A SOFTWARE DEVELOPER'S PERSPECTIVE OF STABILITY CRITERIA

Patrick Couser, Formation Design Systems Pty. Ltd. (Australia)

Abstract

The assessment of vessel stability to specified stability criteria is now required for virtually all forms of water-craft. This is routinely done using computer software that models the vessel's hydrostatic properties and evaluates its stability against specified criteria. Over the last 24 months, Formation Design Systems has implemented a wide rage of stability criteria in its hydrostatics analysis computer program Hydromax.

This paper describes some of the outcomes, observations and questions arising from this software development cycle, from a software development and naval architecture perspective. It provides a viewpoint of stability criteria which is different from that of both regulatory bodies (such as IMO) and naval architects dealing with the day-to-day aspects of vessel design. It also presents some cross-fertilisation ideas from the software industry that could enhance the understanding of stability criteria. It is hoped that the suggestions made in this paper can lead to clearer, more concise and more accurate stability criteria which will, in turn, lead to safer vessels.

Many stability criteria and the way in which vessels' hydrostatic properties are evaluated and presented are inherited from the pre-desktop computer era. Now that desktop computers are commonplace in the design office, evaluation of hydrostatic properties and stability criteria can be made more accurate, less error prone, more precisely defined and faster. For instance, with modern computers, it is possible to evaluate a complete free-to-trim, GZ curve, whilst simulating the shift of fluids in tanks in a couple of seconds thus making criteria evaluated from upright GM and traditional free surface moment correction to vertical centre of gravity obsolete.

During the software development process, many stability criteria from many different organizations were reviewed. It is clear that the criteria of most regulatory bodies derive from the same original source, though there have often been different approaches taken to unit conversion and the derivation of constants. It was also extremely apparent, when translating criteria from the "plain English" of the stability documents to computer code, that many of the criteria are vague and open to different interpretation; sometimes, it even seemed that the *intent* of the criterion was different from the *specification* of the criterion. Computer code can only have one meaning – a computer does *exactly* what it is told to do. Determining whether a criterion can be specified in computer code provides an excellent test of its unambiguity. Another observation was that there was no reference to accepted definitions of many common naval architecture terms; this can lead to difficulties and confusion where slight differences in accepted meanings for these terms vary from one country to another or from one naval architect to another.

NOMENCLATURE

A	Acceleration [m s^{-2}]
B	Vessel beam [m]
CB	Centre of buoyancy
CG	Centre of gravity
C_B	Block coefficient
DS	Dynamic stability [m rad]
DWL	Design waterline
F	Force [N]
FSM	Free surface "moment" [kg m]
g	Standard acceleration due to gravity (9.80665 m s^{-2})
GZ	Righting lever (arm) [m]
GZ_{fluid}	GZ adjusted for fluid free surfaces in tanks [m]
GZ_{solid}	GZ not adjusted for fluid free surfaces in tanks [m]
h	Lever [m]
HA	Heeling lever (arm) [m]
HM	Heeling moment [N m]
$HM_{kN\,m}$	Heeling moment [kN m]
$HM_{t\,m}$	Heeling "moment" [t m]
I	Transverse 2nd moment of area about area centroid [m^4]
KG	Vertical distance from keel datum to centre of gravity [m]
L	Vessel length [m]
r	Radius of turn [m]
RM	Righting moment [N m]
T	Vessel draught [m]
v	Vessel or wind velocity [m s^{-1}]
v_{kts}	Vessel or wind velocity [kts]
v_{max}	Maximum speed of craft [m s^{-1}]
VCG	Vertical centre of gravity [m]
Δ	Mass displacement [kg]
Δ_t	Mass displacement [t]
∇	Volume of displacement [m^3]
∇_{DWL}	Displacement corresponding to design waterline [m^3]
Ù	Angular velocity [rad s^{-1}]
ϕ, Φ	Heel angle [rad or °]
ϕ_D	Heel angle at which downflooding occurs [rad or °]
ϕ_{GZmax}	Heel angle at which maximum GZ occurs [rad or °]
ϕ_V	Heel angle of vanishing stability [rad or °]
ρ	Fluid density [kg m^{-3}]

1. INTRODUCTION

The last 24 months has seen considerable development of Formation Design Systems' vessel stability program Hydromax. Amongst other analysis modes, Hydromax is able to perform a large angle stability analysis and then evaluate specified stability criteria based on the calculated righting lever, GZ, curve. (A similar approach is also used to evaluate limiting vertical centre of gravity, VCG, for different vessel displacements.) The aim was to add more flexibility to the way stability criteria are defined in the program. This was done by providing the user with the underlying stability criteria calculations (such as area under the GZ curve between specified limits, angle of maximum GZ, etc.). These basic calculations could then be duplicated, grouped together and customised to fulfil the requirements of virtually any regulatory body.

This development required a review of a wide range of stability criteria from many regulatory bodies; analysis of users' requirements through discussions with many naval architects, designers and ship yards; and finally development of computer code to evaluate the stability criteria.

This process gave the author a broad view of the different stability criteria throughout the world and the needs and day-to-day practices of naval architects and designers with regard to the evaluation of stability criteria. This is perhaps a somewhat different perspective than that which the regulatory bodies and practitioners might have and the author feels that there are some interesting insights to be shared. With this in mind, the author hopes that any criticisms levelled in this paper can be seen in the constructive light in which they are intended.

1.1 Do naval architects speak a common language?

Working for several different companies and research institutes and particularly working with Formation Design Systems for the last five years, has brought the author in contact with hundreds of naval architects and designers from all over the world. Through the course of discussions with these naval architects, it has become clear that although naval architects may speak a single language there are many different dialects. Each design office has its own way of doing things and many have different interpretations of common (and less common) naval architecture terminology and stability criteria. Take for example, the vessel's block coefficient, C_B (Equation 1).

$$C_B = \frac{\nabla}{LBT} \quad (1)$$

Depending on the definition used for length (L), beam (B), draught (T) and the shape of the vessel, there can be around 45 different values for C_B[1]! (And things become much more confused if the definition is applied to a damaged vessel, multihull, inclined vessel or offshore structure.)

