Developing a Shared Vision for Naval Stability Assessment.

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on behalf of the

Naval Stability Standards Working Group

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Abstract

Surface combatants are required to operate in conditions of high military threat and be capable of deployment to any area of conflict or crisis at any time. This requirement calls for the vessel and crew to be capable of safely contending with the full range of environmental conditions that may be encountered while pursuing their primary objective. Achieving and maintaining this capability is strongly influenced by the application of naval stability standards, many of which have a common origin, based on experiences from World War II and before. Although such standards have apparently served the navies admirably over many years, there are many reasons to question their limitations and applicability in the context of modern ship design and procurement. This paper addresses presents the efforts to date of the Naval Stability Standards Working Group to investigate the relationship between existing intact stability standards and capsize risk with respect to frigate forms.

1. Introduction

The maintenance of a maritime strategic capability demands the ability to rapidly deploy to any area of conflict or humanitarian crisis. The attainment and maintenance of this capability is strongly influenced by the application of naval stability standards. Over half a century of warship design and operational experience has lead many navies to adopt and apply very similar standards to design and life-cycle management of stability.

The stability standards have apparently served the navies admirably over the last forty years or so; they appear to have resulted in warship designs having a low level of capsize risk. Despite this apparently good service there are many reasons to investigate their validity and applicability, including:

- The level of safety assured by compliance with such standards is unknown.
- It is questionable whether the essentially static measures truly reflect the dynamic behaviour in extreme conditions.
- Modern naval hull forms are becoming increasingly less similar to those against which such standards were originally developed.

2. The Naval Stability Standards Working Group

The Co-operative Research Navies (CRNav) Dynamic Stability group was established in 1989 to undertake research into the underlying physical phenomena and characteristics of dynamic stability. The work has lead to the development and application of suitable dynamic stability simulation tools in pursuit of this objective. In light of the significant advances made by the group, the concerns with current stability standards could now be investigated in more detail.

The Naval Stability Standards Working Group (NSSWG) was formed in 1999 from the naval members of the CRNav group. The objective of the group is '*To develop a shared view on the future of naval stability assessment and develop a Naval Stability Standards Guidelines document which can be utilised by the participating navies at their discretion.*'

At a practical level, this involves identification of methods of relating stability criteria to risk. In the short-term, this means identification of level of safety extant in the current standards, focusing on the strengths and weaknesses of existing standards, and using a standard set of environmental conditions. In the long term, it means developing methodologies for assessing stability characteristics and practical limits for both design and life-cycle management.

3. Background

Currently, the stability of naval vessels is assessed using hydrostatic criteria and methodologies based on concepts that date back over two centuries. The hydrostatics-based standards (e.g.,[1], [2], [3], [4], [5] and [6]) have attempted to incorporate some consideration of dynamic issues through the application of gust factors to wind heeling levers, the use of roll back angles, and in some cases the consideration of the diminution of the righting arm when the vessel is balanced on a wave [3][4].

It is known that the static stability criteria values include some margin to account for the relatively crude nature of the calculation methods employed at the time of their inception. However, the exact rationale behind the determination of these factors and other approximations is no longer clear. It is this lack of clarity in conjunction with the apparently good service provided by such standards over the last forty years that has resulted in situations where strict compliance to a standard is demanded by the stability authority, with extremely small short-falls against even a single criterion considered unacceptable. At the same time, it is not unusual to see the same set of intact stability criteria being rigorously applied to vessels ranging from harbour tugs to aircraft carriers. It is assumed that this broad brush application also results from the lack of alternatives and the perception of good service rendered by the standard.

3.1 The Impact of Modern Ship Designs

Radical departures from conventional displacement designs are now becoming increasingly common. These include the application of 'tumble home', deep 'V' and wave-piercing bow forms, and the inclusion of more hull integrated watertight superstructure. There are also gradual changes such as the evolution of aft body design, with notably wider transom forms emerging in modern ship designs. It is questionable if the types of vessels against which Sarchin and Goldberg [7], for example, developed their criteria (two designs pre-dating WWII), exemplify their modern equivalents.

