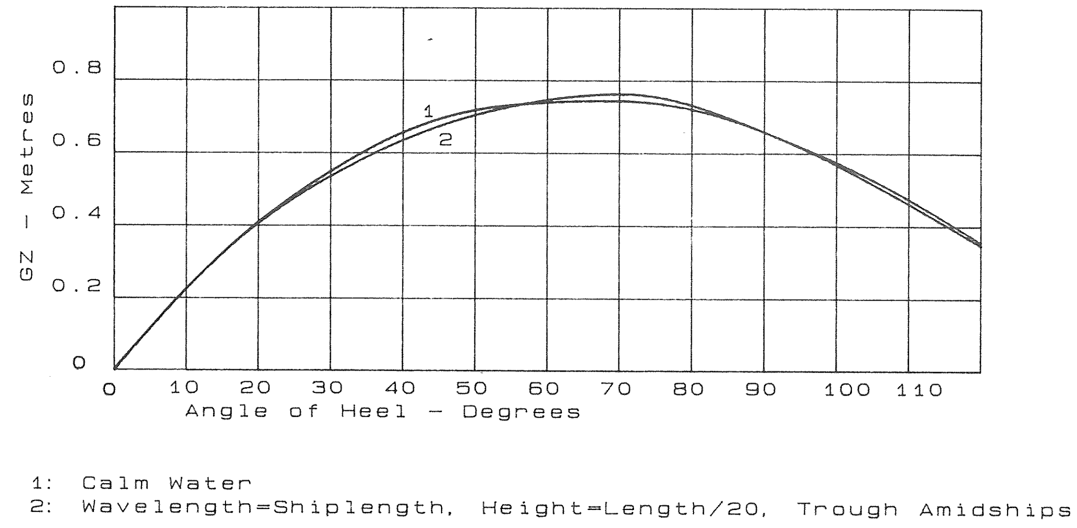


Figure 2: 36 ft Yacht Form
Stability on Self Propogated Wave

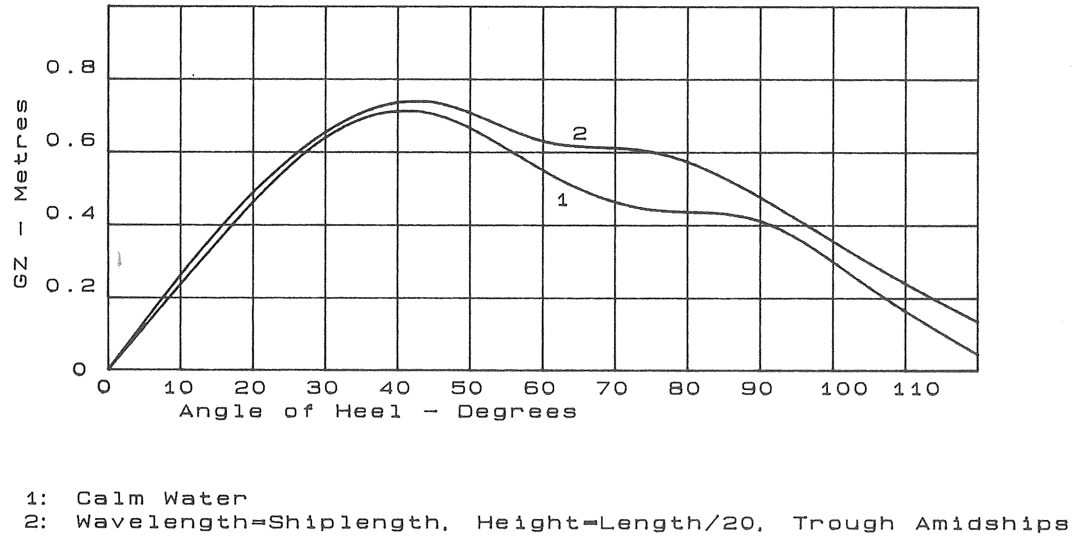
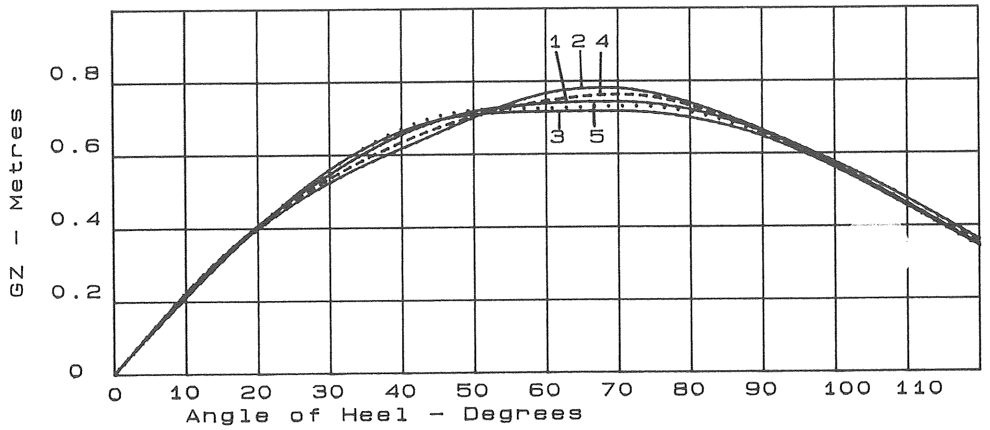
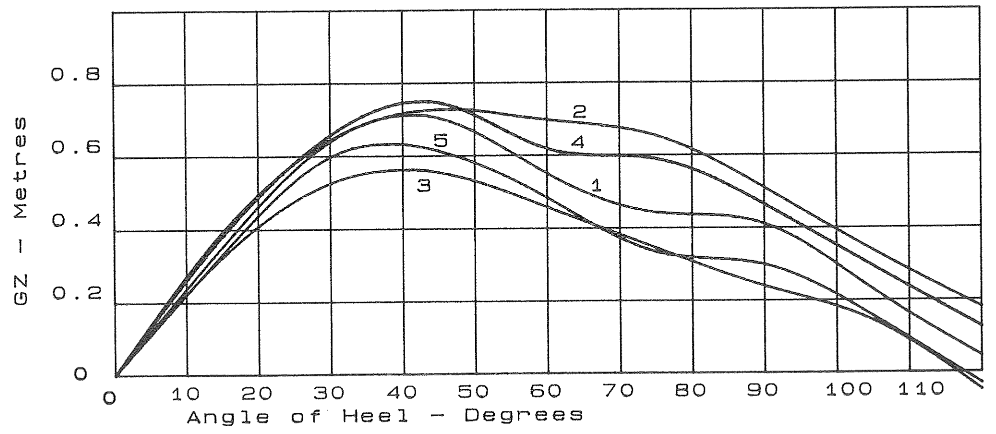