Given that naval architects cannot agree on a single definition of C_B, it is evident that stability criteria and their evaluation (which are considerably more complicated) must be very precisely defined if they are to be applied consistently. There is no intrinsic reason why stability criteria based on static stability cannot be defined in an unambiguous manner – the physics of static stability are simple and can easily be defined mathematically and computed using numerical methods with high accuracy and certainty. They do not suffer from the problems encountered in, for example, the field of computational fluid dynamics (CFD) where a large number of assumptions, simplifications and approximations are required to build a tractable physical model which is subject to further approximations when converted to a numerical method for solution on a computer.

[1] 5 lengths {waterline (WL), datum WL, immersed hull, overall, between perpendiculars} ×
3 beams{max beam at WL, WL beam at midships, beam at specified station} ×
3 draughts {max draught to underside of keel (USK), draught at midships, draught at specified station} = 45

1.2 Terminology and jargon

Jargon pervades all aspects of our lives; its main aim seems to be to make it harder for newcomers to grasp the ideas that are being put forward and to make it harder for "outsiders" to penetrate the field.

Although definitely not as bad as in some areas of technology, jargon is also rife in naval architecture and without any standard definitions that can be referenced, misunderstandings and different interpretations are bound to occur. It is clear that some level of technological jargon is required. However, precise, standard definitions of these terms, that are understood and accepted by all naval architects, should be adopted.

There are a number of standard texts used by most naval architects. In English-speaking countries, these are often Lewis[1] and Rawson and Tupper[2]; in other countries and cultures, other reference books are used. However, despite these *de facto* standards, there is no accepted reference for the definition of naval architecture terminology. If criteria are to be consistently applied, there must be a set of universally accepted and documented terminology.

One example of different terminology used to describe the same thing is in the field of damage stability. In [1] and [2] calculations of damage stability using the methods of "lost buoyancy" and "added displacement" are described whereas [3, page 55] states that calculations are to be made using the method of "constant displacement" [2].

[2] Presumably this is the same as the "lost buoyancy" method, although this is not specifically stated.

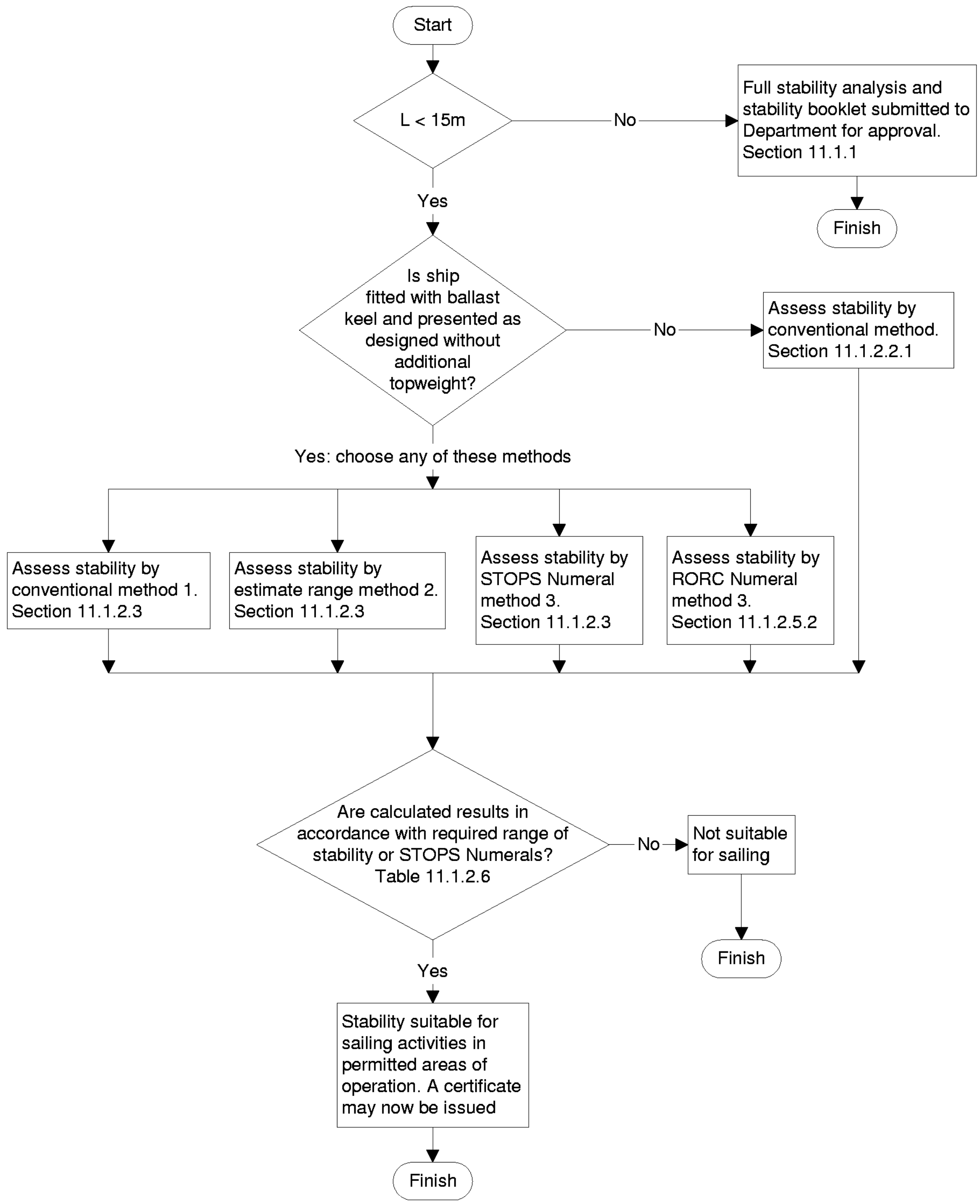

Figure 1: Flow chart showing the procedure for assessing stability for MCA[4, §11.1.2.8]

2 CLARIFYING STABILITY CRITERIA

Unclear or imprecise stability criteria make it difficult for these criteria to be consistently applied by different naval architects around the world. Another, perhaps less obvious problem, occurs when (or if) the originators of criteria move on. If the criteria are not clear, they may be misinterpreted and their original intent missed.

