Approaches for Evaluating Dynamic Stability in Design

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ABSTRACT

There are many ways of treating dynamic stability. No single approach is always best, but must be defined relative to each design and each yields a fidelity proportionate to resources and technological maturity. During the ship design process choices must be made that balance the approach within a wide trade space encompassing ship design characteristics, operational doctrine, technical risk management, operational safety, cost and schedule. Existing static approaches do not directly account for ship dynamics. There is a clear need to develop a frame work for integration of technical approaches into the ship design/acquisition process. The objective of this paper is to define a basis for outlining the range of intact dynamic stability methodologies that can be employed to naval ship design that address dynamic stability in such a way as to minimize technical and safety risks in an economical manner. The paper summarizes ongoing work by the Naval Stability Standards Working Group (NSSWG), and outlines relevant technical approaches suitable for employment on naval ship designs from preliminary/concept design stages through to operator guidance.

Keywords: *Dynamic Stability, Risk Management, Naval Stability Standards Working Group, Static Stability, Probabilistic, Empirical, Criteria*

[1] The opinions expressed in this paper are those of the author and not necessarily those of the Naval Sea Systems Command or the United States Navy.

Background

There is no single approach that is best for addressing dynamic stability as part of a ship design effort. Many factors encompassing design characteristics, technical maturity, methodology, resources, cost, and safety must be balanced to find the most appropriate treatment. Risk management techniques are well suited to defining the most cost-effective approach for treating dynamic stability in the design process.

The Naval Stability Standards Working Group (NSSWG) has worked to define these issues over a number of years. The NSSWG has representatives from Canada, Great Britain, Australia, France, United States, and the Netherlands. The development of specific methodologies addressing dynamic stability has been in the work plan for that group since its inception. As efforts have progressed, it has become increasingly clear that a wide range of approaches would have to be defined to meet all the requirements of every Navy.

Historically, dynamic stability has been represented by static measures including GZ area margins, and variation of GZ on prescribed waves, and other empirical rules. This approach is relatively simple and the least onerous for cost and schedule. Treatment of dynamic stability based on vessel dynamic response is still in the research and development stages. Even so, there are many approaches that can yield useful information, but no means to knit them into a coherent process. Thus there is a clear need to develop a framework for integration of intact dynamic stability assessment into the ship design/acquisition process.

NSSWG Definitions for Intact Dynamic Stability

There are three principle factors affecting dynamic stability:

1. The static restoring moment
2. The dynamic response (including damping and added moment of inertia)
3. The hydrodynamic forces on the vessel from waves/wind

Estimating and understanding these three factors and their relationship to stability failure modes, and developing appropriate safety margins governing allowable KG and Displacement for the ship design forms the basis for risk control in the acquisition process.

The Naval Stability Standards Working Group (NSSWG) uses the categories below as the basis for stability discussion.

<u>Static Capsize</u> **-** A static capsize may occur suddenly when a disturbance is encountered that is sufficient to overcome the ship's inherent ability to remain in an equilibrium state at or near upright. The event has traditionally been characterized by parameters which relate to a reduction in the righting arm lever (or GZ curve) which represents the static stability of a vessel independent of forward speed and time. Conditions that could lead to static capsize include improper loading, lifting or topside icing (increasing VCG); towing, wind, or load shift, (increasing heel angle); trapped fluids on deck (increasing free surface effects); and loss of watertight integrity (loss of buoyancy/water plane area).

Dynamic Capsize - A Dynamic Capsize is defined as a very large amplitude roll caused principally by seaway and wind excitation on a moving vessel or as a function of time. This wind and wave action may lead to equipment damage, personnel injury, loss of system functionality and/or weather-tight/watertight integrity from which the ship is unable to maintain its intact upright state. A dynamic capsize is characterized as a time-dependent event occurring in unrestrained 6 degrees of freedom motion. The loss of dynamic stability may occur under a variety of conditions (intact or damaged) once the forcing function exceeds the available restoring force.