3.2 Changing Procurement

Increasingly, commercial standards are being adopted in place of defence standards, with the rationale being that they offer better value for money. This may indeed be true in many instances, provided the role and fitness for purpose of the commercial standards are fully compatible with the required naval capability. Understanding the level of safety inherent in the stability standard used – whether commercial or military – and how that level of safety varies with changes in the values of the constituent criteria (both individually and jointly) is required for rational and cost-effective assessment of the dynamic stability of a vessel.

3.3 Through Life Stability Management

While total compliance may be easily achievable at the start of a warship's life, maintaining full compliance becomes increasingly difficult later in life due to increases in KG and displacement. To facilitate a balanced and efficient approach to through-life stability management, it is imperative to know how "growth" affects the ability of the stability standard criteria's ability to indicate risk.

4. Approach

The work to date concentrates on investigating the level of safety associated with current standards. Figure 1 maps the process adopted. This approach uses an extensive series of FREDYN (v 8.2) time domain ship motion simulations coupled with probabilistic data describing the environment and the vessel operating parameters. An explanation of this time domain tool is given in reference [8].

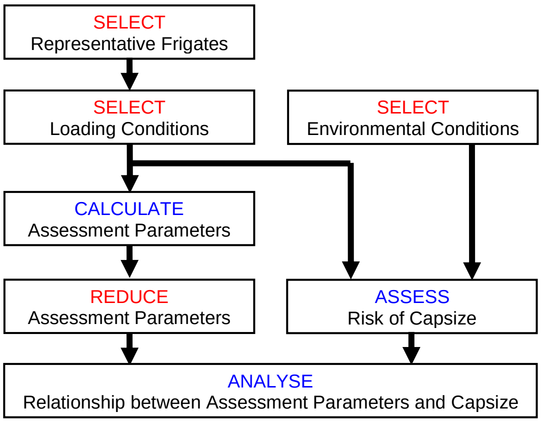

Figure 1 . Schematic view of approach adopted.

4.1 The Probabilistic Methodology

The probability of capsize is directly related to the probability of exceeding a critical roll angle: $P(\phi>\phi_{critical})$. The methodology employed in determining the probability of exceeding a critical roll angle in a particular loading condition is that described by McTaggart and de Kat [9]. Time domain simulations from FREDYN [8] are combined with probabilistic input data for the wave conditions and heading and speed of the ship via the programs Pcapref and Pcapsize, collectively known as the PCAP analysis [9]. The probability of exceeding the critical roll angle within a given time is given by:

$$P(\varphi > \varphi_{crit}) = \sum\sum\sum\sum p(V)p(\beta)p(H_{s,}T_p) \\ \times P(\varphi > \varphi_{crit}|V,\beta,H_s,T_p)$$

where V is the vessel's speed, β is the vessel's heading, H_s is the significant wave height, T_p is the peak wave period, and their joint probability density is $p(H_s,T_p)$. The final term is the conditional probability of exceeding the critical roll angle given a specific combination of speed, heading, and seaway conditions, $P(\phi > \phi_{critical}|V, \beta, H_s, T_p)$. It is determined from the FREDYN numerical simulations based on the maximum roll angles.

4.2 **Assumed Distributions**

4.2.1 Operational Conditions.

There are two basic operational probability distributions assumed. The first, $P(V)$, is a discretised distribution for calm water speeds derived from a representative naval frigate operational speed profile. The second is $P(\beta)$, a uniform distribution of headings. It is important to note that these operating distributions are independent of any operator action; there are no voluntary heading related speed reductions. Therefore the probability of exceeding the critical roll angle determined should be considered a baseline and reflects only the influence of the 'quasi-static' stability standards and hull form characteristics, and not the added influence of the good seamanship of the operator.