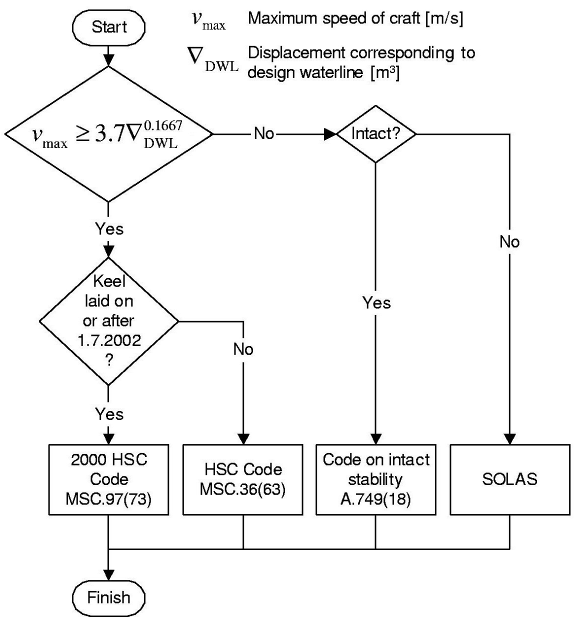

Figure 2: Sample flow chart indicating use of IMO documents

For consistent and easy application of stability criteria, they must be defined in the most concise and precise way possible. In the following sections a number of ways in which the specification and formulation of stability criteria could be made clearer and more precise are discussed. In addition to precise definition, the "logic" of the criterion text or f ormulation should also be checked.

2.1 Precise criteria specification

In the field of software engineering, much is made of precise requirements specification, traceability and testing. Requirements specification is one of the main foci since errors or imprecise requirements will lead to greater errors, which are more costly to rectify when discovered later in the project. The requirements also provide the benchmark for testing. It is extremely important that the requirements are atomic and precise. Atomic means that each requirement defines only one task to be done, or one value to be calculated. Precise means that the requirements are not open to interpretation; there must be only one possible interpretation.

Flow charts

Flow charts can be a concise and precise way of describing some of the more complex criteria where there are different choices to follow. In these cases, flow charts are often easier to follow than text.

Flow charts are used effectively in [4, §11.1.2.8], although the clarity of this particular flow chart could be improved by using standard flow charting conventions: different shape boxes to differentiate between operations and decisions, and consistent "Yes / No" flow directions as shown in Figure 1.

Another example, giving a simple indication of which IMO documents are required for different vessels, is given in Figure 2. Of course this could be expanded to indicate which sections are applicable under different conditions, but that is beyond the scope of this paper.

Pseudo code

Pseudo code is a generic form of a high-level computer programming language, often used to express logic and algorithms. It can be an alternative to a flow chart, but may be harder to interpret by people with no computer programming experience. The flow chart of Figure 1 can be expressed with the pseudo code in Figure 3.

```
IF (L < 15m)
  IF (ship fitted with ballast keel...)
    IF ( (method 1. §11.1.2.3 > rq'd stab. range )
    OR (method 2. §11.1.2.3 > rq'd stab. range )
    OR (STOPS method 3. §11.1.2.3 > rq'd STOP S)
    OR (RORC method 3. §11.1.2.5.2 > rq'd RORC ) )
    bSuitableForSailing = TRUE
  ELSE IF (§11.1.2.2.1 > rq'd )
    bSuitableForSailing = TRUE
ELSE IF (stab. book §11.1.1 approved by Dept.)
  bSuitableForSailing = TRUE
ELSE
  bSuitableForSailing = FALSE
```

Figure 3: Pseudo code showing the procedure for assessing stability for MCA[4, §11.1.2.8] (c.f. Figure 1)

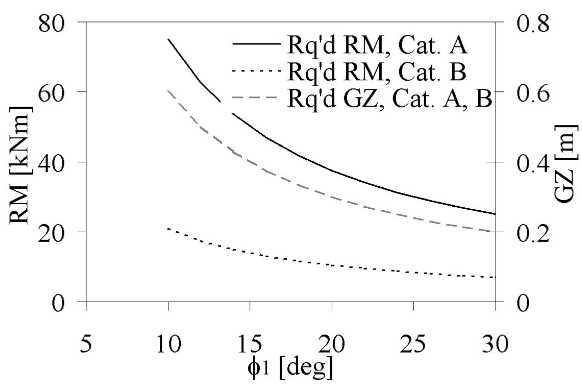

Figure 4: Required minimum righting moment and righting lever

Walk-throughs and verification

It is essential that the criterion specifies what it is supposed to specify. Walk-throughs are used extensively in the field of software engineering. During a walk-through, a number of programmers will go through a section of computer code together, verifying the logic. Walk-throughs could be employed for stability criteria to ensure that the logic is correct and unambiguous.

Symbolic notation

Symbolic (and mathematical) notation is somewhat similar to pseudo code. It often provides greater clarity and simplicity than "plain English"; what can be precisely defined in one short line of symbolic notation may require a whole paragraph of text. This idea has been applied to the field of law[5] and could be used for more precise definition of stability criteria.

For example in [6, §6.3.3] (reproduced below) the criterion could be explained much more succinctly by the use of mathematical notation and possibly a graph.