Large Amplitude Motions - Large amplitude motions are a part of dynamic stability considerations and include large roll angles, “knock downs”, yaw, lateral accelerations, pitch, etc. These motions are caused by the dynamics of the vessel as it is excited by wind and seaway. Large amplitude motions in the non-linear range tend to be in the range of roll angles where the GZ curve is softening but still able to provide sufficient restoring force to resist capsize. Dynamic capsize occurs once roll has reached an extreme point on the GZ Curve, and restoring force can no longer bring the ship back to an upright position.

Static Stability Standards and Practice

Navies assess stability using static methodologies. Existing stability criteria are a composite based around compliance with specific safety elements. In the case of the DDS-079-1 these are the following:

Principal Safety Elements in DDS-079 Criteria

Intact Ship

- Beam Winds Combined With Rolling
- Lifting of Heavy Weights
- Crowding of Passengers to One Side
- High Speed Turning
- Topside Icing

Damaged Ship

- Stranding Involving Moderate Flooding
- Bow Collision
- Battle Damage Involving Extensive Flooding

Flooded Ship

- Beam Winds Combined With Rolling
- Progressive Flooding

Each of the safety elements listed above is defined through various criteria. Naval ships must comply with the most restrictive limit resulting from the application of several criteria such as beam wind, passenger crowding, icing, high speed turning, and damage stability [1].

In general a range of loading conditions is bounded by the envelope established by the governing limits. This limit becomes a composite curve as shown in the Figure 1 below. An acceptable loading condition is one which the KG is below the limiting curve.

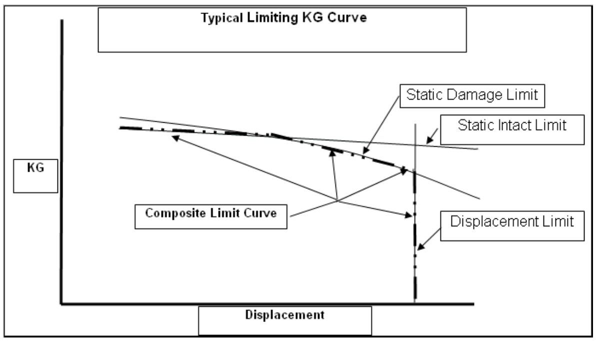

Figure 1 Typical Limiting KG Curve and Components

Historically static stability criteria do not directly address dynamic stability and large amplitude motion; although it is generally acknowledged that the margin of safety for seaway motions is included as the A1/A2 area ratio and roll back angle. The historical record supports the adequacy of this approach. However, the adequacy of such factors of safety using static methods may not be adequate when applied to hull forms with novel features. Consequently there is a need to integrate dynamic stability methodologies into the criteria stability criteria.

Intact Dynamic Stability Assessment Methodologies

There are many ways to categorize dynamic stability assessment methodologies, the definitions of which are still under discussion. Discussion of these methodologies is best handled in the context of a risk management process.

The starting point is to form a lexicon by which everybody involved in the risk management process can talk from the same common understanding.

One example is provided in Belenky, DeKat, Umeda [2]. Four basic approaches were described which can be summarized as: probabilistic performance-based criterion, deterministic performance-based criterion, probabilistic parametric criterion, and deterministic parametric criterion.

Within the NSSWG, ongoing efforts have been based around a categorization of dynamic stability methodologies as “Empirically Based Rules”, “Rules Based on Probabilistic Dynamic Approaches”, “Direct Probabilistic Assessment” and “Relative Probabilistic Based Assessment. Although these don’t agree exactly with those of Belenky, DeKat, Umeda, they are complimentary and generally convey the similar concepts based on naval ship stability practices. The NSSWG categorizations are defined as follows:

1. Empirically Based Rules - Development of criteria based on a set of "rules" established from a study of hull form characteristics using engineering principles based on evaluation of design characteristics such as the GZ curve. A suitable body of ships is assessed to form the basis for establishing criteria. The resultant criteria are typically binary and expressed as "pass/fail" and will have factors of safety to account for physical properties which can not be fully modeled. Typically static stability criteria fall into this group. This rules-based methodology is largely based on heuristics – experience with previous designs. It may not be readily applicable to evolutionary or novel designs.

