Stability Criteria for Sailing Vessels

P. Izaguirre-Alza[1], L. Pérez-Rojas[1], R. Zamora-Rodriguez[1]

([1]): Model Basin Research Group (CEHINAV), Naval Architecture Department (ETSIN), Technical University of Madrid (UPM).

Abstract

What do you know about sailing yacht stability? Which are the peculiarities of the stability of a sailing yacht? Is there any supposition different from those applied in conventional ships? If you have to verify the stability of your yacht, would you be sure of which criteria you should applied? The aim of this paper is to answer these questions among others. The authors assume that the readers of this paper come from varied backgrounds and experience. Some of you may not be totally familiar with these stability requirements whereas others may use them every day. It is hoped that this paper will be some enlightenment for the former and be an interesting review for the latter.

In this paper the philosophy of sailing yacht stability will be presented. It will be also examined the criteria in force in countries such as Spain, United Kingdom, United States and The Netherlands among others and the assumptions upon which they are based will be highlighted. In order to clarify ideas two reference sailing yacht will be subjected to different criteria and compared their severity.

1. Introduction

In the nineteen nineties a Technical Committee of the International Standards Organization (ISO) developed a standard for the assessment of the stability of pleasure craft with a length up to 24 m, which included sailing crafts (ref [1], ref [2]). These criteria left the small sailing yacht stability scenario sufficiently studied. Furthermore, Australia (ref [3]) and United Kingdom (ref [4]) have special criteria for small vessel which permit answering the most questions above easily. The problem comes when asking for large vessels and specially passenger vessels.

Nowadays there is a big concern in large vessels because there are large monohull sailing vessels over 130 m in length under construction, each of which can take up to 300 passengers. There have been carry out some studies to analyze the influence of the size with the stability and develop new criteria.

But there already exist conventional passenger vessels over 130 m, where is the difference? Usually a sailing vessel under bare poles is safer than a conventional vessel because of her low center of gravity but under sail is more likely to suffer a risky situation because of the wind. Several criteria of different countries establish for sailing vessels the requirements for conventional vessel and additionally specific criteria. This paper will be focused on the specific rules of sailing monohulls.

The specific classic requirements of stability for sailing vessels were in general developed in the beginnings of nineteenth when computers enabling precise determination of ship characteristics were not available. Most of the rules which are applied in these days are a compendium of classic simple formulae for determining the stability of vessels under sail. Now that the characteristics of a vessel are obtained fast and with a high degree of accuracy is has been able to establish modern requirements for sailing ships. The wind heeling moment and the dynamic aspects of stability are still under a comprehensive analysis. Current wind tunnels, new measurement systems, increasing electronic technology and many other progresses have made achievable to take into account factors which were impossible to assess so far.

Another important feature that is at its peak is the information and operational guidance to the master in the stability booklet, ref [5]. The new standards available to analyze and predict a sailing vessel's characteristics may now give an opportunity to provide better assistance to the captain for avoiding dangerous situations.

2. The Philosophy of Sailing Yacht Stability

The capability of a sailing vessel to withstand the action of the wind is represented by the righting moment curve (see figure 1). Some of the most important parameters that describe the stability of sailing yachts are the area under the righting moment curve up to the angle of vanishing stability, the righting lever at 90 degrees of heel and the downflooding angle, ref [2]. It is also important the shape of curve and the range of positive stability. Generally different criteria demand minimum values of these parameters.

For classic methods there are some characteristics of the vessel that must be known, apart from the righting moment curve, such as the displacement in different loading conditions, sail area and the general arrangement with and without sails.

- **Classic methods**

There are mainly two types of requirements that usually are presented together, static and dynamic stability.

In the first type, the righting arm (GZ) curve is calculated and compared with the heeling arm curve which is produced by a stationary wind. Both curves are plotted together and at the point which they cross the steady heel angle is defined. This angle must be below a certain value proposed by the corresponding administration.

Usually in each criterion a formula, a pressure and an angle are proposed. The formulation of the heeling arm curve is normally:

$$\text{Heeling Arm} = P \times A \times H / \Delta \times \cos^{\alpha}\theta$$

where,
A: sail area
H: distance between the geometric center of sails and geometric center of underwater body.
Δ: displacement
α: it was always 2 but new approaches have discovered that 1.3 fits better.
θ: heel angle
P: wind pressure. It is very variable. Some countries propose a pressure depending on the class of the vessels but others have standard pressure independently of the size and operation area of the yacht.

The proposed maximum angle it is usually the deck immersion angle. But in other cases, such as in the Spanish proposal (see appendix B), a fixed angle of 12º is required.

The second kind of requirements is traditionally known as the “dynamic stability” and refers to the capacity of the vessel to withstand a gust. The work done by a gust is represented by the area under the wind heeling arm curve, as the energy absorbed by the yacht which is represented by the area under the righting arm curve. The angle at which these areas are equal defines the angle to which a vessel will be dynamically heeled by the gust. Depending on the administration, there are several ways of representing the heeling arm curve. Sometimes, as in the static stability case (formula-pressure-angle) are proposed but in others a fixed value of area is requested. The criteria of the American Coastguard Agency (USCG) are based in the same philosophy but the minimum values are presented as numerals, both in static and dynamic stability.

As well as these two types of requirements some countries such as United States and the Netherlands require a minimum metacentric height specifically calculated for sailing vessels.

But there are some assumptions in classic calculation of wind heeling and its effects on stability that have been lately discussed, ref[6] and ref[7]:

(1) The wind is of uniform velocity at all elevations.