Resistance to waves. The curve of the righting levers at angles of heel up to ϕ_D, ϕ_V or 50° whichever is the least, shall comply with the following.

a) Where the maximum righting moment occurs at a heel angle of 30° or more, the righting moment at 30° shall be not less than 25kN m for design category A, and 7kN m for design category B. In addition, the righting lever at 30° shall be not less than 0.2m.

b) Where the maximum righting moment occurs at a heel angle of less than 30°, the maximum righting moment shall be not less than $(750/\phi_{\text{GZmax}})$ kN m for design category A, and $(210/\phi_{\text{GZmax}})$ kN m for design category B. In addition, the maximum righting lever shall not be less than $(6/\phi_{\text{GZmax}})$ m, where ϕ_{GZmax} is the heel angle, in degrees, at which the maximum righting lever occurs, considering only that part of the curve for heel angles less than the downflooding angle.

In fact there is no need to break down this criterion into two parts and the whole criterion could be more clearly expressed as follows:

Define $\phi_1 = \min(\phi_D, \phi_V, 30^\circ)$, then the vessel's righting moment (RM) and righting lever (GZ) must satisfy the following (see also Figure 4):

Category A:

$$\text{RM}(\phi = \phi_1) \geq \frac{750}{\phi_1} \text{ kN m}$$

Category B:

$$\text{RM}(\phi = \phi_1) \geq \frac{210}{\phi_1} \text{ kN m}$$

Category A and B:

$$\text{GZ}(\phi = \phi_1) \geq \frac{6}{\phi_1} \text{ m}$$

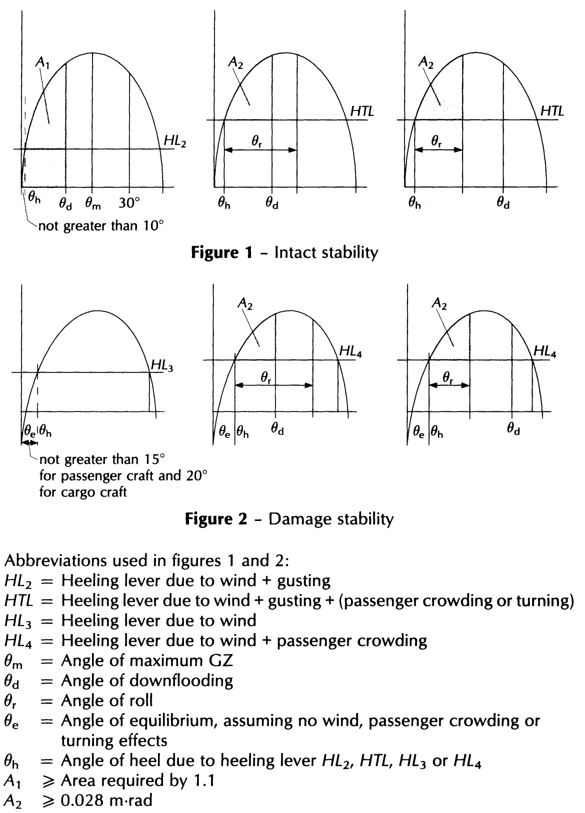

Figure 5: Multihull criteria after [7, Annex 7]

Diagrams

The old idiom that a picture is worth a thousand words is very true. It is often the case that an explanation becomes trivial when a diagram is used.

It is also useful if the diagrams cover the more unusual cases as well as the simple cases. For example, what should be done if the vessel has an unusual GZ curve? (e.g. asymmetric loading producing an angle of list.)

The multihull craft criteria diagram in [7, Annex 7 figs. 1 and 2] (reproduced in Figure 5) is a very good example of how suitable diagrams, with clearly defined terms, are a clear and concise way of describing criteria. In this example, these figures effectively summarise and clarify three pages of text.

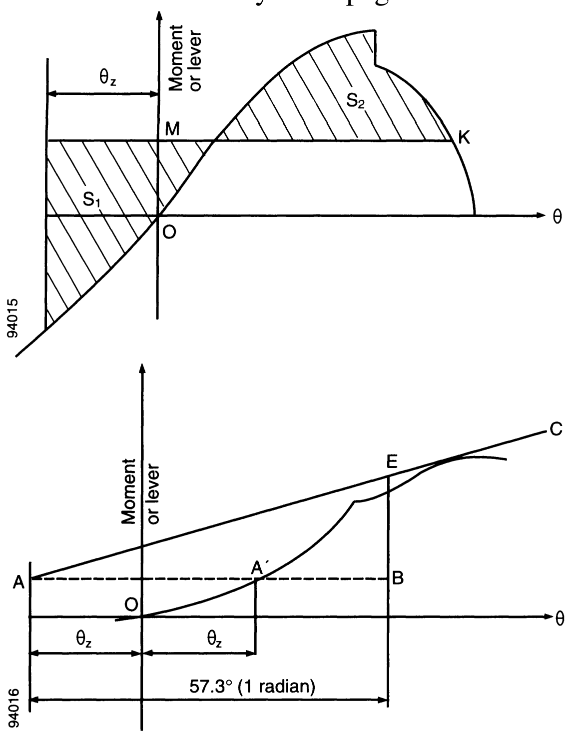

Figure 6: GZ curve and corresponding dynamic stability curve after [7, Annex 6]

It is also imperative that the diagrams are correct. For example, the dynamic stability curve in [7, Annex 6 figs. 1 and 2] (reproduced in Figure 6) is difficult to interpret. After some investigation, it was determined that, in this context, the dynamic stability curve, DS, is the integral of the GZ curve – Equation 2. This figure is confusing because:

- there is no definition of "dynamic stability"[3];
- the graph has ordinates of "moment or lever" and not "moment $\times$angle or lever$\times$angle" (as would be expected had the integration with respect to heel angle been carried out) and
- the graph is an odd function rather than an even function[4], with non-zero slope at zero heel[5].

$$\mathrm{RM}(\Phi) = \int_{\phi=0}^{\Phi} \mathrm{GZ}(\phi)\, d\phi \qquad (2)$$

<u>Transparent physics</u>

It is much easier to interpret what the criterion is trying to achieve if the physical analysis being undertaken is readily seen in the way in which the criterion is formulated. With many criteria, the underlying physics is quite effectively hidden by conversion factors and unexpected parameters. In some cases it may also be appropriate to describe the theoretical models and assumptions to be used to evaluate the criterion.