2. Rules Based on Probabilistic Dynamic Approaches - A probabilistic study for a series of ship types is used as the basis to determine suitable design characteristics to be used as part of dynamic stability criteria. Design characteristics are identified as being the most closely correlated to capsize probability for the type of ship assessed. A suitable criterion is then derived for the design characteristics identified which provides a reasonable mitigation of capsize risk. The NSSWG has been actively developing this approach as reported in Perrault et al. [3]

3.Direct Probabilistic Assessment - Direct determination of a capsize probability for seaway environments using a validated simulation tool and/or a series of model tests. The resultant capsize probability is assessed as acceptable or unacceptable based on some risk level established for specific seaway operations or for lifetime risk. Some risk comparison can be made using tools such as Farmer's curves (Ayyub [4]) to establish acceptable risk levels in comparison to other occupation or modes of transportation. In Peters [5] a discussion is provided on approaches to establish acceptable risk levels for naval frigates. The authors conclude that an acceptable risk of capsize for a naval frigate on an annual basis could be approximately $1x10^{-4}$.

4. Relative Probabilistic Assessment - A probability index is established based on comparisons of the design ship capsize probability to a known baseline ship operating in identical conditions. The resultant probability index is assessed as acceptable or unacceptable based on a relative measure against the baseline. A probability index must be developed for the baseline ship as part of the comparison. The assessment is done for the baseline ship when in compliance with an existing static criteria. The index must not only have the baseline determined by the existing ship, but must have a rationally derived scale in order to provide meaningful comparisons between the existing ship and the design ship. Note that the baseline ship will have been assessed by one of the above methods by necessity.

The Intact Dynamic Stability "Tool Kit"

The categories defined above provide the building blocks from which integration of dynamic stability into the design process can begin. The integration is centered on developing a measure of the risks associated with the proposed hull form, definition of the tools available, their fidelity and the resources necessary to use them. Thus a "Tool Kit" of technical approaches is developed. Each tool in the kit has a fidelity and cost associated with its application.

The dynamic stability risk characterization of the hull form should be made through a set of measures. The characterization can be made qualitatively at initial stages but should move into development of quantitative (e.g., probabilistic) measures as the design develops. These risk measures can be broadly characterized as follows.

- Heuristic/Historical Experience (Qualitative)
- Early design assessment/rules of thumb developed from simple design parameters. (Qualitative/Quantitative)
- Simulation and/or Test Data (Quantitative)

Determination of the appropriate approach might be accomplished in the context of a risk assessment. The "tool kit" represents the means by which hazards and consequences can be quantified and managed.

For example, the use of vulnerability criteria as proposed by Bassler [6] very good starting point establishing both the early stage risk and mitigation through the level 1 and level 2 vulnerability criteria.

The risk characterization should be revisited several times as the design matures.

Measures for risk mitigation must also be considered along with the risk. In a formal sense risk may be thought of as fitting into the following. Ayyub [4].

- Risk Reduction or Elimination
- Risk Transfer
- Risk Avoidance
- Risk Absorbance

For dynamic stability, some of the most prominent mitigation measures can be generally though of as follows:

- Criteria (Risk Reduction)
- Operational Restrictions (Risk Avoidance)
- Operator Guidance (Risk Avoidance)
- Training (Risk Avoidance)

The addition of training and operator guidance specifically to reduce or avoid a dynamic stability risk is an attractive option. In general operator guidance can be as follows:

- Simple rules of thumb compiled from historical experience/data
- Operator guidance based on dynamic stability assessment to produce either polar plots and/or rules of thumb based on specific loading conditions, speeds, headings and environmental conditions, and vulnerabilities.
- Training involving real time simulation and classroom lectures.

Each has an associated cost, fidelity and effectiveness.

Process for Dynamic Stability Risk Characterization

In broad terms there are several types of risk. Also interrelated are the risks associated with technological maturity and programmatic costs.

Early in a design it may not be possible to develop a quantitative risk assessment for dynamic stability due to a lack of available data. Decisions may have to be made based on judgment, past experience and historical evidence. For some designs this may be sufficient and the process can end there with the application of static criteria. More radical hull form designs may have to be approached with the object of developing a quantitative risk assessment.