4.2.2 Environmental Conditions.

Intact capsize is clearly related to encountering a critical environment in manner such that one or a number of capsize mechanisms are invoked. The probability of exceeding the critical roll angle is therefore related to the probability of occurrence of a given environment (see Equation (1)). For the purposes of this study the Bales North Atlantic scattergram [10] was modified slightly [9] and used to define the probability distribution of unidirectional Bretschneider wave spectra.

Since the wind conditions are typically related to the wave conditions, an approximation was employed that assumed that winds were not only collinear with waves but related to the significant wave height via a linear relationship [9][10].

4.3 **The Frigates**

A total of twelve frigates representing all participant navies were selected. Table 1 shows the range of basic form parameters of the selected frigates. Each vessel is of a class that is either currently in service or that has seen significant periods of service. The designs can be considered to span at least the last 40 years. Some of the designs predate the inception of the Sarchin and Goldberg criteria, but were required to meet them later in life. The majority of the vessels were designed from the outset to meet either Sarchin and Goldberg or derivatives of that standard.

Table 1. Range of Basic form Parameters.

Parameter:	**Min**	**Max**
Displacement (tonnes) - Δ	2478	5490
Length at Waterline (m) - L	106.68	124.50
Beam at Waterline (m) - B	12.19	15.23
Draft (m) - T	3.81	5.33
Depth (m) - H	8.89	11.69
Vert. Center of Gravity (m) - KG	5.00	7.20
Metacentric Height (m) - GM	0.250	1.649
$C_B = \nabla/(L*B*T)$	0.440	0.548
$C_{WP} = A_{WP}/L*B$	0.718	0.810
$C_{VP} = C_B/C_{WP}$	0.593	0.698
L/B	7.873	9.160
KG/H	0.539	0.738
KG/B	0.404	0.497
KG/T	1.120	1.671
GM/B	0.020	0.121
A_{WP}: Waterplane Area ∇: Volumetric Displacement		

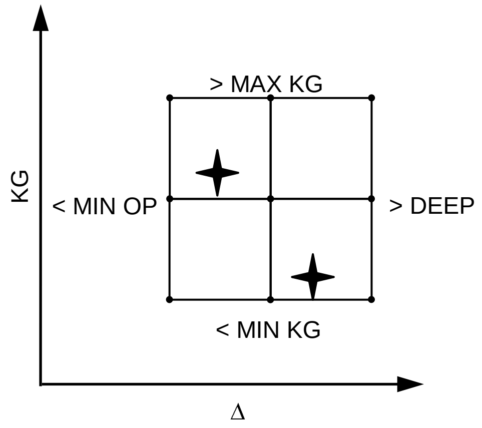

Figure 2 . The Conceptual Matrix of Loading Conditions.

Each navy selected a matrix (3 displacements x 3 KGs) of loading conditions for their vessels. The matrix bounded actual operating load conditions, whether they were driven by intact stability considerations or those of damage stability. The outer boundaries of the matrix were required to include combinations of KG and displacement that would fail a number of criteria in order to expose their associated probability of capsize (see Figure 2).

4.4 GZ Parameters

A set of ‘quasi-static’ measures that represent the majority of the criteria used to evaluate stability performance in the various naval and commercial standards was assessed. The selected GZ assessment parameters can be considered, or categorised, by the degree by which the dynamic environment is considered.

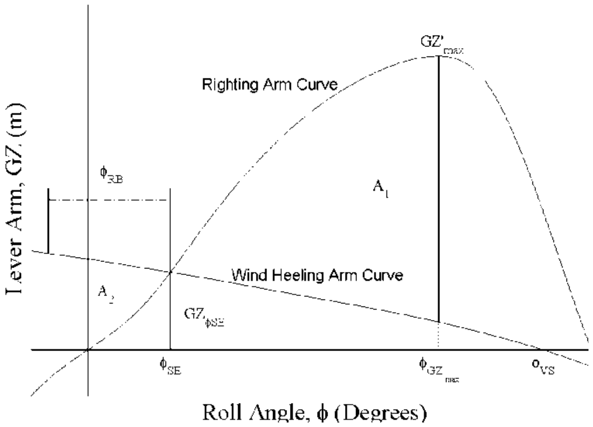

Figure 3. Typical GZ Curve with Wind Heeling

4.4.1 Fully Static

At the most basic level we have the fully static approach whereby the shape (Table 2) and area (Table 3) characteristics of the calm water righting curve are assessed.