It is not uniform, there is a wind gradient. This makes that the upper part of the rig contributes more than the hull which is in a very low velocity region. The gradient also reduces de heeling moment when sailing at large angles.

(2) All sails have a heeling force coefficient of unity

That is, the force generated by the wind is always equal to the pressure times the sail area. But it has been demonstrated in wind tunnel tests that the coefficient depends on plan forms, sail sheeting and camber. The value can vary from 1 or 1.2 for high aspect ratio triangular sails to 1.6 or even 2 for four sided sails, ref [6].

(3) Overlapped sail areas produce no heeling moment.

When sails are trimmed correctly the total area is working in heeling the yacht. When struck by a gust from the beam, however, the sails will probably stall and their projected area will be more relevant.

(4) The heeling moment is maximised with the wind on the beam.

This is not always true. For example for a fore and aft rigged vessel the heeling moments is maximised with the sails sheeted in tight, but with the apparent wind angle between 40 and 60 degrees, ref [7].

(5) Heeling moments vary with $\cos^2$(heel angle)

The moment was found to vary with $\cos^{1.3}$ in the work in wind tunnel undertaken by the Wolfson Unit to develop stability criteria of sailing vessels, ref[7]. The new exponent makes the best fit to the data for different types of rig even bare pole and makes the value of the heeling moment be higher for every heeling angle, see figure 2.

The full scale data obtained in the SLIP (ref [5]) project appeared to validate the $\cos^{1.3}$ as opposed to the $\cos^2$ function used by the USCG regulations.

(6) When considering response to a gust, the increase in wind speed is instantaneous.

Significant gusts have a rise time of 10 to 20 seconds and because this rise is normally greater than the natural roll period of a sailing vessel, it does not respond as if to an impact on the mast. The yacht is able to adjust its heel angle as the heeling moment increases. It is clearly explained in ref [7].

(7) The vessel's inertia and damping have no effect on its gust response.

With bare poles the damping is purely the hydrodynamic contribution from the hull. The addition of sails causes a significant increase in the damping, and a further increase is provided with wind applied to the sails. The high damping provided by the rig prevents the vessel from responding in the dynamic way normally considered by naval architects as they assume for conventional vessels.

In the work of the Wolfson Unit (ref [7]) variations of inertia were studied and resulted in no alteration to the rate of change of heel angle in response to the gusts, or to the maximum heel angle measured. Consequently the effects were considered negligible in comparison to the damping and stability of a vessel when struck by a gust.

As it has been presented, several assumptions of traditional methods have been sufficiently refuted by experts. International community realized that a new point of view was necessary. Subsequently the relevance has been focused in the relation between the new stability approaches and the operational guidance to the master who should know when sailing at a certain angle the effect of a severe gust strike. This guidance should be useful for any sailing condition, weather, sail set, among other factors.

- **New developments**

The Wolfson Unit and sponsored by the UK Department of Transport developed new stability criteria appropriate for the safe operation of sailing vessels which were included in the Maritime Coastguard Agency's (MCA) Large Commercial Yachts Code (ref [8]) and they have turned into a reference in sailing vessel stability methods.

These criteria are clearly explained in ref [9]: "The wind speed required to heel a yacht to its downflooding angle will depend on the sails set, apparent wind angle, sheeting and other factors, but the moment required to heel to that angle will be the same regardless of the circumstances. It therefore a simple matter to use the heeling arm required to cause downflooding or capsize, calculate the corresponding heeling arm when the yacht is upright, then halve this value to derive a heeling arm curve and its intersection with the GZ curve which defines the maximum "safe" angle of heel in the mean wind. See figure 3. Provided this angle is not exceeded the yacht should be safe from downflooding in the event of severe gusts."

It was decided to establish a lower limit of 15 degrees after consideration of the values derived for known vessels including casualties. This decision was taken in order to guard against the operation of a vessel with a particularly low downflooding angle, which would result in an unrealistically low maximum steady heel angle, ref [7]. In the Spanish requirements (appendix B), the lower limit is 15 degrees for vessels operating in protected waters but as the operation area is further away from the coast the limit increases up to 28º.

There are two remarkable ideas in this new criterion. The first is that when struck by a gust a sailing vessel will heel to the corresponding steady heel angle at the gust wind speed (pressure) during the gust, ref [7]. The second idea is that the standard refers to gusts and not to squalls. The term squalls refers to a large scale turbulence, resulting from a small scale weather system whereas the gust is defined as the higher velocities of the fluctuating wind speed which occur in the earth's atmospheric boundary layer. Different studies indicate that the maximum likely gust speed factor is 1.4, and such a gust will increase the wind pressure and heeling moment by a factor of 2 (this is why the heeling arm at downflooding angle must be halved). Squalls, which can reach speed factors as high as 10, are taken into account in the stability booklet thanks to a graphical presentation that relates the intensity of the squall (wind speed) to the stability of the vessel (steady heel angle).

- **Range of stability**

This is a very important stability parameter which has always been included in the criteria even in the new developments.

With the new stability approach the effective range of stability can be found by drawing the heeling arm curve that is tangential to the righting arm curve. This situation will only be found however if the range of stability is less than 90 degrees (see figure 4). That is, a yacht whose range is less than 90 degrees is particularly vulnerable whilst a yacht with a range of 90 degrees or more cannot be capsized by the wind unless if has a downward component. The standards that come from this new approach consequently require a minimum range of 90 degrees.