The quantitative risk assessment should consider several factors some of which are outlined below.

1. Dynamic Stability Risk Inherent in the Hull Form
    a. *Quantification of Risk*
        i. *Data*
        ii. *Availability and Reliability of Data*
        iii. *Historical Experience*
    b. *Maturity of Technology*
        i. *'Measures' of Risk; i.e., Criteria*
        ii. *Fidelity of Risk Assessment*
    c. *Resource Requirement*
        i. *Cost of R&D*
        ii. *Cost of Implementing*
2. Measures for Risk Mitigation
    a. *Criteria*
    b. *Operator Guidance*
    c. *Operational Limits*
    d. *Design Changes*

A technical risk assessment team should be established. This team would be composed of a group of subject matter experts covering stability, seakeeping, analytical tools, model testing and ship handling.

The team starts by attempting to quantify the technical risk associated with the hull form. The risk is estimated based on availability of data; historical, analytical or model testing. Lack of available data ("Unknown") for an informed judgment could make the risk high. Other sources of data and their fidelity are evaluated accordingly. Mitigations are also identified. The process is iterated until the risk is considered to be in an acceptable range (Figure 2 below)

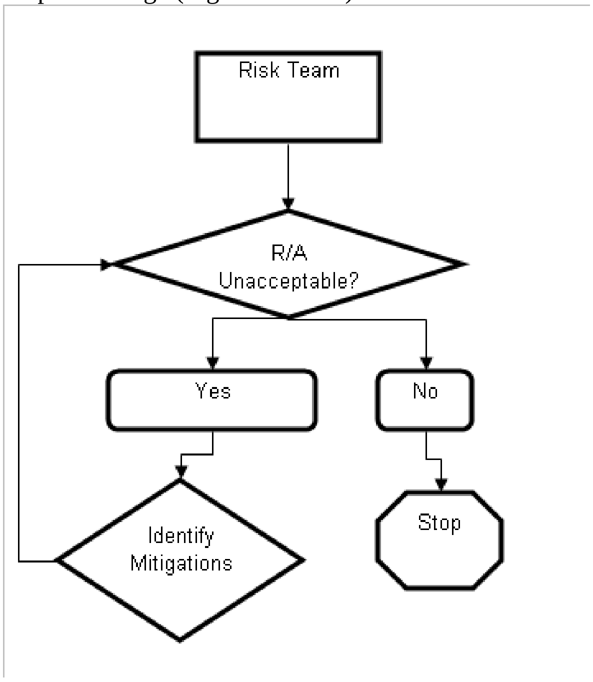

Figure 2 Dynamic Stability Risk Assessment Process

The results of an initial risk estimate for a hull form "A" might look like figure 3. In this case a review of available data suggests that there is a "likelihood" of a "critical" dynamic stability failure in a specified operational time frame.

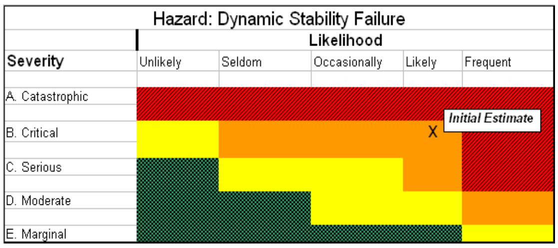

Figure 3 Initial Hull Form Risk Assessment

It is also important to consider available technology and its fidelity or 'maturity' as part of this process. The available "tools" may be categorized as follows:

- Heuristics/historical studies
- Simulation-based methods
- Systematic Model testing in regular, unidirectional waves to develop an index
- Direct results of (extensive) model testing in irregular, multidirectional waves

The team must answer the question "how much do I believe the data and what is the cost impact"? Table 1 below illustrates how a series of methodologies or "tools" might be ranked for fidelity and cost in developing the risk of dynamic stability failure. Actual metrics would have to be developed for a ranking process.