Figure 3: 120 ft Ship Form
Stability on Self Propogated Wave



1: Calm Water
2: Wavelength=Shiplength, Height=Length/14, Trough Amidships
3: Wavelength=Shiplength, Height=Length/14, Crest Amidships
4: Wavelength=2xShiplength, Height=W.Length/10, Trough Amidships
5: Wavelength=2xShiplength, Height=W.Length/10, Crest Amidships

Figure 4: 36 ft Yacht Form
Stability on Ocean Waves



1: Calm Water
2: Wavelength=Shiplength, Height=Length/14, Trough Amidships
3: Wavelength=Shiplength, Height=Length/14, Crest Amidships
4: Wavelength=2xShiplength, Height=W.Length/10, Trough Amidship
5: Wavelength=2xShiplength, Height=W.Length/10, Crest Amidships

Figure 5: 120 ft Ship Form
Stability on Ocean Waves

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

Thus both had a capacity of 16^{m3} 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 the masthead than at the deck.

   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 16 knots was used.

   The results are presented in the table below.

UNIFORM WIND

	Force kg	Lever m	Moment kg.m
Ketch	724	8.38	6067
Barque	4991	15.75	78610

WIND GRADIENT

	Force kg	Lever m	Moment kg.m
Ketch	589	9.84	5796
Barque	5173	18.00	93110

The ketch has a wind heeling moment some 4.5% lower when gradient effects are taken account of, even though its centre of effort is more than a metre higher. The barque, on the other hand, because of the greater height of the rig, has a moment 18.5% greater than that calculated by the conventional method.