Another important feature of a large range of positive stability is that increases the survivability after a breaking wave capsize. Yachts with low range of stability use to remain inverted following such capsize. The larger the wave encountered, the more likely is the capsize, so smaller vessels have a higher probability of capsize. Frequently standards require a greater range of positive stability for small yachts or for those sailing in exposed waters where a larger wave is more probable. For example in the MCA standard there is an alternative for vessel of more than 45 m, ref[8]. In this particular case a range of less than 90 degrees may be considered but it can be subject to agreed operational criteria. In the Spanish requirements it is only oblige the yachts sailing far away from the coast to have a range of stability of more than 90 degrees, see appendix B. More examples can be seen in next part "Exposition of Different Criteria".

- **Large vessels**

As it is has been raised in the introduction the size of the sailing vessel is increasing as the number of passengers does. The problem is that the size of these yachts is larger than of those included in the database used to develop the new stability approach. The question is if the increase in size affects the stability. Because the designers of these large yachts experienced difficulties in complying with the stability criteria, they proposed arguments in favour of a relaxation of the requirements.

In October 2006 it was published the report of the research project of the Wolfson Unit (ref [10]) which described a review of the sailing vessel stability requirements of the Large Yacht Code of United Kingdom, and considered the validity of their application to modern, very large yachts.

According to the report, in general, the relationship between heeling moment and righting moment does not tend to vary with size, so that there is no justification for relaxing the requirements for large yachts on the basis of size alone. But it is also recognised in the report that some vessels may have a very high initial stability and/or small rig, such that it would require unreasonably high wind speeds to caused a capsize. For such cases a criterion is proposed alternatively.

The Maritime and Coastguard Agency of UK published a notice (June 2007) advising of the research of the Wolfson Unit mentioned before and making clear that the work validated the method for larger yachts and recommends how the stability of large yachts which fail to achieve the criteria in full may be managed, ref[11].

- **Stability booklet**

Once the administration of each country has approved the stability requirements of a certain vessel there must be a bridge between that information developed by the naval architect and the master. This is materialized in the stability letter, or stability booklet, and it should be a practical stability guidance to the master and the crew and a method to assess risky situations. Because of these motives the letter must be clearly and understandable presented. It shouldn't include operational orders but means of assessing dangerous situations based on the sail combinations, weather and other factors.

Thanks to the development of new stability approaches it can be easier achieve these objectives. Following, two presentation models will be introduced.

The MCA requires in the stability booklet a graphical presentation of the maximum heel angle at which the vessel may be sailed in a given wind speed, in order to withstand a squall of a certain strength. It must be remember that their stability criteria are based on gusts and that maintaining a mean heel angle below the maximum recommended by the new approach will not necessarily provide protection against downflooding in a squall, since the wind pressure produced by a squall may be many times that of the preceding wind.

The curves of maximum steady heel angle in this graphical presentation (see figure 5) are derived using the same philosophy as was developed for deriving the corresponding angle for gusts, ref [7] and ref [8].

The second presentation model is being developed in the SLIP (Stability Letter Improvement Project) project of SNAME, ref [5]. They have realized that the required stability letters by the USDG are not fully useful and need to have a renewal.

The first change is the point of view of the stability method since until now, the classic requirements are used. One of the aims of the project is developing new stability analysis approaches. They will likely be based in similar assumptions to the ones used in the modern methods and include new assumptions on weather parameters such as potential wind gust magnitudes and durations that could be experienced.

One of the graphical models proposed in the project is the color code matrix. For this format (see figure 6) the color coding is used to indicate the level of risk present. The basic colors are proposed to indicate the following risk levels.

Green: indicates an angle of heel below deck immersion.

Yellow: indicates the deck edge is likely to be submerged but the heel angle remains in the safe zone established by the MCA code.

Orange: indicates a heel angle greater than the MCA code limit but less than the angle which corresponds to bulwark immersion.

Red: indicates an angle of heel corresponding to between 84% and 100% of GZ max and results in a high level of weather related risk form downflooding through hatches.

Black: indicates sailing at heel angle at or beyond GZ max.

For all color zones, the position in each color band also provides an additional indication of the risk.

3. Exposition of Different Criteria

In this part the regulations of seven countries will be explained. Only the Spanish rules are included in the appendix B because the other can easily be obtained. The aim of this paper it is not applying rules but be aware of the basis of the different criteria.

- **United Kingdom, ref[8]**

The rules are applied to sailing vessels of 24 metres in load line length and over (and less than 85 m) in commercial use for sport or pleasure and carry no cargo and no more than 12 passengers. The Code only applies to vessels of less than 3000GT. Sail training vessels are included in this application.

a) Curves of statical stability (GZ curves) for at least the Loaded Departure with 100% consumables and the Loaded Arrival with 10% consumables should be produced.

b) The GZ curves should have a positive range of not less than 90º. For vessels of more than 45 m, a range of less than 90º may be considered but may be subject to agreed operational criteria.

c) The angle of steady heel should be greater than 15 degrees (see figure 3). The angle of steady heel is obtained from the intersection of a "derived wind heeling lever" curve with the GZ curve. This criterion is based in the new stability approaches.

- **SPAIN (see appendix B)**

These regulations are not compulsory and for the time being are solely indicative under an equivalent point of view. The rules are applied to passenger sailing monohulls and are based on both classic and new stability approaches. Vessels should meet:

a) General rules of conventional passenger vessels issued by de Spanish administration.

b) Static stability (Pressure + angle + formula). The pressure depends on the class of operation, the angle is 12º (and the vessel will not immerse more than half the freeboard). The formula is similar to the one presented before with 1.3 in the exponent.

b1) Alternatively, for vessel in sport use, the requirement c) of United Kingdom can be applied. The only difference is that the steady heel angle must be greater than a value that depends on the class: 28º 23º, 19º and 15º (from unlimited waters to protected waters).

c) Dynamic stability: the areas up to the angle of maximum arm and up to the angle of vanishing positive stability (or downflooding if less) should be greater than certain values that depend on the operational class and the displacement.