Hull Form A Notional Tool Fidelity for Risk Estimation		
Method	Effectiveness	Cost
1	Limited	Less
2	Medium	Moderate - High
3	High	High
4	Very High	Very High

1 - Heuristics/Historical Studies
2 - Simulation Based Methods
3 - Systematic Regular Wave Tests
4 - Extensive Random Wave Testing

Table 1 Notional Tool Fidelity Ranking

The process of developing the data required to assess the dynamic stability risk may require a considerable outlay of resources involving personnel and lead time and funding. This should be assessed early on in the design when it is still possible to make hull form changes. The cost of developing the required methodology to refine the risk estimate needs to be addressed and balanced against the benefit of the hull form.

Mitigations should be defined and addressed immediately. The mitigations are defined such that the severity and probability of the risk may be controlled or reduced. The mitigations are also developed based on an understanding of the nature and the magnitude of the assessed risk for the hull form.

In many cases the outcome should simply be a validation of existing practice. For instance an assessment of a conventional hull form 'should' confirm the adequacy of existing stability techniques in managing the risk. In other cases, the risk assessment should serve as a warning flag of potential dynamic stability problems and provide a basis from which to develop an outline of the technical and programmatic challenges associated with addressing dynamic stability for the proposed design. Cost benefit analysis should be developed for the decision process.

Specific risk management techniques for ranking dynamic stability methods and mitigations should be developed according to the needs of the Navy or organization conducting the assessment. There are many references covering application of specific risk management 'tools'. A good example of the application of risk management to submarine weight engineering is provided by Tellet [7]. Similar approaches could be adapted to dynamic stability risk management.

Example Approaches for Defining Dynamic Stability Risk Mitigation

1. Early design assessment/rules of thumb developed from simple design parameters **-** This approach uses simple design parameters resulting from studies of static stability characteristics on waves, or model test/simulation data using one of the criteria-based approaches. Results may include rules of thumb for distribution of waterplane area, vertical prismatic coefficient, specifications for righting energy and minimum positive GZ. The results are used for guidance during design but not as specific criteria to set the displacement/KG curve. The displacement/KG curve is developed based solely on compliance with unmodified intact static/ damage static criteria in the traditional manner. This approach is fairly easy to implement providing sufficient studies have been conducted to provide a basis for the rules of thumb. While it can provide design guidance, these approaches are most useful in highlighting design characteristics which may be problematic from a dynamic stability perspective and will require more rigorous investigation. An example of the structure of such an approach can be found in Belenky [8].

2. Integrate dynamic stability into existing stability criteria to produce a unique dynamic stability limit or modified static stability limit. - In this approach dynamic stability becomes one of the safety elements in the existing criteria. This results in a more formalized process. Consequently some strategy to augment existing criteria must be found by identifying the safety element associated most closely associated with dynamic stability. That safety element can be modified by one of the four methodologies defined above to address dynamic stability. This then produces a new dynamic stability limit as a function of mass properties and KG. This new limit is used in combination with the intact, damage and other limits to set the displacement/KG limit for the operation of the ship.

It is interesting to note that the watertight/weather tight boundaries used for static stability assessments may not directly coincide with the weather deck of the ship. This can make integration of dynamic stability/ static stability limits problematic as the buoyant volume and restoring force and wave forcing used in large amplitude motions may not match that of the static criteria limits.

In the modified criteria, mass properties are maintained within the resulting envelope throughout service life as shown in Figure 4 below.

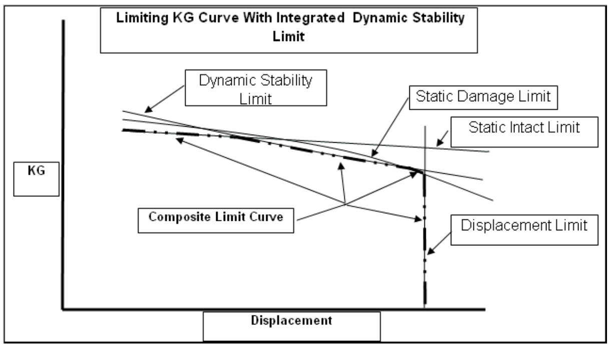

Figure 4 Typical Limiting KG Curve with Integrated Dynamic Stability Limit

The complexity of the criteria in both definition and implementation is directly related to the methodology. Criteria-based approaches using design parameters, and GZ curve assessment techniques are more readily implemented and socialized throughout the design community, although they may not provide sufficient flexibility to address designs outside of the data base from which they were developed.