Table 2 . Fully Static Shape Parameters.

Parameter	Description
GM	The metacentric height (fluid) (metres).
ϕ_{GZmax}	The angle at which the maximum righting lever arm occurs (degrees).
RPS	Range of positive stability (degrees).
GZ_{max}	The maximum righting lever arm (metres).
GZ_{30^o}	The righting lever arm at 30° (metres).

Table 3 . Fully Static Area Characteristic.

Parameter	Description
$A_{0^\circ-30^\circ}$	The area under the GZ curve between 0° and 30°. (m·rad)
$A_{0^\circ-40^\circ}$	The area under the GZ curve between 0° and 40°. (m·rad)
$A_{30^\circ-40^\circ}$	The area under the GZ curve between 30° and 40°. (m·rad)

A further set (Table 4) of fully static assessment parameters were derived by the CRN group [8] through an extensive series of FREDYN simulations of the dynamic behaviour of 30 frigate type hulls.

Table 4 . Further Parameters.

Parameter	Description
$A_{\phi_{SE}-\phi_{VS}}$	Total (dynamic stability) area under the GZ curve. (m rads)
C_{VP}	Vertical prismatic coefficient

4.4.2 Energy Balance

The set of terms in Table 5 assess the relationship between the characteristics of the calm water righting curve and an induced wind heeling curve. It is this set of criteria from Sarchin and Goldberg [7] that has formed the basis, or core, of the majority of current naval stability standards. In the original criteria and therefore DDS 079-1 [1] (the US navy standard), these parameters are related to the application of a 100 knot beam wind heeling lever.

Table 5 . Energy Balance Parameters.

Parameter	Description
ϕ_{SE}	The angle of intersection of the wind heeling lever with the GZ curve. (degrees)
$\frac{GZ_{\phi_{SE}}}{GZ_{\max}}$	The GZ at ϕ_{SE} divided by the maximum GZ.
A_1	The area between the GZ curve and the wind heeling lever between ϕ_{SE} and the down flooding angle. (m rad)
A_2	The area between the GZ curve and the wind heeling lever between ϕ_{SE} and a roll back angle of 25°. (m rad)
A_1 / A_2	The ratio of the A_1 to A_2

4.4.3 Wave Adjusted

The final set of parameters (Table 6) are those that, in place of the calm water righting curve, employ a righting curve determined from the vessel being balanced in a trough and/or on the crest of a wave of wavelength proportional to the vessel length. Such standards [4] also tend to apply an energy balance assessment.

Table 6 . Wave Adjusted Parameters.

Parameter	Description
$GZ'_{\phi REF}$	The residual righting lever arm at ϕ_{REF} with a beam wind.
$RRPS$	The residual range of positive stability.
$A'_{\phi SE-\phi VS}$	The residual area under the GZ curve, above the wind heeling lever arm curve, and above the $GZ = 0$ axis.

4.4.4 Form Parameters

A number of hull form parameters were also selected for inclusion in the analysis in order to allow the differentiation between traditional and more modern forms. These include basic particulars, form coefficients, and characteristic ratios.

4.5 Performance Assessment

A total of 124 ship loading conditions representing 12 ships were investigated. It is to be noted that all analysis undertaken assumes that superstructure is included with respect to the determination of the wind heeling lever only. It was excluded from consideration with respect to buoyancy since it was considered that its inclusion would obfuscate the important issues of hull geometry.

The above parameters were determined for each ship loading condition. A comprehensive regression analysis was undertaken, the objective of which is to allow the determination of the ability of measures, either individually or in combination, to reflect dynamic stability.