The values are related to the ones obtained by the working Group 22 of Technical Committee 188 of the International Standards Organization when developing the standard for the assessment and categorization of the stability of pleasure craft with a length up to 24 m, ref [2].

d) The righting arm curve must have a range of positive stability beyond 90º for vessels that sail 20 miles away from shelter and class B (less than 20 miles away).

- **USA, ref[12]**

The criteria is applied to sailing monohull vessels to be operated on exposed waters and/or to be operated during non-daylight hours and/or of unusual type and/or carry more than 49 passengers and/or school vessels and/or on which downflooding occurs at angles of 60º or less and/or have a cockpit longer than Length Over Deck (LOD)/5. These vessels must fulfil three requirements that are based on the classic stability methods:

a) The metacentric height in each loading condition must be equal or greater than a value calculated with a formula that depends on the length between perpendiculars, the area of service (ocean, Great Lakes, protected waters), the projected lateral area without sails, the displacement and the angle of deck immersion.

b) The range of positive stability must be equal or greater than 70º for vessels operating in partially protected water or in protected waters. In the case of sailing in exposed waters the minimum range is 90º.

c) Depending on the service (exposed waters or not) three numerals must be exceeded. The regulation considers three events with physical significance:
c1) Deck immersion
c2) Immersion of downflooding points
c3) Capsize
The first is static stability and is related to the heeling moment provided by a steady wind of Force 5. The other two events are dynamic stability requirements of the response to a gust. This criterion (c) is still based on the classic methods.

- **NETHERLANDS, ref[13]**

These rules for sailing vessels of Commercial Cruising Vessels (CCV) apply to seagoing cruising vessels for commercial use with a length exceeding 12 metres, designed and built for recreational use by passengers but not more than 36. In all possible load conditions, the following specific criteria for sailing vessels shall be met, as well as some others of conventional vessels:

a) A minimum initial metacentre height for all type of sailing vessels.

b) Static stability (Pressure + angle + formula). There are two values for pressure, one for lowered sails and another for under sail. The angle is 20º (or the deck immersion angle if it is less) and the formula is similar to the one presented before with the same exponent of the cosine, 2.

c) Dynamic stability. In this case there are also two pressures, for lowered sails and for sails up. The aim of this requirement is that the mentioned pressures caused by a gust shall not result in an angle of heel of more than 50º or the downflooding angle if it is less.

- **AUSTRALIA, ref[3]**

The Australian rules apply to commercial vessels. There is an additional comprehensive stability criteria for all sailing ships that have an alternative for vessels up to 24 metres and another alternative for monohulls less than 15 metres in areas of operation D(partially smooth water operation) and E (smooth water operation). All monohulls that set sails must comply with:

a) A positive range of stability of not less than 90º for A (unlimited domestic operation) and B (offshore operation) and not less than 70º for C (restricted offshore operation),D and E.

b) Static stability (pressure + angle + formula). The pressure is the same for all sailing vessels and the angle is the one of deck immersion.

c) Dynamic stability. In this case the method is also (pressure + angle + formula). The pressure depends on the operational area and the angle is the downflooding angle (or 60º if it is less).

d) Dynamic stability. It is also (pressure + angle + formula) but the angle is the vanishing positive stability angle (or 90º if it is greater) and the pressures differ from the ones in c).

The criteria are similar to the requirements of USA except next differences:
- The moment is obtained with $\cos^{1.3}$ instead of $\cos^2$.
- The criterion b) in the case of USA(c1) is divided in two. This criterion will be equivalent of the partially protected waters of the American criterion.
- It is not used a numeral as in the American case but a certain pressure that is equivalent.
- The formula for calculating the heeling levers in c) and d) is different from the American but the concept is the same.

The alternative criteria for vessels up to 24 m are similar to the English. The only difference is that the requirement of positive range of stability in this case is 110º instead of 90º. And the alternative for vessels less than 15 m in operation areas D and E is a criterion based on static stability (pressure + angle + formula). Both alternatives can be found in ref[3].

- **NEW ZELAND**

With regards to design, construction and equipment there is no maritime rule specifically for sailing ships. As a consequence, Maritime Rule Part 40A *Design, construction and equipment – Passenger ships which are not SOLAS ships* is being used instead. This rule is not suitable for sailing ships as it is written for ships that are primarily powered by an engine, not by sail. The new rule under development is titled Maritime Rule Part 40E Design, construction and equipment – sailing ships. It has been drafted using reference from the MCA's Large Yacht Code, MCA's Small Yacht Code and their own Maritime Rules. It applies to every New Zealand commercial sailing ship except ships of 45 metres or more in length that proceed beyond restricted limits, fishing ships and open sailing boats other than sail training ships of 15 metres or less in length.

It is basically the same as the Large Commercial Vessels Yacht Code of MCA. The significant differences are in the positive range of stability. In this rule, the curves of statical stability (loaded departure and loaded arrival conditions) must have a positive range of stability of:
- L(length) ≥ 24 m: 90 degrees;
- 15 m ≤ L < 24 m (that do not proceed beyond offshore limits): not less than 110 degrees;
- 15 m ≤ L < 24 m (that proceed beyond offshore limits): not less than 115 degrees;
- L < 15 m: the positive range of stability of the loaded departure condition must not be less than 95 degrees.