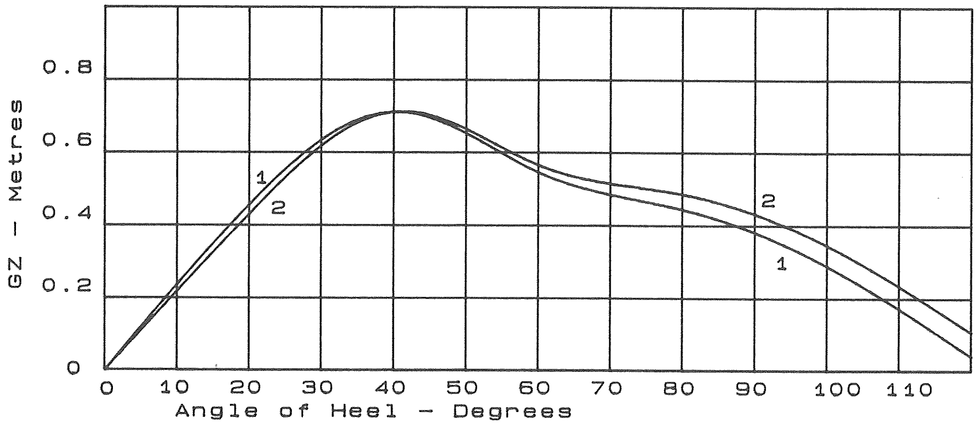
Current regulations are therefore more stringent for small yachts and more lenient for big ships. When considering gusts of wind, however, the wind gradient is thought to be significantly altered and the gust speed at sea level may be the same as at the masthead. In addition it is claimed that several recent incidents have been caused by gusts with a significant downward component.

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.

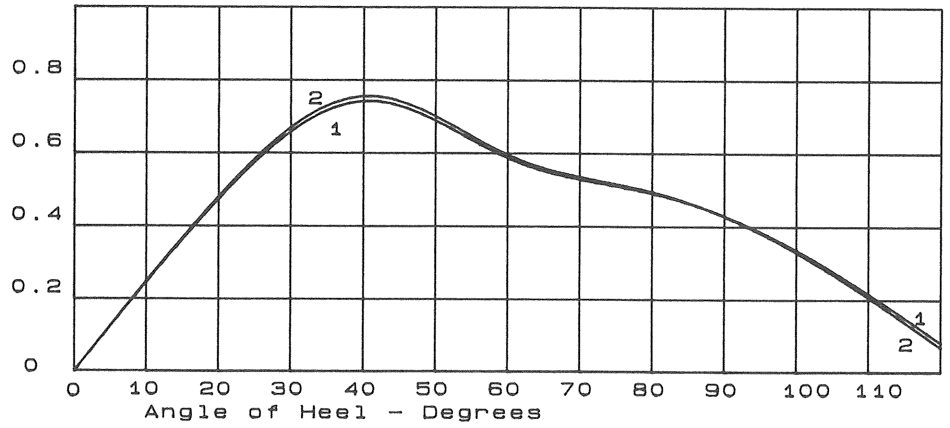
   Wind tunnel tests have demonstrated that sails of different plan forms generate very different force coefficients. High aspect ratio triangular sails do, indeed, have heeling force coefficients of about 1 or 1.2 but four sided sails, such as gaffs and square sails, have coefficients as high as 1.6 or 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. when struck by a gust from the beam,



1: Calculated Using Conventional Free Surface Correction
2: Calculated Using Correct Shift of Fluid

Figure 7: Effect of Free Surface Correction
Tank 2, A Wide Shallow Tank



1: Calculated Using Conventional Free Surface Correction
2: Calculated Using Correct Shift of Fluid

Figure 6: Effect of Free Surface Correction
Tank 1, A Deep Narrow Tank

however, the sails will probably stall and their projected area will be more relevant.

8. All sailors will be familiar with the fact that their vessels heel most when pressed hard to windward and hence with an apparent wind from well ahead of the beam. Wind tunnel tests have shown, however, that heeling moments are maximised 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 under-estimated by perhaps 50% in such circumstances.

9. Many performance prediction methods use the assumption that heeling moment varies with cos(heel angle) rather than $\cos^2$(heel angle). This may indeed be the case with all sails drawing when working to windward, but again, when considering the gust from abeam, $\cos^2$(heel angle) is more likely to be representative. When at 90 degrees of heel, however, both these functions reduce to zero when 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 tonne metres and for the barque 9.6 tonne 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 downward component, the wind heeling moment will reach a maximum at some heel angle other than upright.

10. The downward component of the aerodynamic driving force for the barque at 10 degrees heel would be 1.1 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 draught increases of about 4 mm and 10 mm 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 of 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 vessel. 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.