4.6 Collation of ‘Quasi-Static’ and Probabilistic Data

The outputs from PCAPSIZE and FREDYN, along with externally-calculated, wave-balanced GZ curves and the North Atlantic scattergram information, are post processed using MATLAB.

4.6.1 Conditional Probabilities

In addition to the probability of exceeding the critical roll angle within one hour under all sea conditions, the probabilities of exceeding the critical roll angle within one hour given a specific sea state were also calculated. The classic sea state definitions [11] are used with the selected (North Atlantic) scattergram [10]. These probabilities can be further discriminated by ship speed and/or heading, allowing the identification of significant speed-seaway or heading-seaway combinations.

Further, in order to gain an insight into those combinations that were most likely to be the cause of extreme dynamic events, an approach was employed that determined those speeds, headings, and wave parameters that were associated with highest (hourly) conditional probability given capsize. The parameters exposed in this manner are as follows:

- Significant wave height (m).
- Peak wave period (s).
- Nominal wave steepness – H_s/λ.
- Speed (knots).
- Heading (degs).

5. General Results

The parameters associated with current stability standards show mixed results. The results of this study indicate reasonable relationships, in many instances, between risk of exceeding the critical angle and those GZ parameters that are employed in current naval standards. This tends to validate the use of these parameters. The variation in relative ranking of the parameters for each ship, however, would indicate that few if any of the parameters can be used across all ships.

In general, the van Harpen criteria (wave balanced GZ curves) provided stronger results than the nominal (no wave balancing) GZ curve parameters.

It should also be noted that the form parameters are less useful than GZ parameters for indicating the risk of extreme motion. This may be because risk of capsize is related to geometry and inertial properties of the ship, and the latter are not reflected in the form parameters.

The study has also shown that, on an individual parameter basis, many naval standards employ criteria, or measures, that are superfluous or redundant due to collinearity. Additionally, although many standard parameters show high linear correlation with probability of extreme motions, there are other parameters, not currently used in the standards, that have higher correlation.

When the ships are considered as a group, none of the standard parameters have a strong correlation with the probability of exceeding the critical roll angle.

6. Discussion

Loading conditions used in the present study do not necessarily reflect real working conditions for the ships involved. The loading conditions used are intended to give broad indication of risk of capsize, and in some cases may even be outside the bounds of proper and normal operation of the ship.

There has been some debate over the probability values determined in the PCAP analysis (Pcapref and Pcapsize). It is generally felt that the PCAP method over-predicts capsize in the long term (e.g., one year). Although the issue is primarily apparent in the long-term probabilities, the debate has fostered a desire to look at alternative probability methods. It has also lowered the confidence in the current probability values.

FREDYN 8.2 and the inherent assumptions in the strip theory employed therein, may cause inaccuracies in some of the simulation results, also affecting the probability results.

Taken together, this means that the regression analysis results cannot be taken to be accurate, and thus the relative strengths and weaknesses of GZ parameters for indicating risk of exceeding the critical roll angle are not strictly valid. The methodology, however, is a reasonable process, and further work is waranted.

7. Recommendations

Capsize risks determined on the basis of FREDYN version 8.2 simulations should be used in a relative manner, for assessing the relevance of ship stability parameters. Absolute values of capsize risks are likely to be inaccurate due to limitations in FREDYN 8.2 accuracy and some uncertainty in the probability methodology employed.

The investigation into the level of risk accepted by using current naval standards should use a FREDYN version 9.8 or higher where the approach based on the long wave assumption is replaced by a three-dimensional panel methodology for the determination of Froude-Krylov forces. Furthermore, the panel method for determination of the wave radiation and diffraction forces should be used.

A selected number of the original ship set should be chosen for further simulations with their actual operational minimum and maximum loading conditions and an intermediate 50% condition. In order that they truly reflect accepted levels of capsize risk, said cases should be, where practically possible, those used in practice, whether driven by intact or by damage stability.

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