- **FRANCE**

Over 24 m of length, the IMO resolution A.749(18), transposed within Division211 of the French Arrêté du 23 novembre 1987 relatif à la sécurité des navires should be met. This regulation will be soon superseded by an adaptation of the MCA Code, which includes specific criteria for sailing vessels as it has been explained.

4. Application to Reference Yacht

In order to compare the different criteria mentioned before, they are applied to two yachts. The first of them, A, smaller than B, is a yacht already in operation and has all the convenient stability certificates. The yacht B has been obtained from a project of a passenger sailing vessel of 100 feet in length. In the appendix C the fundamental features of both yachts are included and all the data that is necessary for the application of the criteria that are presented in this paper.

The results of the application can be observed in table 1. The criteria of Spain, United Kingdom, United States and the Netherlands have only been applied since they are the most characteristics.

As it can be seen on the table, both yachts fulfil the Spanish criteria as long as the alternative criterion b1) is met instead of b). It can be also deduced that the American requirements are the strictest. Both yacht A and B meet the criteria of United Kingdom and Netherlands.

The requirement B) of Spain is similar to c1) of United States and b2) of the Netherlands. In this last one the wind pressure, independently of the operational area, is 7 kg/m² which is equivalent to a Beaufort 5. Furthermore, the maximum steady heel angle is 20 degrees. Therefore the Spanish requirement is stricter because it demands for a wind pressure of 12.6 kg/m² a steady heel angle lower than 12º. It must be also be highlighted that because of the fact that in the Spanish criteria the exponent of the formula of the heeling arm is 1.3 instead of 2 as in the Netherlander the requirement becomes even stricter. Regarding the American criterion, it demands an steady heel angle lower than the deck immersion angle for a wind pressure of 10.9 kg/m², which is equivalent to a Beaufort 6, and with exponent 2. It can be also concluded that the Spanish is stricter assuming that the angle of deck immersion is considerably greater than 12º.

The philosophy of the criterion c2) of Spain is the same as the American c2) but the requirements are different. In both cases the objective is that there should be sufficient area under the righting arm curve up to the downflooding angle to dynamically withstand a wind gust. In the Spanish requirement a certain value is directly demanded whereas in the American criterion the gust pressure is proposed for the heeling moment formula.

The requirement d) of Spain is similar to the b) of United Kingdom and American b). In the three cases it is required a range of positive stability beyond 90º.

If it is compared the value of metacentric height that must be exceed depending of the country we realized that the differences are enormous. Conventional vessels need a minimum value of GM of 0.15 m. According to the criterion a) of the Nederland the value should be higher than 0.5 m. The value GM of the American requirement a) must be calculated with a formula as it has been explained before. In the application to the reference yacht the values obtained are 1.75 m for A and 1.59 m for B.

It is worth considering if yacht A and B would verify the equipments that are not fulfilled if a lower operational area is supposed, (see table 2). It has been checked that none of them verify the criterion b) of Spain even if the vessel sail in port zones. In the case of the American requirements if the yacht A is supposed to sail in protected waters (or partially protected waters) the criteria a) and c1) would be met but not c2). Yacht B would meet c3) but neither c1) nor c2).

Another point that should be emphasized when comparing different criteria is the definition of classes and the application. Usually assigned class depend on the operational area of sailing. Some countries such as Spain distinguish 5 classes (A, B, C, D and E) that go from unlimited waters to port areas. In United States there are only two possibilities: protected waters (or partially protected) and exposed waters. Other countries either don't have different classes or the operational area is unlimited waters.

With respect to the scope of application there is not a common denominator, in the number of passengers above all. The criteria of UK apply to vessels carrying no more than 12 passengers. The American is obligatory when carrying more than 49 but it may be applicable if for example, sailing in unlimited waters even if with one passenger. The Netherlanders requirements are applied for vessels carrying no more than 36 passengers. As it can be seen there is a broad range of possibilities.

5. Conclusions

Through the previous paragraphs several aspects of the stability of the sailing ships have been presented. The following conclusions can be considered:

- The stability of the sailing ships shows such characteristics that specific criteria are needed.

- The traditional criteria based on conventional calculation of wind heeling have been lately discussed.

- The new approach refers to gust and a sailing vessel when struck by a gust heels to the corresponding steady angle at the gust wind speed. Squalls are considered in the stability booklet.

- These criteria proposed by the English Maritime Administration have turned into a reference in sailing vessel stability methods.

- Some classic requirements are stricter than the new approach.

Acknowledgment

This work was based in the restlessness of the Spanish Maritime Administration about sailing ship criteria and the work done under a contract signed between Dirección General de la Marina

Mercante and Universidad Politécnica de Madrid about this topic. The authors express their gratitude to this support.

References

[1] UNE-EN ISO 12217-2. Pequeñas embarcaciones. Evaluación y clasificación de la estabilidad y la flotabilidad. Embarcaciones propulsadas a vela de eslora igual o superior a 6 m., 2002.

[2] P. Van Oossanen, *Development of Proposed ISO 12217 Single Stability Index for Mono-Hull Sailing craft,* The 13th Chesapeake Sailing Yacht Symposium, 1997.

[3] The National Standards for Commercial Vessels (NSCV), Subsection 6A of Part C, chapters 6A, 6B and 8A, Australian Transport Council, April 2008.

[4] *The Small Commercial Vessel and Pilot Boat Code of Practice,* Maritime and Coastguard Agency, Department for Transport of United Kingdom, November 2004.