The roll motion of a sailing vessel is undoubtedly reduced by the damping effects of the hull and keel moving through the water and the sails and rigging moving through the air. Moreover, when the vessel is travelling at speed and rolling these damping effects will be increased. Again, the effects are extremely difficult to quantify but that their qualitative effects are well known is demonstrated by the number of merchant and naval ships fitted with bilge keels.

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 sails, 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 condition.

15. The righting moment is defined as GZ x displacement and displacement is mass x acceleration. With the passage of a wave crest, the vessel will accelerate downwards and experience a reduction in stability. Whilst the reduction may be substantial it is fortunately also likely to be short lived. If, however, the vessel were to be struck by a gust during that short period, it would be heeled to a greater angle than if it were on a flat sea.

Of all items discussed it would appear that the most significant are the effects of waves on the GZ curve, particularly for ship forms, and the effects of wind gradient and sail planform on the wind heeling curve. The effect of inertia and damping on the dynamic response of the vessel, whilst undoubtedly of importance, are as yet a relatively unknown quantity.

GOVERNMENT IMPOSED STABILITY REGULATIONS

The decline of sail driven merchant shipping preceded the regulation of ship stability by governmental bodies. As a result the regulations of the IMO and of most countries' governmental bodies contain no special considerations for sailing vessels. The growing interest in sail training and sailing vessel chartering in recent years has forced some authorities to consider their particular characteristics. Reference 1 summarises the regulations for the nine countries known to apply them.

The regulations for sailing school vessels applied by the US Coast Guard are probably the most comprehensively researched of those currently in use. They are based on a statistical survey of a number of sailing vessels, including three stability casualities, in an attempt to define the requirements for avoidance of such incidents. References 3 and 4 present details of the work. The regulations are summarised in Appendix 1.

The regulations consider three events which have physical significance to the sailor: immersion of the deck edge; immersion of downflooding points; and capsize. For the first of these events, it is the heeling moment provided, when under full sail, by a steady wind of Force 5 which is regulated. For the others it is the vessel's response to a gust which is considered.

The steady wind heeling criterion should not pose a problem for large sailing vessels which tend to have relatively low sail area/displacement ratios and therefore heel only a few degrees. Furthermore, because of their relatively high freeboard, they often have large angles of deck edge immersion. Small yachts, however, may find it a difficult criterion to meet because they are designed to sail close to their deck edge immersion angle, and they are penalised by wind gradient effects. This does not necessarily mean that they are deficient in stability since they might be in no danger from downflooding or capsize until considerably greater heel angles are reached.

The downflooding criterion requires that all new vessels must remain watertight up to at least 60 degrees and must have a range of positive stability up to at least 80 degrees. The criteria govern the gust strength required to knock the vessel down to these angles, the limiting values depending upon the actual downflooding and capsize angles and on the displacement of the vessel. For example, a vessel with a range of stability of 90 degrees or more would only be required to survive a gust of 70% of the pressure (or 84% of the velocity) that a vessel of the same displacement with a range of 80 degrees would be required to survive.

The main technical disadvantages of these regulations are considered to be:

1. By incorporating a steady wind heeling criterion without a wind velocity gradient, small vessels are penalised and very large vessels not tested severely enough.

2. By using a heeling force coefficient of 1 for all profile areas and sails, the regulations are thought to be more lenient on square rigged vessels and those carrying gaffs or fisherman staysails.

3. By calculating the downflooding numeral, Y, using the area under the GZ curve up to 60 degrees or the angle of downflooding, whichever is less, the regulation gives little benefit to those vessels with downflooding angles greater than 60 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, Z, using the area under the GZ curve up to a maximum angle of 120 degrees, there is little incentive for designers to maximise the range beyond that angle. Designers of small vessels should be encouraged to strive for the greatest possible range of stability to ensure recovery from a wave induced capsize.

5. The stability numerals used, whilst not particularly complicated, contain a factor which means they are not wind pressures and are therefore not familiar to naval architects. If wind pressures were used they might be more readily received by the designers, although of course they would not represent accurately the true wind pressures which would result in the various events.

6. The required numerals are based on a statistical group containing some samples for which important parameters were estimated.

7. The GM criterion for the vessel in storm conditions is of doubtful value because it is virtually impossible to calculate accurately the effective windage of the complex rig of a traditional sailing vessel.

Whilst the regulations do not make accurate predictions of the response of a vessel in a seaway, they do enable a comparison of vessels with those of the statistical sample. The regulations of other countries vary considerably in their ease of application. Similar variations in their severity suggest that they were not all derived with thorough investigation into their validity for a range of vessel types. Rather, they have been produced by adaptation of criteria applied to merchant or fishing vessels with which the authorities are more familiar.