Novel hull forms will rely more heavily on relative probabilistic and direct probabilistic approaches as they are likely outside of any data base used for development of criteria. [9] There may also be methodologies based on a 'simplified deterministic waves approach". [6] These approaches provide for the greatest flexibility but are the most challenging to implement as criteria and enforce through out the acquisition process. The cost associated with these approaches can be daunting as extensive engineering and risk studies are necessary to demonstrate compliance.
The complexity of the approach chosen bears a direct relationship to the perceived risk and/or the factors of safety assigned. Table 2 illustrates a notional ranking for effectiveness of criteria in mitigating dynamic stability risk on a design for a notional hull form "A".

Hull Form A

Notional Criteria* Fidelity for Risk Mitigation

Method	Effectiveness	Cost
1	Limited	Less
2	Medium	Moderate - High
3	High	High
4	Medium-High	High

1 - Emperically Based Rules
2 - Rules Based on Probabilistic Dynamic Approaches
3 - Direct Probabilistic Assessment
4 - Relative Probabilistic Assessment

* Criteria using mitigation method 2

Table 2 Notional Criteria Ranking

3. Operator guidance based on dynamic stability assessment to produce either polar plots and/or rules of thumb based on specific loading conditions, speeds, headings and environmental conditions and/or Operability Envelopes - Another complimentary approach is to provide operator guidance as a means of risk mitigation for dynamic stability. Dynamic Stability operator guidance may be as simple as rules of thumb or it may involve a direct probabilistic assessment of dynamic capsize risk or large amplitude motions risk. Key motion parameters are identified and assessed for specific seaway environments, and limits are imposed based on application of risk methodologies. These limits are displayed as polar plots and form the basis for operational guidance to the ship handler.

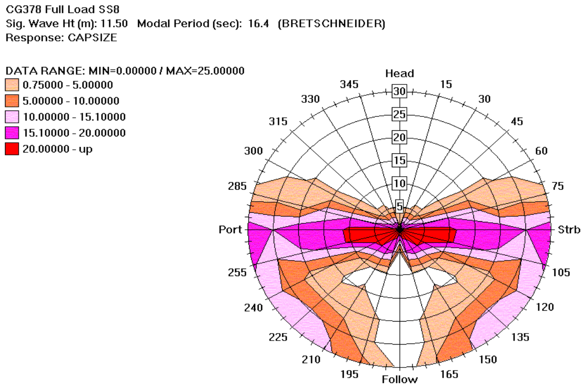

Figure 5 Example Capsize Risk Polar Plot

In some cases when operator guidance is provided, it may be considered sufficient to minimize dynamic stability risk without new dynamic stability criteria. Simulation or model testing maybe required developing the appropriate polar plots. Some training and socialization is required to implement the operator guidance.

There appears to be an unquantified margin between safe operability and acceptable intact stability implied by current standards. In many cases, safe operability is determined by practice of good seamanship. In spite of the margin being unquantified, it is relatively easy to determine operability envelopes and specify them as part of an acquisition. Dynamic stability events occurring inside the operability envelope would be expected to have a very low probability of occurrence and this may be checked by simulation and/or model testing as required and supplemented by existing operability criteria (e.g., IMO/SLF 49). The operability approach doesn't rely on an annual or lifetime risk which is likely to be non-discriminate (i.e. in all headings, sea states, etc) without the influence of the operator or operability factors, and therefore very high.

In development of the operability envelope approach three questions should be addressed:

- What is tolerable from a corporate and societal viewpoint?
- What inherent level of risk is associated with current standards?
- What level of risk is inherent in good ship-handling (reaction to cues)?

Training for the crew should be developed which addresses the use of the operator guidance system, identification of cues, and how to identify and manage risk when in heavy weather. Shaw[10] The Operator Guidance and Training Working Group (OGTWG) is a group of naval operators convened by invitation of the NSSWG to provide input and insight into the issues involved with operating ships in high seas. Work done to date by the OGTWG has identified appropriate class room and simulator curricula associated with specific bridge team positions.