[5] J. C. Miles, B. Johnson, J. Womack, I. Franzen, *SNAME's Stability Letter Improvement Project (SLIP) pro Passenger Sailing Vessels,* The 18th Chesapeake Sailing Yacht Symposium, 2007.

[6] B. Deakin, *Sailing Vessel Stability: A Review of the Current State of the Art and Proposals for Worthwhile Research*, New England Sailing Yacht Symposium, March 1988.

[7] B. Deakin, *The Development of Stability Standards for UK Sailing Vessels*, RINA Spring Meetings, 1990.

[8] *The Large Commercial Yacht Code*, Maritime and Coastguard Agency, Department for Transport of United Kingdom, August 2005.

[9] A.R. Claughton, *Sailing Yacht Design*, Ed. Longman, 1998.

[10] *Stability Criteria for Large Sailing Yachts*, Wolfson Unit Report No. 1924 for the Maritime and Coastguard Agency, October 2006.

[11] Research Project No: 534, *Research into Stability Criteria for Large Sailing Yachts*, Marine Information Note 286 (M). Maritime and Coastguard Agency, United Kingdom, June 2007.

[12] *Code of Federal Regulations, 46 Shipping, Chapter I, Parts 170-171*, National Archives and Records Administration of United States of America, Revised 2006.

[13] *Rules for Commercial Cruising Vessels*, Nederland Maritiem Land, May 2004.

Appendix A: Pictures and Charts

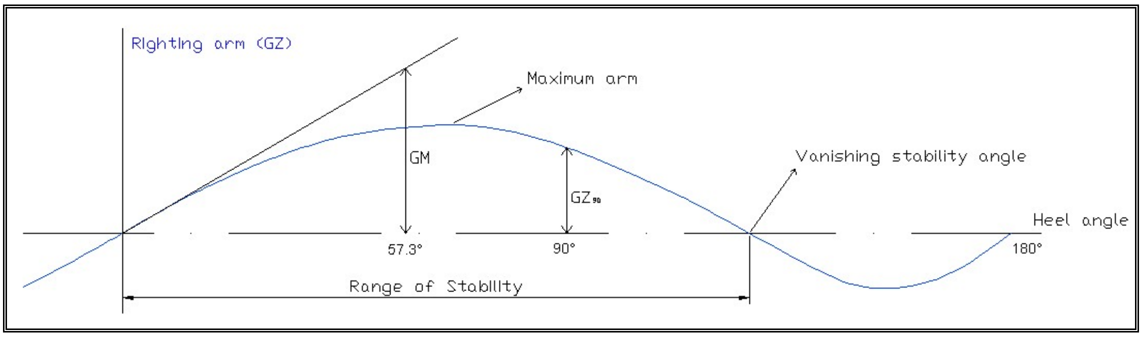


Figure 1: Righting arm curve

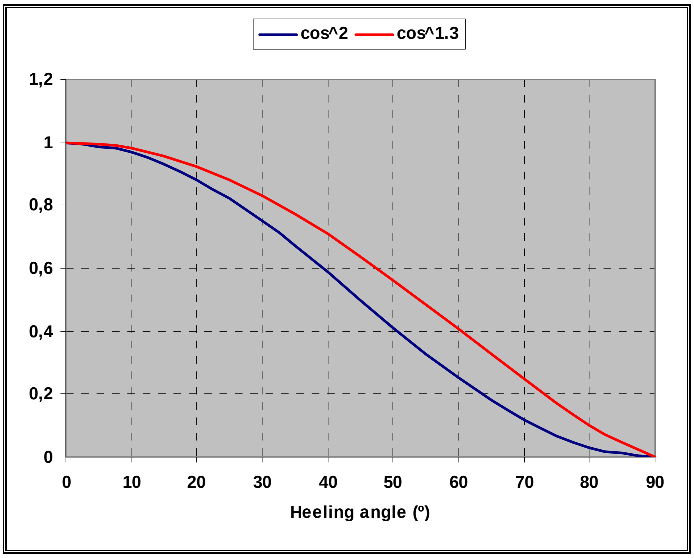


Figure 2: Influence of the exponent on the heeling arm curve

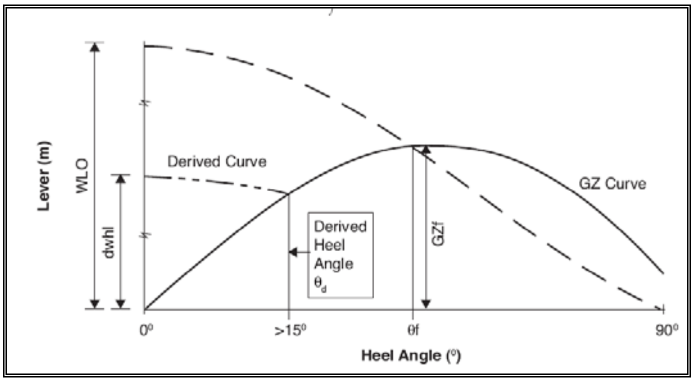


Figure 3: New stability approach, MCA's Large Commercial Yacht Code, ref [8]

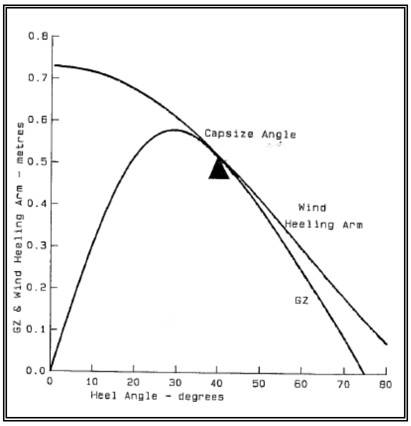


Figure 4: The stability curve of the 'Isaac H. Evans' with a heeling arm curve leading to capsize, ref[7].