In spite of these substantial variations, all but one of these authorities assume a uniform wind pressure over the full height of the rig. They all assume a heeling moment coefficient of 1 for sails which in turn are assumed to be sheeted along the centreline of the vessel and they all consider the vessel to be floating in equilibrium in flat water. Where the 'dynamic' gust criteria are included, with again only one exception, they incorporate only a simple energy balance taking no account of damping or inertia.

The regulations currently under development by the UK Department of Transport have benefitted from all the previous research and this authority has taken the unusual step of circulating all designers and operators of sail training vessels with proposals and discussion documents with invitation to comment and criticise. The resulting regulations should therefore take account of the range of vessel types currently in use and be at least as good as previous regulations in identifying the vessels most at risk.

It is the hope of many designers and operators that the authorities will discontinue the regulation of steady wind heeling angle and leave its control in the hands of the skipper. He will shorten sail when he considers it appropriate in the prevailing conditions, having given due regard to such factors as the strength and 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 for the skipper to obtain from the calculations is an assessment of what increase in wind strength would be required to increase his heel angle from that at which he typically sails the vessel, to that at which it may suffer downflooding or capsize. Whilst none of the current regulations specifically addresses the problem in this way, the naval architect, Roger Long, has proposed such a method, based solely on statical stability and steady wind heeling, which the authorities might consider as the basis of an alternative to their present methods (see Ref 1).

PROPOSALS FOR FUTURE RESEARCH

With the growing interest in sailing large vessels and in sail training there is now a substantial amount of data available in the hands of authorities on the stability of vessels of all types. These data should be brought together for a statistical study to assist in a realistic choice of criteria values. To obtain the greatest number of vessels, and hence the maximum benefit, the authorities of several countries should make available the data held on their files which might then be assembled for analysis by the appointed research body.

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 logging 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 characteristics might then be gained.

Whilst several methods have been proposed in the past 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 100% in some cases. Work currently in progress in the United States on fishing vessel stability (Ref 5) may yield improved methods which could be adapted for application to sailing vessels. If such is the case it may be possible in the near future to incorporate inertia effects into the stability regulations.

Much interest has been shown in recent months in methods of screening racing yachts to eliminate those considered deficient in stability, from racing offshore. Such screening systems might be of considerable value to authorities who wish to identify vulnerable yachts without recourse to detailed and expensive calculations. Great care must be taken, however, to ensure that the values chosen by these screening methods are well researched and reliable. The Stability and Safety Screening Calculation Scheme (SSSCS) developed by the Royal Ocean Racing Club for example, considers many design aspects which affect the general seaworthiness of a vessel and allocates factors to each one in a rather subjective manner. These are then combined to produce a single numeral. Such a system may not be acceptable to a governmental authority who normally prefers to ensure the adequacy of a vessel's stability, structural integrity, fire fighting and safety equipment independently of each other. There is scope therefore, for a more detailed investigation of these and other possible screening formulae to establish the most accurate method compatible with low cost application.

APPENDIX 1

UNITED STATES COAST GUARD REGULATIONS FOR SAILING SCHOOL VESSELS

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 unusual 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 auxilliary propulsion) without immersing half the freeboard. Particular attention would be paid to vessels of broad, shallow form with little external ballast.

b) Other vessels

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

PAH/Dtan(A)

where P varies depending on the region of service. A is the angle of deck edge immersion or a third of the angle of downflooding, whichever is less. D is displacement

ii) The GZ curve is drawn to the angle of vanishing stability (but not to less than 90 degrees or more than 120 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

$HZ = HZ'\cos^2(\text{heel angle})$

where HZ' is the heeling arm when upright.

Three heeling arm curves are then calculated to provide: static balance at the angle of deck edge immersion; dynamic balance to the downflooding angle or 60 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 120 degrees. (The vessel whose 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 H_{ZA}, HZ_B and HZ_C respectively.

In each case this arm is then multiplied by the factor 1000 /Ah and the results denoted X, Y and Z respectively, where A is the projected windage area with all sail set but neglecting overlapping areas (except in the case of spinnakers); H 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:

X must be at least 0.6 tons/sq ft Y and Z must lie above boundaries presented graphically in Figures AI-1 and AI-2 which should first be adjusted for the size of vessel by multiplying by a factor obtained from Figure AI-3.

c) Separate regulations apply for multihulls.

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