Take, for example, the application of a heeling moment due to the vessel turning, Figures 7 and 8. The heeling moment can be computed by examining the centripetal force required to make the vessel turn in a circle of constant radius, *r*, at constant angular velocity, Ù. In this case the centripetal force is provided by the hydrodynamic forces acting on the underwater portion of the hull and appendages. The centripetal acceleration of a body turning in a circle of radius *r*, at velocity $v = r\omega$, is given by Equation 3.

$$a = \frac{v^2}{r} \qquad (3)$$

From Newton's Second Law, $F = ma$, the centripetal force is given by Equation 4.

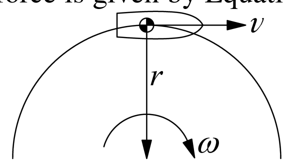

Figure 7: Vessel turning in a circular path at constant angular velocity

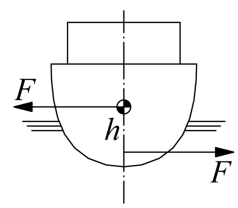

Figure 8: Forces acting on a vessel turning in a circular path at constant angular velocity

$$F = \frac{\rho \nabla v^2}{r} \qquad (4)$$

where ∇ is the vessel's volume of displacement in a fluid of density ρ .

The reaction force (Newton's Third Law), acts at the vessel's centre of gravity and if, in the upright condition, the vertical separation of the centre of gravity and the hydrodynamic centre of pressure of the underwater body is given by *h*, the vessel experiences a heeling moment, HM, given by Equation 5. The $\cos(\phi)$ term is included because the centripetal force acts in the horizontal plane and the vertical separation of the force couple decreases as the cosine of the heel angle.

$$\mathrm{HM}(\phi) = \frac{h\cos(\phi)\rho\nabla v^2}{r} \qquad (5)$$

[3] It could mean the integral of the GZ curve, or the stability curve taking into account the effects of forward speed, or something else entirely.

[4] The integration of an odd function, such as $y = x^3$, produces an even function, in this case $y = 0.25x^4 + c$. Given that the GZ curve is an odd function ($f(x) = -f(x)$, symmetrical vessel, symmetrically loaded), its integral would be an even function($f(x) = f(-x)$).

[5] The GZ curve is the derivative of the dynamic stability curve, the accompanying GZ curve passes through (0,0) implying that the dynamic stability curve should have zero slope at zero heel.

Finally the heeling arm is given by Equation 6.

$$\mathrm{HA}(\phi) = \frac{\mathrm{HM}}{\rho g \nabla} = \frac{h\cos(\phi)v^2}{rg} \tag{6}$$

The corresponding heeling arm or moment is variously defined by different authorities.

In [8, §3.1.2.6 (General intact stability criteria for all ships)] (amended by [9]), the heeling moment is given by Equation 7.

$$\mathrm{HM}_{\mathrm{kNm}} = \frac{0.196 v^2 \Delta_{\mathrm{t}}}{L}\left(\mathrm{KG} - \frac{T}{2}\right) \tag{7}$$

where $\mathrm{HM}_{\mathrm{kNm}}$ is the heeling moment in kN m; v the ship velocity in m s^{-1}; L the ship waterline length in m; Δ_{t} the displacement in t and $(\mathrm{KG} - T/2)$, in m, defines the vertical separation of the forces when the vessel is upright. The variation of heeling moment with heel angle is not clearly specified. Should a constant heeling arm be assumed or the theoretically correct $\cos(\phi)$ decreasing heel arm be used?

Equation 7 implies a relationship between L and r, and comparison with Equation 5 gives $r/L = 5.102$. Also comparison with the original definition in [8] (Equation 8[6]) with the amendment in [9] implies a value of $g = 9.8$ m s^{-2}

$$\mathrm{HM}_{\mathrm{tm}} = \frac{0.02 v^2 \Delta_{\mathrm{t}}}{L}\left(\mathrm{KG} - \frac{T}{2}\right) \tag{8}$$

In [8, §4.8.7.1.1.2 (Dynamically supported craft)] and [7, Annex 6 §1.1.2 (Stability of hydrofoil craft)], the heeling moment is given by Equation 9.

$$\mathrm{HM}_{\mathrm{kNm}} = \frac{0.196 v^2 \Delta_{\mathrm{t}} \mathrm{KG}}{L} \tag{9}$$

It is also stated that: "*This formula is applicable when the ratio of the turning circle to the length of the craft is 2 to 4.*"[7] Comparison with Equation 5 indicates that this will underestimate the turning moment by between 22% and 61% since Equation 9 only corresponds with the theoretical heeling moment due to turning when $r/L = 1/0.196 = 5.102$. Perhaps some assumption about the vessel leaning into the turn is being made?

However, in the same document [7, Annex 7 §1.4.2 (Stability of multihull craft)], the heeling arm is given by Equation 10

$$\mathrm{HA} = \frac{v^2}{gr}\left(\mathrm{KG} - \frac{T}{2}\right) \tag{10}$$

which follows the physics, providing a much clearer understanding of the criterion and its purpose. Why are all heeling arms and levers in IMO documentation not consistent and not of the form give in Equation 10?