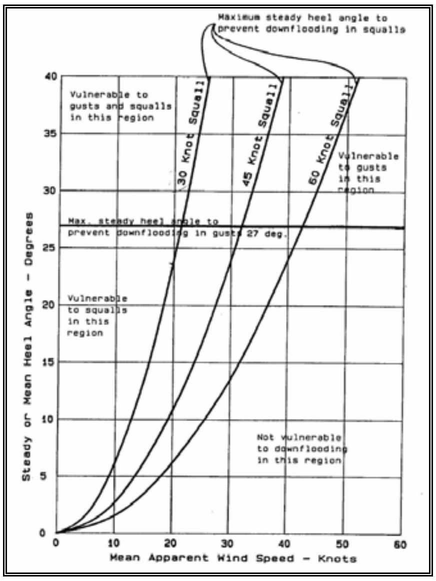


Figure 5: Stability booklet, graphical representation, ref [7]

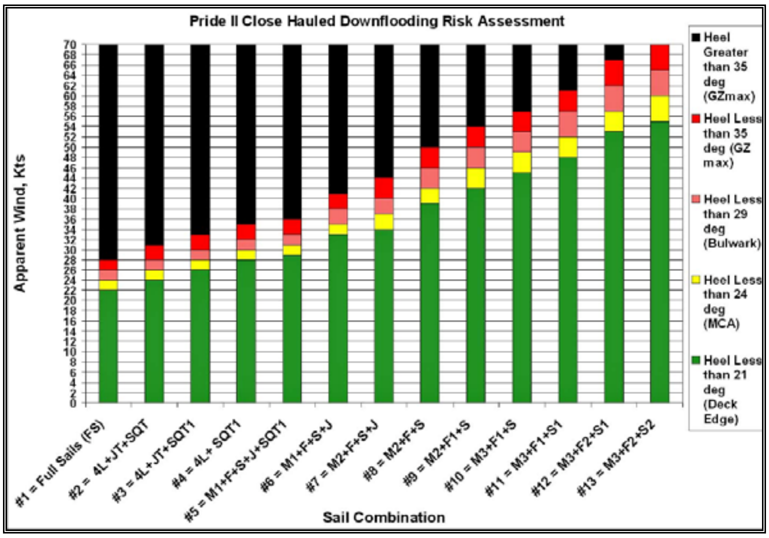


Figure 6: Stability letter, graphical representation, ref [5]

	Yacht A	Yacht B
UNITED KINGDOM		
b) [Positive range stability]	√	√
c) [Steady heel angle > 15º]	√	√
SPAIN		
b) [Static Stability (StatStab), angle < 12º]	X	X
b1) [Steady heel angle > 15º, 19º, 23º, 28º]	√	√
c1) [Dynamic stability (DynStab), maximum arm]	√	√
c2) [DynStab, vanishing GZ or downflooding]	√	√
d) [Positive range of stability]		
UNITED STATES OF AMERICA		
a) [Metacentric height, GM]	X	√
b) [Positive range stability]	√	√
c1) [StatStab, deck immersion]	X	X
c2) [DynStab, downflooding]	X	X
c3) [DynStab, vanishing positive stability]	√	X
NETHERLANDS		
a [Metacentric height, GM]	√	√
b1) [StatStab, lowered sails]	√	√
b2) [StatStab, under sail]	√	√
c1) [DynStab, lowered sails]	√	√
c2) [DynStab, under sail]	√	√

√: it is verified; X: it is not verified.

Table 1: Application of different criteria to reference yachts

	Yacht A	Yacht B
SPAIN		
b) [Static Stability (SS), angle < 12º]	X →X	X → X
UNITED STATES OF AMERICA		
a) [Metacentric height, GM]	X → √	
c1) [StatStab, deck immersion]	X → √	X → X
c2) [DynStab, downflooding]	X → X	X → X
c3) [DynStab, vanishing positive stability]		X → √

√: it is verified; X: it is not verified.

Table 2: Reduction of class

Appendix B: Summary of the Criteria of Spain

Stability of passanger vessels propelled by sails (Estabilidad de los buques de pasaje navegando a vela. Dirección General de Marina Mercante) Agust 23, 2003.

Rules of stabilty for passenger sailing monohulls:

a) General rules of passenger vessels issued by de Spanish administration.

b) In addition to a), with all sails set, the angle of balance with the wind pressure corresponding for each class (indicated in the next table) will be less than 12º and the vessel will not immerse more than half the freeboard.

Class	Wind Pressure (kg/m^2)
> 20	12,6
B	10,0
C	8,0
D y E	5,0

The heeling moment will be:

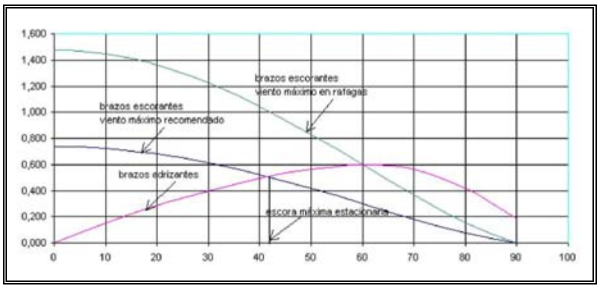
$$M= P\ A\ h \cos^{1,3} q$$

P= wind pressure en kg/m^2
A = longitudinal projected area of sails and lateral area of the vessel above the water in m^2
h= distance between the geometric centre of immerse and not immerse surfaces in m.