Table below lists a notional ranking of operator guidance/operational limits that may be identified for the risk assessment.

Hull Form A Notional OG/SOE Fidelity for Risk Mitigation		
Method	Effectiveness	Cost
1	Limited	Less
2	Medium	Moderate - High
3	Medium-High	High
5	High	Low-Moderate

1 - Emperically Based Rules of Thumb
2 - Polar Plots/Rules of Thumb
3 - Polar Plots/Training
4 - SOE Restrictions

Table 3 Operator Guidance SOE Ranking

4. Changes to Hull Form - If approached early in the design the most effective mitigation may be the identification of specific design changes that reduce the dynamic stability risk. However it may not be possible to make sufficient geometry changes or mass property changes and still meet requirements for the overall design. In that case some combination of approaches to dynamic stability risk mitigation should be identified that includes hull form changes to the extent possible, coupled with operator guidance, operational limits and criteria.

Final Hull Form Risk Ranking

Finally, a combination of options assembled from the tables could be assessed for mitigation effectiveness and cost. The best combination will be the one that provides the most effective risk reductions and least cost, taking into account the limitations on both these measures.

Risk reduction/cost plots can be used as a tool to select the best combination of options. For notional "Hull Form A", it could be determined that the best options are achieved using a combination of the following

- Rules Based Probabilistic Dynamic Approaches
- Polar Plots/Rules of Thumb

It may take several iterations to finally get to an acceptable risk for the hull form as shown in Figure 6 below.

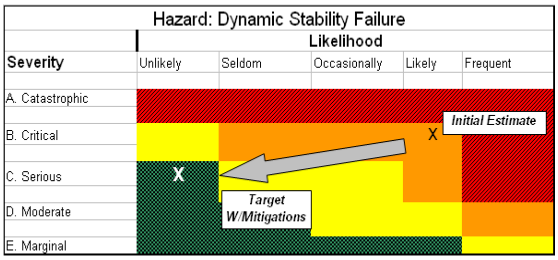

Figure 6 Estimated Reduction in Hull Form Risk After Mitigation

Conclusion

The process of developing rational approaches for consideration of dynamic stability is in its infancy. Through intelligent use of analytical tools, test data, and historical evidence it is possible to establish a rational process to manage and reduce the risk of a dynamic stability event occurring at sea. The tools employed to accomplish this should be used carefully and with an eye to economy without sacrificing safety. Risk management techniques provide a rational framework to accomplish this goal. Although not addressed in this paper, similar processes can be tailored to damage dynamic stability.

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References

1. Alman, P.R., Minnick, P.V., Sheinberg, R., Thomas, W. L. III; "Dynamic Capsize Vulnerability: Reducing the Hidden Operational Risk", SNAME Transactions, Society of Naval Architects and Marine Engineers, Vol. 107, New York, 1999.
2. Belenky, DeKat, Umeda; "Toward Performance-Based Criteria for Intact Stability",SNAME 2008
3. Perrault, Hughes, Marshall; "Developing a Shared Vision for Naval Stability Assessment", STAB 2010
4. Ayyub; "Risk Analysis in Engineering and Economics", pages 95-109, 2003, Chapman and Hall/CRC

5. Peters; "Tolerable Risk of Capsize of a Naval Vessel", STAB 2010
6. Bassler, Belenky, Bulian, Franscescutto, Spyrou, Umeda; "A review of Available Methods for Application to Second Level Vulnerability Criteria", STAB 2009
7. Tellet, Cimino; "Marine Vehicle Weight Engineering", pp231-245, 2007, SAWE
8. Belenky, Bassler, Spyrou; "Dynamic Stability Assessment in Early Stage Ship Design", STAB 2009
9. Ayyub, Kaminsky, Alman, Engle, Campbell, Thomas; "Assessing the Probability of the Dynamic Capsizing of Vessels", Journal of Ship Research, SNAME, December 2006, 50(4), 289-310
10. Shaw, CDR, (USCG); "Practical Experience and Operational Requirements for Onboard Risk Management Under Marginal Stability Conditions", STAB 2001