In [10, §C.1.1.4 (Class I vessels)]. the heeling moment is given by Equation 11.

$$\mathrm{HM}_{\mathrm{tm}} = \frac{0.0053 v_{\mathrm{kts}}^2 \Delta_{\mathrm{t}} \mathrm{KG}}{L} \tag{11}$$

This is similar to Equation 8 when the conversion of speed from knots to m s^{-1} is taken into account, but introducing more inconsistent units and yet more conversion factors makes the equation's purpose less clear.

In [10, §C.8.4.2 (Surface piercing hydrofoils)], the heeling moment is also given by Equation 11 with the proviso that: "*The formula is applicable when the ratio of the radius of the turning circle to the length of the craft is 2 to 4.*" As mentioned before, this will underestimate the turning moment. This is a clear example of where a criterion has been copied from another code, some attempt has been made to "personalise" it by an unnecessary change of units and yet the main error has not been corrected!

[6] This equation does not represent a moment since the units are mass×length, not force×length, implying that a division by g has occurred.

[7] This actually means $2 \le r/L \le 4$ not $r/L = 2/4 = 0.5$.

In [11, §C.1.6.1], the heeling arm is given by Equation 12.

$$\mathrm{HA}(\phi) = \frac{v_{\mathrm{kts}}^2}{3.785} \frac{h\cos(\phi)}{rg} \quad (12)$$

where the velocity is given in knots and 3.785 is the appropriate conversion factor.

However, arguably the simplest and clearest heeling arm is defined in [12, §1.2.4] and [13, §079-1-c(9) 5] Equation 13.

$$\mathrm{HA}(\phi) = \frac{h\cos(\phi)v^2}{rg} \quad (13)$$

This equation exactly follows the physical derivation using consistent units, hence there are no conversion factors required and no unexpected parameters. Also, unlike most of the other criteria, the variation with heel is clearly defined.

Consistent units

Consistent units should be used throughout the codes, these should preferably follow SI conventions (except perhaps where the Metric system is not used). This would alleviate the need for conversion factors that are often included in criteria, which can sometimes lead to confusion.

Some common bad practices are:

- specifying equations using parameters in inconsistent units, then having to apply conversion factors, e.g. speed in knots and displacement in tonne;
- use of incorrect units: units of a moment are force×distance, not mass×distance;
- use of incorrect units: units of the dynamic stability curve obtained by integrating the GZ curve are length×angle, not length.

Physical constants

Definition of standard values for physical constants and consistent use thereof would be helpful. For example *g* is used in many stability criteria, especially those that include righting or heeling moments or levers. Despite the fact that *g* has a standard value of 9.80665 m s^{-2}[14] it is given various different values in different (or even the same) documents. For example, comparing the equation in [8, §3.1.2.6] and the amended version in [9] implies a value of g = 9.8 m s^{-2} whilst in §3.2.2.2 of the same document, a value of g = 9.81 m s^{-2} is defined. Similarly in [7, §4.3] g = 9.806 m s^{-2}, in Annex 3 Table 1 g = 9.81 m s^{-2}, in Annex 6 §1.1.5.2 an implied value of g = 9.81 m s^{-2} is used, in Annex 7 §1.3 and §2.2 the implied value of *g* is 9.8 m s^{-2} and finally in Annex 7 §1.4.2, an unspecified value of *g* is to be used to calculate the heeling lever due to turning. In virtually all cases where a heeling moment is required, the value of *g* to be used to calculate the righting moment from the righting arm is not specified.

It is noted that due to rounding, derivation of *g* from the constants in formulae is not necessarily an accurate reflection of the value that was originally used to calculate the constant, but more transparent physics, i.e. keeping *g* out of the constant would resolve this confusion.

Perhaps a number of standard densities for common fluids would also be useful.

Consolidation

There are what, at times, seems to be a plethora of stability criteria. Most of which are virtually identical except for different constants due to parameters in inconsistent units. Most stability codes for commercial vessels seem to be based on those of the International Maritime Organisation (IMO). While the attraction of having autonomy can be seen, there must also be significant advantages in simply referencing criteria from internationally recognised bodies such as IMO. Some of these advantages are: internationally ratified criteria; criteria that have been thoroughly researched;

documentation readily available to users and less documentation to keep up to date.

The U.S. Navy (USN)[13], Royal Navy (RN)[12, 15] and Royal Australian Navy (RAN)[11] all use stability criteria that are virtually identical, and all seem to come from the same sources [16, 17, 18]. Again it can be seen why autonomy would be desirable, but in many cases the criteria are identical except for changes in parameters' units and accordingly, constants. These changes seem a little pointless, especially when they do not make the criteria simpler. Of the three, the RN

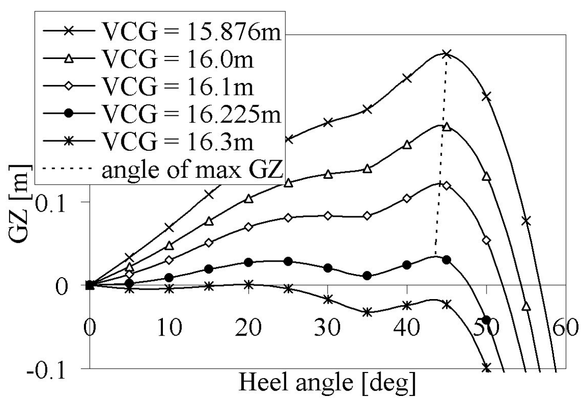

Figure 9: Variation of ϕ_{GZmax} with VCG for a typical container ship

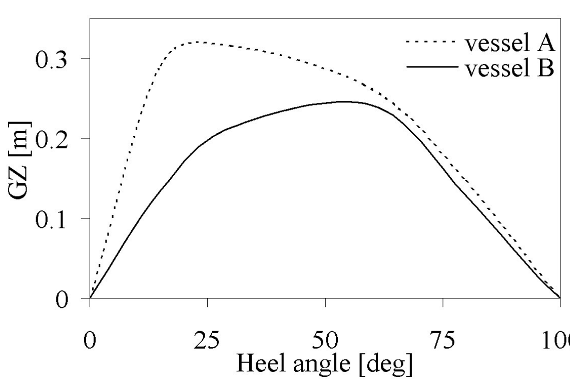

Figure 10: Two GZ curves

criteria[12] seem to be the best: most terms are well-defined, the criteria follow the physical derivations closely and the guidance for numerical implementation and evaluation of criteria are in line with taking full advantage of computers to provide accurate simulation of static stability characteristics.