Alternatively, for vessel in sport use, the angle of balance must be more than 15º for a heeling moment half the one needed for heeling the vessel up to 60º or downflooding angle if this is less. Therefore, the recommended maximum wind pressure is half the maximum wind in gust.

The navigation category that corresponds to the vessel according to this criterion will be imposed by the angle of steady heel that fulfils the condition mentioned in the previous paragraph:

Class	Minimum value of the angle of steady heel
> 20 miles	28º
B	23º
C	19º
D y E	15º



c) The minimum dynamic stability will be in accordance with the values indicated in the next table. (D is displacement)

Class	Dynamic stability up to the angle of maximum arm (m·gr)	
	D < 40 T	D > 40T
> 20 miles	(42,9-0,57D)	20,1
B	(28,6-0,38D)	13,4
C	(13,3-0,17D)	6,5
D y E	(9,9-0,13D)	4,7

Class	Dynamic stability up to the angle of arm zero o the downflooding angle (m·gr)	
	D < 40 T	D > 40 T
> 20 miles	(102-1,35D)	48
B	(68-0,9D)	32
C	(31,7-0,41D)	15,3
D y E	(23,4-0,3D)	11,4

d) The righting arm curve must have a positive range of stability beyond 90º for vessels that sail 20 miles away from shelter and class B.

Appendix C: Characteristics of the References Yachts

Yacht A

- Class A, unlimited ocean voyages
- Displacement, W = 26.3 t
- Total sail area, Osail =151.3 m²
- Total lateral area, A = 182.82 m²
- Lateral area in of the hull above the water, including the deckhouse, Orl = 22.81 m²
- The total wind area of the rigging, Origging = 8.7 m²
- The vertical distance between the center of gravity of Orl and the center of flotation, Arl = 2.21 m.
- Half the vertical distance from the top of the highest mast to the center of flotation, Arigging = 18.89 m.
- Vertical distance between the center of effort of sails to the center of flotation, Asail = 10.1 m.
- Vertical distance from the center of the projected lateral area above the waterline to the center of the underwater lateral area, H = 10.45 m
- Vertical distance between the center of gravity and waterline, OG = 0.6 m
- Initial metacentric height, GM = 1.32 m
- Draught = 2.3 m
- Length, L = 15.52 m
- Beam, B = 4.7 m
- Deck immersion angle = 30º
- Downflooding angle > 60º
- Angle of vanishing stability = 128º

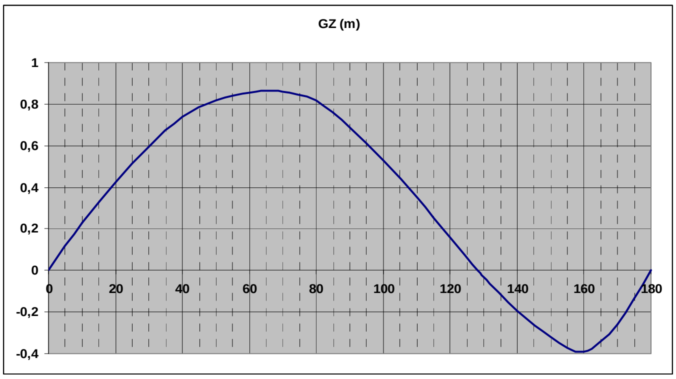


Figure 6: Righting arm curve of Yacht A

Yacht B

- Class A, unlimited ocean voyages
- Displacement, W = 81.9 t
- Lateral area in of the hull above the water, including the deckhouse, Orl = 56.96 m²
- The total wind area of the rigging, Origging = 26.15 m²
- Total sail area, Osail =466 m²
- Total lateral area, A = 549.11 m²
- The vertical distance between the center of gravity of Orl and the center of flotation, Arl = 1 m.
- Half the vertical distance from the top of the highest mast to the center of flotation, Arigging = 14.2 m.
- Vertical distance between the center of effort of sails to the center of flotation, Asail = 15.8 m.
- Vertical distance from the center of the projected lateral area above the waterline to the center of the underwater lateral area, H = 16.1 m
- Vertical distance between the center of gravity and waterline, OG = 0.428 m
- Initial metacentric height, GM = 1.887 m
- Draught, d = 3.848 m
- Length, L = 29.174 m
- Beam, B = 7.1 m
- Block coefficient, C_B = 0.429
- Deck immersion angle = 30º
- Downflooding angle = 114º
- Angle of vanishing stability =104º

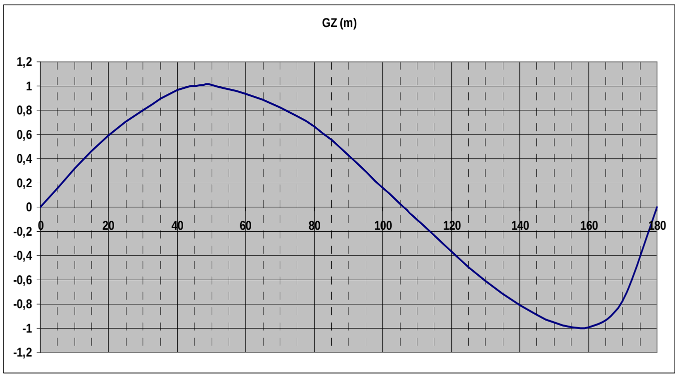


Figure 7: Righting arm curve of Yacht B