Smaller, national agencies sometimes have poor "mix 'n' match" sets of criteria. They might have a more consistent set of criteria if they were to follow IMO, with, if necessary, modified required values.

Redundant criteria

Some criteria seem to be a poor measure of vessel stability; a good example of this is "Angle of heel at which maximum GZ occurs" (ϕ_{GZmax}). This becomes particularly apparent when searching for a maximum allowable VCG. Although the righting lever changes as $\delta VCG \sin(\phi)$, ϕ_{GZmax} is particularly insensitive to variation of VCG as shown in Figure 9.

In Figure 10, although vessel B exceeds vessel A according to the ϕ_{GZmax} criterion, vessel A is better than vessel B by virtually all other measures of stability. Rather than requiring $\phi_{GZmax} > \phi_{min}$, a better measure of stability would be to specify a minimum required GZ: $GZ(\phi_{min}) > GZ_{min}$.

2.2 Physical modelling

Whilst it is acknowledged that stability criteria based on a vessel's static stability are a great simplification of the actual problem of assessing a vessel's safety in a seaway, they remain, at present, the main method of assessment. Treating the vessel as a dynamical system for safety analysis is still some way from being a procedure that can be routinely applied during vessel design.

This is widely recognised [8, Preamble]:
... the safety of a ship in a seaway involves complex hydrodynamic phenomena which up

to now have not been adequately investigated and understood. Ships in a seaway should be treated as a dynamical system development of safety criteria, based on hydrodynamic aspects and stability analysis of ships in a seaway, poses, at present, complex problems which require further research.

Given that the assessment of vessel safety and seaworthiness is currently almost entirely based on the static GZ curve, what level of accuracy and detail is appropriate for the numerical model of static stability and the evaluation of stability criteria? With today's powerful computers (a 3GHz P4 PC has comparable processing power to a 1982 Cray super computer) an accurate numerical model can easily be made and evaluated. Virtually all design and analysis is now done on computers: from surf boards to oil tankers, radio controlled models to America's Cup yachts and everything in between. For these reasons, it is a worthy aim to have the most accurate model of static stability possible. The numerical shortcuts used before the advent of the PC are no longer relevant except for the most approximate estimates. Since hydrostatics are derived from simple geometry and not mathematical approximations to physical processes (as, for example, in CFD), hydrostatic properties can be precisely defined and computed. In fact some casualties have occurred in relatively calm water conditions where static stability is a reasonably accurate representation of the true situation (e.g. the loss of the *Herald of Free Enterprise*).

It is understood that existing static stability criteria have quite large margins of safety included to account of unknown dynamic effects. This raises the question: why should static stability be evaluated accurately? The author's answer would be: that it is no more difficult to evaluate stability accurately than it is to evaluate stability inaccurately; and that accurately calculated stability may, in turn, make it easier to review stability criteria because of reduced uncertainty.

Slope vs. ordinate vs. area

Most stability criteria, based on the static GZ curve, fall into one of three categories:

GM – rate of change of GZ with heel angle at a particular heel angle: $d\mathrm{GZ}/d\phi$.

GZ – righting lever at a single heel angle.

Dynamic stability – area under GZ curve between specified limits: $\int \mathrm{GZ}d\phi$

The first two (GM and GZ) provide information at a single heel angle. GM gives an indication of whether the vessel is gaining or losing GZ at this heel angle, but no information about the actual value of GZ (a vessel can have positive GM and negative GZ at certain heel angles). GM is a useful measure when the vessel is in equilibrium (GZ = 0); positive GM indicates that the vessel is in stable equilibrium at that heel angle whilst negative GM indicates unstable equilibrium. Dynamic stability provides information about the vessel's stability over a range of heel angles but no detail at a single heel angle. This gives an averaging effect when comparing two vessels: they can have the same dynamic stability but quite different GZ curves.

All three of these measures provide useful information about the vessel's stability. However, because of the different information that they provide, they should only be used together and not in isolation. Some codes (e.g. [10]) allow some vessels to be assessed purely on GM and large angle stability inferred from GM. In some extreme cases, designers have the option of selecting either GM or GZ based criteria; this choice is often made according to which criteria the vessel will pass.

It is the author's opinion that, in many cases, GM-based criteria are included to make hand calculations easier. Now that hydrostatic software is readily available, this is no longer appropriate. Full, large angle, GZ analysis should always be used; assessment of vessel safety and large angle stability should not be made solely on its upright characteristics.

Free surface effects

Traditionally the effects of slack tanks are modelled by computing the free surface moment (FSM) of the tanks and raising the VCG by an amount δVCG see Equation 14.

$$\delta\text{VCG} = \frac{1}{\Delta} \sum_{t=1}^{\text{number of tanks}} \left(I_t \rho_t \right) \qquad (14)$$

where I_t is the transverse second moment of area of the tank waterplane about its centroid with the vessel upright, ρ_t is the density of the fluid in the tank and Δ is the mass of the vessel.

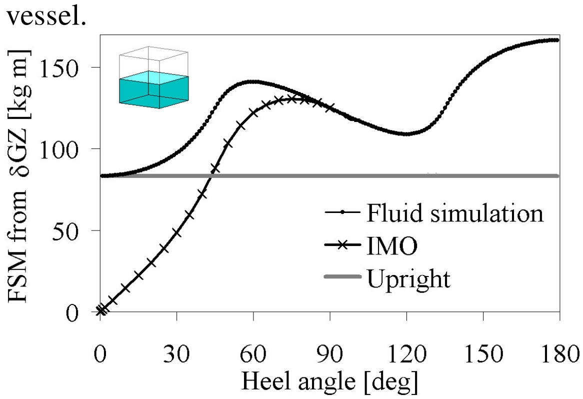

Figure 11: Effective FSM for 1m cube tank, 50% full of fluid, using different methods

This produces the correct upright GM and a reduction to GZ of $\delta\text{VCG}\sin(\phi)$. These corrections are only valid for small heel angles because variation of tank free surface with heel and the vertical shift of fluid CG in the tank are ignored.

Using a suitable hydrostatics program, it is easily possible to model the actual fluid shift in slack tanks and its effect on CG and GZ, which exactly takes into account the effects of *both* heel and trim. The correction to GM is then calculated from the actual tank free surface in the inclined condition.

IMO[8, §3.3] propose a correction method for computing the variation of FSM with heel angle. The correction is based on the tank's aspect ratio and block coefficient[8]. This is rather a convoluted approach with questionable accuracy, compared with calculating the actual fluid position in the tank. (A trivial computation with modern computers and software.) It is questionable why IMO bother with this method at all. See [19] for further analysis of the effect of tank free surfaces on static stability.

Figure 11 shows the simple case for a half-filled, 1m cubic tank. The variation of FSM with heel using the upright FSM correction, IMO approximation and exact variation derived from the change in solid and simulated fluid movement GZ curves (Equation 15) are all shown. It can be seen that both the upright and IMO approximations differ considerably from the true effect.

$$\text{FSM} = I_t \rho_t = \frac{\Delta\left(\text{GZ}_{\text{solid}} - \text{GZ}_{\text{fluid}}\right)}{\sin\phi} \qquad (15)$$

It is noted that the Royal Navy[15] recommend the use of modelling the actual fluid shift in slack tanks, since this accounts for changes in CG and GZ due to trim and heel.

Heeling due to wind pressure

Wind heeling arms should be based on actual heeled projected areas, local wind speeds and drag coefficients, rather than being approximated by a $\cos^2(\phi)$ heeling arm. This practice is used in [20, §3.2] but is not widely specified elsewhere.

[8] However, it is interesting to note that in the most simple case of a rectangular tank at zero heel, the FSM at zero heel is incorrect!

2.3 Guidance

It would be helpful if guidance in a number of areas were provided by the regulatory bodies. Some areas where guidance and clarification would be most welcome are listed below.

Some of the clearest and most comprehensive guidelines for calculation of stability criteria are given in [15].

Methods of calculation

In some cases it is appropriate to precisely define how some calculations should be preformed.

Probabilistic damage: Reference [21] is a good example, as is [22].

Intermediate stages of flooding: How is this defined when there is more than one damaged compartment? (Time domain rate of flow estimate? Intermediate percentage of final compartment flooding, e.g. 10% of final fluid level in each compartment? Some other method?)

Numerical modelling

Numerical implementation: Guidelines on the following would be helpful: required accuracy; discretisation of model; Simpson's vs. trapezoidal integration; number of sections. Other issues include: error in surface area calculation based on sections rather than triangulation.

Error estimates and accuracy: Analysis procedure should involve estimating errors and verifying that these are within acceptable limits. For example, convergence criteria for ∇, Δ and CG, CB.

Significant figures to be used for calculations, rounding effects. E.g. $\phi \leq 10°$; $\phi = 10.45°$ rounded to zero decimal places would pass, but rounded to one decimal place would not.

Possibly a suitable guide as to the required accuracy of the calculations would be the accuracy to which KG is known.

Terminology, nomenclature and accepted values

Where possible, references to standard terminology should be made. Where new terminology is introduced, this should be clearly defined. Some particular items that should be addressed are listed below:

Glossary of terms and jargon:

"initial metacentric height" – [8, §3.1.2.4]. Does this mean GM at zero heel or GM at equilibrium? What is meant if the vessel has an angle of list or loll?

Evaluation of "dynamic stability curve for dynamically supported vessels" – [7, Annex 6 §1.1.5]. How is this calculated, $\int GZ d\phi$, or a GZ curve calculated taking into account dynamic effects of forward speed?

"constant displacement" damage stab ility method – [3, II-1/B 8.6.1].

Hull measurements: Precise definitions of any hull measurements should be given. These should also cover unusual hullforms (which is normally when confusion arises). Ref [24] is a good example.

Physical constants: Required values for any physical constants used should be defined. These should be consistent with accepted standard values for these constants and should be applied consistently in the criteria.

3. CONCLUSIONS AND RECOMMENDATIONS

This paper has looked at a wide range of areas that affect consistent and accurate implementation of stability criteria. Whilst some may feel that this paper is too pedantic, it is important that stability criteria are applied consistently and it is with this in mind that this paper has been written. The key points that can improve the specification of static stability criteria are summarised below:

Clear and precise specification of criteria through the use of *flow charts* and *pseudo code*. Verification of criteria logic using *walk-through* techniques.

Efficient criteria definition using *symbolic notation* and *mathematical formulae* where possible. Mathematical formulae should be used to define all numerical calculations.

Diagrams to clarify criteria are appropriate in virtually all cases.

Criteria should never be open to interpretation; they should have *one, unambiguous*, meaning.

Transparent physics Where equations are used to represent physical phenomena, the physical process being modelled should be transparent from the form of the equation. Equations should employ *consistent units* (preferably SI, at least where the Metric system is used). Finally, accepted, standard values for *physical constants* (such as acceleration due to gravity) should be used.

Guidance for the evaluation of stability curves and the corresponding stability criteria should be given. These should also include *acceptable levels of accuracy* to which calculations should be made.

Terminology All *terms*, equation *parameters* and values for *constants* should be defined.

It is noted that most of the concerns raised in this paper are addressed in the RN documents [12, 15].

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